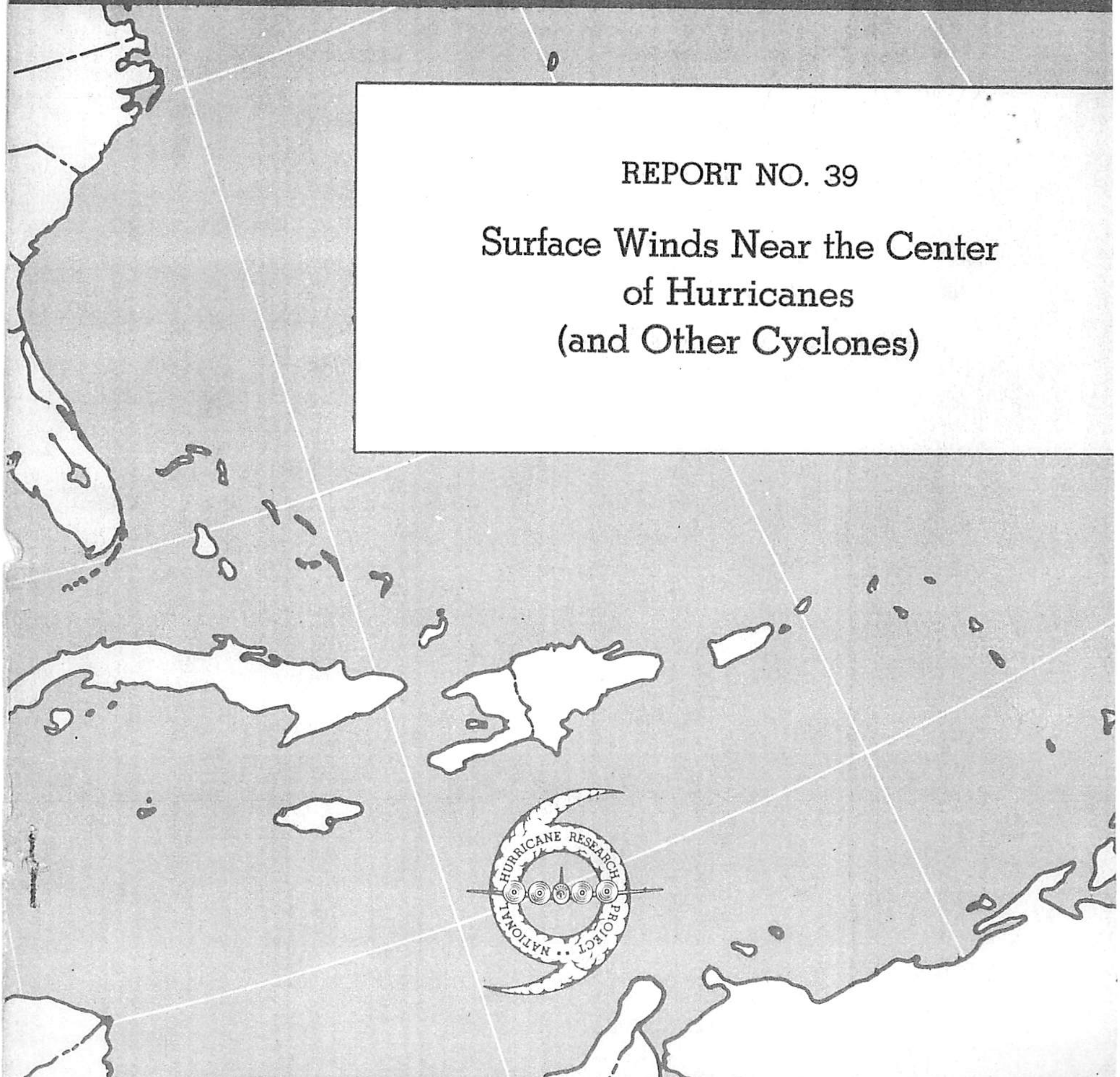
NATIONAL HURRICANE RESEARCH PROJECT

REPORT NO. 39

Surface Winds Near the Center of Hurricanes (and Other Cyclones)



U. S. DEPARTMENT OF COMMERCE
Frederick H. Mueller, Secretary
WEATHER BUREAU
F. W. Reichelderfer, Chief

NATIONAL HURRICANE RESEARCH PROJECT

REPORT NO. 39

Surface Winds Near the Center of Hurricanes (and Other Cyclones)

by

Howard E. Graham and Georgina N. Hudson
Hydrometeorological Section, Hydrologic Services Division, U. S. Weather Bureau

A partial report of work accomplished under P.L. 71, 84th Congress

Washington, D. C.
September 1960

NATIONAL HURRICANE RESEARCH PROJECT REPORTS

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

No. 1. Objectives and basic design of the NHRP. March 1956.
No. 2. Numerical weather prediction of hurricane motion. July 1956.
Supplement: Error analysis of prognostic 500-mb. maps made for numerical weather prediction of hurricane motion. March 1957.
No. 3. Rainfall associated with hurricanes. July 1956.
No. 4. Some problems involved in the study of storm surges. December 1956.
No. 5. Survey of meteorological factors pertinent to reduction of loss of life and property in hurricane situations. March 1957.
No. 6. A mean atmosphere for the West Indies area. May 1957.
No. 7. An index of tide gages and tide gage records for the Atlantic and Gulf coasts of the United States. May 1957.
No. 8. Part I. Hurricanes and the sea surface temperature field.
Part II. The exchange of energy between the sea and the atmosphere in relation to hurricane behavior. June 1957.
No. 9. Seasonal variations in the frequency of North Atlantic tropical cyclones related to the general circulation. July 1957.
No.10. Estimating central pressure of tropical cyclones from aircraft data. August 1957.
No.11. Instrumentation of National Hurricane Research Project aircraft. August 1957.
No.12. Studies of hurricane spiral bands as observed on radar. September 1957.
No.13. Mean soundings for the hurricane eye. September 1957.
No.14. On the maximum intensity of hurricanes. December 1957.
No.15. The three-dimensional wind structure around a tropical cyclone. January 1958.
No.16. Modification of hurricanes through cloud seeding. May 1958.
No.17. Analysis of tropical storm Frieda, 1957. A preliminary report. June 1958.
No.18. The use of mean layer winds as a hurricane steering mechanism. June 1958.
No.19. Further examination of the balance of angular momentum in the mature hurricane. July 1958.
No.20. On the energetics of the mature hurricane and other rotating wind systems. July 1958.
No.21. Formation of tropical storms related to anomalies of the long-period mean circulation. September 1958.
No.22. On production of kinetic energy from condensation heating. October 1958.
No.23. Hurricane Audrey storm tide. October 1958.
No.24. Details of circulation in the high energy core of hurricane Carrie. November 1958.
No.25. Distribution of surface friction in hurricanes. November 1958.
No.26. A note on the origin of hurricane radar spiral bands and the echoes which form them. February 1959.
No.27. Proceedings of the Board of Review and Conference on Research Progress. March 1959.
No.28. A model hurricane plan for a coastal community. March 1959.
No.29. Exchange of heat, moisture, and momentum between hurricane Ella (1958) and its environment. April 1959.
No.30. Mean soundings for the Gulf of Mexico area. April 1959.
No.31. On the dynamics and energy transformations in steady-state hurricanes. August 1959.
No.32. An interim hurricane storm surge forecasting guide. August 1959.
No.33. Meteorological considerations pertinent to standard project hurricane, Atlantic and Gulf Coasts of the United States. November 1959.
No.34. Filling and intensity changes in hurricanes over land. November 1959.
No.35. Wind and pressure fields in the stratosphere over the West Indies region in August 1958. December 1959.
No.36. Climatological aspects of intensity of typhoons. February 1960.
No.37. Unrest in the upper stratosphere over the Caribbean Sea during January 1960. April 1960.
No.38. On quantitative precipitation forecasting. August 1960.

USCOMM-WB-DC

CONTENTS

AUTHORIZATION

The 84th Congress, first session, through the instrument of Public Law 71, authorized and directed the Secretary of the Army in cooperation with the Secretary of Commerce and other Federal agencies concerned with hurricanes, to cause an examination to be made with respect to hurricanes of the eastern and southern seaboard of the United States. This survey was to include, among other things, the securing of data on the behavior and frequency of hurricanes, and possible means of preventing loss of human lives and damages to property with due consideration of the economics of proposed breakwaters, seawalls, dikes, dams, and other structures. The participation of the Weather Bureau, as agreed upon, was defined under seven Subprojects in a memorandum prepared by the Office of the Chief of Engineers, Civil Works Division, dated November 25, 1955. The studies described in this report are part of Subproject 2 and Subproject 7. The first calls for a study of selected hurricane characteristics and correlation of these with probabilities of occurrence in various regions; the second calls for special wind analysis pertinent to determination of wave and tidal effects at specific locations involved in engineering studies, such as Narragansett Bay, R. I.

SURFACE WINDS NEAR THE CENTER OF HURRICANES

(AND OTHER CYCLONES)

Howard E. Graham and Georgina N. Hudson
Hydrologic Services Division, U. S. Weather Bureau, Washington, D. C.

[Manuscript received July 10, 1958; revised May 6, 1960]

INTRODUCTION

The purpose of this report is to supply factual data, analyses, and reasonable inferences on the surface winds near the center of large hurricanes. Such data are indispensable to oceanographers concerned with wind-surge relationships, engineers charged with the design of hurricane protective works, and officials responsible for operation of protective works and the development of evacuation plans for hurricane situations [5].

Few users will have occasion to read the whole report. The chapter on each hurricane is self-contained in order that the reader interested only in one geographical area may proceed from the first chapter to the storm in the region of his interest.

Some notable omissions for which analyses have not been completed are: (a) the 1900 storm at Galveston, (b) "Carol" of 1954 and (c) "Helene" of 1958. Three extratropical storms are included: one in April 1956 that produced the second highest surge of record at Norfolk, Va.; the other two in November of 1950 and 1953, which were notable storms for the New Jersey, Long Island, and southern New England areas. An attempt is made to include enough cases that the user will find a typical example of a severe storm reasonably close to his area of interest.

Isotach patterns or some equivalent are indispensable to wind-surge studies, and constitute, in fact, the most important part of this compendium. While the report deals primarily with winds, pressure analyses of each storm have been included to permit evaluation of the inverted barometer effect in surge studies. Along the coasts of the North Atlantic States there can be no clear divorce of hurricanes from other cyclones as creators of damaging surges. Isotach patterns for three extratropical storms producing outstanding surges have therefore been included.

The isotach patterns were originally prepared for the Corps of Engineers in connection with hurricane protection studies along various coastal reaches.

The general method used in developing the isotach patterns is explained in Chapter I while necessary variations in this method are described in the sections dealing with particular storms. The analysis of one storm, the September 21, 1938 hurricane (No. 6), has been published previously but is included here in summary form to complete the compilation of isotach patterns.

The technique, or approach involved in the analysis of each storm was included, not for its own sake, but rather to give the user an opportunity to judge the reliability of the work for himself. There is no intention of solving any problems as such, but to present data already digested in such a form that certain problems may be more readily attacked.

In the process of adjusting observed wind speeds to a common height and frictional surface, several key stations were examined in considerable detail. Chapter IV on "Local Wind Relations" discusses these adjustments.

Observed data used in constructing the isotach patterns have been included either on the figures or in the appendix. In this way, the reader is spared the search for original data should he evolve improved methods of analysis.

Chapter I

SYNTHESIS OF WIND PATTERNS

1. ANALYSIS PROCEDURES

BASIC DATA

The observations along the path of each storm applied to developing isotach patterns consisted of autographic wind records (triple-register sheets and gust speed records), barograph traces, observations from airway stations, ships, aircraft reconnaissance, lightships and other Coast Guard stations, and unofficial pressure observations and estimates of wind velocity. Wind speeds reported in old newspapers were also considered, especially for storms during the earlier years when few official observations were made. The greatest weight was given to data from autographic wind records which were averaged over 10- or 15-minute intervals.

WIND OBSERVATIONS

For most storms, few ship observations were available and the over-water winds in each hurricane had to be reconstructed primarily from observations from land stations, preferably at the coast. Successive observations at each station were converted from time to space variation by plotting all data on a single chart, each in its position relative to the storm center at the time of the observation. This kind of plot gives the illusion of holding the hurricane still and moving the observation station in the direction opposite to hurricane movement [7].

Adjustment for height of anemometer and frictional surface. Wind speeds were adjusted to a common height of 30 feet and to common frictional surface of "over-water". Height adjustments were made under the assumption that wind-speed variation with height fits a logarithmic law ($V_2-V_1=K \log_e z_2/z_1$), where V is the wind speed at corresponding height z. This variation was shown at the Brookhaven National Laboratory in hurricanes Carol and Edna [51]. Values of K, the proportionality factor for the variation of wind with height, were derived from experimental data from several authors. The curves of estimated variation of wind speed from the surface to the 1000-m. gradient level and over various frictional surfaces in figure 1-1 taken from Myers and Jordan [6] were employed to make the reduction to 30 ft.

Studies at Lake Okeechobee, Fla. [8, 9] determined the feasibility of stratifying wind speeds into the three categories of winds blowing over open water (over-water), winds blowing onto a shore from open water (off-water), and winds blowing from land to water at a coast (off-land) and these categories were employed in the present report. On the average, for a relatively smooth shore, the off-water wind speed is 89 percent of the over-water wind speed. The ratio is less when the shore line is more irregular as described in section 21. The ratio of off-land to over-water wind speed seems to vary with speed and the character of the land and is a more uncertain factor.

For the 1949 and 1950 hurricanes at Lake Okeechobee, the ratio ranged from 62 percent of the over-water wind when the latter was 50 m.p.h. to 77 percent when the latter was 80 m.p.h. (fig. 1-2). In most cases off-land winds with a long over-land trajectory over moderately rough terrain were reduced to 60 percent of the over-water speed at the coast.

It was found from a comparison between simultaneous wind observations at downtown and airport sites that the downtown wind speeds at comparable heights above the ground were significantly lower. Empirical factors were determined to adjust the downtown winds at Washington, D. C. (section 20), New Orleans, La., (section 22), and Baltimore, Md., (section 6), to more open airport exposures. The latter in turn were adjusted to "over-water."

INDIRECT ANALYSIS OF WIND-SPEED PATTERNS FROM PRESSURE FIELD

In synthesis of winds around a hurricane where wind-speed observations were lacking in part or all of the storm, speeds were determined by indirect methods. This was accomplished by computing wind speeds from the pressure gradients or through use of a combination of the pressure gradient and available wind-speed observations.

Model of pressure field. The empirical formula describing hurricane pressure profiles from [9] and [4] was used as a starting point for extending winds

$$\frac{P - P_o}{P_n - P_o} = e^{-R/r} \qquad (1\text{-}1)$$

P_o is the central pressure, P_n the asymptotic pressure, R the radius to region of maximum winds and P the pressure at radius r.

Where the minimum central pressure of the hurricane was not observed, a value for P_o was obtained by fitting a curve defined by formula (1-1) to the available data using methods described in [4]. The formula also yields a parametric value of P_n. Other means of obtaining P_n are by using either the standard atmospheric sea level pressure (29.92 in.) or the pressure at the approximate position on a synoptic map at which the curvature of the isobars changes from cyclonic to anticyclonic. In those cases where the wind speed profile was computed, the value of P_n was determined by one of these methods and checked by another.

Computed gradient winds. Gradient wind speeds were computed from the pressure profile of each storm. The primary method was from the pressure profile parameters of formula (1-1). Differentiating this formula:

$$\frac{dP}{dr} = (P_n - P_o)\frac{R}{r^2} e^{-R/r} \qquad (1\text{-}2)$$

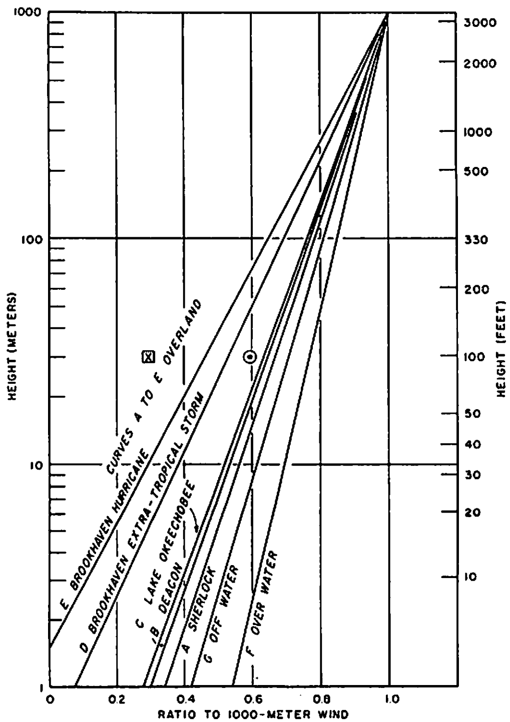


Figure 1-1. Variation of wind speed with height and over various frictional surfaces. Derived from extrapolation of empirical data. Computed ratios (Rossby and Montgomery formula) as shown by ☒ for rough hilly country and ʘ for open grassland.

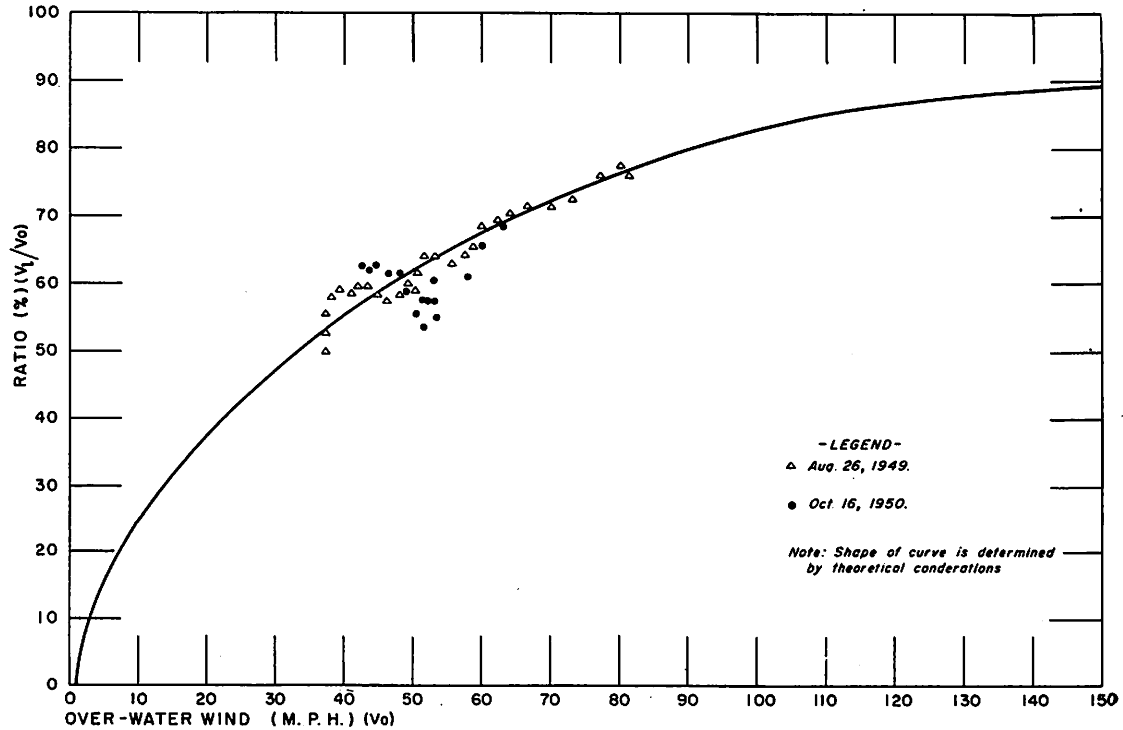


Figure 1-2. Ratio of average off-land wind (V_L) to average off-water wind (V_o).

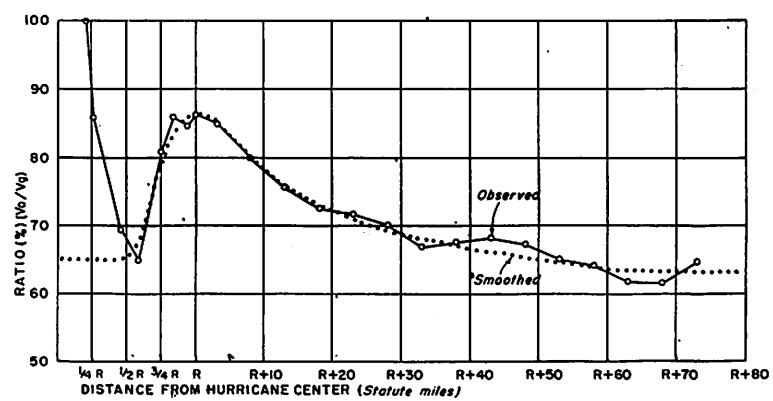


Figure 1-3. Ratio of 10-minute-average over-water wind (V_o) to gradient wind (V_g), August 26-27, 1949.

Substituting in the cyclostrophic wind equation

$$\frac{V_c^2}{r} = \frac{1}{\rho}\frac{dP}{dr} \qquad (1\text{-}3)$$

where V_c is the cyclostrophic wind and ρ the density of the air, gives

$$V_c^2 = \frac{1}{\rho}(P_n - P_o)\frac{R}{r}e^{-R/r} \qquad (1\text{-}4)$$

Over the range of speeds and storm radii encountered in a hurricane the difference between the cyclostrophic wind and gradient wind, V_g, is

$$V_c - V_g = 1.15\,(f/2)r \qquad (1\text{-}5)$$

where r is the radius in nautical miles, the speeds are in m.p.h., and f is the Coriolis parameter in units of hours $^{-1}$ /4/. Equations (1-4) and (1-5) yield the gradient wind at any r from the pressure parameters. Sometimes the pressure profile defined by formula (1-1) fits only the inner 50 to 80 miles. In such cases the gradient wind was then computed for the outer portion either from values of dp/dr scaled directly from a pressure profile visually fitted to the data or by modifying formula (1-1) so as to fit the data better as described in section 12.

Reduction to 30-ft. over-water speeds. The radial profile of gradient winds was reduced to a mean radial profile of 30-ft. over-water winds by use of empirical ratios determined from the 1949 hurricane at Lake Okeechobee (fig. 1-3) as in /4/, and modified for storm asymmetry, a step not used in /4/. The final wind patterns are a combination of these computed winds and observed winds. In a few recent storms observed winds predominated in the isotach analysis and the computed winds were used only as supplementary information. For earlier storms the reverse was true.

Asymmetry of observed hurricanes. It has long been recognized by students of hurricanes that the strongest winds in a hurricane are most often on the right side. Wind-speed patterns by Hughes /10/ shows the greatest sustained wind speeds in the right rear quadrant. Analyses by the Hydrometeorological Section have also tended to show this /6/. The degree of asymmetry is uncertain. Sherman /11/ states that some asymmetry from the right to the left side of the storm is frequently observed to be greater than twice the speed of propagation of the storm, but asymmetry has also been observed to be considerably less than the speed of propagation of the storm (section 10).

When conclusive data from which to make a wind-speed determination were lacking, a fraction of the forward speed of propagation was added to a mean radial profile of the wind speed on the right half and subtracted from the left half according to the formula

$$V = V_a + bT \cos \alpha \tag{1-6}$$

where V is the wind speed at any point, V_a the average wind speed at the same radial distance from the center, T the forward speed of hurricane translation, b an asymmetry factor, and α the angle between the hurricane translation vector and the wind vector. An asymmetry factor of 0.5 appeared to yield isotach patterns most nearly in accord with Hughes' results /10_7 and all other available empirical information and was adopted.

WIND-SPEED VARIATION WITH PRESSURE CHANGES

In the synthesis of wind speeds, it was often necessary to transpose a "master" pattern, based on the best concentration of data, to an earlier or later position in the same storm where very little data were available. As long as the pressure difference ($P_n - P_o$) remained constant, an over-water pattern derived in the area of the most data was transposed without change. If filling had been experienced, as indicated by a change in ($P_n - P_o$), all wind speeds were adjusted by the formula:

$$\frac{V_1}{V_2} = \left[\frac{(P_n - P_o)_1}{(P_n - P_o)_2}\right]^{1/2} \tag{1-7}$$

where V_1 and V_2 are wind speeds at a given radial distance in the hurricane at times t_1 and t_2. Formula (1-7) is derived from formula (1-4) by holding R, r, and ρ constant. In some instances the variation of central pressure, P_o, was determined directly from observations. In other cases, winds were reduced corresponding to the average rates of filling for selected hurricanes derived by Malkin /23_7. Tables 1-1 and 1-2 from his paper were applied.

WIND DIRECTION

Wind direction patterns are shown either as arrows on the isotach charts (as in fig. 6-2) or as separate charts of deflection angles (as in fig. 7-6).

Observed deflection angles. Deflection angle is defined as the angle between the wind vector and a tangent to a circle about the storm center. The observations of wind direction in the path of the storm were converted to deflection angles. The observations consisted mostly of reports from land stations (10 or 15-minute averages from autographic records); a few ship and lightship reports were available. Plots of deflection angles in position with respect to the storm center, in the same manner that speeds were plotted, show a large scatter. The scatter itself is considered a typical hurricane characteristic. The angles were considerably smoothed in the final analysis. Some of the factors producing scatter in deflection-angle plots are differences in frictional surfaces (land vs. water), spiral bands, and isobaric asymmetry.

Table 1-1. - Factors for reducing wind speeds in hurricanes over land due to average change in pressure gradient*

Time hours	Adjustment ratio for wind speeds
T (center at the coast)	1.00
T + 1	0.92
T + 2	0.88
T + 3	0.85
T + 4	0.82
T + 5	0.80
T + 6	0.78
T + 7	0.76
T + 8	0.74

*Based on 13 selected storms.

Table 1-2. - Factors for reducing wind speeds in hurricanes over the Florida Peninsula due to average change in pressure gradient*

Time hours	Adjustment ratio for wind speeds
T (center at the coast)	1.00
T + 1	0.97
T + 2	0.95
T + 3	0.92
T + 4	0.89
T + 5	0.86
T + 6	0.82

*Based on 4 storms.

Assumed deflection angles. The deflection angles in storms with data too limited to define a pattern were considered to be 25° from 10 miles outside of the area of maximum winds and outward, and 20° inside the area of maximum winds, with a transition between. A composite wind-direction pattern derived by Hughes /10/ shows deflection angles of about 18° to 28° over the area within 60 n. mi. of the center. A comparison of the angle made by the wind direction and a tangent to the isobar for hurricane Audrey of June 1957 (section 15) and other cases indicated that the angle across the isobars averaged very close to 25° outside the zone of maximum winds. Theoretical considerations suggest that the deflection angle should be less at the area of the maximum winds than farther out.

TRACKS

Before analyzing the wind and pressure fields in each storm, it was necessary to have a detailed track of the storm. When they were available, the tracks of storms with hourly positions indicated were taken from previous studies /2, 3, 4/, Monthly Weather Review articles, and the original U. S. Weather Bureau weather maps for the period of the storm. Principal steps in determining hourly positions for most hurricanes that occurred in early years were based on the assumption that the isobaric field was symmetrical. The details of track determination are listed in /4/. Basically, the steps involve a series of approximations (usually two) based on pressure and wind observations. The time of lowest pressure at a station, wind shifts, and comparative pressure readings define the storm track, readjusted so that the pressure observations fall as close to the mean profiles as possible. For hurricanes that occurred in later years, such as Hazel of October 1954 (section 12) and Audrey of June 1957 (section 15), aircraft reconnaissance and radar reports were used as an aid in determining the positions of storm centers.

Hourly positions along the storm tracks, in this report, unless indicated otherwise, show the locations of the pressure center. In several of the hurricanes it has been shown that the pressure and wind centers were not coincident.

Chapter II

WINDS AND PRESSURES ASSOCIATED WITH HURRICANES

2. HURRICANE OF SEPTEMBER 3, 1821, NEW YORK CITY

INTRODUCTION

The hurricane of September 3, 1821, produced the highest storm surge (difference between observed tide and predicted astronomical tide) of record at New York Harbor /13/. The maximum storm surge during this storm at New York has been estimated at about 10 feet (see newspaper account No. 5, Appendix B). A comparison of datum planes indicates that sea level may have been as much as a foot lower in 1821 than it is now.

The hurricane, first observed off Turks Island on September 1, 1821, later moved through North Carolina, north-northeastward to near New York City, and then into the New England States. The overall track is reproduced from Redfield /14/ in figure 2-1 together with his historical notes.

DATA

Most of the observations pertaining to the 1821 hurricane are from newspapers. These include information pertinent both to storm intensity and the level of the storm-induced tide. The more informative excerpts are reproduced in Appendix B.

Considerable weight was given to the account of observations in a letter to the editor (newspaper account No. 2). The "citizen's" barometer pressure range for July and August 1821 is stated to have been from 29.9 to 30.1 inches; the current normal New York City sea level pressure for August is 30.01 inches.

The most important meteorological data about the storm, taken from the newspaper accounts, are summarized below.

(1) At New York City

	Account No.
Most violent winds from east-northeast lasting 2 hours after sunset. (Sunset about 6:30 p. m. local time)	1
Wind increased from 5:00 p.m. to 6:00 p.m.	2
Extremely violent from east-southeast from 6:00 to 7:30 p.m.	2
Pressure values taken during the storm with lowest pressure reported at 7:30 p.m.	2

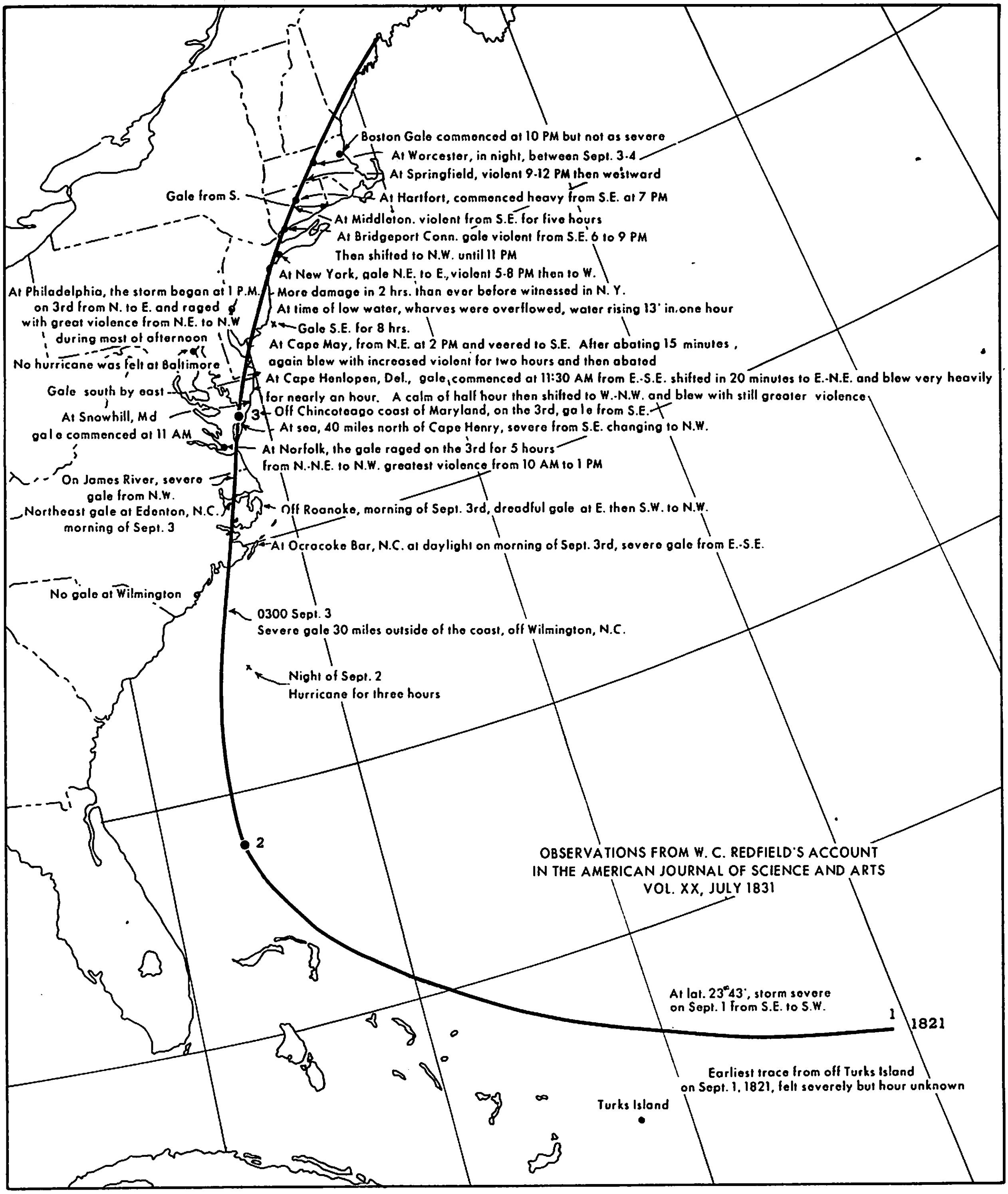


Figure 2-1. Hurricane track and observations, September 1-3, 1821.

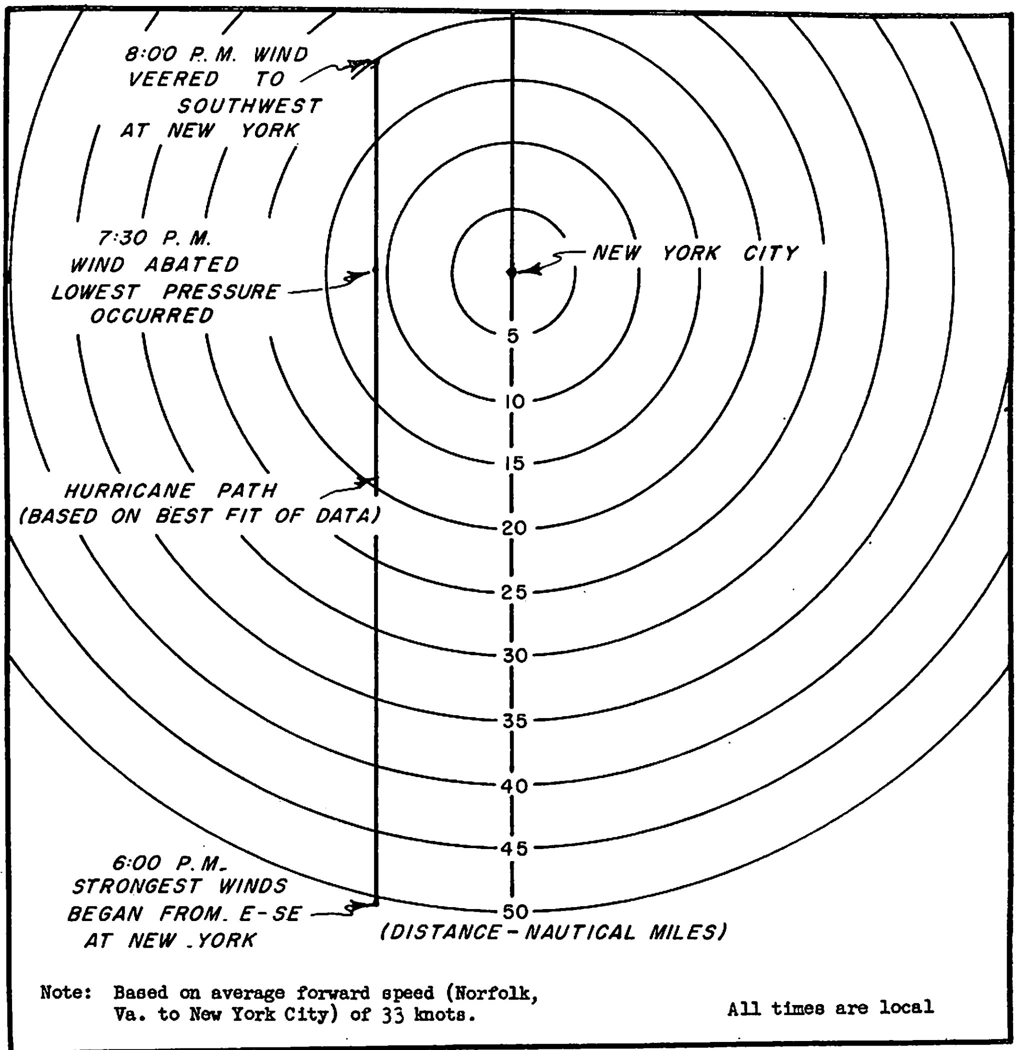


Figure 2-2. Approximate path of September 3, 1821 hurricane relative to New York City.

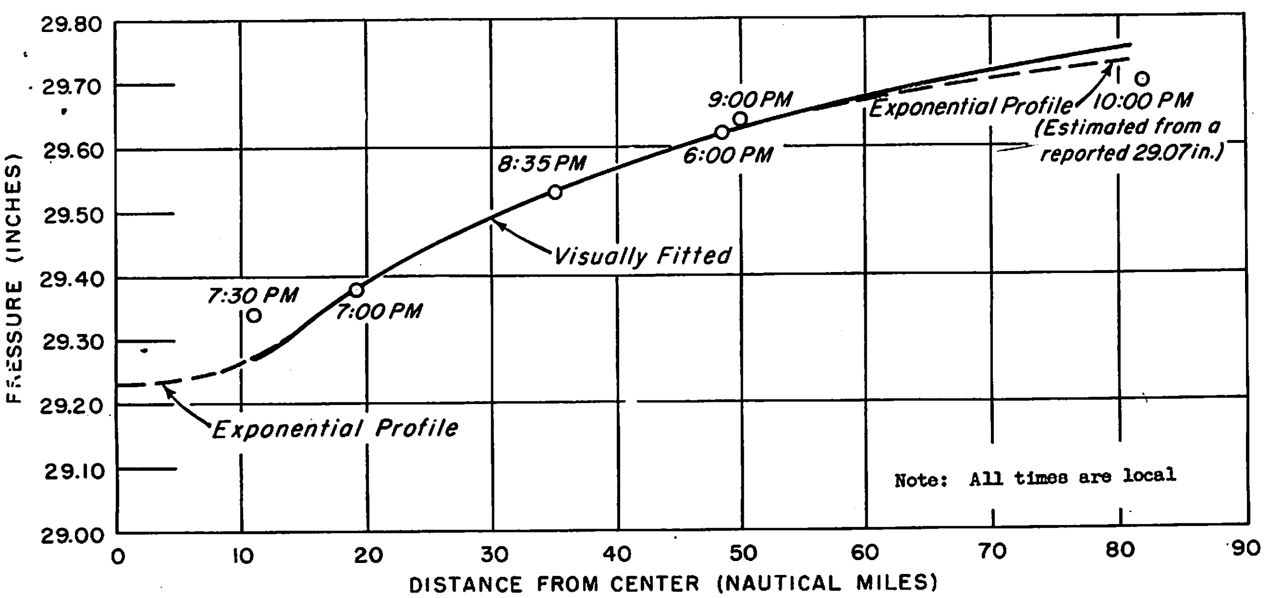


Figure 2-3. Pressure profile, September 3, 1821, at New York City.

	Account No.
Wind abated from 7:30 p.m. to 8:00 p.m.	2
Wind veered to southwest at 8:00 p.m.	2

During the hurricane, temperatures occurred as follows

Time	Temperature (°F.)	
6 a.m.	74	
2 p.m.	79	
6 p.m.	76	
8 p.m.	72	2

Strongest winds from 6 p.m. to 7 p.m.	4

(2) At Norfolk, Va.

Strongest winds from 11:30 a.m. to 12:30 p.m.	10
Wind shifted to northwest at noon	10
Wind shifted to southwest and calmed at 4 p.m.	10

TRACK NEAR NEW YORK CITY

A schematic representation of the path of the storm center as the hurricane moved by New York City is shown in figure 2-2. This was developed to agree with the reported changes of wind speed and direction at New York City. The assumed forward speed of 33 knots is the computed average speed from Norfolk to New York City.

The temperature observations listed in newspaper account No. 2 show that warm air remained in the storm as far north as New York City. Since there was no evidence of the entry of cold air it is assumed that metamorphosis to an extratropical storm was not advanced and that, for the purpose of synthesizing, the storm was relatively circular.

Pressure. The lowest reported pressure was 29.34 inches at an estimated 11 nautical miles east of the pressure center. The plot of pressure versus distance from the center (fig. 2-3) suggests that the lowest pressure at the site of the "citizen's" barometer was probably less than the reported 29.34 inches. This is also indicated by the note in newspaper account No. 2, that pressure was falling during the lowest reported 7:30 p.m. observation. Extrapolating inward from the plot of pressure versus estimated distance from the hurricane center (fig. 2-3) by formula (1-1) yields a central pressure of 29.23 inches. In view of the lack of quantitative information on this storm the central pressure estimate is subject to error. It is believed, however, the central pressure was above 28.70 inches, and by no means comparable to the more recent severe New England hurricanes.

Wind speed. The range of maximum 30-ft. over-water wind speeds, corresponding to the above range of P_o, when combined with normal sea level pressure for P_n, is 45 to 65 m.p.h. The storm was clearly relatively weak. In view of the indicated 10-ft. height of the storm surge, factors such as storm path and forward speed are suggested as of importance in high storm surge occurrence at New York City.

Hurricane parameters. Because of the nature of the observations and the indirect method of analysis, the derived values of the various parameters indicating the hurricane characteristics (table 2-1) are not as reliable as most of the corresponding values derived for other hurricanes.

Table 2-1. - Parameters of September 3, 1821 hurricane at New York City

P_o, Central pressure (in.),	28.70 to 29.30
P_n, Asymptotic pressure (in.),	29.92 (standard atmosphere sea level pressure)
V_{gx}, Maximum gradient wind (m.p.h.),	52 to 75
R, Radius of maximum winds (n. mi.),	Computed 31 Observed 30-40
12-hr. average forward speed (kt.),	33

Definitions for this table and similar tables for the other storms surveyed:

Central pressure - minimum pressure at the center of pressure symmetry either observed or computed by use of formula 1-1 as described in section 1.

Asymptotic pressure - the normal or asymptotic pressure at the outer periphery of the hurricane; see section 1 (used in computing maximum-gradient wind speed).

Maximum gradient wind speed - theoretical friction-free instantaneous wind speed at the radius of maximum winds, see formulas 1-4 and 1-5.

Radius of maximum winds - radius at which the wind speed is the greatest computed with formula 1-1 and/or observed from wind speed records.

Average forward speed - speed of movement of the center of pressure symmetry averaged over the indicated period: usually for a 4-hour period, 2 hours before and 2 hours after crossing the coast.

3. LOUISIANA HURRICANE OF OCTOBER 1893

INTRODUCTION

The hurricane of September 27-October 5, 1893 caused the greatest hurricane disaster in the history of Louisiana. Nearly 2000 lives were lost in southeastern Louisiana. Flooding due to the storm surge caused the greatest loss of life /15/. Along the Mississippi River in Plaquimines Parish, La. the highest land was inundated to a depth of 4 feet /15, 16/. As the hurricane moved up the eastern Louisiana coast and crossed into Mississippi October 2, it was estimated that 350 craft engaged in coastal shipping were wrecked /17/. In Mobile Bay, Ala. where the water rose rapidly (the rise reported to be as much as 2 feet in a half hour), the surge was the highest recorded there up to that time /18/.

The hurricane formed in the Caribbean Sea then moved northward across the center of the Gulf of Mexico. On October 1, 1893, it approached the Louisiana coast unexpectedly /19/ since there had been no timely significant observations available on the mainland, and crossed the Mississippi River Delta near Bastian Bay, La. between 2300 and 0100 EST October 1-2. The hurricane moved northward through Breton and Chandeleur Sounds on the morning of October 2 inundating the Chandeleur Islands and the islands along the Mississippi coast. The center moved inland between Biloxi and Pascagoula, Miss. at about 1000 EST on October 2.

TRACK

The track of the storm, for the period 2000 EST October 1 to 1700 EST October 2 (fig. 3-1), was reconstructed using the limited data available from stations within 100 miles of the path of the storm as it moved inland, as well as descriptions of the storm and resulting damage as reported in the Monthly Weather Review /19/ and October 1893 newspaper accounts.

PRESSURE

Visually-fitted and exponential profiles were constructed for 1000 EST, when the hurricane passed inland west of Moss Point, Miss., and for 1400 EST, when the center was near Mobile, Ala. These times were selected because of the greater quantity of pressure data near them. A barograph trace was available from New Orleans, La., but aside from a few special observations and a ship report of barometer readings at Moss Point, only 0800 EST and 2000 EST observations were available from Port Eads, La., Mobile, Ala., Pensacola, Fla., and Meridian, Miss.

The pressure profiles at 1000 EST and 1400 EST are shown in figure 3-2. Pressures observed at stations near the storm center at these times are also plotted on the graph. The change in central pressure from 1000 EST to 1400 EST is near the average rate of filling of the hurricanes on which table 1-1 is based. The central pressure at 1000 EST was computed to be 28.22 in. and at 1400 EST, 28.61 in. A more complete list of hurricane parameters is shown in table 3-1.

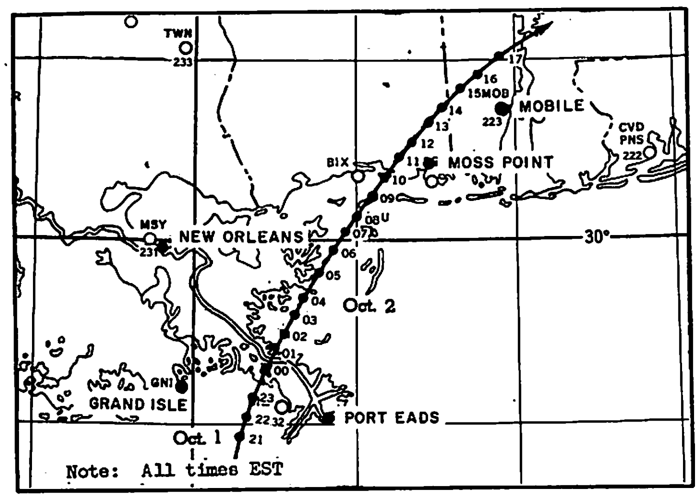


Figure 3-1. Hurricane track, October 1-2, 1893.

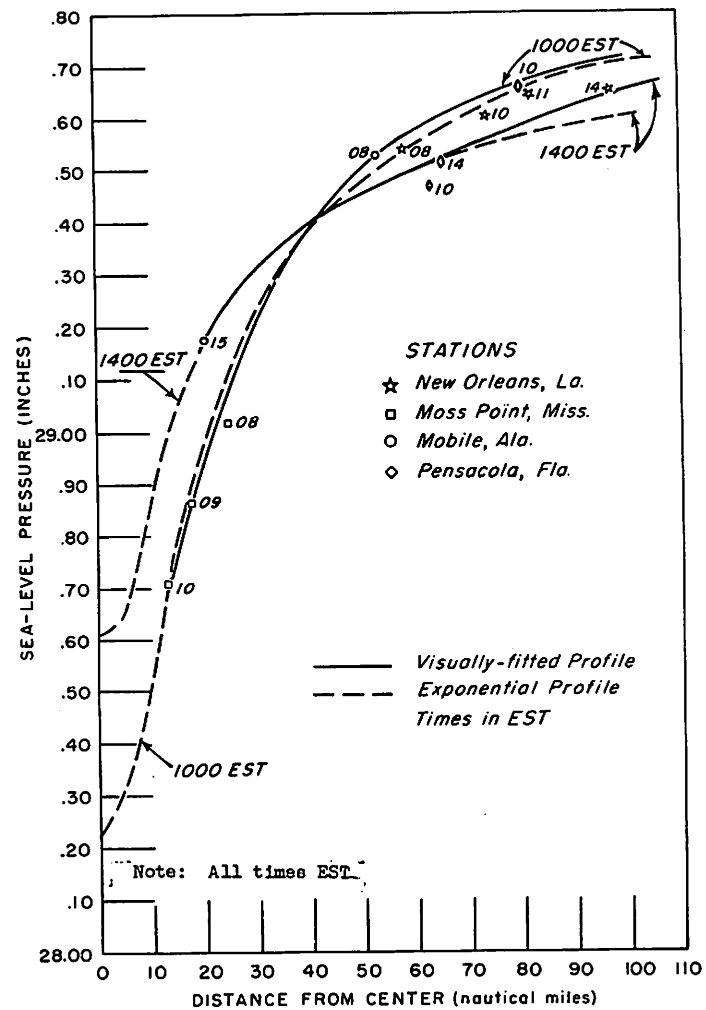


Figure 3-2. Pressure profiles, October 2, 1893, near the Mississippi coast.

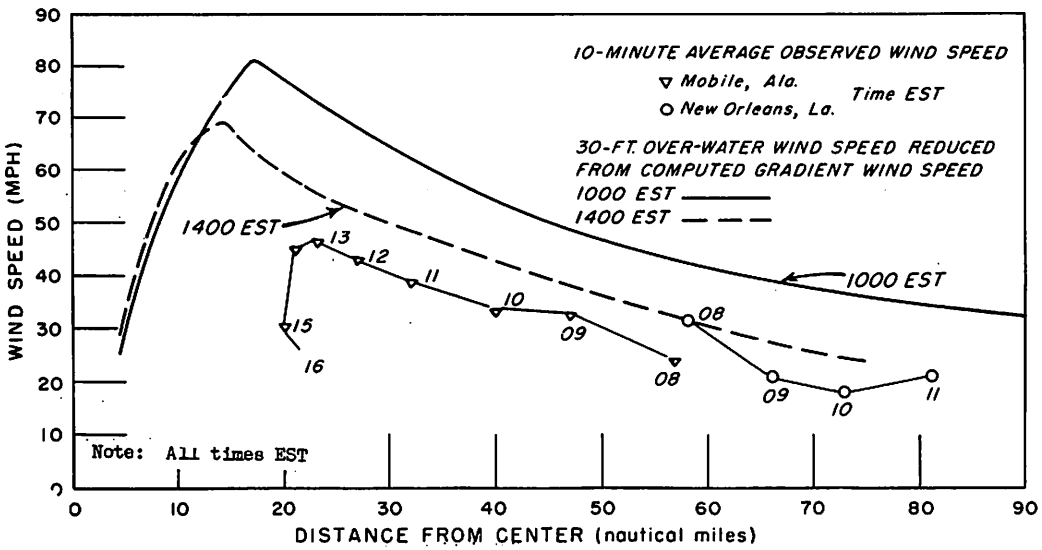


Figure 3-3. Wind-speed profiles, October 2, 1893, near Mississippi coast.

WIND SPEED

The gradient wind speeds computed for 1000 EST and 1400 EST were reduced to 30 ft. over-water speeds by the standard procedure using figure 1-3. These profiles are shown in figure 3-3 and constitute the best general estimate of over-water wind values at the respective times. It can be surmised that the over-water winds at the time the center was near the Mississippi Delta, some 12 hours earlier, were higher than those on figure 3-3, both because of the likelihood of filling of the storm and of the magnitude of the surge over the Delta. However, there is no quantitative confirmation of this.

The observed 10-minute average winds at New Orleans and Mobile, without any adjustments other than instrumental, are plotted in figure 3-3. No attempt was made to adjust these values to over-water winds, as was done with most other storms investigated, because the frictional category in cities, but near water, is quite uncertain. The New Orleans observations are also on what is frequently the weakest side of the storm. However, the general ratio of the observed land winds to the computed over-water winds appears reasonable, lending support both to the over-water wind estimates and to the pressure field estimates from which they are computed.

Radius of maximum winds. The computed radius of maximum winds at 1000 EST was 17 nautical miles. A small radius of maximum winds is verified by eyewitness accounts stating that the violent winds in the storm covered a limited area. Although the storm center passed within 38 nautical miles of New Orleans, winds of hurricane force were not reported in the city.

Table 3-1. - Parameters of hurricane of October 1893 at the Mississippi Coast

P_o,	Central pressure (in.), 28.22
P_n,	Asymptotic pressure (in.), 29.99
V_{gx},	Maximum gradient wind (m.p.h.), 94
R,	Radius of maximum winds (n. mi.), Computed 17
c,	4-hr. average forward speed at the coast (kt.), 7

4. HURRICANE OF AUGUST 17, 1915, GALVESTON, TEX.

INTRODUCTION

The hurricane of August 17, 1915, caused 275 deaths and damage estimated as high as $50,000,000, $6,000,000 of which occurred at Galveston. The tide at Galveston was 11.7 feet above Mean Gulf Level /20/. The highest reported tide was 15.3 feet above Mean Gulf Level, at Virginia Point across the bay and west of Galveston /21/.

The hurricane, apparently of Cape Verde origin /1/ was first observed as a severe storm between the Windward Islands of Barbados and Dominica on August 10, 1915. Its center passed north of Jamaica on the night of August 12 with gale winds over the island. Moving northwestward it crossed the western tip of Cuba on August 14 as a hurricane of great force [21]. Continuing on its northwestward path, it crossed the Gulf of Mexico and moved inland 30 miles southwest of Galveston, Tex., around midnight of the 16th (fig. 4-1).

VARIATIONS IN WIND SPEED ANALYSIS

The path of the hurricane was such that Houston and Galveston, Tex., remained in the right half of the storm. Observations of pressure and wind speed from these stations formed the principal basis for the estimated wind-speed patterns. The visually-fitted profile through the pressure data, mostly from Houston and Galveston, is shown by the solid line in figure 4-2. The exponential curve defined by the model (formula 1-1) was fitted to the inner 70 nautical miles of the storm but was below the pressure data outside that radius, and is indicated by the dashed line in figure 4-2.

Wind speeds from Houston and Galveston, adjusted to 30 feet over water, and gradient winds computed from the exponential pressure profile are shown in figure 4-3. A smoothed curve was drawn to the Houston and Galveston 30-ft. speeds in figure 4-3, giving extra weight to the Galveston data because of that station's near-coastal location. Speeds from this curve defined the open sea wind-speed pattern in the portion of the storm which passed over Galveston. Speeds were computed for other sectors of the storm from this curve by applying formula 1-6.

Beyond a radius of 60 nautical miles, a value of 1.0 was used for b instead of the usual 0.5. This was because the isobaric field on historical weather maps appeared to have a greater than usual degree of asymmetry, with the strongest gradient on the right. The span from the radius of maximum winds to a radius of 60 nautical miles from the center was a transition zone of linear change in b. Inside R, b was held at zero.

The 30-ft. composite over-water wind speed pattern is shown in figure 4-4. The 30-ft. wind speed at selected times is shown in figure 4-5, derived from adjustments to the composite 30-ft. over-water pattern (fig. 4-4) for frictional variations of the underlying surface.

Table 4-1. - Parameters of August 17, 1915 hurricane at the Texas Coast

P_o,	Central pressure (in.), 28.01		
P_n,	Asymptotic pressure (in.), 29.65		
V_{gx},	Maximum gradient wind (m.p.h.), 89		
R,	Radius of maximum winds (n. mi.),	Computed	28
		Observed	29
c,	4-hr. average forward speed (kt.), 11		

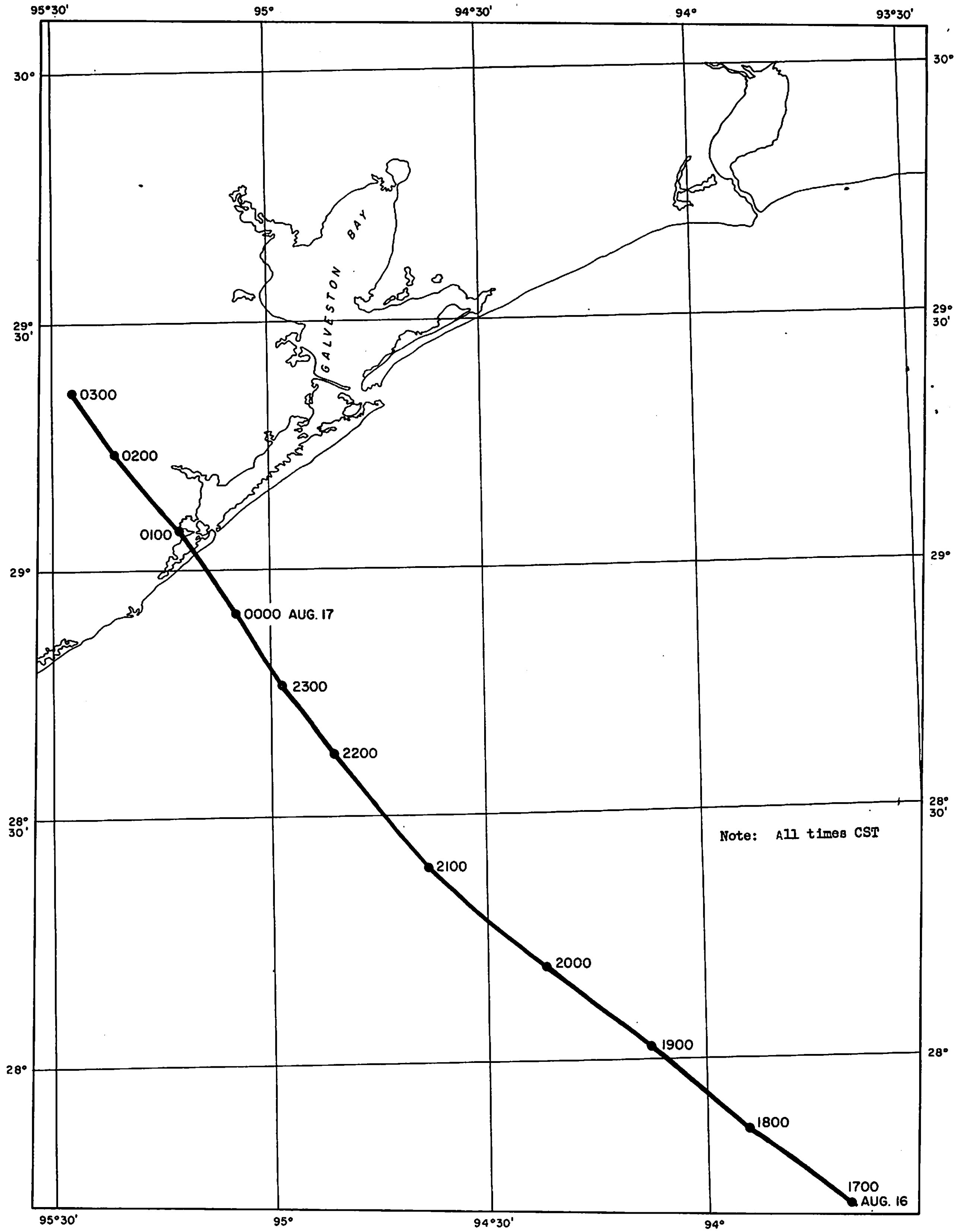


Figure 4-1. Hurricane track, August 16-17, 1915, near the Texas coast.

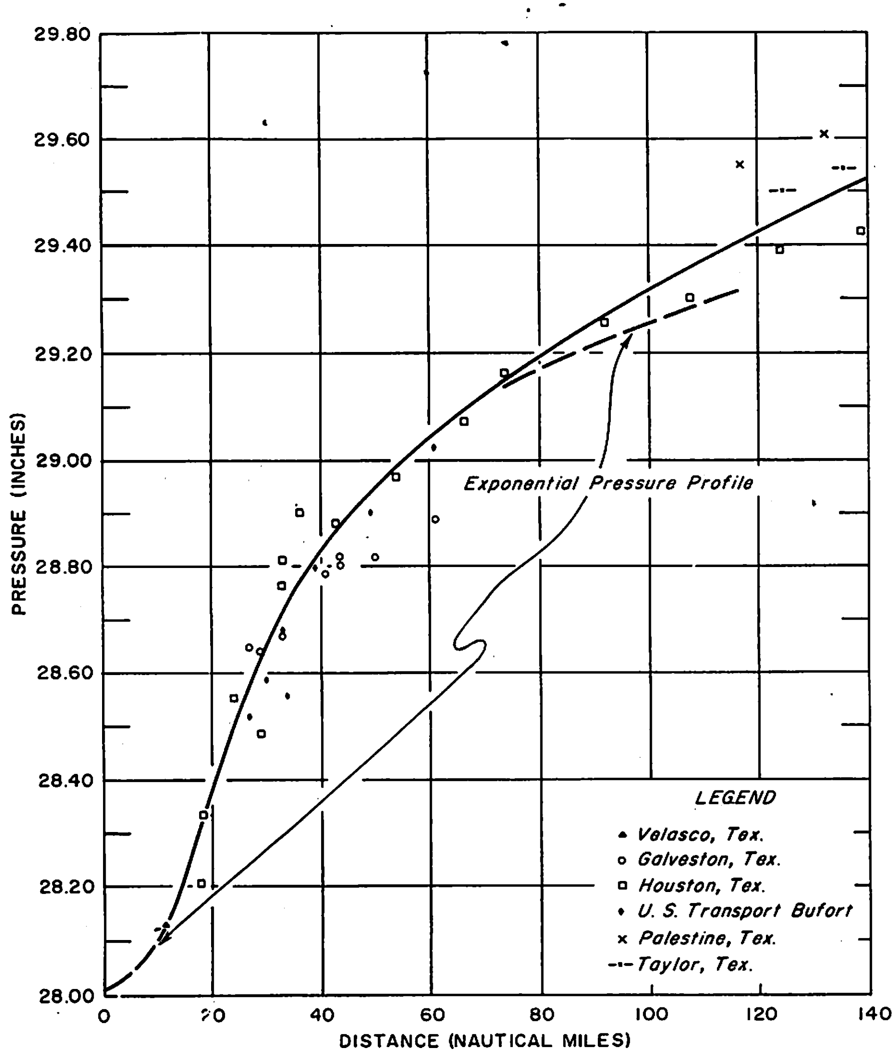


Figure 4-2. Pressure profile, August 17, 1915, near Galveston, Tex., about 0100 CST.

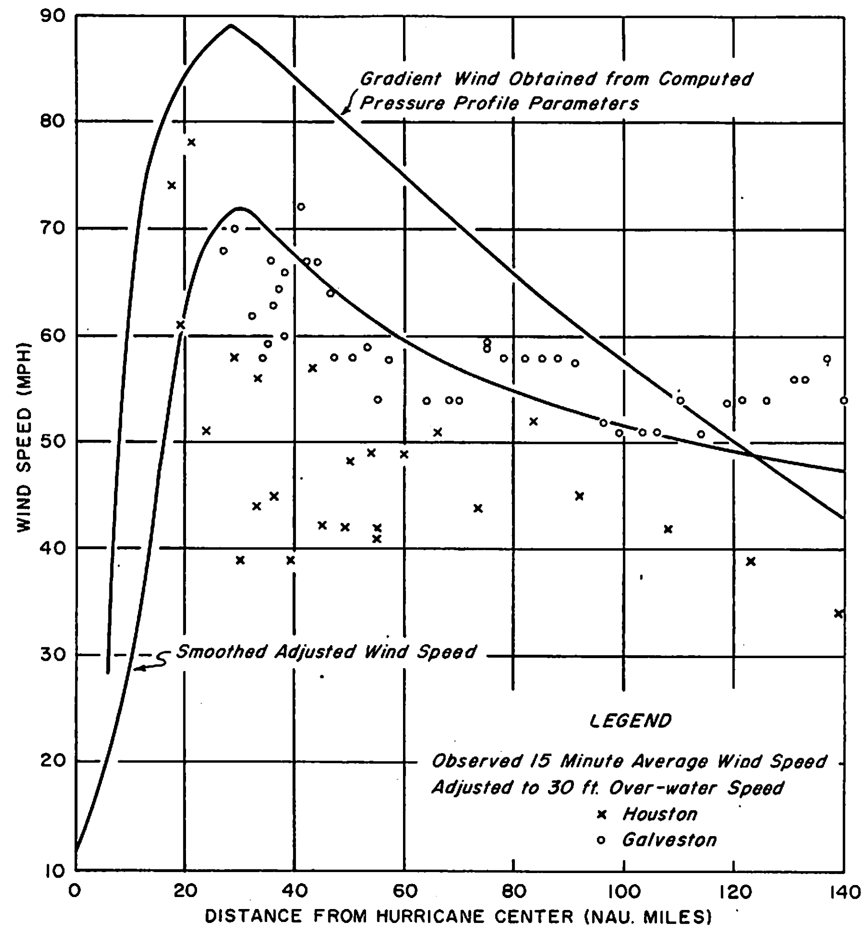


Figure 4-3. Wind-speed profiles, August 17, 1915, near the Texas coast.

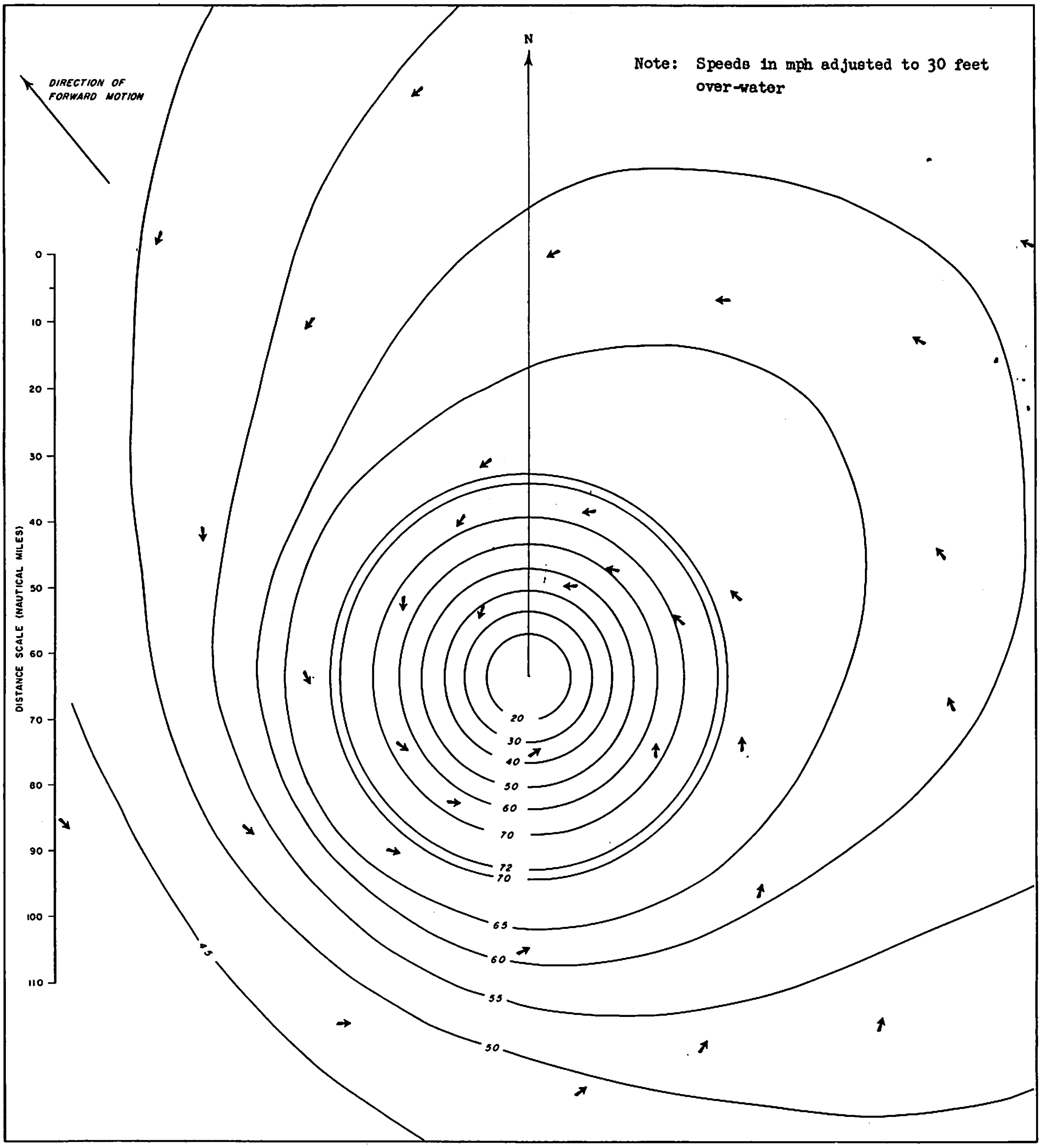


Figure 4-4. Composite wind-speed and direction pattern August 17, 1915, vicinity of Texas coast.

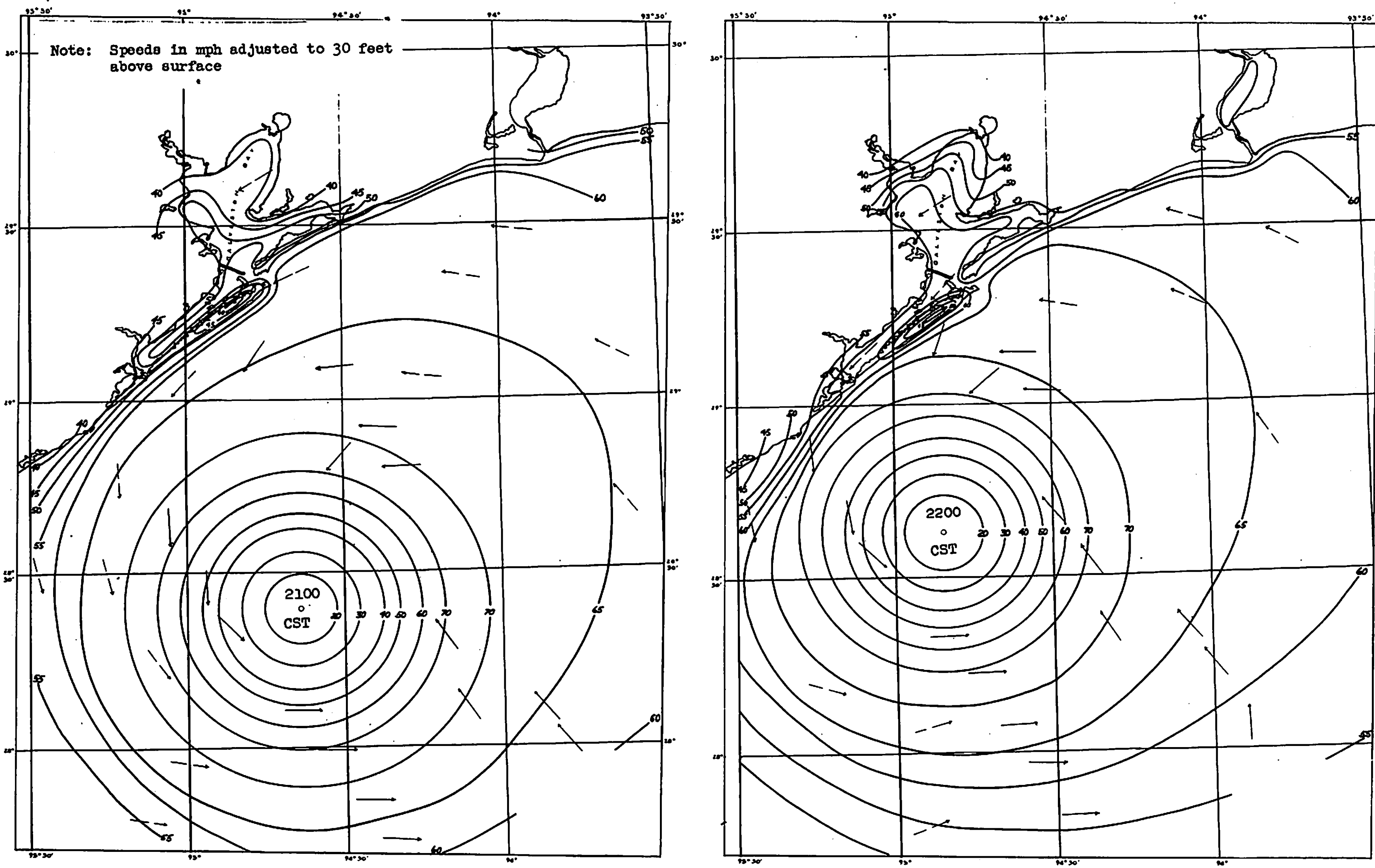


Figure 4-5a. Wind speeds and directions, August 16, 1915, 2100 CST-August 16, 2200 CST.

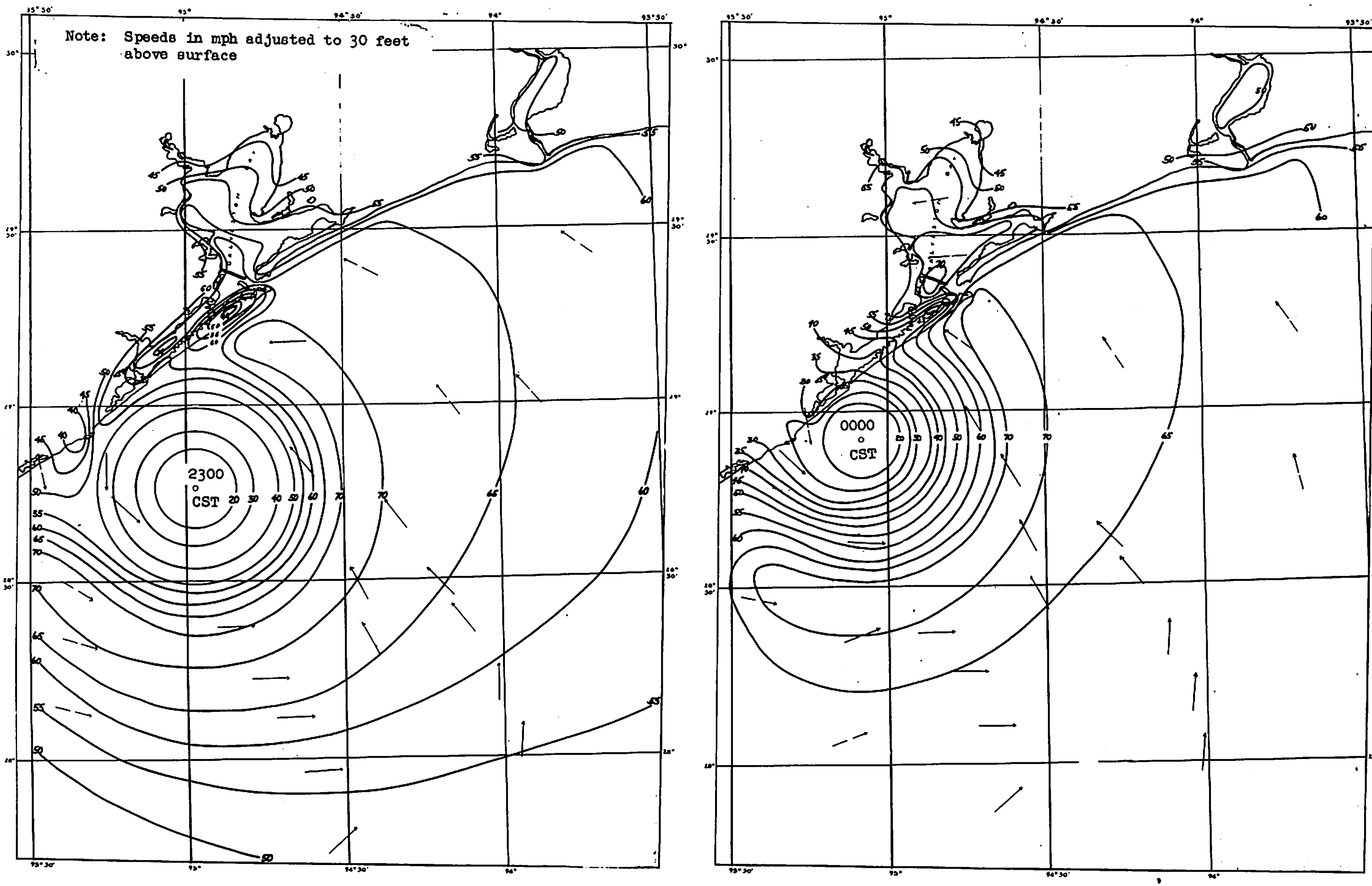


Figure 4-5b. Wind speeds and directions, August 16, 1915, 2300 CST-August 17, 0000 CST.

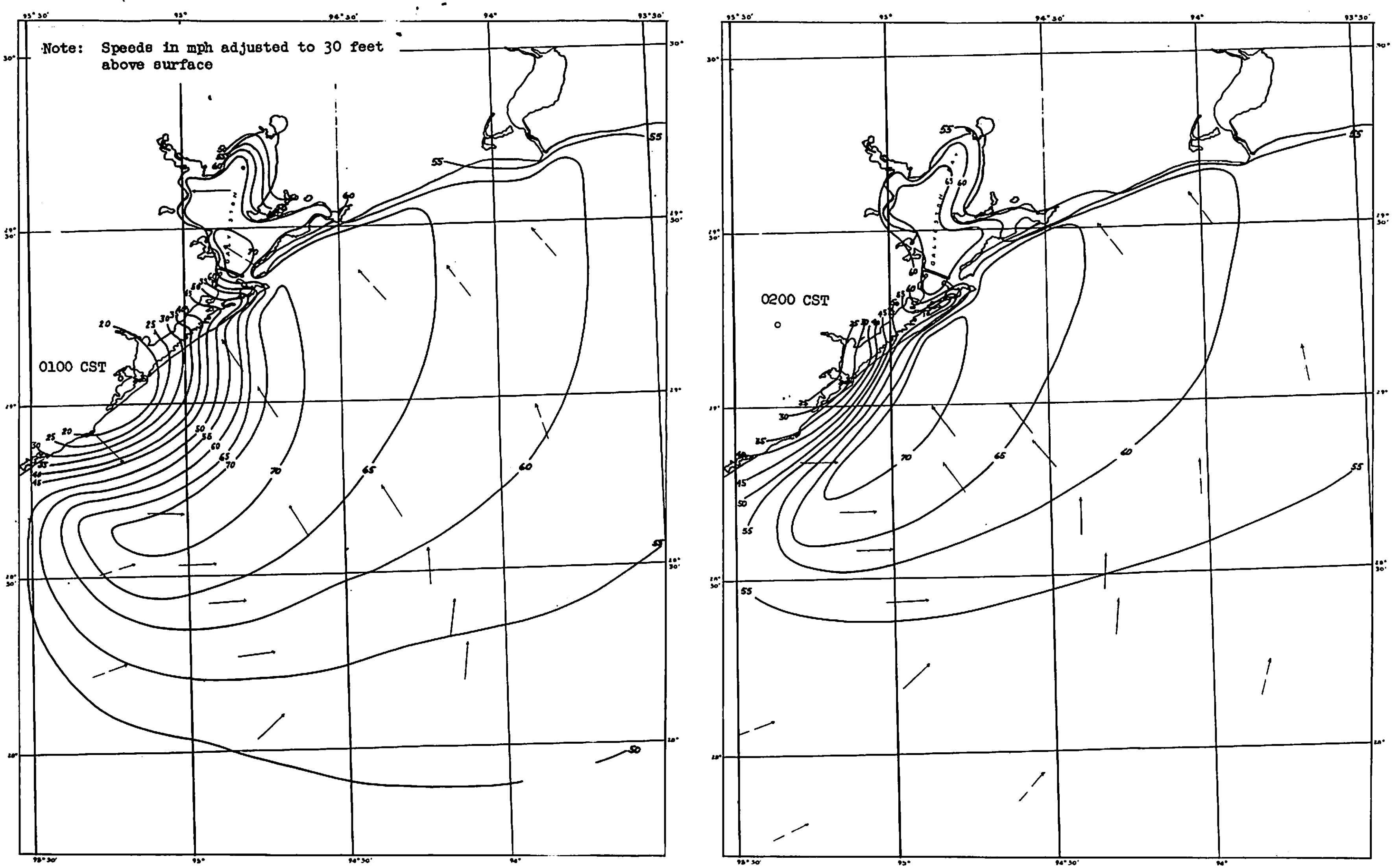


Figure 4-5c. Wind speeds and directions, August 17, 1915, 0100 CST-August 17, 0200 CST.

5. HURRICANE OF SEPTEMBER 29, 1915, AT NEW ORLEANS, LA.

INTRODUCTION

The hurricane of September 29, 1915, was the most intense of record for the city of New Orleans, from the standpoint of central pressure and wind speed. The center of this storm passed within a few miles of the city. Wind observed at the New Orleans downtown Weather Bureau Office reached a maximum 5-minute speed of 86 m.p.h.; the fastest mile was 98 m.p.h. For 4 hours the storm subjected the city to wind speeds of 50 m.p.h. or higher. There was a total of 275 deaths and about $13,000,000 worth of damage along the middle Gulf Coast /22/.

Wind records of value in reconstructing the storm were available only from New Orleans and Burrwood, La. Since wind data were lacking for many sections of this storm, an indirect method of analysis was used.

TRACK

The track of the center of lowest pressure is depicted in figure 5-1. The center of wind rotation is a few miles to the left of the pressure center.

CENTRAL PRESSURE

The known information on the central pressure of the hurricane is shown on a time scale in figure 5-2. This includes the minimum observed pressures at the New Orleans Weather Bureau Office and the ship, Ceiba, in dock at New Orleans. Another ship in the Gulf that experienced some of the conditions of the eye of the storm was at an unknown distance from the point of minimum pressure. Figure 5-2 also shows average rates of filling from hurricanes moving inland over extensive land masses (table 1-1), over the Florida Peninsula (table 1-2), and over a land area but with movement back toward a body of water, each of the three curves being projected from New Orleans back to the coast. Several possible variations of central pressure with time are shown by the heavy curves a, b, and c. Curve b was considered the most probable and was selected for further computations. An average radial pressure profile for 1200 CST (about the time of landfall) is shown in figure 5-3.

RADIUS OF MAXIMUM WINDS

Computation of the radius of maximum winds from the pressure field in the hurricane at various times (formula 1-1) gave values averaging slightly over 31 n. mi. The apparent radius of maximum winds as determined from the wind-speed records at New Orleans WBO was 23 n. mi. An average value of 26 n. mi. was used in developing the reconstructed wind patterns.

COMPARISON OF OBSERVED AND COMPUTED WIND SPEEDS

The gradient wind speeds were computed by formulas (1-4) and (1-5) for various times. For this, central pressures were taken from curve b of figure

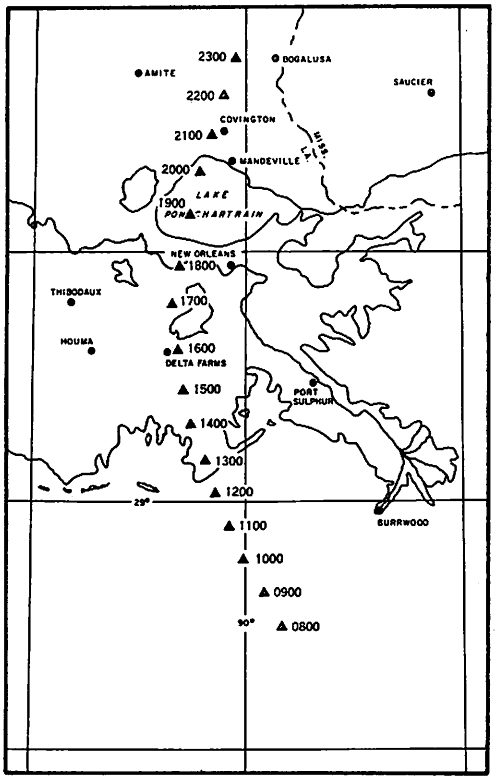


Figure 5-1. Hurricane track, September 29, 1915, near the Loussiana coast.

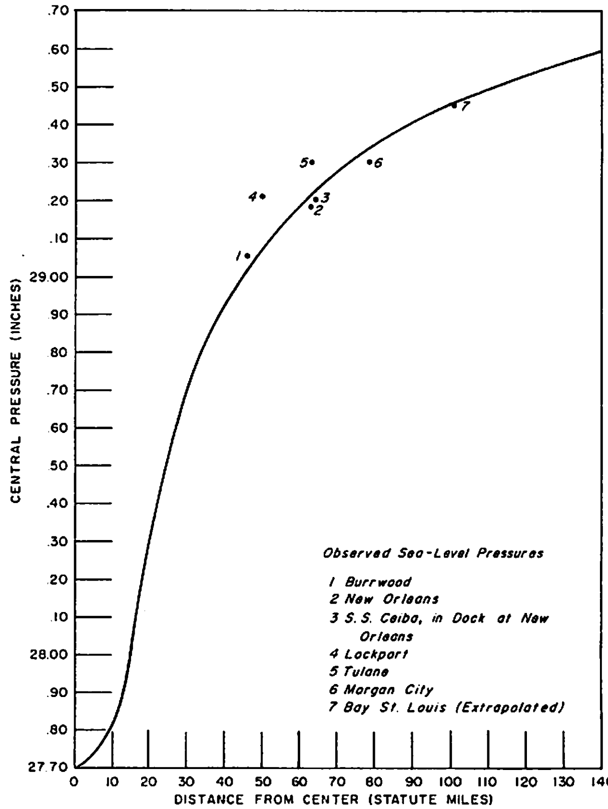


Figure 5-3. Radial pressure profile, September 29, 1915, about 1200 CST.

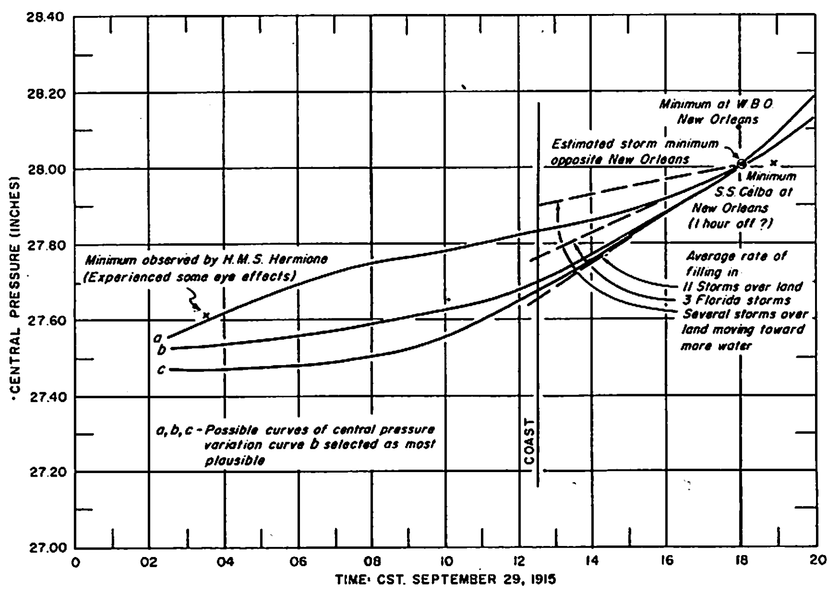


Figure 5-2. Data concerned with variation of central pressure with time, hurricane of September 29, 1915.

5-2 and P_n was held constant at 29.92 in. The gradient winds were reduced to 30 ft. over water by ratios 2 percent higher than the ratios shown at various distances in figure 1-3. This adjustment was determined by trial and error as best fitting this particular hurricane in comparison with observed winds as described here. Computed 30-ft. over-water winds at New Orleans and Burrwood were then determined by a final step, adding the factor $1/2T \cos \alpha$ (formula 1-6).

To standardize the observed winds, 10-minute average speeds at New Orleans and Burrwood were adjusted to 30-ft. over-water values by multiplying by 1.83 and 1.14 respectively. The ratio for New Orleans is from the 1947 study. It is concluded in section 22 that ratios of New Orleans WBO speeds to open water speeds determined from 1947 data are applicable to 1915 data. The ratio for Burrwood is for an off-water exposure (general flooding in that area) from figure 1-1.

The computed and observed winds at New Orleans and Burrwood, all adjusted to 30 feet over water, are compared in figures 5-4 and 5-5. The computation method is considered verified at New Orleans and was thereby applied over the rest of the storm. Only qualitative correspondence was expected at Burrwood (fig. 5-5) because of the unusual wind speed variation at that station. The large surge of high speed between 1500 and 1700 CST at about 70 n. mi. from the center of the storm was not thought to be representative of the speed distribution in other quadrants of the storm or at other times.

ISOTACH CHARTS

Isotach charts were constructed by using the computed radial profiles of the wind speed with an adjustment for forward motion of the storm (formula 1-6) and adjustments for variation in frictional surfaces, as shown in figure 1-1, in the vicinity of shorelines. Attempts were made to estimate shorelines at various hours from a chart of maximum flooding during the hurricane. Final wind fields are shown in figure 5-6.

WIND DIRECTIONS

For over water and over flooded areas a deflection angle of 30 degrees toward low pressure was adopted as a reasonable compromise among the distribution of fluctuations noted in the wind directions at the New Orleans WBO. The deflection angle was kept constant at 30 degrees regardless of radial distance or bearing from the center.

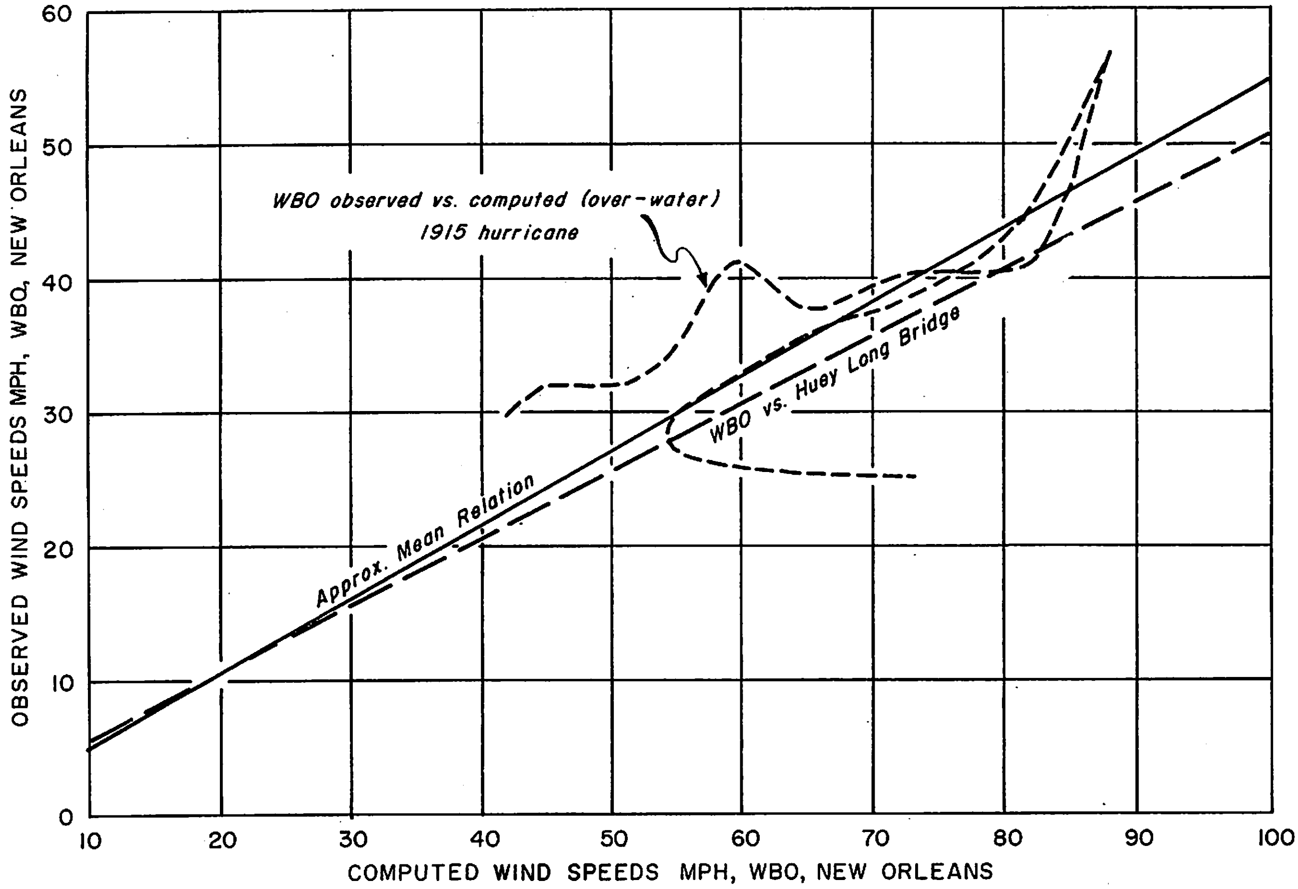


Figure 5-4. Observed versus computed over-water wind speeds, Weather Bureau Office, New Orleans.

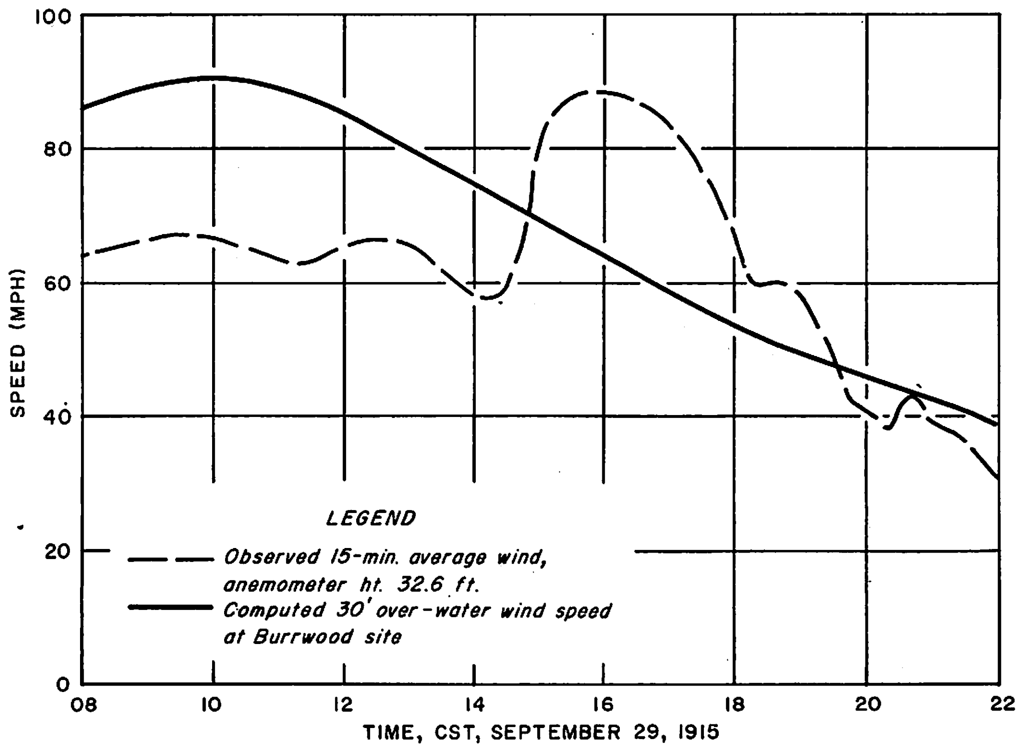


Figure 5-5. Observed versus computed wind speeds at Burrwood, La., September 29, 1915.

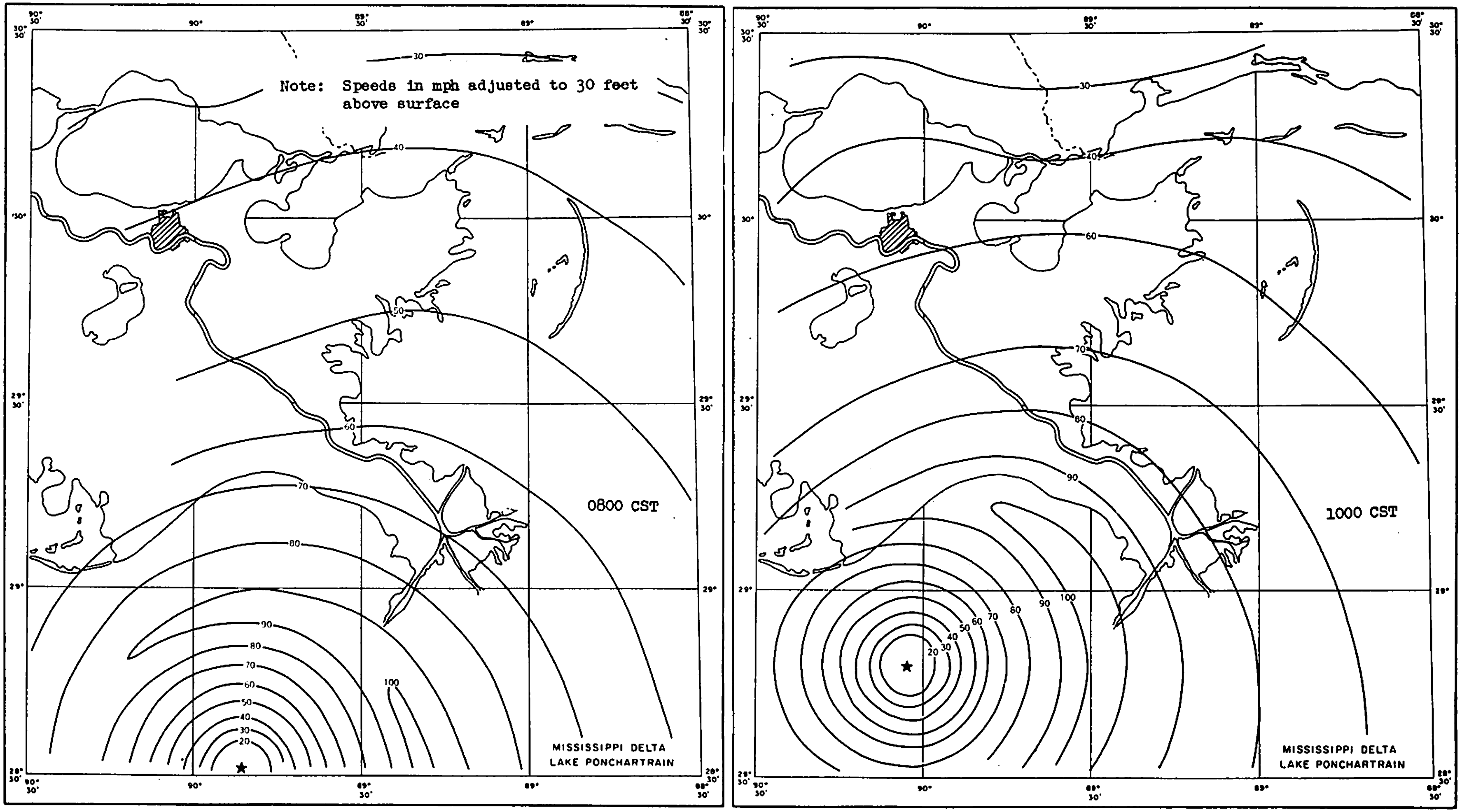


Figure 5-6a. Wind speed, September 29, 1915, 0800 and 1000 CST.

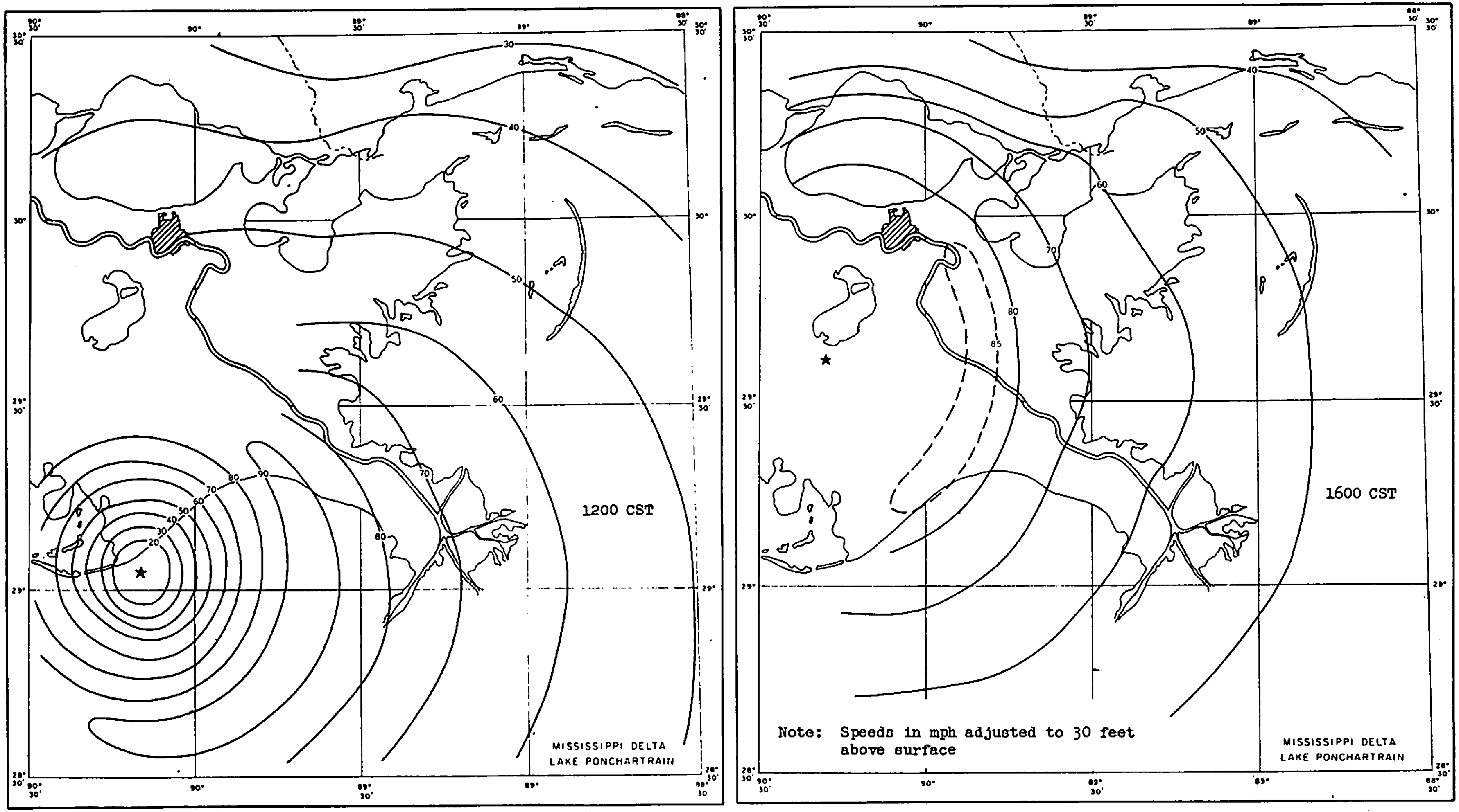


Figure 5-6b. Wind speed, September 29, 1915, 1200 and 1600 CST.

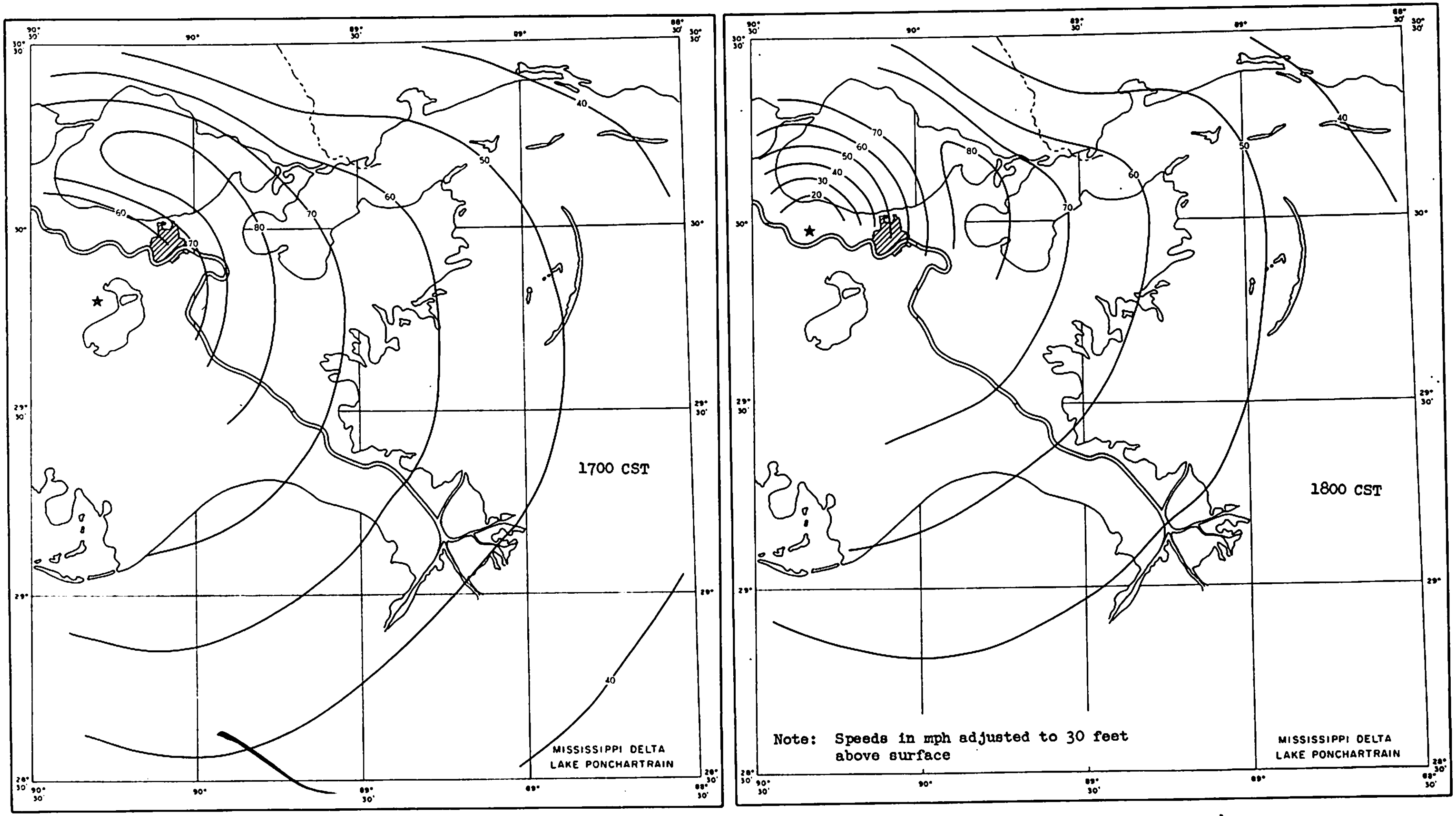


Figure 5-6c. Wind speed, September 29, 1915, 1700 and 1800 CST.

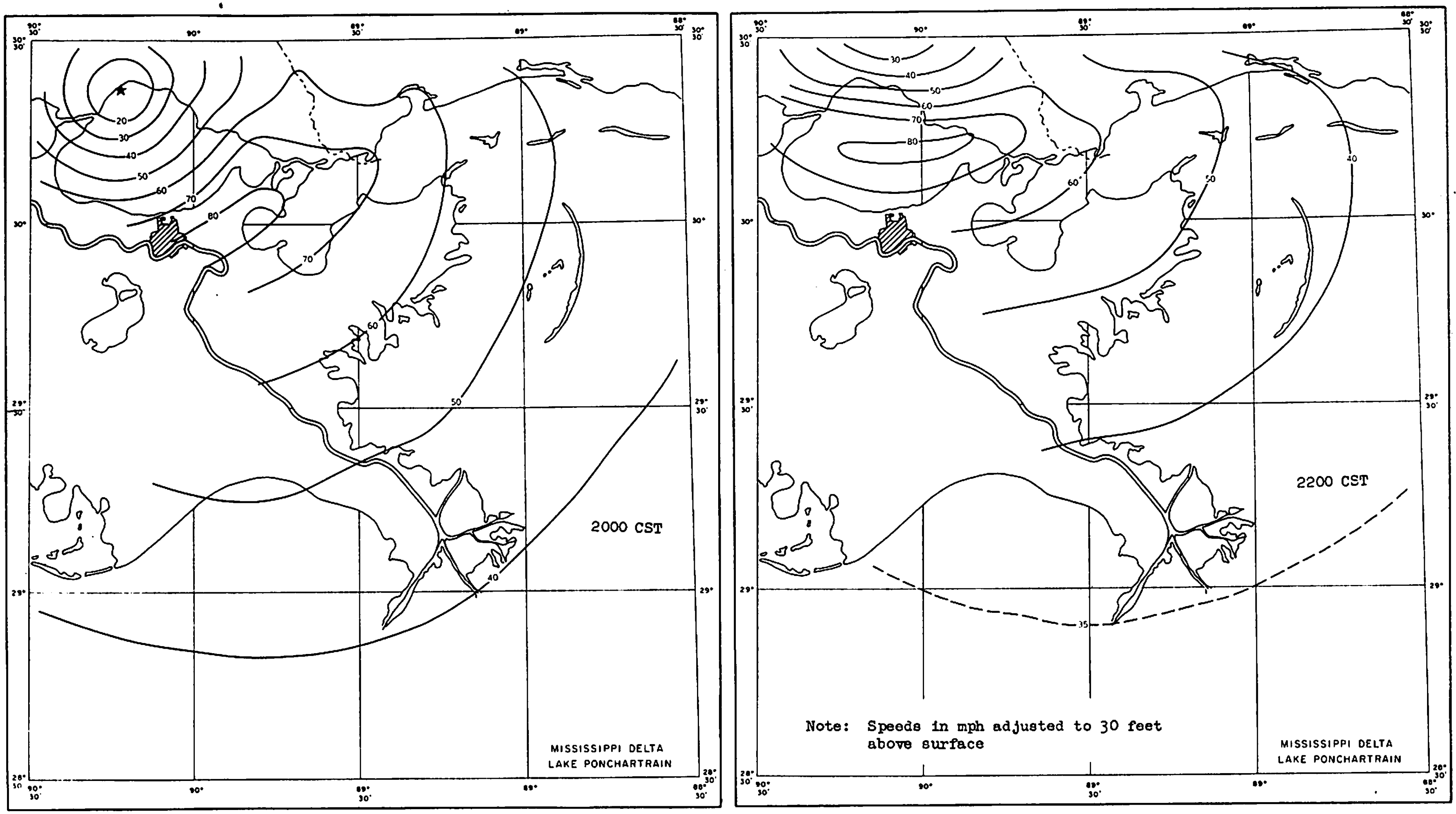


Figure 5-6d. Wind speed, September 29, 1915, 2000 and 2200 CST.

Table 5-1. - Parameters of hurricane of September 29, 1915, at New Orleans, La.

P_o,	Central pressure (in.), 27.70		
P_n,	Asymptotic pressure (in.), 30.14		
V_{gx},	Maximum gradient winds (m.p.h.), 106		
R,	Radius of maximum winds (n. mi.),	Computed	31
		Observed	23
	Isotach patterns based on 26		
c,	4-hr. average forward speed (kt.), 10		

6. HURRICANE OF AUGUST 23, 1933, IN THE CHESAPEAKE BAY AREA

INTRODUCTION

The August 23, 1933 hurricane caused extensive damage in northeastern North Carolina, central and eastern Virginia, Maryland, Delaware, and New Jersey. Most of the damage was caused by the high tides and waves. Some of the highest tides of record were experienced in the Norfolk, Va., area where tides about 7 feet above the predicted astronomical tide occurred flooding the business district with 4 to 6 feet of water. Damage from the storm was estimated at $17,500,000 in Maryland and Delaware /12/, $10,000,000 in Virginia /24/, and $3,000,000 in New Jersey /25/.

When the hurricane was first reported east of the Windward Islands on August 18, it was already an intense storm. Moving north-northwestward, the storm center passed by Cape Hatteras at about 0400 EST on August 23, crossed the coastline at Norfolk, Va., about 6 hours later, and moved northward up the western shore of Chesapeake Bay and into Pennsylvania.

CENTRAL PRESSURE

The central pressure of 28.63 inches at the coast was computed for the approximate time when the center passed between Cape Henry and Norfolk, Va., and is a fairly reliable estimate.

TRACK

The track of the storm with hourly positions of the pressure center is shown in figure 6-1. During the period when the northward progression of the storm was parallel to the western shore of Chesapeake Bay, the wind center was slightly west of the pressure center.

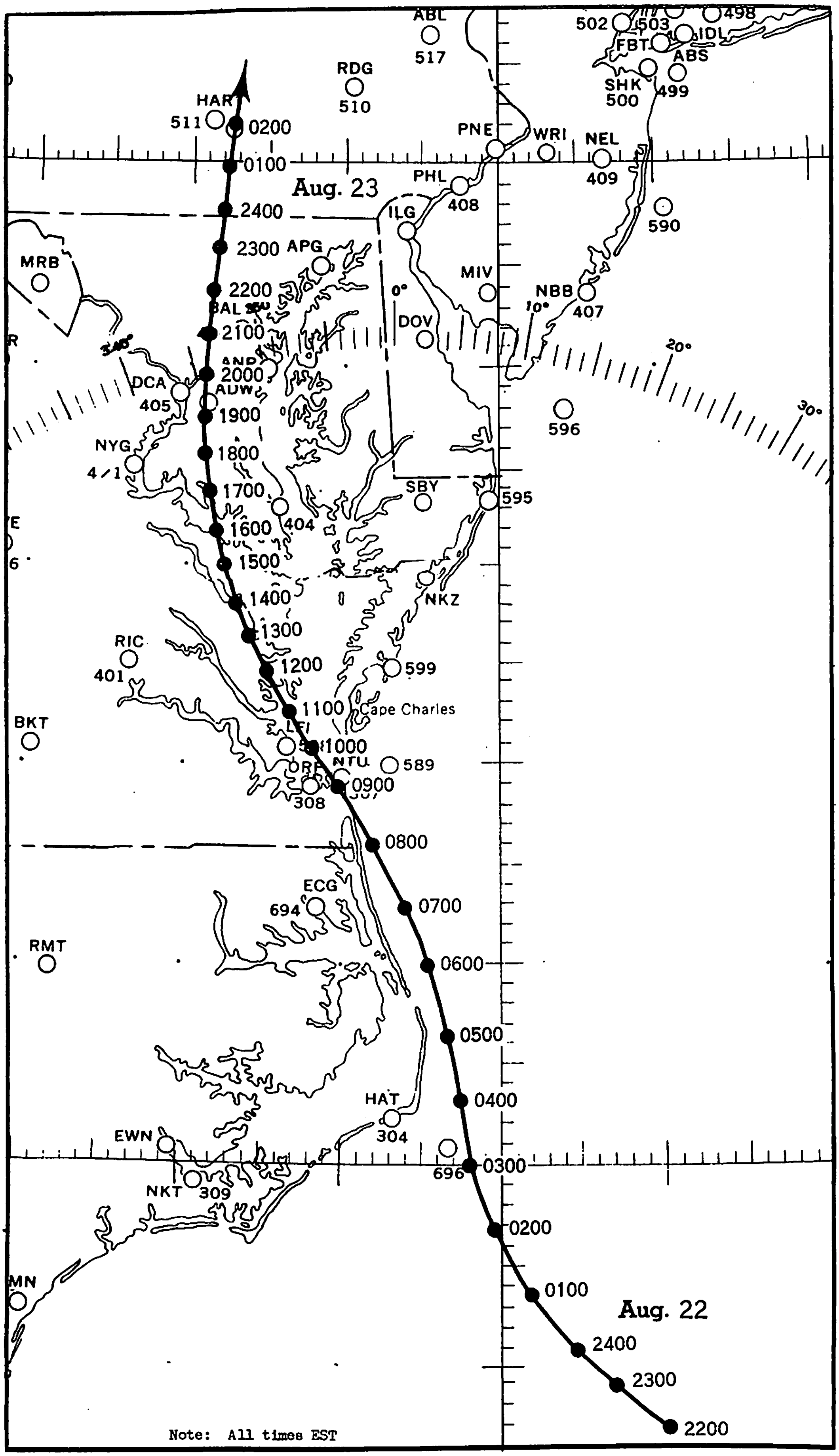


Figure 6-1. Hurricane track, August 22-24, 1933, near Chesapeake Bay.

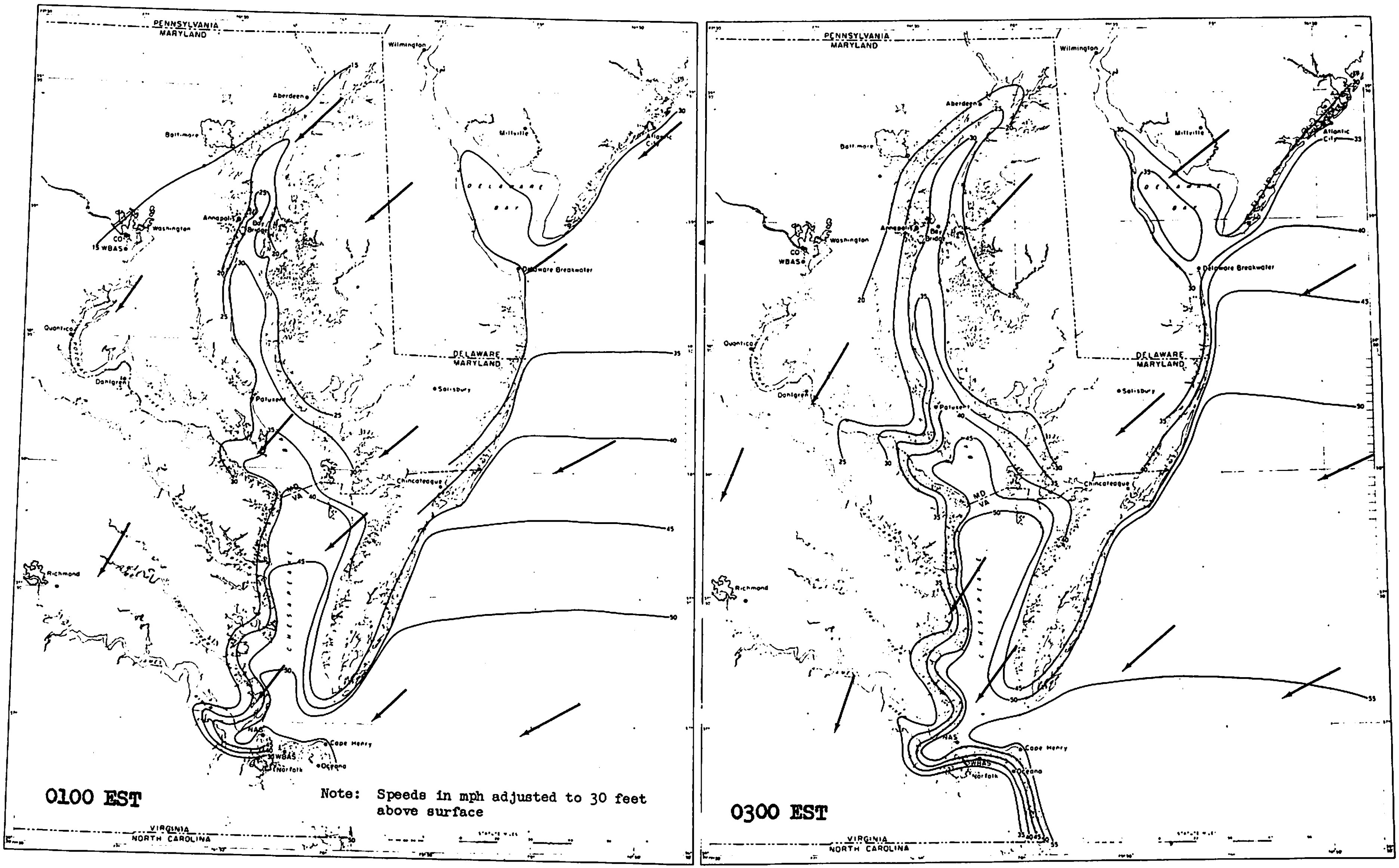


Figure 6-2a. Wind speeds and directions, August 23, 1933.

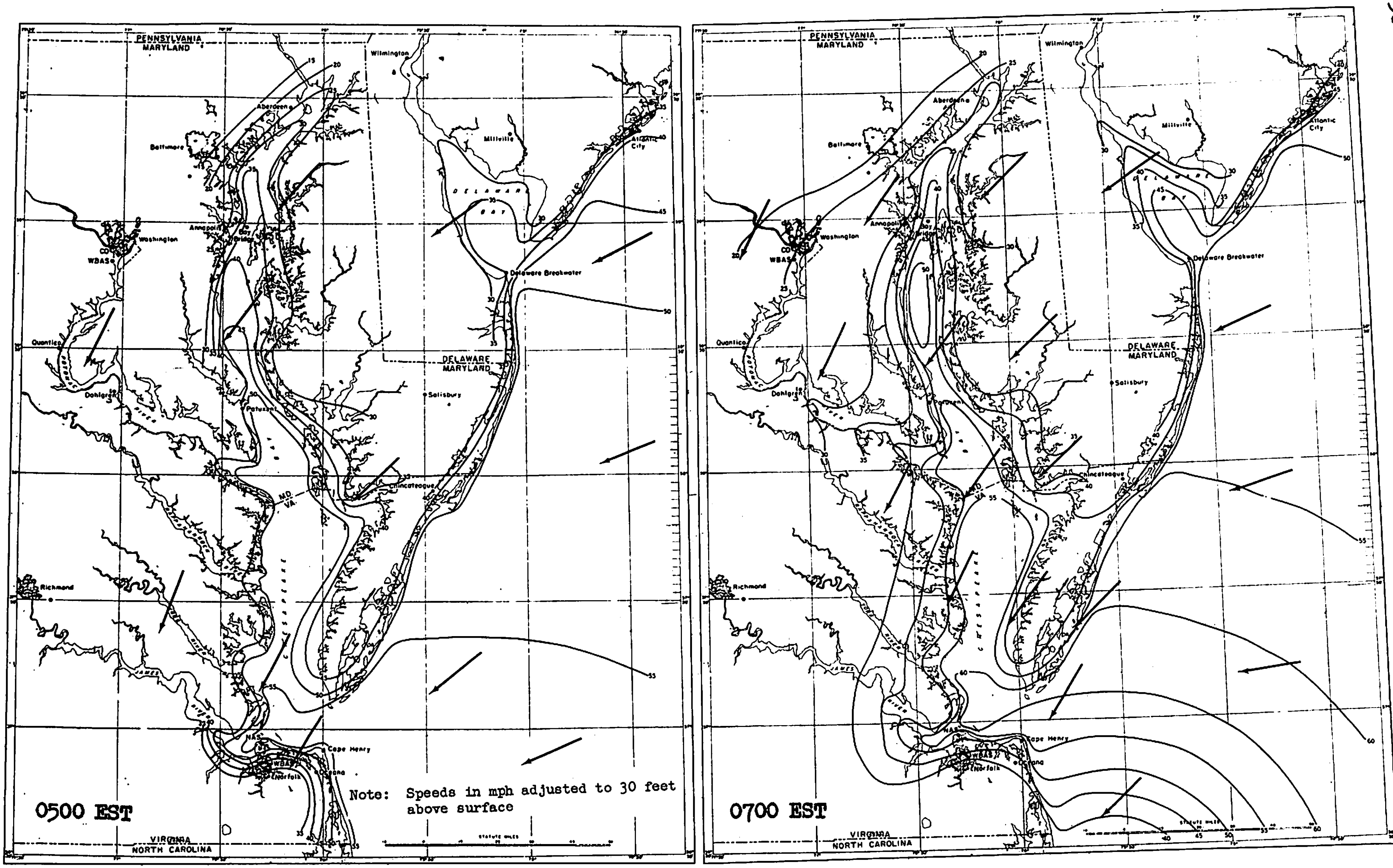


Figure 6-2b. Wind speeds and directions, August 23, 1933.

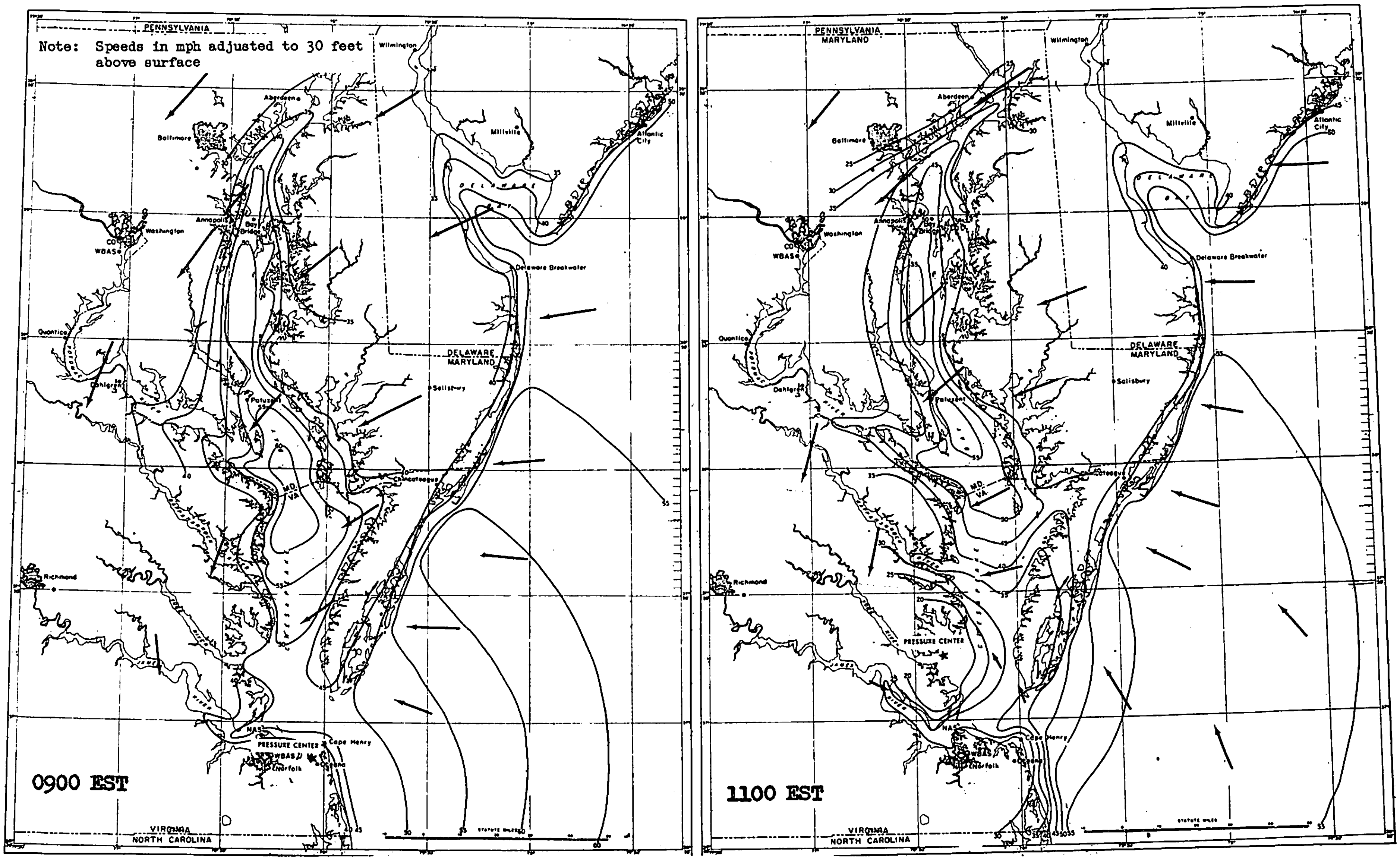


Figure 6-2c. Wind speeds and directions, August 23, 1933.

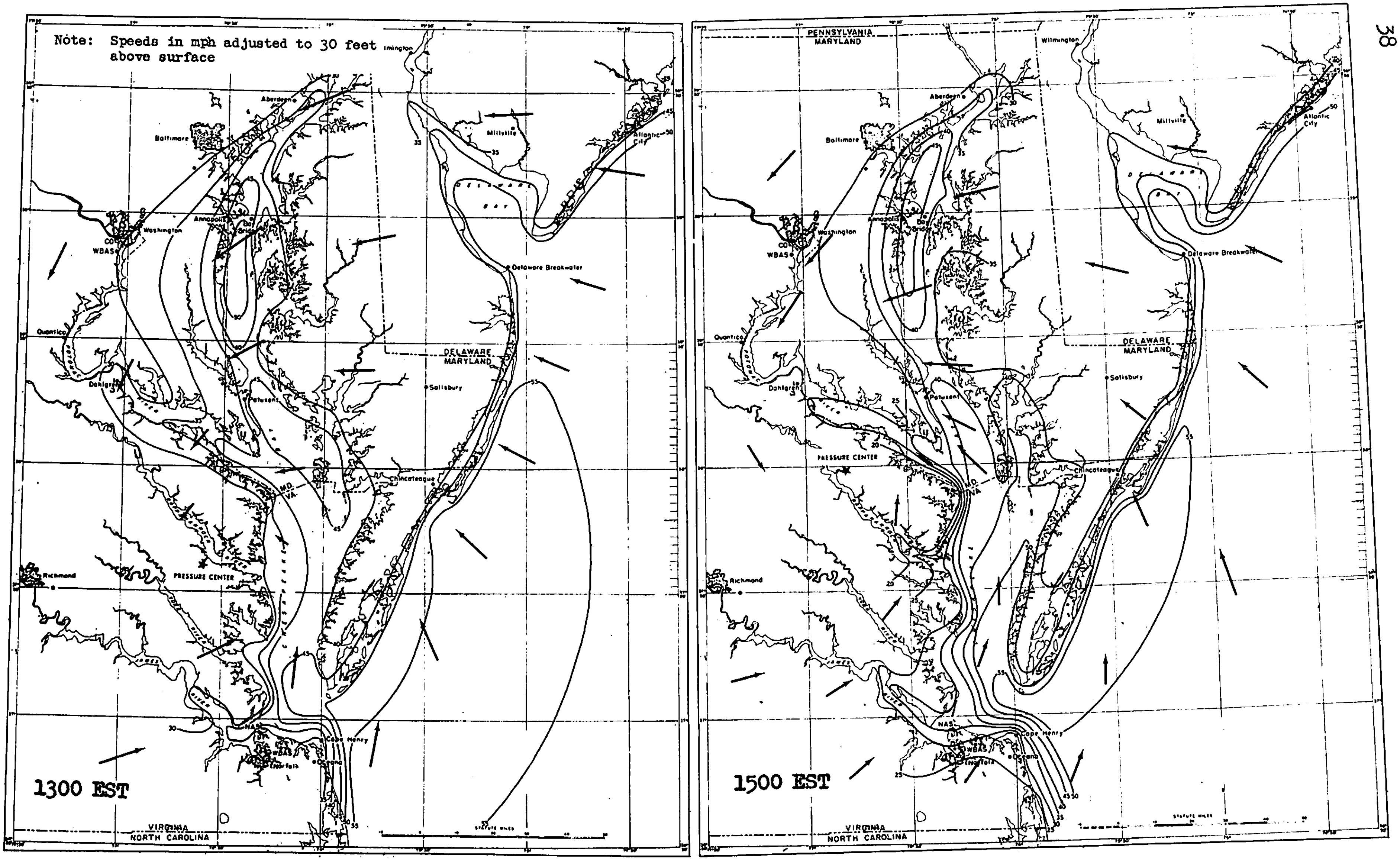


Figure 6-2d. Wind speeds and directions, August 23, 1933.

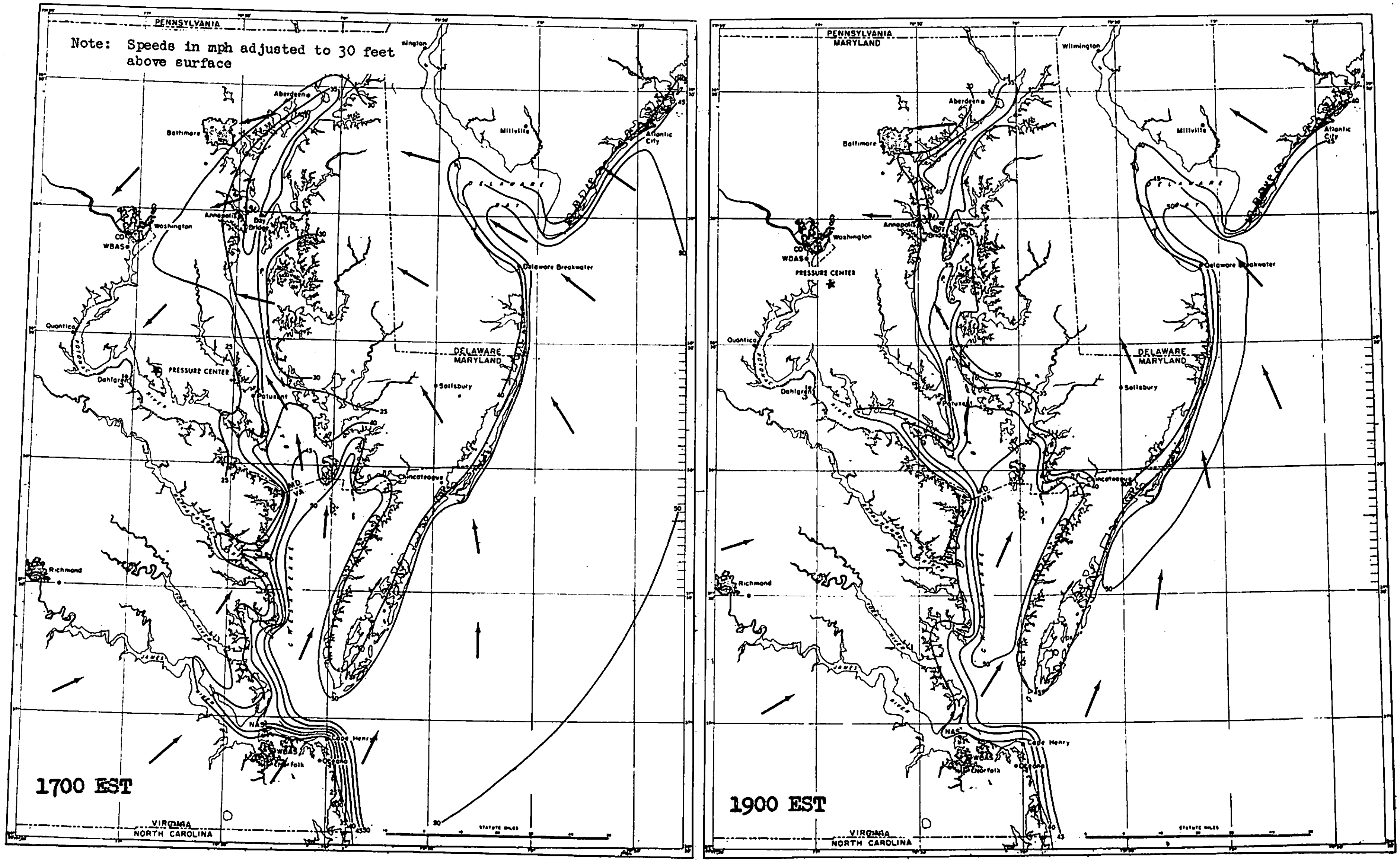


Figure 6-2e. Wind speeds and directions, August 23, 1933.

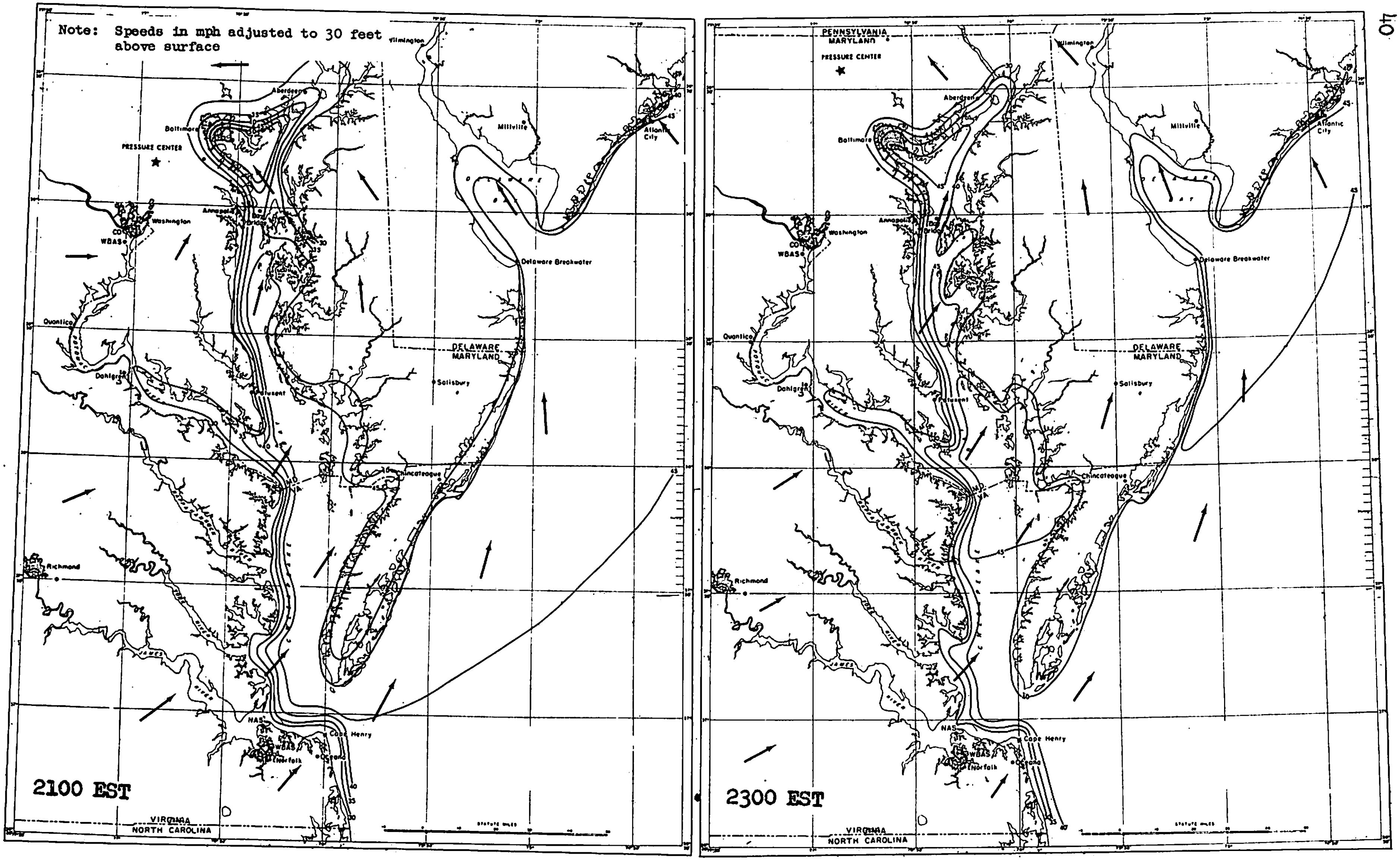


Figure 6-2f. Wind speeds and directions, August 23, 1933.

WINDS

Since no wind-speed observations over Chesapeake Bay were available, Bay winds were estimated by making full use of speeds adjacent to the Bay. Observations of wind speed made near the southern end of the Bay at Norfolk and Cape Henry, Va., were adjusted to 30-ft. over-water values, as described in section 1. The washington, D. C., downtown observations were used as an indication of wind speed after an evaluation from a comparison with the Washington National Airport for later years (section 20). The only useful observations near the north end of Chesapeake Bay were taken at the Baltimore Weather Bureau Office. Speeds from certain directions were reduced at this site because of high structures adjacent to the anemometer. Adjustment ratios were determined for the Baltimore Weather Bureau Office from a wind-speed comparison with Baltimore Harbor Field.

Baltimore Weather Bureau Office and Harbor Field wind comparison. Autographic wind records were maintained concurrently for a time at the Baltimore Weather Bureau Office and Baltimore Harbor Field. Harbor Field occupied an area on the north shore of the Patapsco River where it has widened and about 5 miles from the main part of the Chesapeake Bay. The exposure seemed to be such that Lake Okeechobee factors (fig. 1-2) could be applied to derive over-water speeds. For the period from 1945 to 1948, a sample of 1-hour average wind speeds in the higher speed range at these two sites was selected for comparison. Ratios of mean speeds from this sample at the two stations are shown in table 6-1.

Observed 10-minute average wind speeds at the Baltimore Weather Bureau Office during the 1933 hurricane were first converted to equivalent Harbor Field speeds by applying the smoothed ratios listed in table 6-1 and then were adjusted to 30-ft. over-water speeds. The winds blowing from the water with the longest over-water fetch were considered "off-water" values and winds blowing from land to water "off-land" (chapter 1). The adjustment factors for other directions were between the two categories with the amount of adjustment dependent upon the estimated effects of the particular frictional surfaces for that direction.

Isotach charts. The hurricane was in the decaying stage at the time it reached Norfolk. The radius of maximum wind had become large and poorly defined and the maximum 30-ft. wind speed had decreased to only 60 m.p.h. (estimated from observations at Norfolk and Cape Henry, Va.). The wind continued to decrease as the storm moved northward and continued to fill. Isotach charts for the period from 0100 EST to 2300 EST August 23, 1933 are shown in figure 6-2a through f.

Table 6-1. - Comparison of wind speeds at Baltimore Weather Bureau Office and Baltimore Harbor Airport (1945-1948)

	Speeds (m.p.h.)						
	WBO		Harbor Field			Ratio of means WBO Harbor Field	
Direction	Highest 1-hr	Mean of Sample	Highest 1-hr	Mean of Sample	No. of pairs in sample	Observed	Smoothed
N	22	16.2	21	17.7	31	0.92	0.92
NE	21	16.4	22	14.1	23	1.16	1.16
E	17	16.0	15	13.5	2	1.18	1.00
SE	19	16.1	28	24.9	8	0.64	0.76
S	25	18.3	34	24.0	52	0.76	0.76
SW	20	17.0	34	21.0	21	0.81	0.81
W	32	23.0	34	22.8	81	1.01	1.01
NW	31	22.9	35	24.9	77	0.92	0.92

Table 6-2. - Parameters of August 23, 1933 hurricane at the coast

P_o,	Central pressure (in.), 28.63	
P_n,	Asymptotic pressure (in.), 29.48	
V_{gx},	Maximum gradient wind (m.p.h.)*	
R,	Radius of maximum winds (n. mi.),	Computed 54 Observed 50 to 85
c,	4-hr. average forward speed at the coast (kt.), 18	

*Maximum 30-ft. over-water wind speed determined from observations to be 61 m.p.h. Maximum gradient winds not computed since hurricane was in advanced mature stage and departed considerably from model.

7. HURRICANE OF SEPTEMBER 21, 1938, IN THE NORTH ATLANTIC*

INTRODUCTION

The hurricane of September 1938 was among the most intense known to have occurred along the Atlantic Seaboard. This rapidly moving storm reached the coastline of southern New England at the time of high tide. Damage to property along the coast was due largely to the storm surge and waves generated

*Abbreviated from [6]

by the hurricane. Six hundred persons lost their lives in the storm and property damage has been placed at a quarter to a third of a billion dollars /26/.

The storm was first charted on the evening of September 16 about 800 miles east-northeast of Puerto Rico when it appears to have already been a fully developed hurricane. It moved westward during the 17th and 18th and during the 19th and 20th recurved to the north with an accelerating rate toward the United States coast. It was not until the morning of September 21, when the center was about 75 miles east of Cape Hatteras, that the hurricane seriously affected any island or coastal area. Shortly before 1600 EST of the same day the center crossed the Connecticut coast near New Haven, then, traveling at a very rapid rate in a north-northwestward direction crossed Massachusetts and Vermont. The winds on the east side of the storm path were very destructive to a distance of about 100 miles; the strong winds did not extend far to the westward.

TRACK

A detailed storm track (fig. 7-1) was taken from Pierce's maps /27/ with certain modifications. The 1200 EST position was moved northward on the basis of more complete ship observations than were available to Pierce. The track was also altered slightly over New England in order to indicate the position of the pressure center only.

PRESSURE

Pressure analyses were made hourly from 1200 EST through 1900 EST, and the maps for 1200, 1400, 1500, and 1900 EST are reproduced in figure 7-2. The pressure pattern was nearly circular through 1600 EST, but by 1900 EST it had become more elongated. Radial pressure profiles in the four cardinal directions were plotted from the maps for each hour, and the hourly continuity of these profiles was in turn used to adjust the analyses in areas of no data. Although the storm was over the ocean for the most part at 1200 and 1300 EST, ship reports to the north and west of the storm center at the 1300 EST observation time provide enough data for a fairly adequate analysis, together with continuity with later times when the storm was over land. Selected profiles along a line to the east of the pressure center, approximately normal to the direction of motion, are shown in figure 7-3. The central-pressure determinations over land are considered reliable within a few hundredths of an inch, the estimates over the sea much less so, with the reliability more appropriately expressed in quarters of inches. A central pressure of 27.75 in. at 1200 EST is derived by extrapolating the pressure profile inward from the ship reports, of which 28.10 in. (corrected) from the Birmingham City was the lowest. The central pressure at the Connecticut Coast is estimated at 27.86 in. A graph of central pressure vs. time appears in /6/.

RADIUS OF MAXIMUM WINDS

The radius of maximum winds was large and seems to have varied somewhat around the storm. In the northern part, Hartford reached its maximum wind speed at a distance of about 50 n. mi. from the wind center. However, after

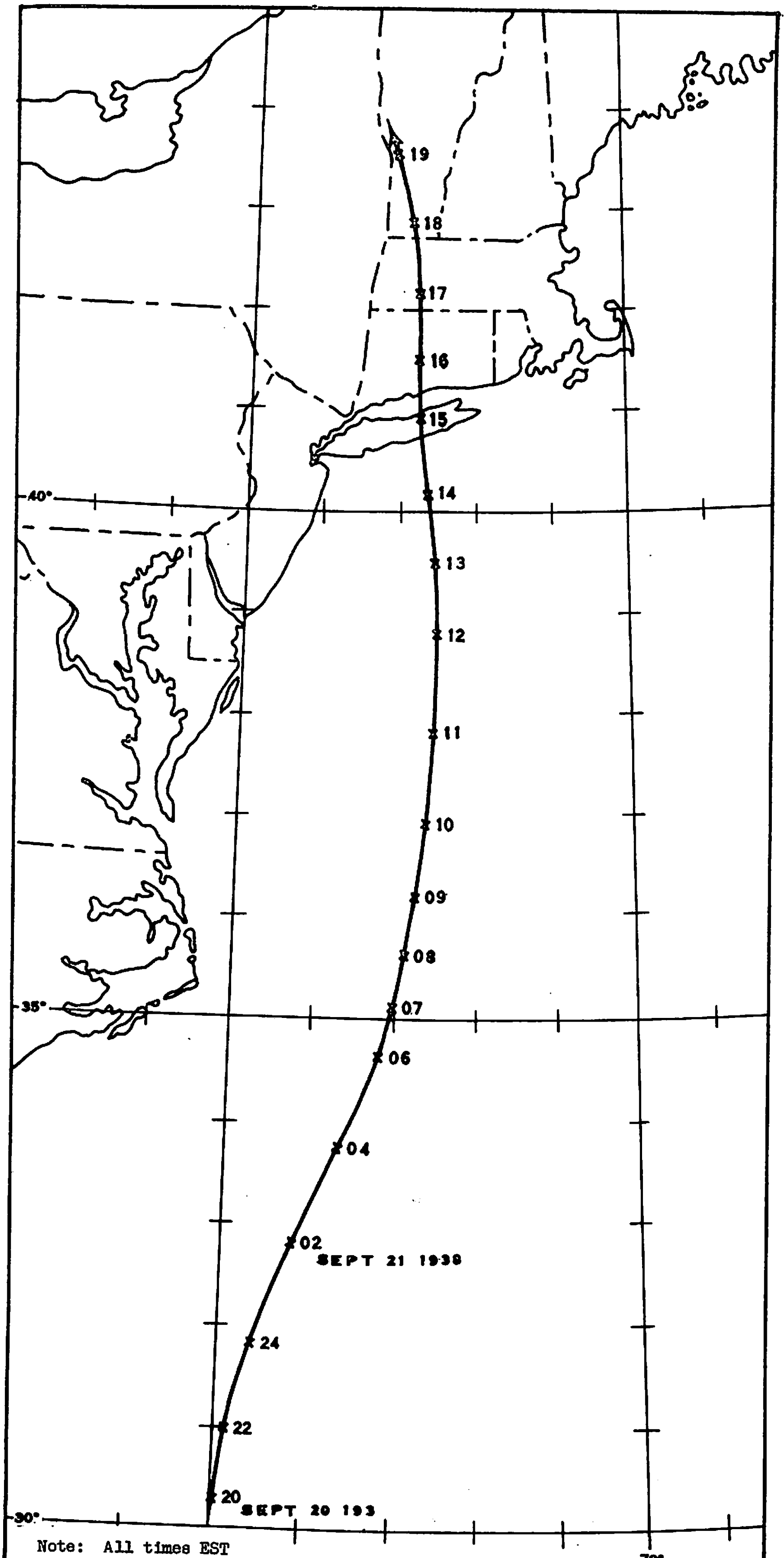


Figure 7-1. Track of pressure center, hurricane of September 20-21, 1938.

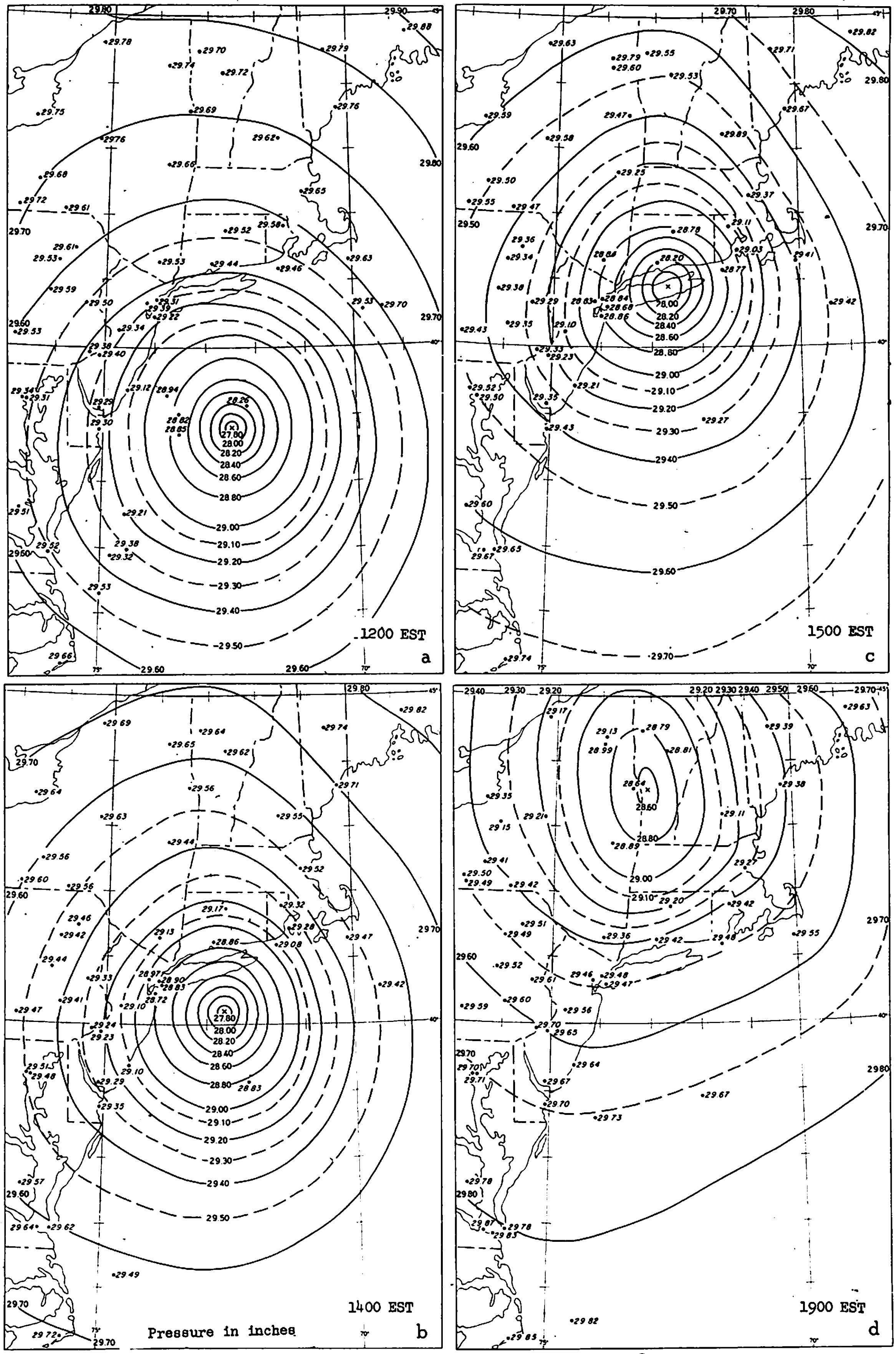


Figure 7-2. Sea-level pressure, September 21, 1938, 1200-1900 EST.

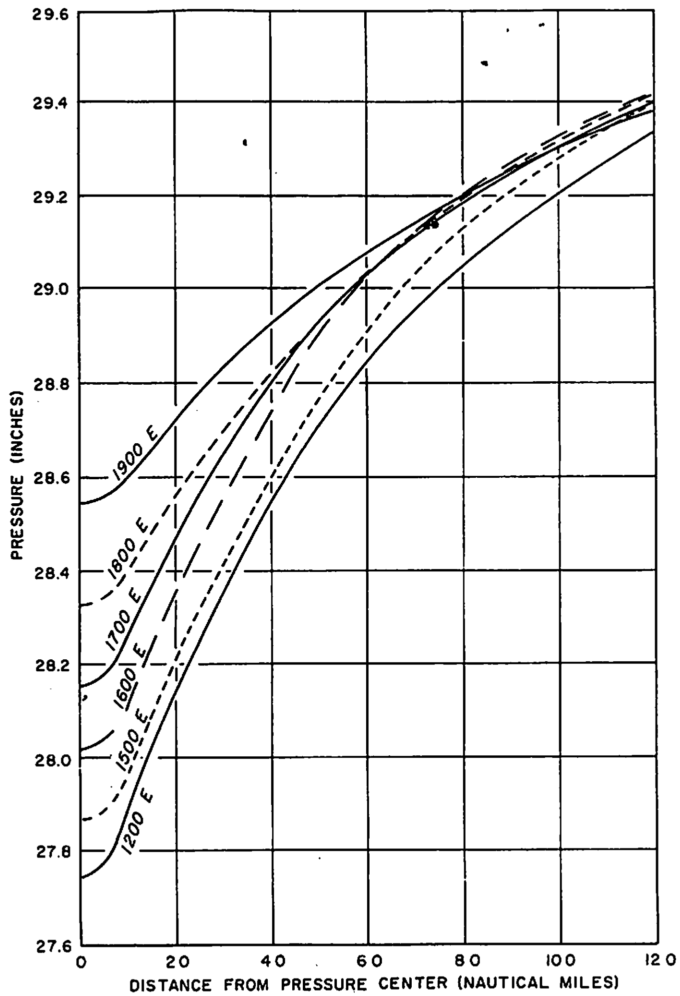


Figure 7-3. Pressure profiles east of center September 21, 1938.

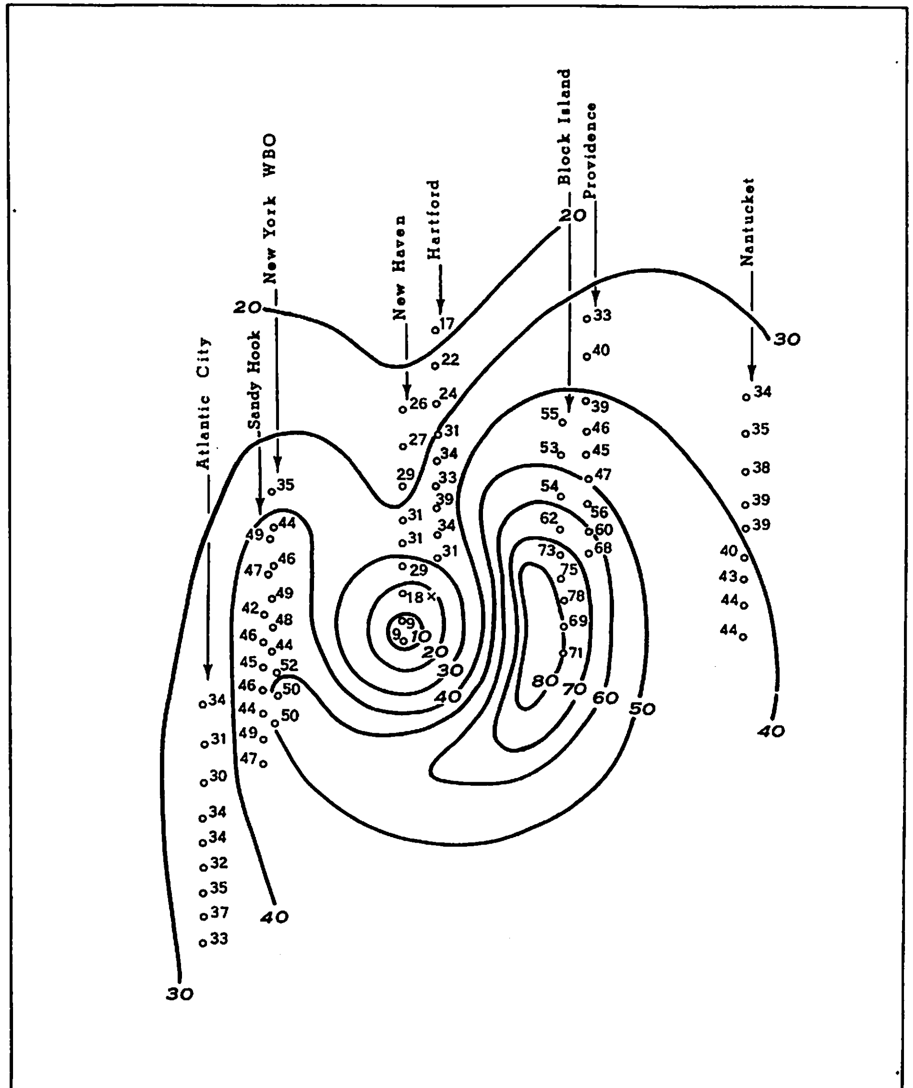


Figure 7-4. Composite isotach pattern or surface wind speeds relative to pressure center (X), 1400-1600 EST September 21, 1938.

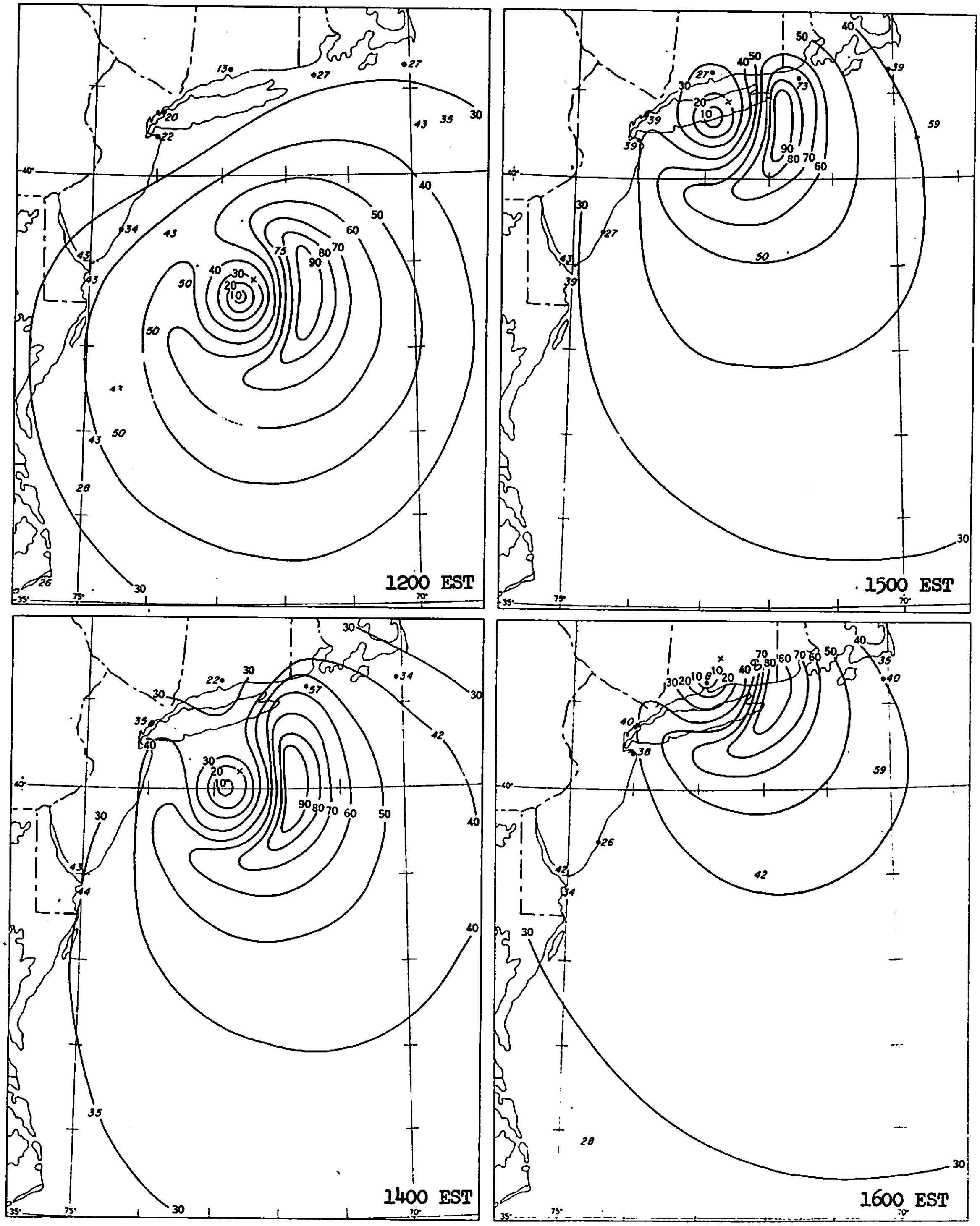


Figure 7-5. Wind speeds at 30 ft., September 21, 1938, 1200-1600 EST, all speeds in m.p.h. Data with dot positions are Weather Bureau station observations, reduced to 30 ft.; data without dot positions are ship reports, unadjusted. X shows location of pressure center.

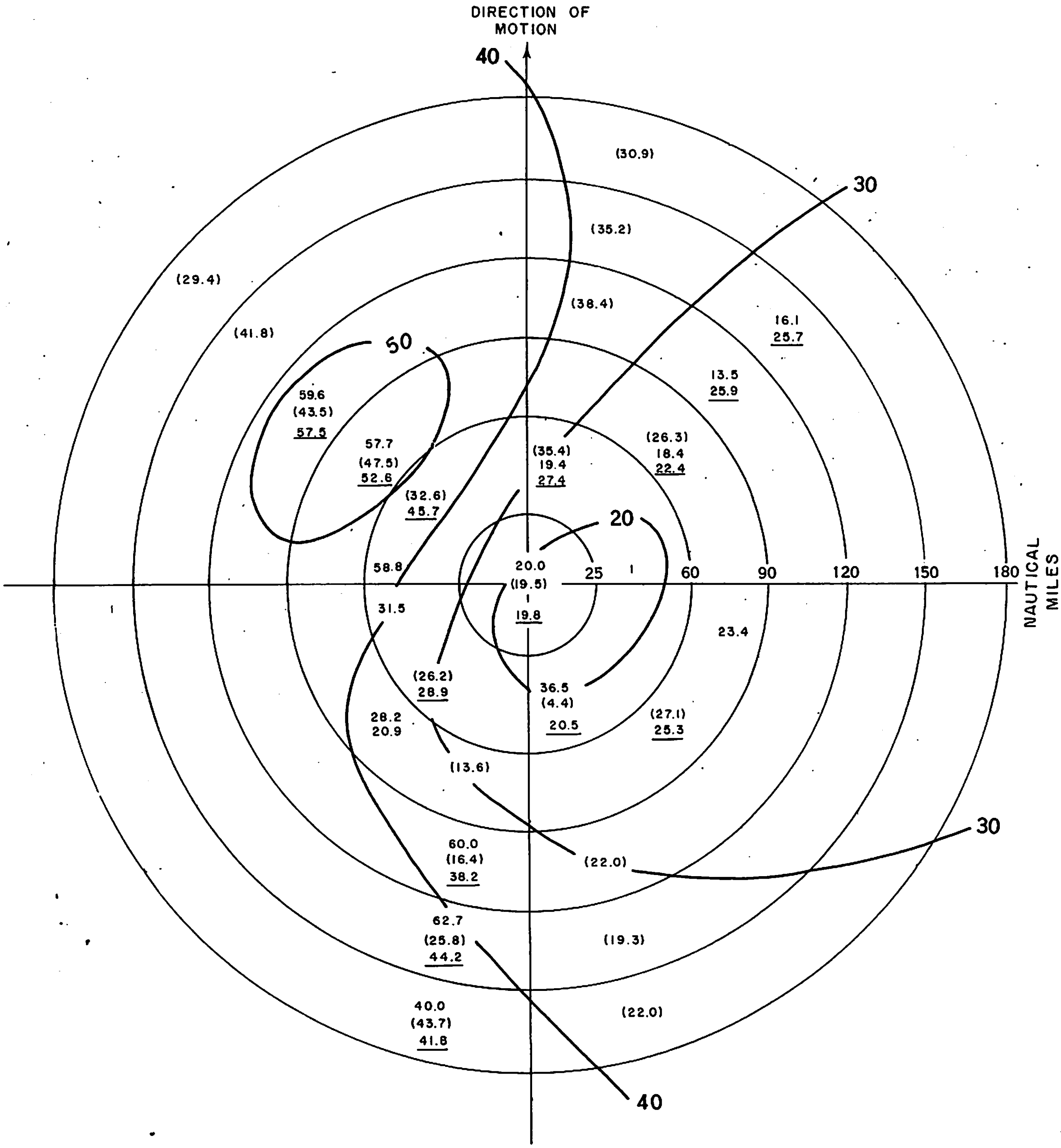


Figure 7-6. Wind deflection angles, hurricane of September 21, 1938.

the storm had passed Hartford, the maximum wind occurred at a distance of 30 n. mi. from the center. The same pattern was shown at New Haven where the maximum speed was observed at about 43 n. mi. to the north of the approaching storm center and 30-35 n. mi. to the south of the center as it moved off. The second maximum was more difficult to distinguish, however. On the east side of the storm, there is a lack of stations between the wind center and about 60 n. mi., and R was placed at the radius indicated by the computed gradient winds in this direction. Other evidence for R is a report of calm winds as far out as 30 n. mi. /28/ and a Corps of Engineers report /29/ in which the region of strongest winds was estimated at a distance of 64 n. mi. to the right of the storm center. There were more ships reporting in the storm area on the afternoon of the 20th, when the storm was at 30°N., than on the 21st. At this time R appears to have been roughly the same (50 n. mi.), or slightly less than at the coast of New England.

WIND SPEED DISTRIBUTION

An empirical relation (not shown) was derived for this storm between observed winds and gradient winds, analogous to and modeled after figure 1-3. For this the observed winds at Block Island, Providence, Nantucket, and New Haven, reduced to 30 ft. and common frictional category, were compared with gradient winds along pressure profiles to the east of the storm shown by figure 7-3. The foregoing relation was then used through the eastern half of the storm to derive winds from the pressure fields of figure 7-2. These derived winds were in turn smoothed into the wind observations to create a single standard composite isotach pattern, figure 7-4. In performing this operation both gradient and observed winds were adjusted to 1500 EST as a common time base, applying the filling adjustments described in Chapter 1.

Over-water isotachs, the end product of the wind-speed analysis, are shown for 1200, 1400, 1500, and 1600 EST in figure 7-5. Winds prior to 1200 EST may be estimated by transposing the pattern for 1200 EST along the track (fig. 7-1). Over-water isotachs for specified times were derived from the composite pattern of figure 7-4 by increasing the speeds by 12 percent to adjust from off-water to over-water and by applying an additional small adjustment for filling of the storm between the time concerned and 1500 EST.

Ship and coastal wind speeds at the time of each map were plotted and the adjusted composite patterns were further modified to fit these. The coastal data were adjusted only for the reduction to the standard 30-ft. elevation. The 1200 EST isotach map is similar to Hughes' mean pattern /10/ even though Hughes' data were south of 30°N. and did not include storms that had recurved.

WIND DIRECTION

Deflection angles were examined in some detail in an effort to find a pattern through the storm as a whole that could be extrapolated from the regions of data to the regions of no data. Since the pattern was not well defined, the deflection angles for another great New England storm, that of September 1944, were added to expand the data. Average angles by zones from both New England storms were plotted on the same figure, together with the mean of the two storms (fig. 7-6), and a rough analysis was drawn to the data. This pattern is only approximately indicative of what occurred in the hurricane over the ocean because of the factors producing variability in deflection angles.

It appears from the right half of figure 7-6, and from Hughes' [10] mean wind-direction pattern, that use of the mean deflection angles of 25° outside R and 20° inside R, would be satisfactory for over-water winds in the shoreward quadrant of this storm.

Table 7-1. - Parameters of September 21, 1938, hurricane in the North Atlantic

P_o,	Central pressure (in.), 27.86
P_n,	Asymptotic pressure (in.), 29.52
V_{gx},	Maximum gradient wind (m.p.h.), 83
R,	Radius of maximum winds, (n. mi.), Computed 50
c,	4-hr. average forward speed at the coast (kt.), 47

8. HURRICANE OF SEPTEMBER 14, 1944, IN THE NORTH ATLANTIC

INTRODUCTION

The "Great Atlantic Hurricane" of September 1944 was one of the most violent hurricanes of record. There were 390 lives lost in the storm /30/, a large portion as the result of marine disasters. Five modern U.S. Navy and Coast Guard ships were sunk. Great damage was done along the New Jersey coast, and as the storm passed by New York, water crept into the subways and stalled trains /31/. The storm moved over Connecticut, Rhode Island, and southeastern Massachusetts at a time of normally low tide and passed over the coast at an oblique angle, with the right sector of the storm remaining over the sea. As a result, the storm surge experienced along the coast in this area was much less than that experienced in the 1938 storm (section 7). Property damage along the coast from North Carolina to Maine was estimated at $100,000,000 /30/.

The hurricane was first detected 1400 miles east-southeast of Miami on September 8. The storm moved in a typical westward track traveling to about 300 miles north of Puerto Rico on September 10 and 11. As the storm approached the northern Bahamas on the 12th, the central pressure was estimated at 26.85 in. /31/. This extremely low pressure was borne out by the weather log of the USS Alacrity. A reconnaissance flight into the storm at this time reported winds of 140 m.p.h.

During the night of the 12th, the storm recurved and moved northward, paralleling the United States coast, at a rate of 25-30 m.p.h. It passed east of Hatteras, N. C. on the morning of the 14th, recurved slightly to the northeast, and increased its forward speed to 40 m.p.h. A reconnaissance flight into the center of the hurricane when it was off Cape Henry, Va., reported an average wind at the flight level, 3000 to 5000 ft., from 309° at 119 m.p.h. in the southwest quadrant /32, 33/. The center of the storm crossed over the Rhode Island coast and southeastern Massachusetts that evening.

Off Cape Hatteras, the central pressure was estimated to be 27.87 in. The central pressure continued to fill as it moved northward to New England until at Point Judith, R. I., it was 28.31 in.

The winds and pressures over the sea from Cape Hatteras to the New England coast have been reconstructed by indirect analysis from coastal observations. Because of wartime security there are no ship observations available for this portion of the storm.

TRACK

The track of the pressure center in the storm is shown with hourly positions in figure 8-1.

PRESSURE

Radial profiles of sea level pressure are shown in figure 8-2. These are extrapolated and interpolated from the coastal observations.

ISOTACH CHARTS

Two basic composite wind patterns were developed by the standard techniques, one pertaining to the time the storm was opposite Hatteras (0820 EST September 15, fig. 8-3) and the other pertaining to the time the storm center crossed the Rhode Island coast (2000 EST, September 15, fig. 8-4). Wind observations from land stations along the coast were adjusted to 30-ft. over-water wind speeds and then to 0820 EST and 2200 EST September 15 by formula (1-7), in the usual manner. The adjusted speeds and reported directions were then plotted at the appropriate bearing distance from the storm center and isotach analyses constructed. In the critical eastern half of the composite pattern at Cape Hatteras where observations were lacking, wind speeds were estimated by computing the gradient wind from the pressure field and reducing it to 30 ft. at various storm radii with empirical adjustment factors as described in Chapter I.

The New England coast composite pattern (fig. 8-4) appeared to be excessively irregular for maximum utility in computing wind effects on the sea surface. The irregularities are due both to the approximate nature of the various adjustment factors applied to the wind speeds and also to real short-period small-area variation in speeds which are present in all hurricanes. The composite pattern was smoothed by applying a smoothing formula along circles around the hurricane center at 10-mile intervals. Wind speeds read from the analysis of figure 8-4 at 20° intervals on each 10-mile circle were smoothed by the formula:

$$\bar{V} = .05\ V_{-40} + .25\ V_{-20} + .40\ V + .25\ V_{+20} + .05\ V_{+40} \qquad (8\text{-}1)$$

where $\bar{V}$ is the smoothed speed at any grid point, V the speed at the same grid point from the original analysis, and the subscripts in the formula denoting grid points the indicated number of degrees counterclockwise or clockwise along the circle. The resulting smoothed wind pattern for the New England coast is shown in figure 8-5. This type of smoothing was not applied to the Cape Hatteras composite pattern (fig. 8-3) because the lesser amount of data would have made it ineffective.

The final wind-speed patterns are shown in figure 8-6. The first pattern of this group is a reproduction of the wind-speed pattern off Cape Hatteras (fig. 8-3) with appropriate modifications of the speed in the vicinity of the coast. The last pattern is a similar replot of figure 8-5, depicting wind speeds with shore modifications for the New England coast. Wind patterns for the intermediate times were constructed by interpolating between these two wind patterns.

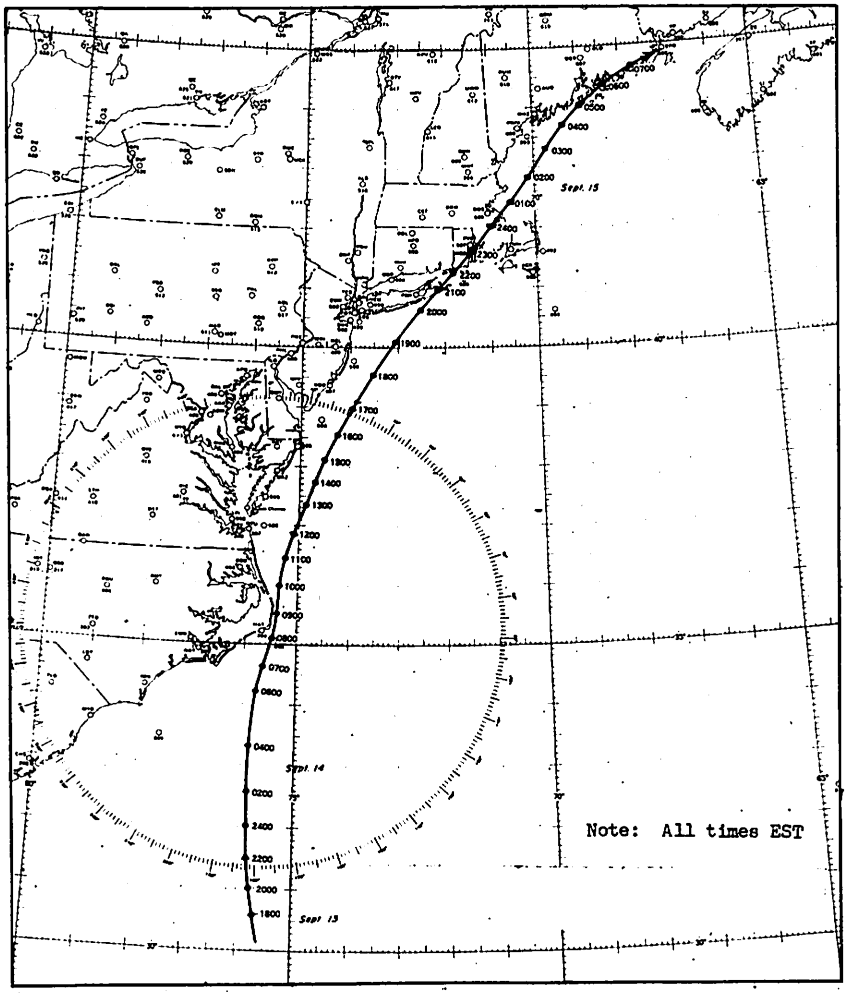


Figure 8-1. Hurricane track, September 13-15, 1944.

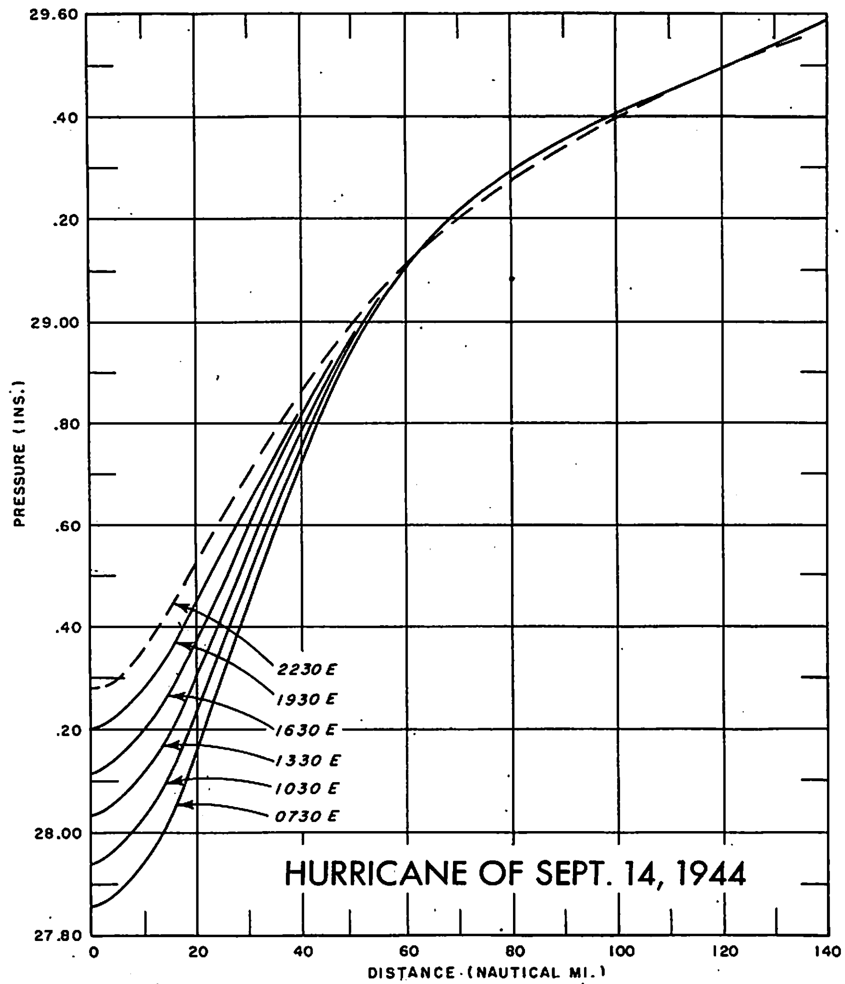
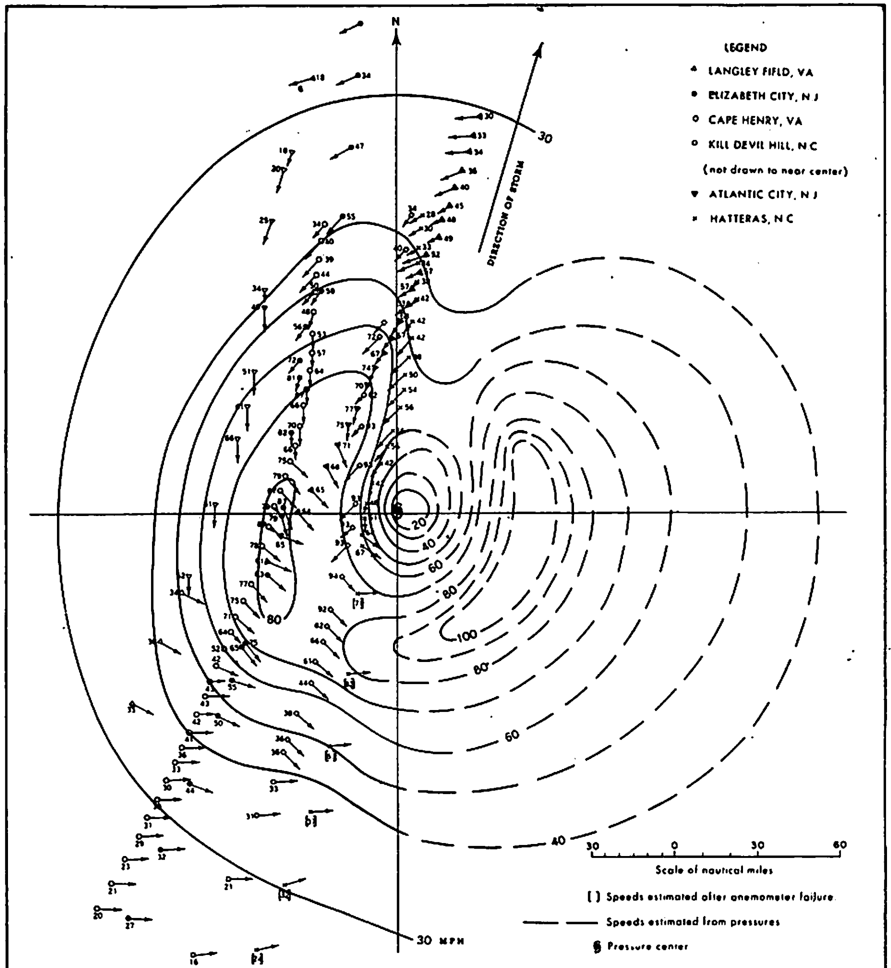
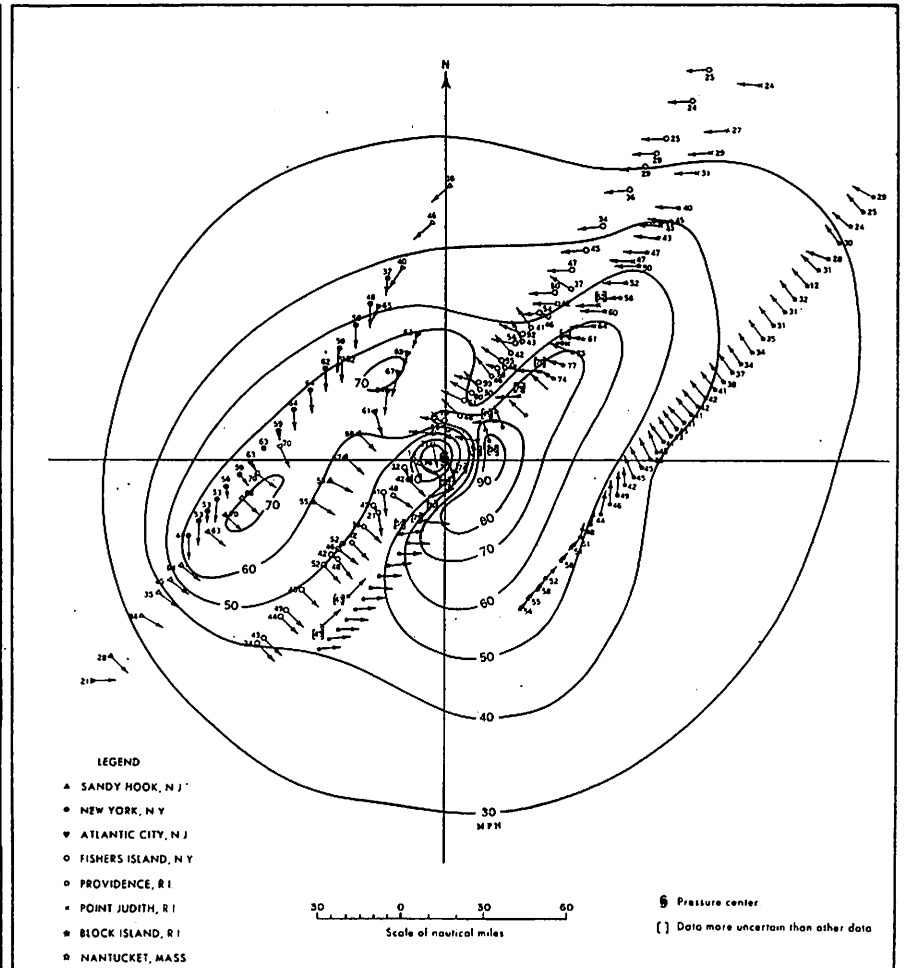


Figure 8-2. Mean radial pressure profiles, September 14, 1944.



Note: Speeds in mph plotted relative to pressure center and adjusted 30 feet over water and 0820 EST strength of storm.

Figure 8-3. Composite wind speed and direction pattern, September 14, 1944 near Cape Hatteras.



Note: Speeds in mph and plotted relative to pressure center adjusted to 30 feet over water and 2000 EST strength of storm.

Figure 8-4. Composite wind speed and direction pattern, September 14, 1944 near New England coast.

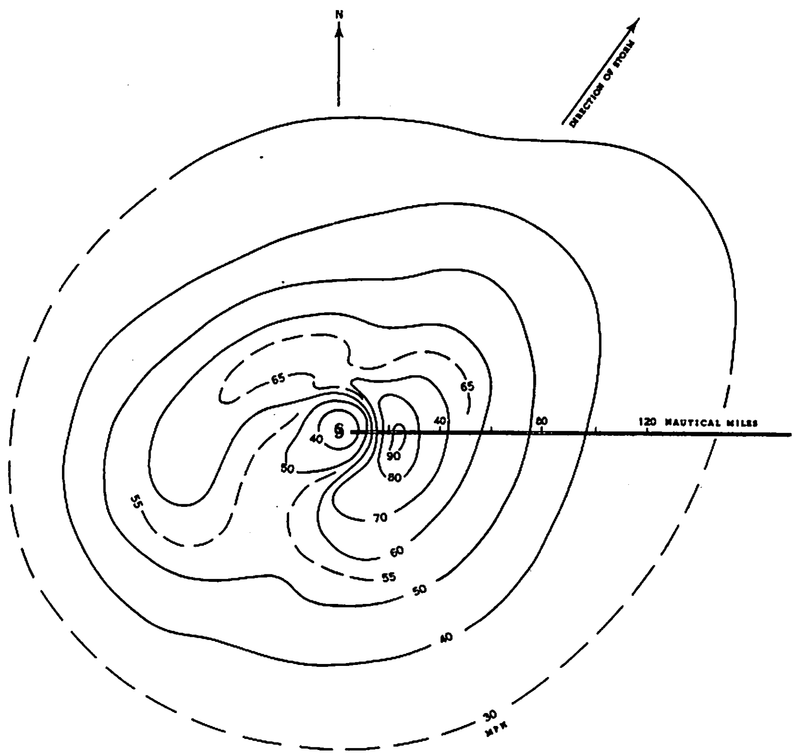


Figure 8-5. Smoothed wind speeds, September 14,1944 near New England coast, derived from figure 8-4. Speeds in m.p.h. adjusted to 30 feet over water.

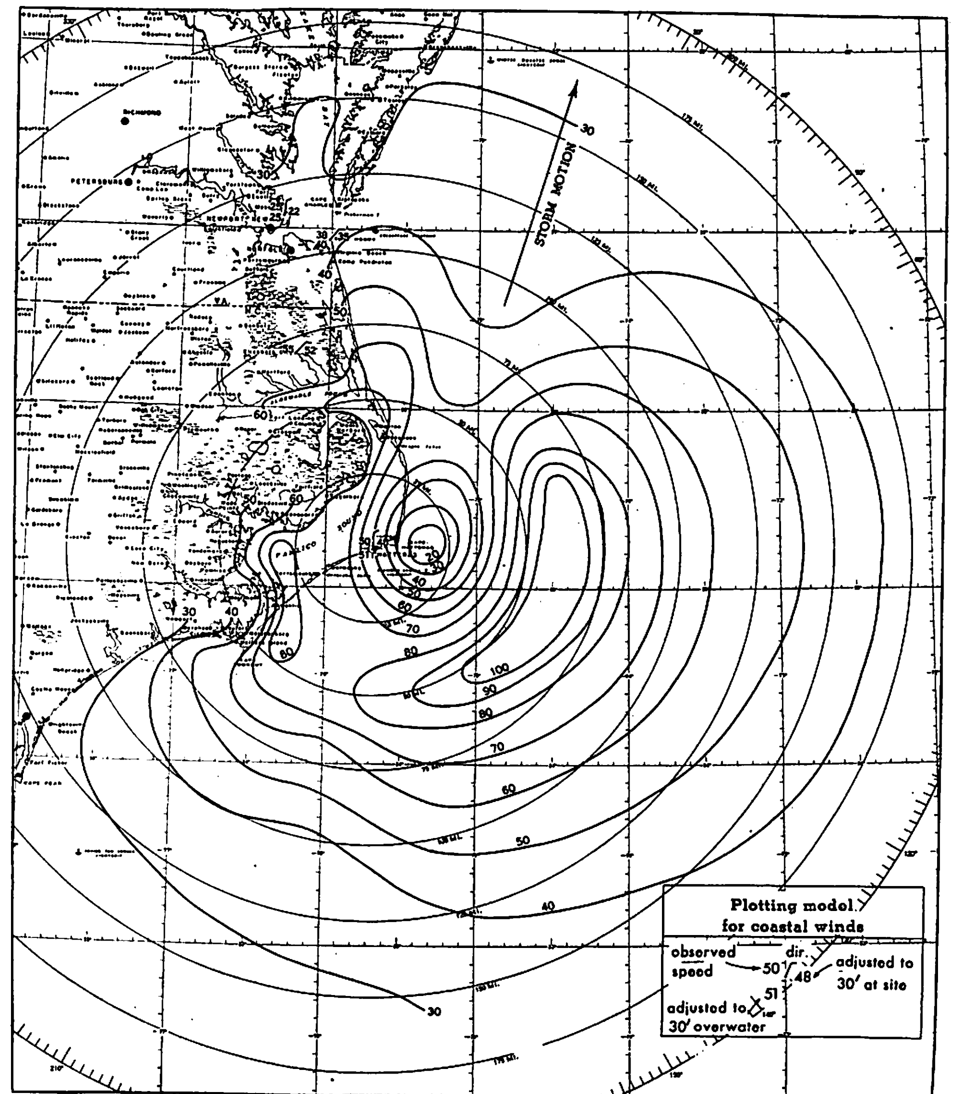


Figure 8-6a. Wind speeds, September 14, 1944, 0820 EST. Speeds in m.p.h. adjusted to 30 feet above surface.

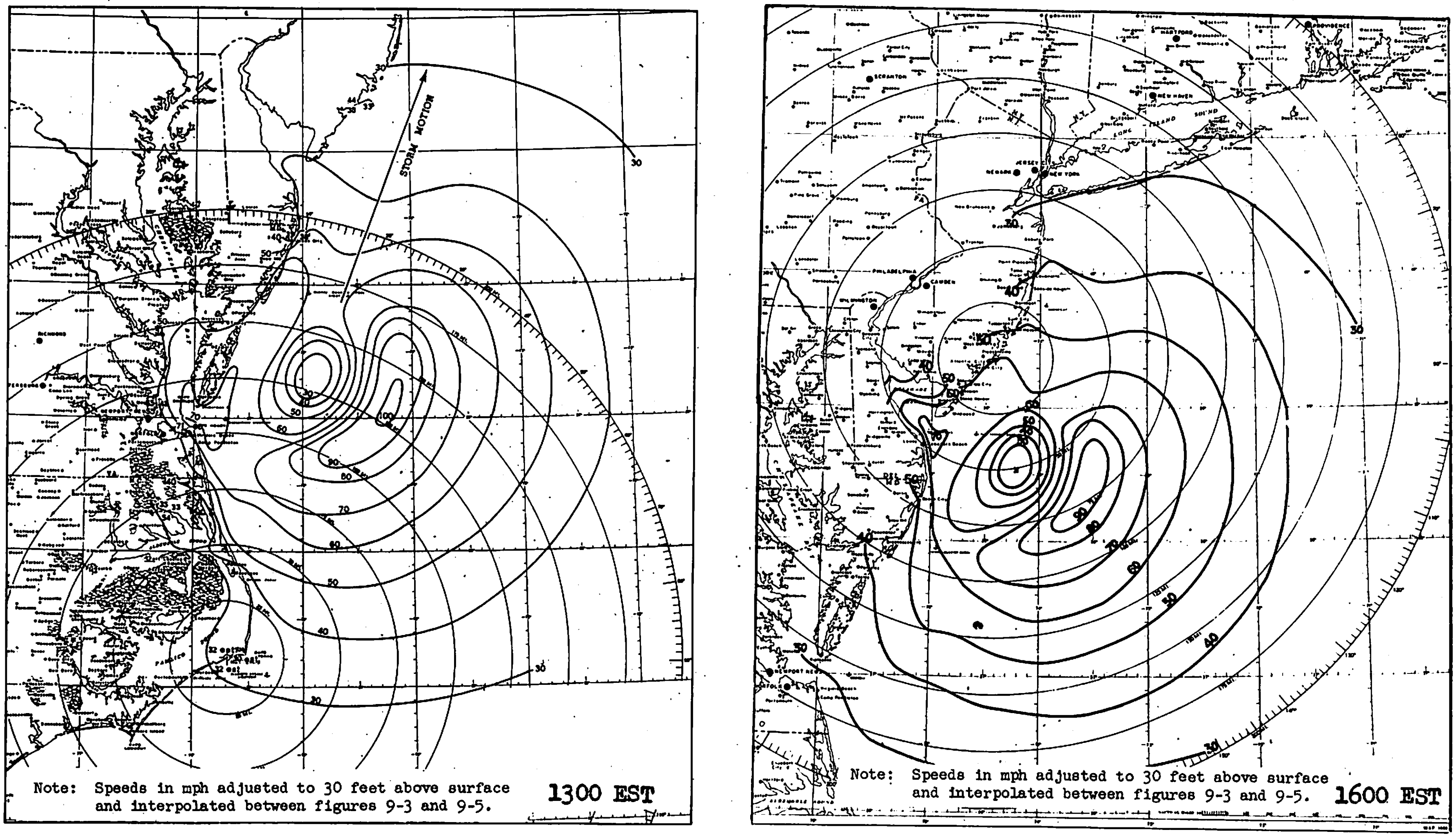


Figure 8-6b. Wind speeds, September 14, 1944, 1300 and 1600 EST.

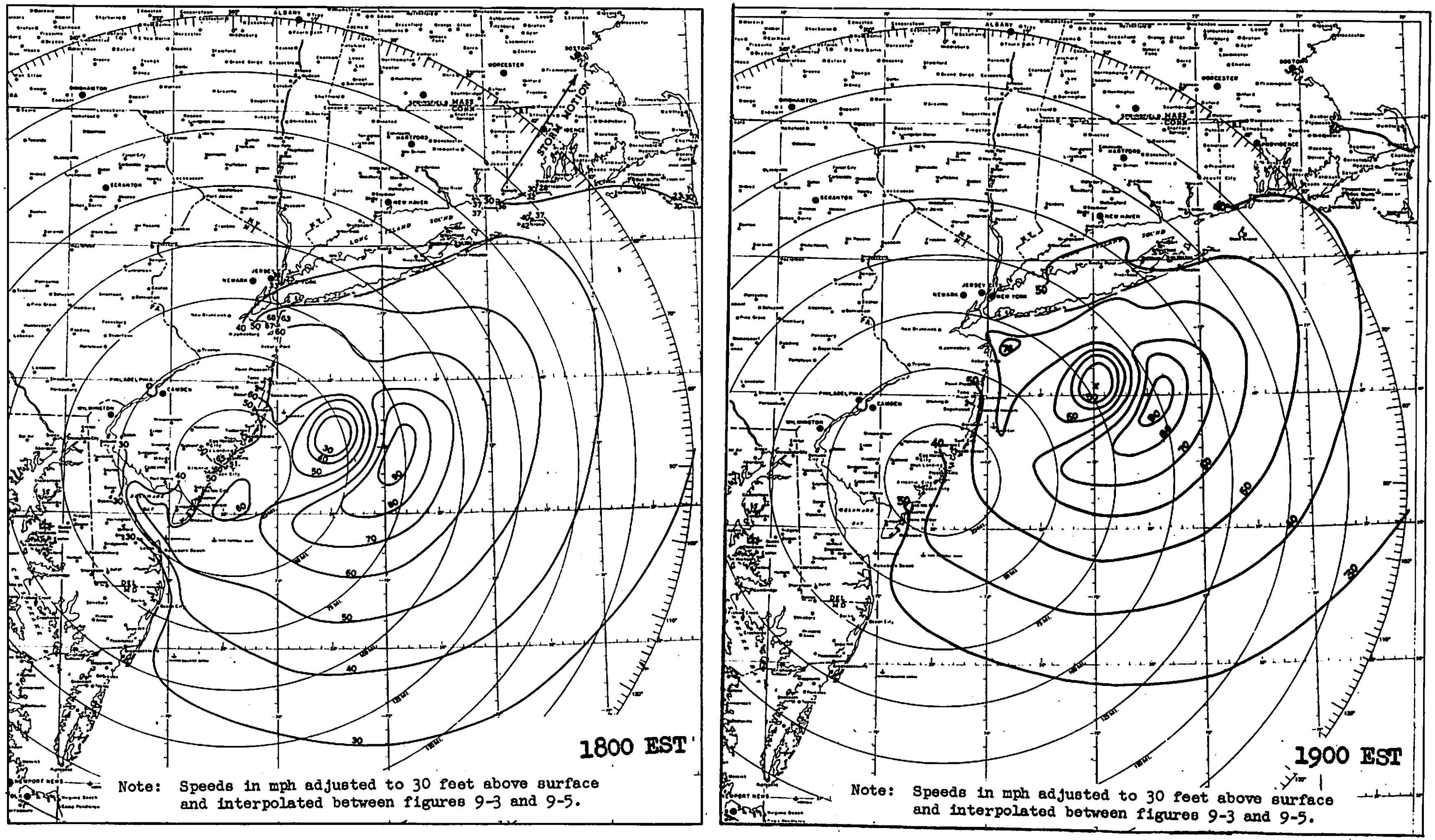


Figure 8-6c. Wind speeds, September 14, 1944, 1800 and 1900 EST.

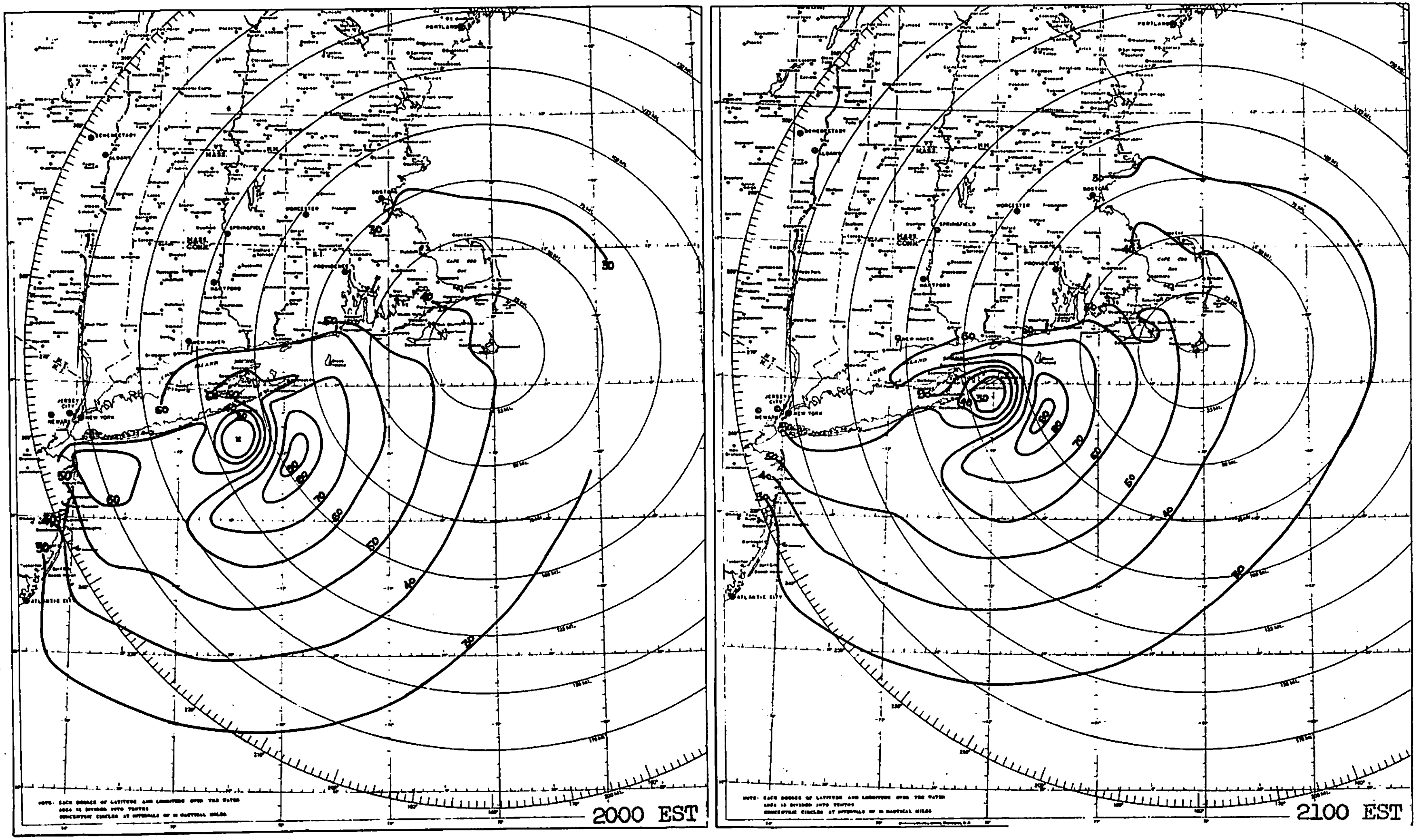


Figure 8-6d. Wind speeds, September 14, 1944, 2000 and 2100 EST. Speeds in m.p.h. adjusted to 30 feet above surface and interpolated between figures 9-3 and 9-5.

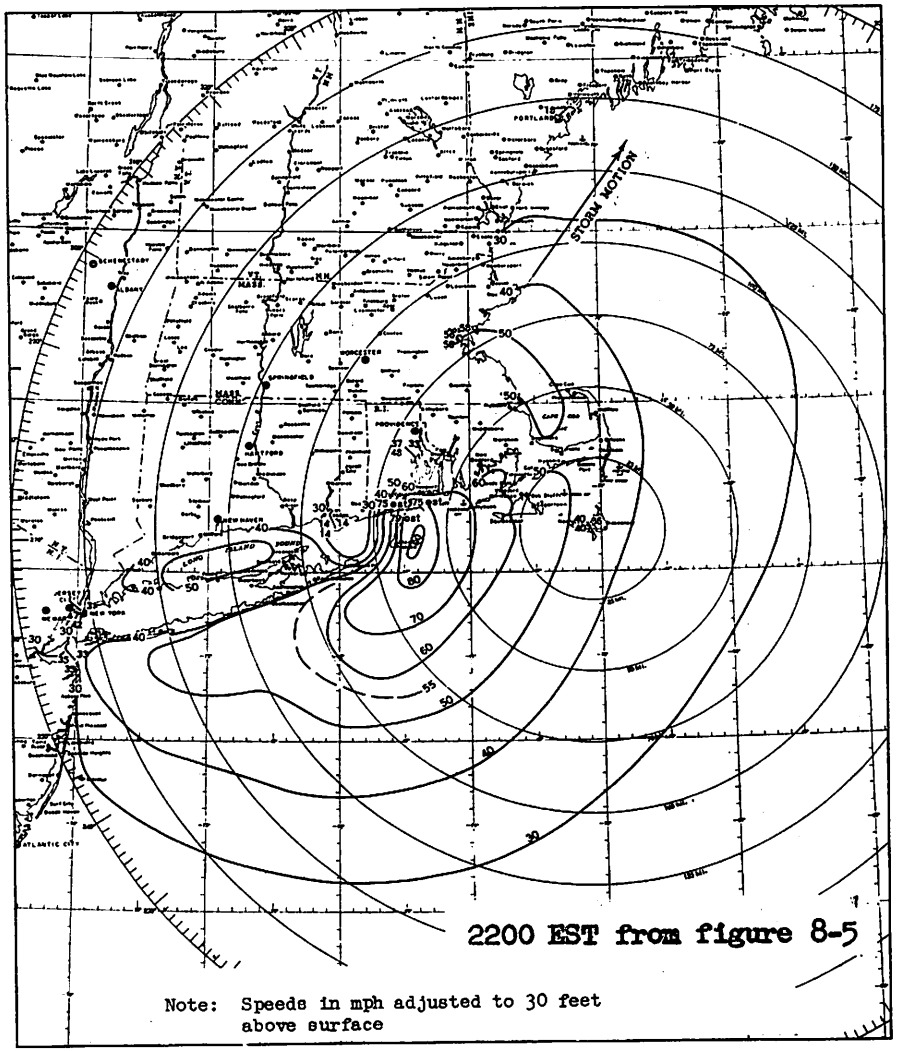


Figure 8-6e. Wind speeds, September 14, 1944, 2200 EST.

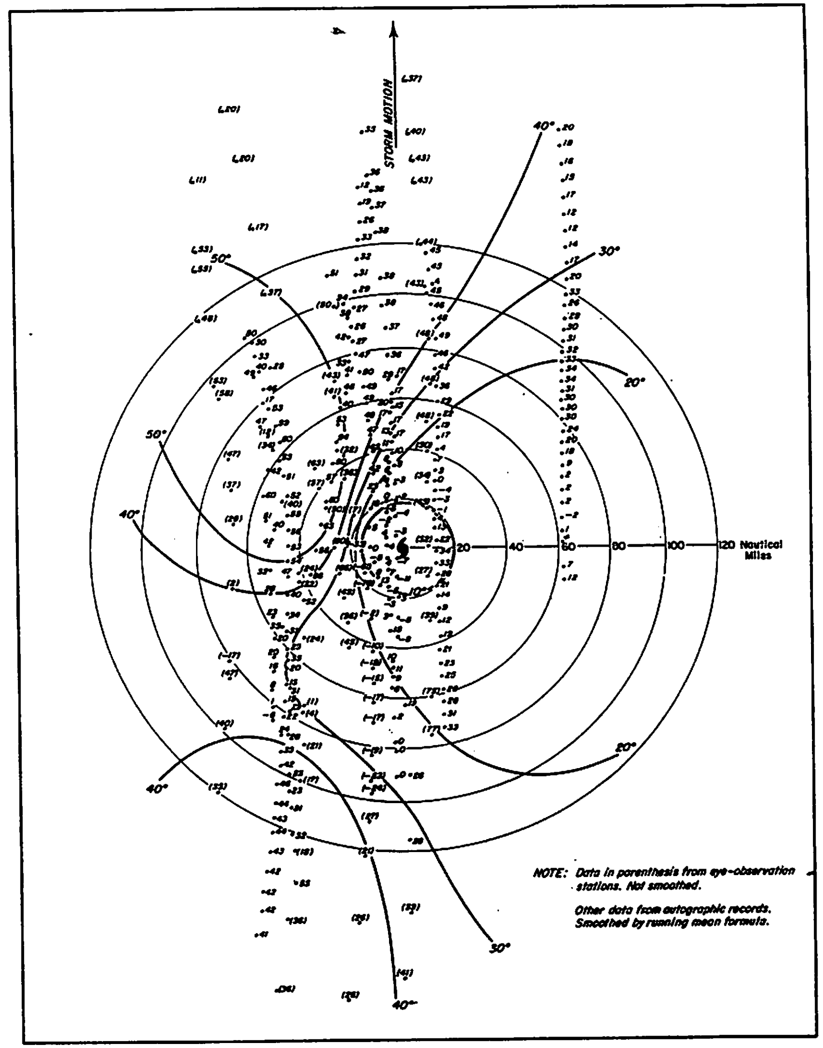


Figure 8-7. Wind deflection angles, September 14, 1944.

WIND DIRECTION

A composite wind-direction pattern was prepared (fig. 8-7) by combining and smoothing the wind directions of figures 8-3 and 8-4. This may be applied to all times from 0820 EST to 2200 EST. For stations with autographic wind-direction records the successive 10-minute mean directions were smoothed by the running mean formula

$$\bar{D}_o = 0.2\ (D_{-2} + D_{-1} + D_o + D_1 + D_2) \qquad (8\text{-}2)$$

where $\bar{D}$ is the smoothed direction for a time interval during which D_o is the observed direction, the other subscripts indicating adjacent time intervals. (Making use of some previous work, 15-minute-average directions instead of 10-minute were abstracted for some stations and were smoothed by $\bar{D}_o = 0.33\ (D_{-1} + D_o + D_1)$. The drawing os isolines on the chart (fig. 8-7) was the final smoothing step.

RADIUS OF MAXIMUM WINDS

The radius of maximum winds on the east side of the storm at Cape Hatteras has been estimated as 49 n. mi. on the basis of pressure observations, with a little supporting evidence from wind observations. At the New England coast the average radius of maximum winds is about 36 n. mi. (fig. 8-4). (The corresponding computed radius from pressure observations is 26 n. mi.) An approximately linear variation of radius of maximum winds over time between these two estimates may be assumed.

Table 8-1. - Parameters for September 14, 1944 hurricane

Near Hatteras, N. C.		
P_o,	Central pressure (in.), 27.88	
P_n,	Asymptotic pressure (in.), 30.66	
V_{gx},	Maximum gradient wind (m.p.h.), 113	
R,	Radius of maximum winds (n. mi.), Computed	49
	Observed	49
c,	4-hr average speed at coast (kt.), 23	
Near Point Judith, R. I.		
P_o,	Central pressure (in.), 28.31	
P_n,	Asymptotic pressure (in.), 29.39	
V_{gx},	Maximum gradient wind (m.p.h.), 71	

Near Point Judith, R. I. (contd.)

R, Radius of maximum winds (n. mi.), Computed 26
Observed 36

Isotach patterns based on 36

c, 4-hr average speed at coast (kt.), 30

9. HURRICANE OF SEPTEMBER 19, 1947, AT NEW ORLEANS, LA.*

INTRODUCTION

The hurricane of September 19, 1947 caused a storm surge along the entire Gulf Coast from Florida to Louisiana. The western end of Mississippi Sound received the greatest buildup. At Bay St. Louis, Miss., an unusually high tide of 15.2 feet overtopped the seawall and inundated a considerable area [20]. It was estimated that 90 percent of the hurricane damage in Mississippi and Louisiana was caused by flood waters. Fifty-one persons lost their lives in Mississippi, Louisiana, and Florida [20, 34], and on the Gulf Coast [7] 649 houses were destroyed and 25,000 damaged. Tidal damage in all areas was estimated at $110,000,000 [20].

The hurricane was first reported by a ship on September 10 at 15°N., 49°W. The storm progressed in a westward direction, crossing the Florida coast near Fort Lauderdale on September 17 and producing winds of over 100 m.p.h. The Mississippi coast and New Orleans, La., first experienced hurricane force winds on the morning of September 19. After landfall, the intensity of the hurricane decreased rapidly.

TRACK

A track of the center of minimum pressure in the hurricane was determined from pressure reports. The displacement of the wind center from the pressure center was determined from a detailed analysis of reports from stations in and around New Orleans when the hurricane passed over that area. It was assumed that the orientation and displacement of the two centers remained fairly constant for the period of analysis. The track of the wind center, based upon this assumption and isotach analysis, is shown in figure 9-1.

PRESSURE

The mean radial pressure profile for approximately 1000 CST, when the center was nearest to New Orleans, is shown in figure 9-2. Using the

*This section prepared by Herman Lake and William Malkin, Hydrometeorological Section, U. S. Weather Bureau, Washington, D. C. 1958.

pressure observations and formula (1-1), the central pressure at this time was computed to be 28.54 in.

ANALYSIS

Wind speeds. To smooth irregularities in the observed winds and adjust estimated winds, observations for each station, corrected for instrumental errors, were plotted on a graph of time versus wind speed. The reported speeds which had been estimated because of instrument failure were noted to be invariably high with respect to the average station profile drawn through all the data. Such estimated speeds were consequently reduced 10 percent, and smooth profiles were drawn for all stations. Figure 9-3 is an example of such smoothing. The values for pertinent hours for each station were reduced to 30 ft., adjusted to the off-water frictional surface, and corrected for forward movement of the hurricane by applying the formula

$$V = V_a - bT\cos\alpha \qquad (9\text{-}1)$$

where the symbols are defined as in formula (1-6). Final smoothed and adjusted values for each station were replotted as a function of radial distance from the center (fig. 9-4). From these several profiles and a computed profile based on pressure parameters, a mean radial off-water wind-speed profile was then constructed (fig. 9-4). Since this curve was based on adjusted observed speeds over the period from 0300 through 1400 CST, it was considered to be the median value for the period. Because of its close agreement with the 0800 CST reduced wind-speed values, it was considered to be representative of the 0800 CST off-water wind-speed profile 30 ft. above the surface. The final profiles for 0300, 0600, 0700, 0900, 1000, 1200, and 1400 CST (not shown) were adjusted for consistency with a family of off-water wind-speed curves computed from asymptotic central-pressure differences. The radius of maximum wind was held constant at 23 n. mi. Surface wind fields were constructed from this final family of curves and formula (1-6). These wind fields are shown in figure 9-5.

Wind directions. A deflection angle of 30 degrees toward the wind center was adopted as a compromise among the distribution of wind direction variations noted at all of the stations. The deflection angle was kept constant at 30 degrees regardless of radial distance, orientation from the center, or character of the underlying surface.

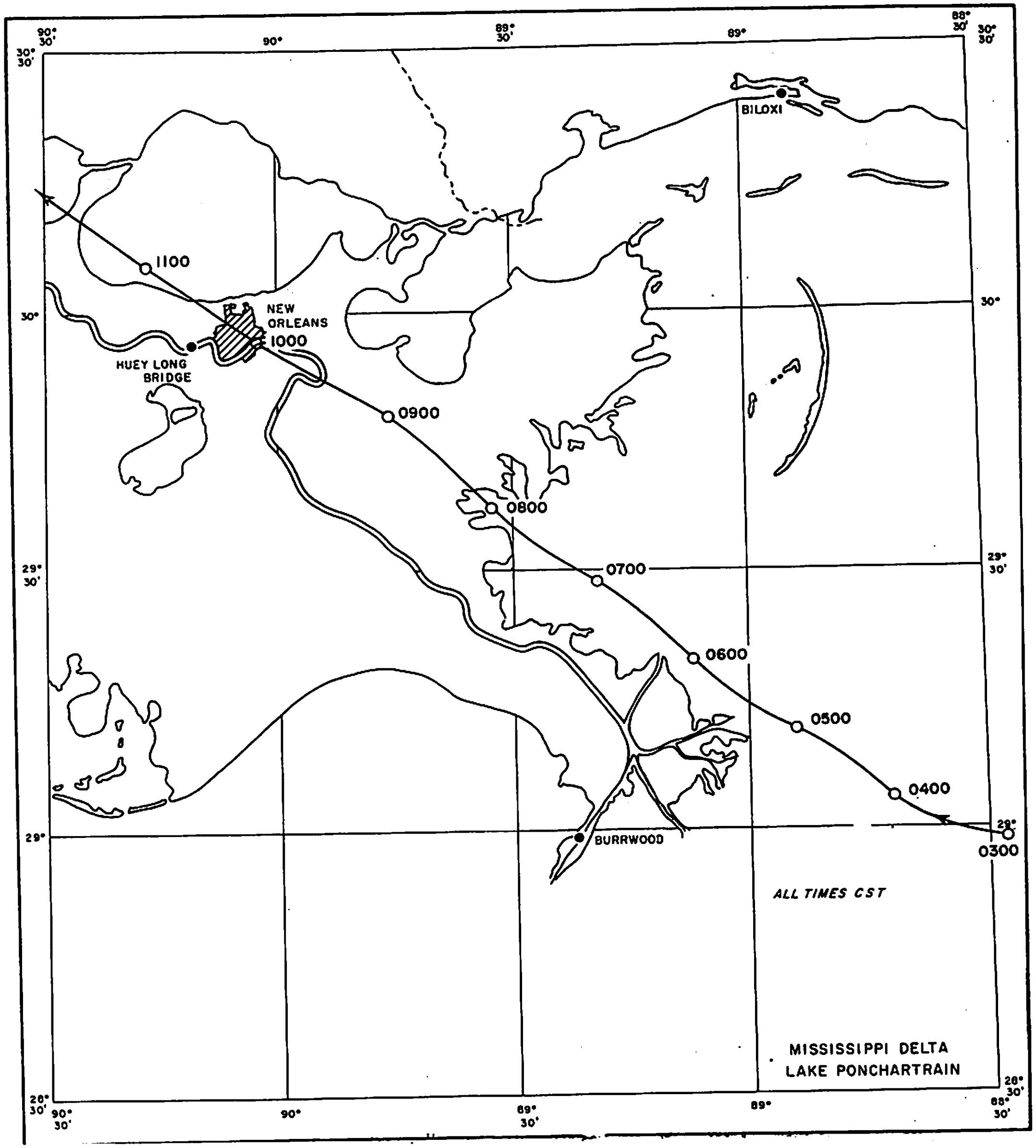


Figure 9-1. Hurricane track, September 19, 1947.

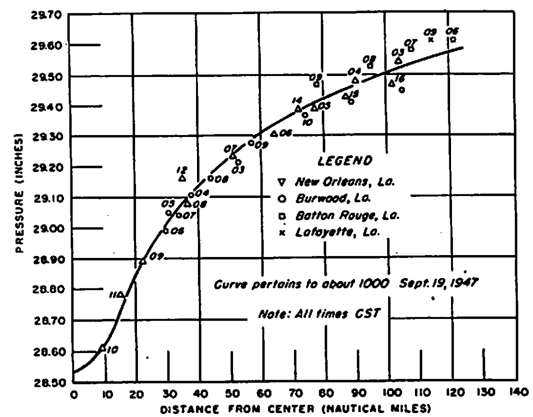


Figure 9-2. Mean radial pressure profile, September 19, 1947.

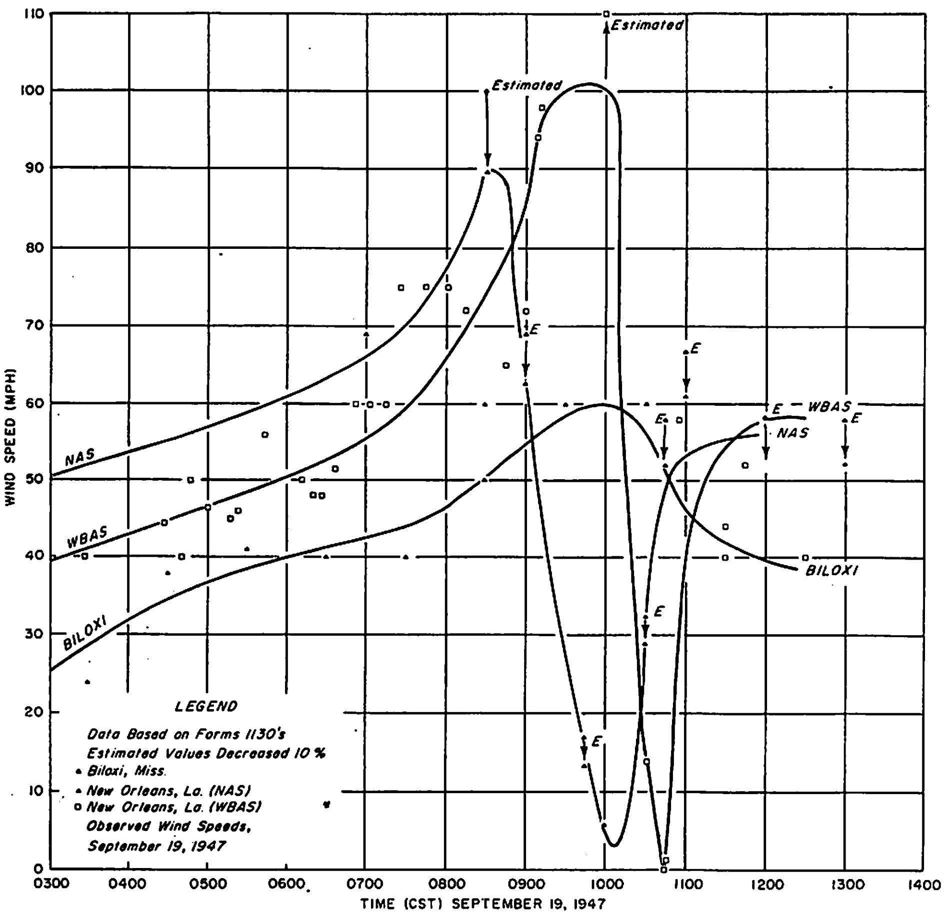


Figure 9-3. Observed wind speeds, September 19, 1947.

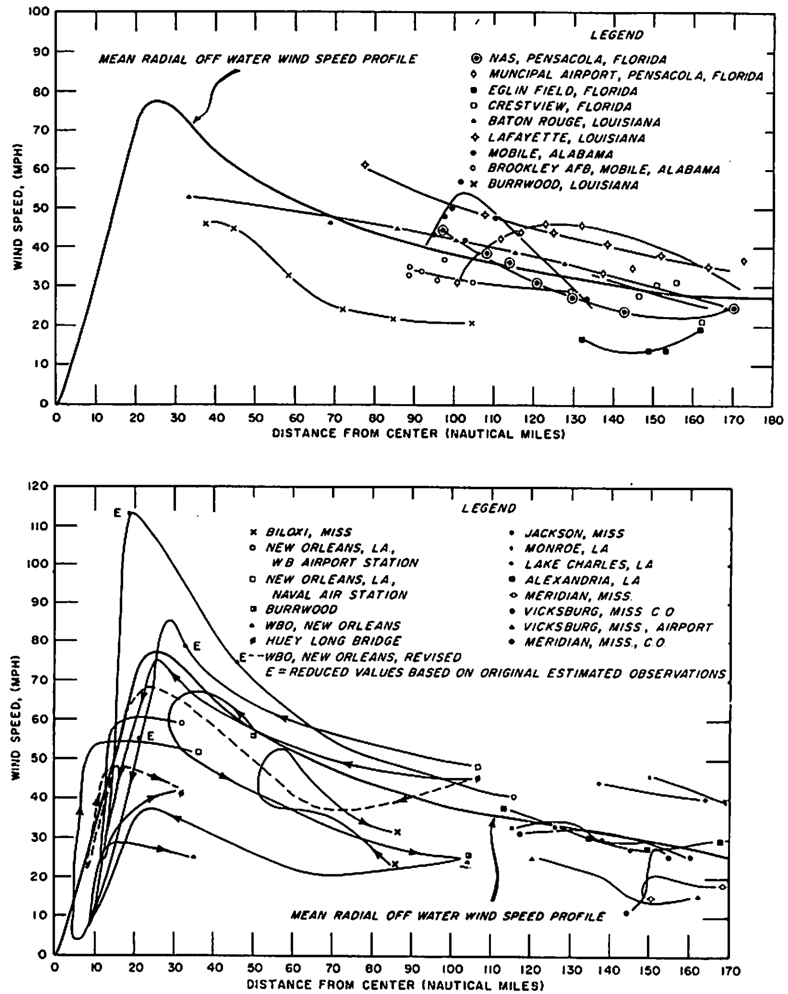


Figure 9-4. Wind speed profiles, September 19, 1947

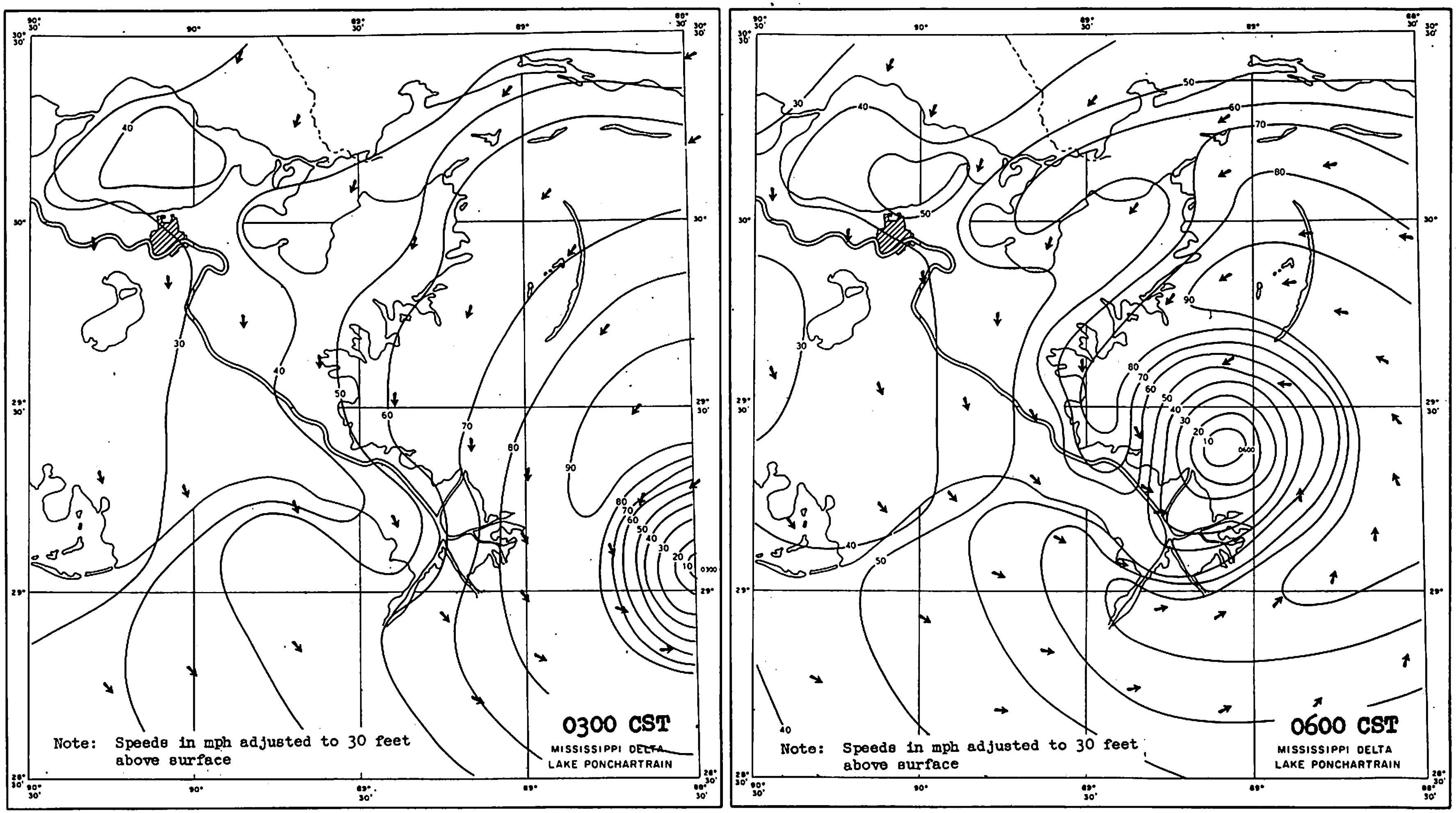


Figure 9-5a. Wind speeds and directions, September 19, 1947, 0300 and 0600 CST.

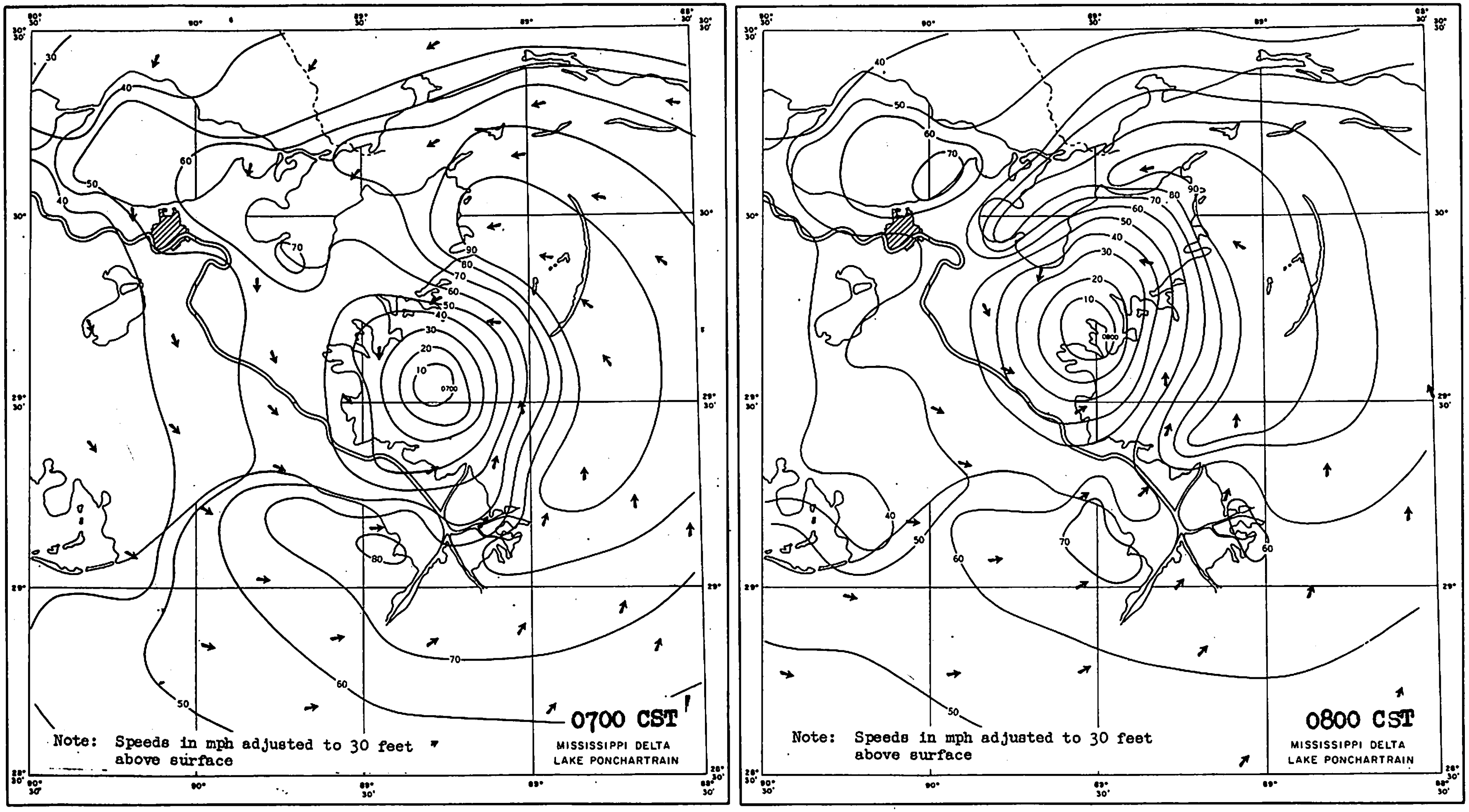
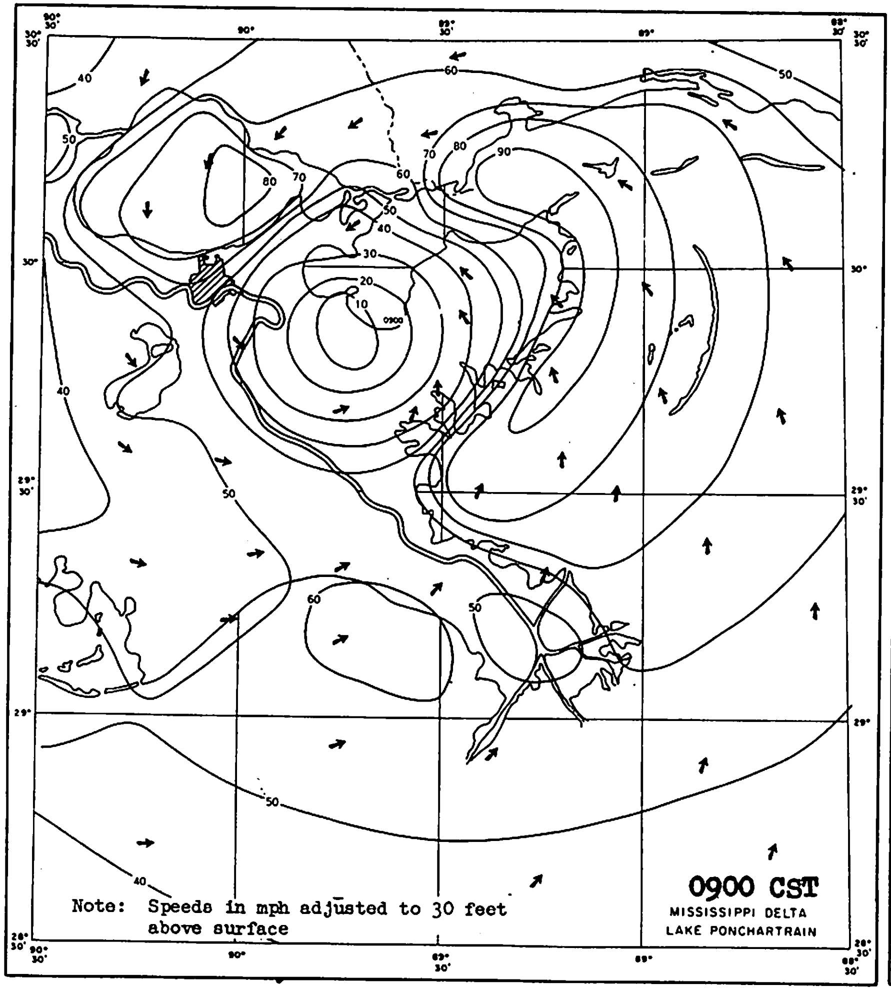


Figure 9-5b. Wind speeds and directions, September 19, 1947, 0700 and 0800 CST.



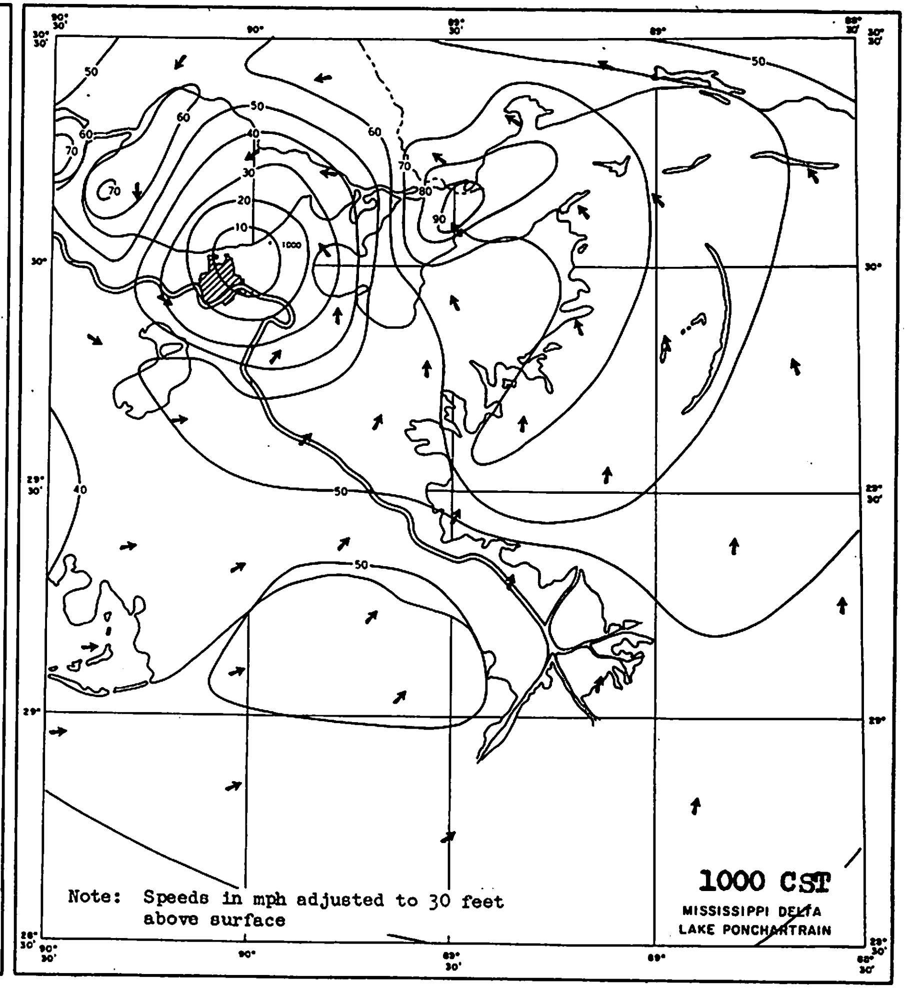


Figure 9-5c. Wind speeds and directions, September 19, 1947, 0900 and 1000 CST.

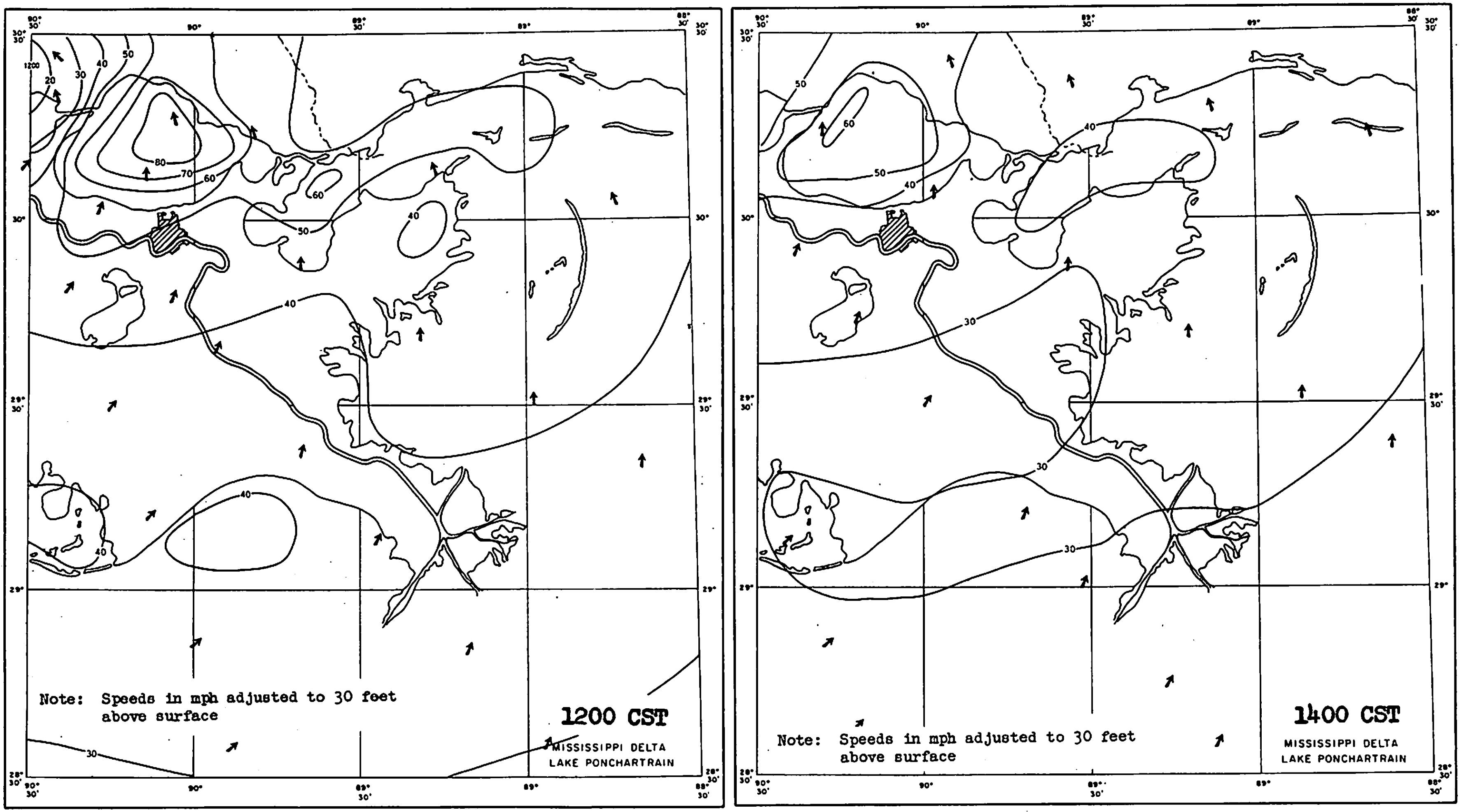


Figure 9-5d. Wind speeds and directions, September 19, 1947, 1200 and 1400 CST.

Table 9-1. - Parameters of September 1947 hurricane

	September 17 in Florida		
P_o,	Central pressure (in.), 27.76		
P_n,	Asymptotic pressure (in.), 29.83		
R,	Radius of maximum wind (n. mi.),	Computed	19
		Observed	34
V_{gx},	Maximum gradient wind (m.p.h.), 102		
Lowest pressure detected by a barometer (in.), 27.97 at Hillsboro, Fla.			

	September 19 in Louisiana		
P_o,	Central pressure (in.), 28.54		
P_n,	Asymptotic pressure (in.) 29.70		
R,	Radius of maximum wind (n. mi.),	Computed	28
		Observed	23
		Isotach patterns based on observed	R
Lowest pressure detected by a barometer (in.) 28.57 at New Orleans, WBO, La.			

10. HURRICANE OF AUGUST 26, 1949, LAKE OKEECHOBEE, FLA.

INTRODUCTION

The hurricane of August 26, 1949 was the most severe to pass over the Lake Okeechobee, Fla., area since the disastrous hurricane of September 1928. The center moved inland near West Palm Beach at about 1900 EST August 26, and crossed northern Lake Okeechobee as it moved west-northwestward. The storm then moved northwestward over the Florida citrus belt and, after passing Tampa, moved northward into Georgia. Only two lives were lost in this storm in Florida. Property damage, however, was estimated as $45,000,000. Almost half of this amount was for crop damage, mainly to the citrus crop /35/.

As the hurricane passed over the Corps of Engineers' meteorological network around Lake Okeechobee, greater detail of pressure and wind formation was obtained by recording instruments than near the center of any other hurricane over land areas of the United States. The data for this storm have been used extensively as a basis for portions of several sections

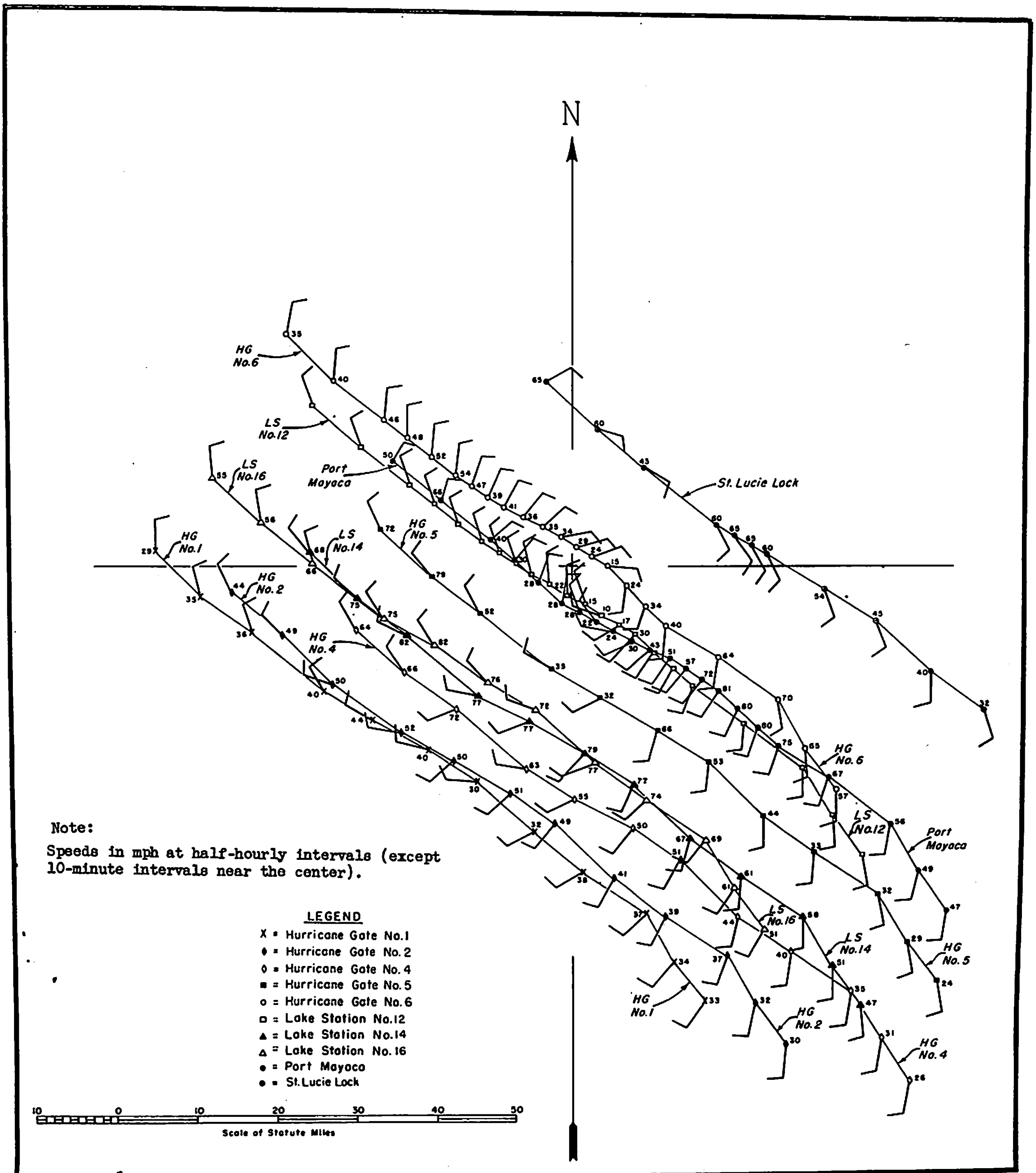


Figure 10-1. Observed 10-minute-average wind speeds and directions, 2000 EST August 26 to 0130 EST August 27, 1949, at Lake Okeechobee, Fla.

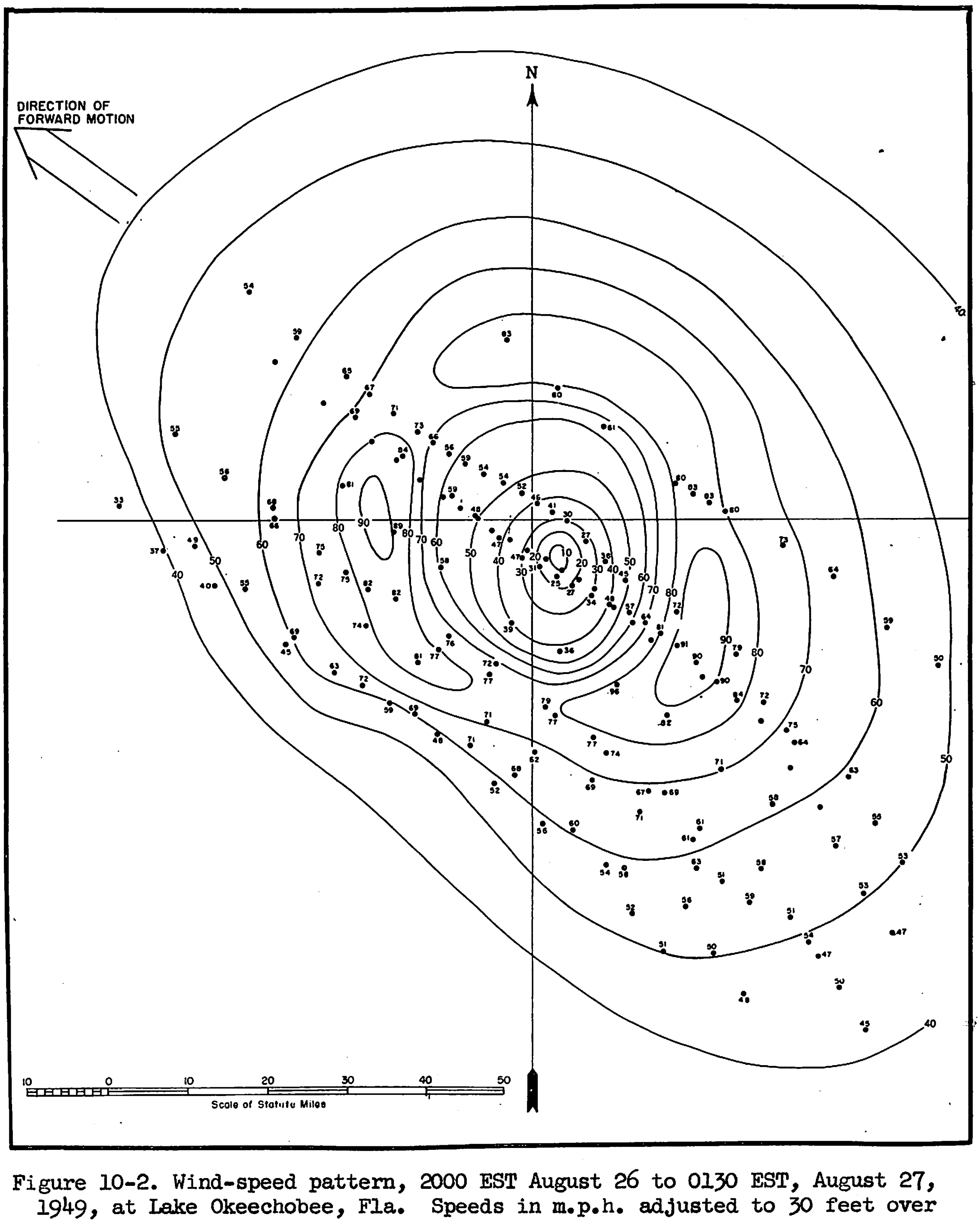


Figure 10-2. Wind-speed pattern, 2000 EST August 26 to 0130 EST, August 27, 1949, at Lake Okeechobee, Fla. Speeds in m.p.h. adjusted to 30 feet over water.

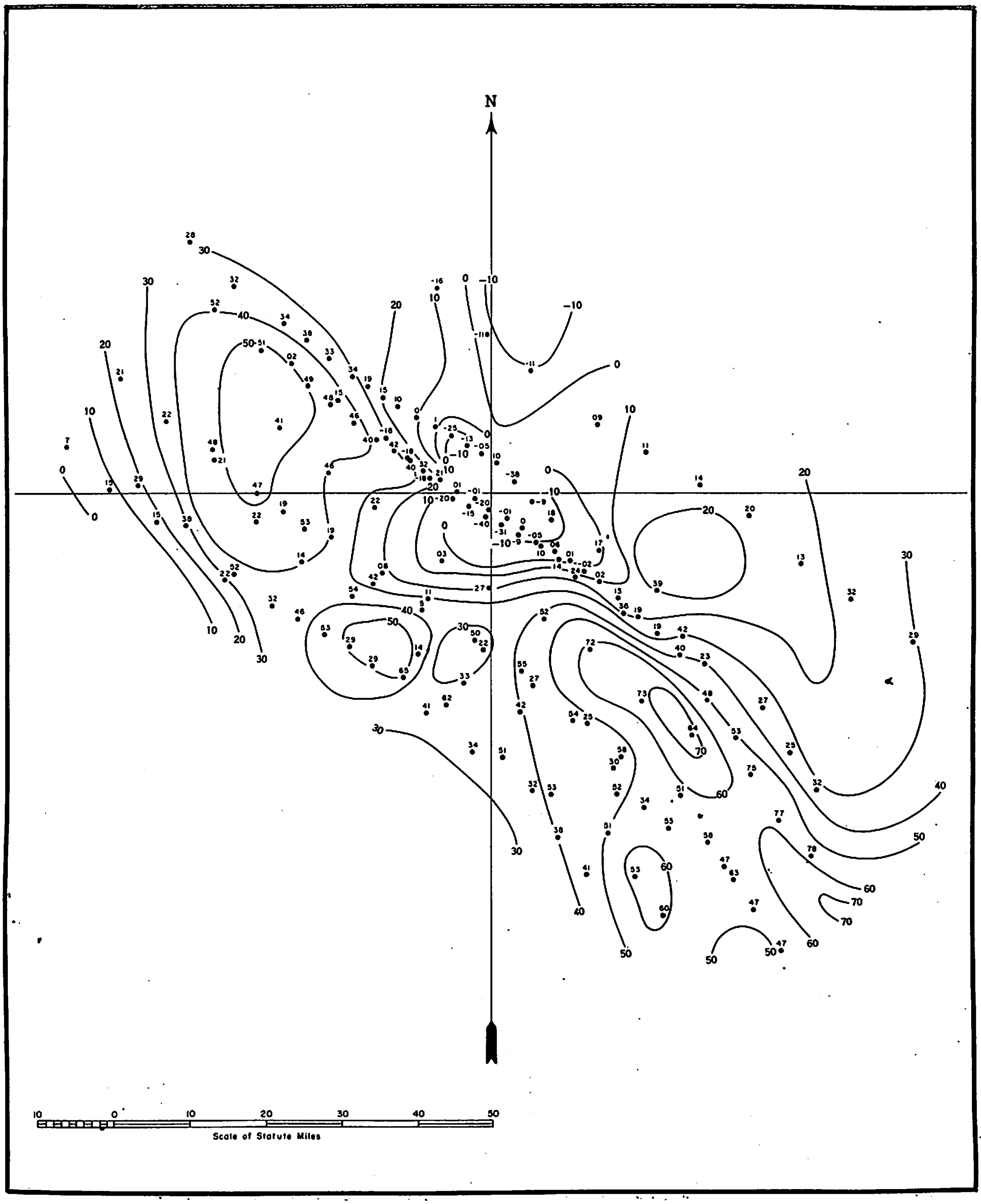


Figure 10-3. Wind deflection angles, 2000 EST August 26 to 0130 EST, August 27, 1949, at Lake Okeechobee, Fla.

in this report.

This hurricane has been analyzed in detail in previous reports /8, 9, 4 /. However composite maps of wind speed and direction which have not been previously published, are shown in the present report. Ten-minute pressure and wind maps over Lake Okeechobee were shown in /8 / and detailed mean radial wind profiles in /4 /.

CENTRAL PRESSURE

The indicated parameters for this storm are quite reliable. The center passed directly over West Palm Beach, Fla., with an observed minimum pressure of 28.17 inches.

WIND SPEED

The basic data available, namely, wind speeds and directions averaged for 10-minute intervals from autographic records, are shown on a composite plot in figure 10-1. Three of the wind recording stations were on pylons in the Lake. The remaining stations were either on top of the levee at the shore or a short distance from the Lake. In the composite wind-speed pattern, shown in figure 10-2, the speeds are plotted as adjusted to the common frictional surface of "over-water". Winds at shore stations with an off-water direction were increased by 12 percent. Winds with an off-land direction were increased by greater factors which varied from station to station. The analysis is somewhat speculative in the quadrant to the right of the storm path and is influenced to a lesser extent in other quadrants by the adjustments of the wind speeds. All of the data are within a time period of about 5 hours. Filling during this period of time probably did not diminish the wind speeds by more than 5 percent. Taking into account the various sources of possible error, the wind-speed pattern seems to be nearly symmetrical about an axis through the center and parallel to the direction of forward motion, with areas of maximum winds occurring to the left front and at the rear. These areas of stronger winds are on the order of 10 to 15 percent higher than in other directions.

WIND DIRECTION

A composite plot and analysis of the deflection angle of the wind direction is depicted in figure 10-3. No adjustments have been made to any of the directions. Smoothing of the isolines was accomplished through the intermediate step of an isogon field. A mean deflection angle curve from these data is shown in /8 / and /4 /.

Table 10-1. Parameters of August 26, 1949 hurricane

P_o,	Central pressure (in.), 28.16 at West Palm Beach 28.20 at Lake Okeechobee
P_n,	Asymptotic pressure (in.), 30.12
R,	Radius of maximum winds (n. mi.), Computed 22 Observed 23
V_{gx},	Maximum gradient wind (m.p.h.), 99
c,	3-hr. average forward speed at coast (kt.), 14

11. HURRICANE OF OCTOBER 3, 1949, FREEPORT, TEX.

INTRODUCTION

The hurricane of October 3, 1949, moved inland about 20 miles southwest of Freeport, Tex., causing storm tides which exceeded 11 feet at several locations over the Texas coast. The highest tides were from the Kemah-Seabrook area northward to the head of Galveston Bay and in the Houston Ship Channel. Two lives were lost in the storm and damage was reported to have been $6,700,000 of which more than four-fifths was crop damage. The remainder of the loss was mainly due to damage to roads and oil rigs [36].

The hurricane formed in the Bay of Campeche and from there moved northward to the Texas coast. After crossing the coast, it moved north-northeastward with the center passing between the Weather Bureau Office and the Weather Bureau Airport Station at Houston, Tex.

TRACK

The track of the storm center on October 3 and 4 with hourly positions is shown in figure 11-1.

VARIATIONS FROM STANDARD ANALYSIS TECHNIQUE

In developing the composite 30-ft. over-water wind speed and direction pattern for the hurricane (fig. 11-2) from coastal observations, several wind speeds were used that were observed at land stations after the storm center had been over land for several hours. Before isotachs were drawn to the data, these speeds were adjusted upward to compensate for a decrease in wind speed due to filling. This was accomplished by computing gradient wind speeds from two composite pressure profiles, from 2000 CST October 3, shortly before landfall of the center, to 0400 CST October 4, shortly after landfall, and 0300 CST to 1000 CST October 4, a period when filling had occurred over land. The pressure-distance profiles for the two periods are shown in figure 11-3 and the gradient wind speed profiles computed from these pressure profiles are shown in figure 11-4. The observed wind speeds after 0300 CST October 4 were increased by the ratio of the gradient winds of the first

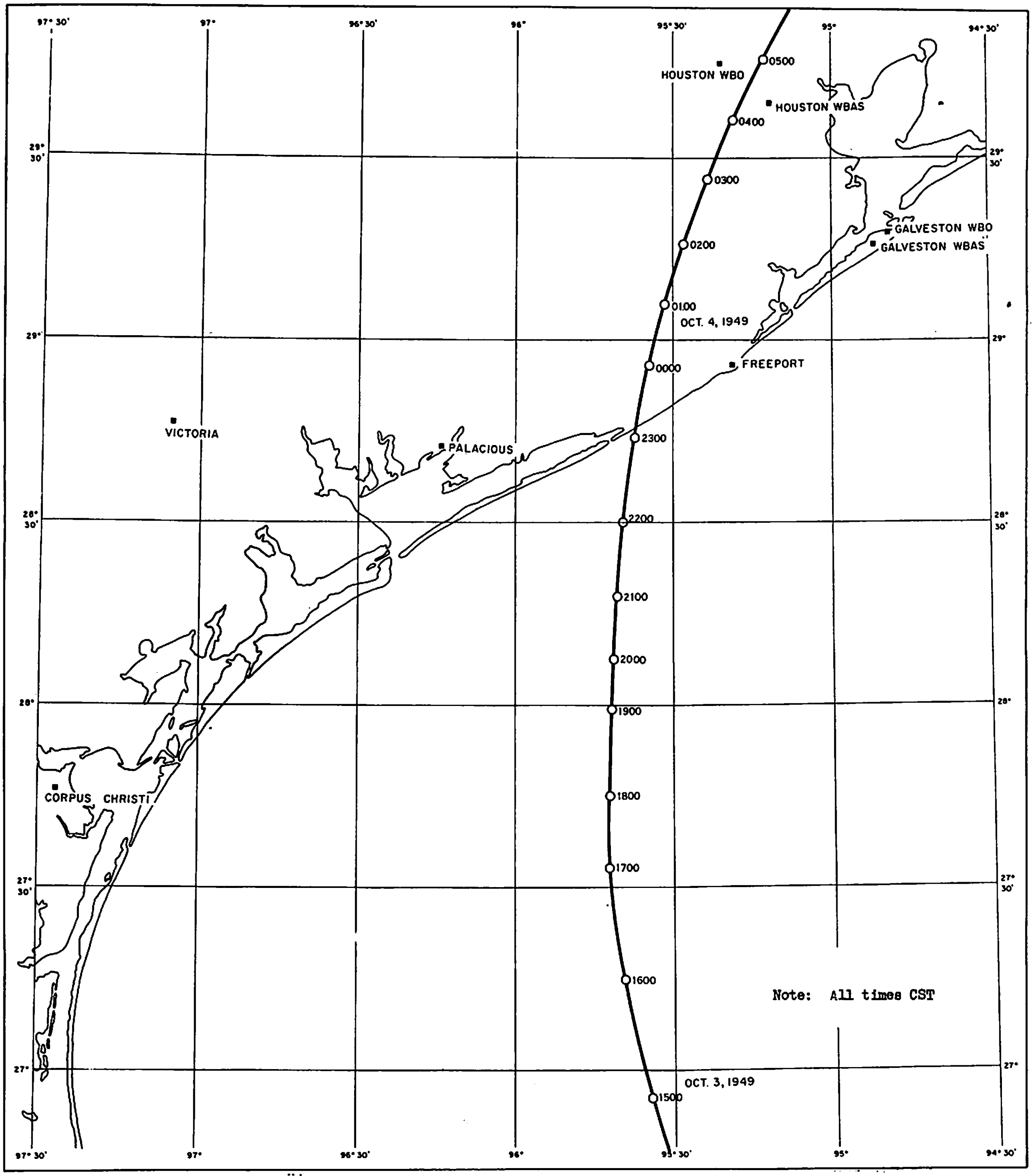


Figure 11-1. Hurricane track, October 3, 1949, near Galveston, Texas.

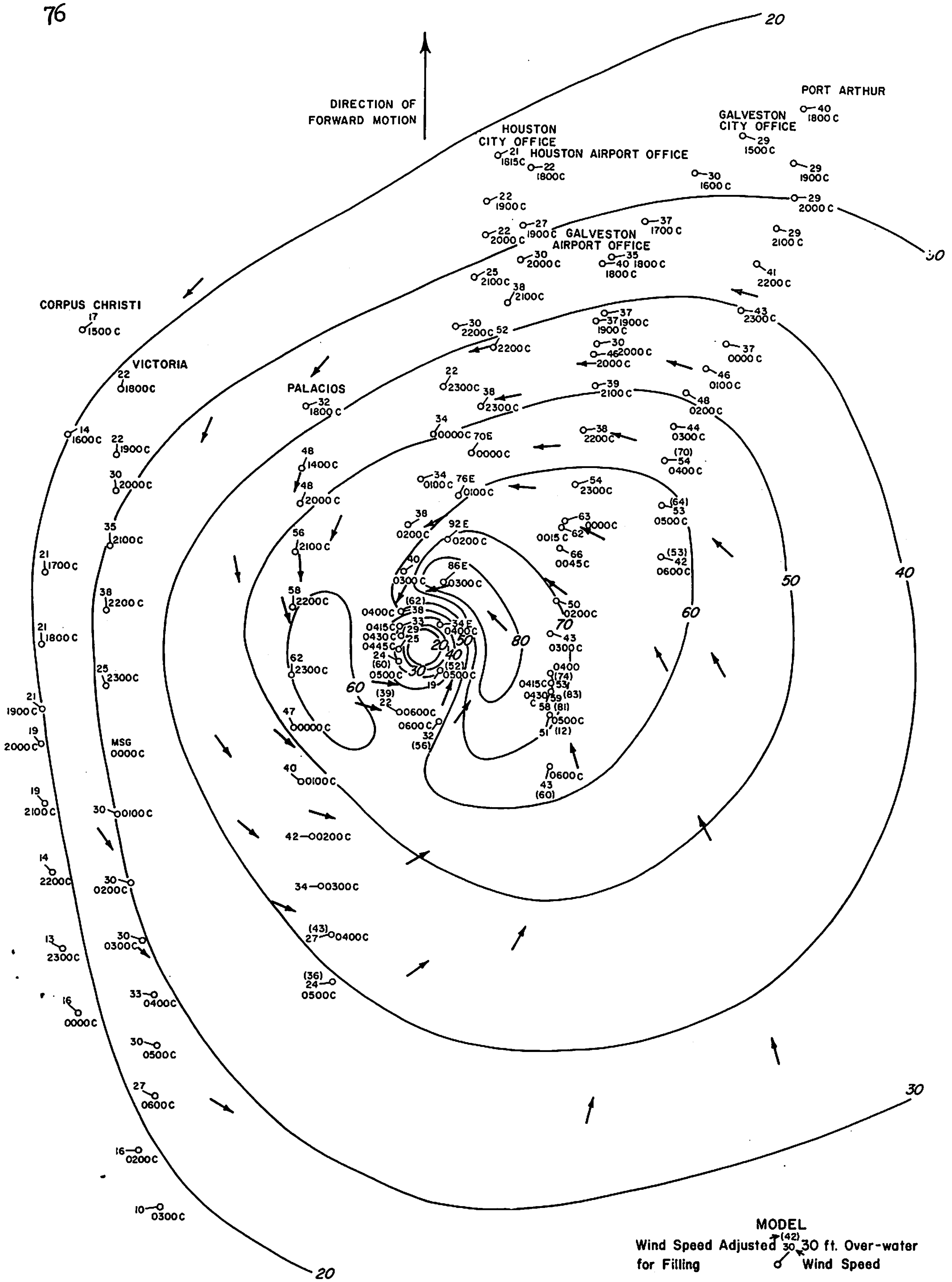


Figure 11-2. Composite wind-speed and direction pattern, October 3, 1949, near the Texas coast. All times CST. Speeds in m.p.h. adjusted to 30 feet over water.

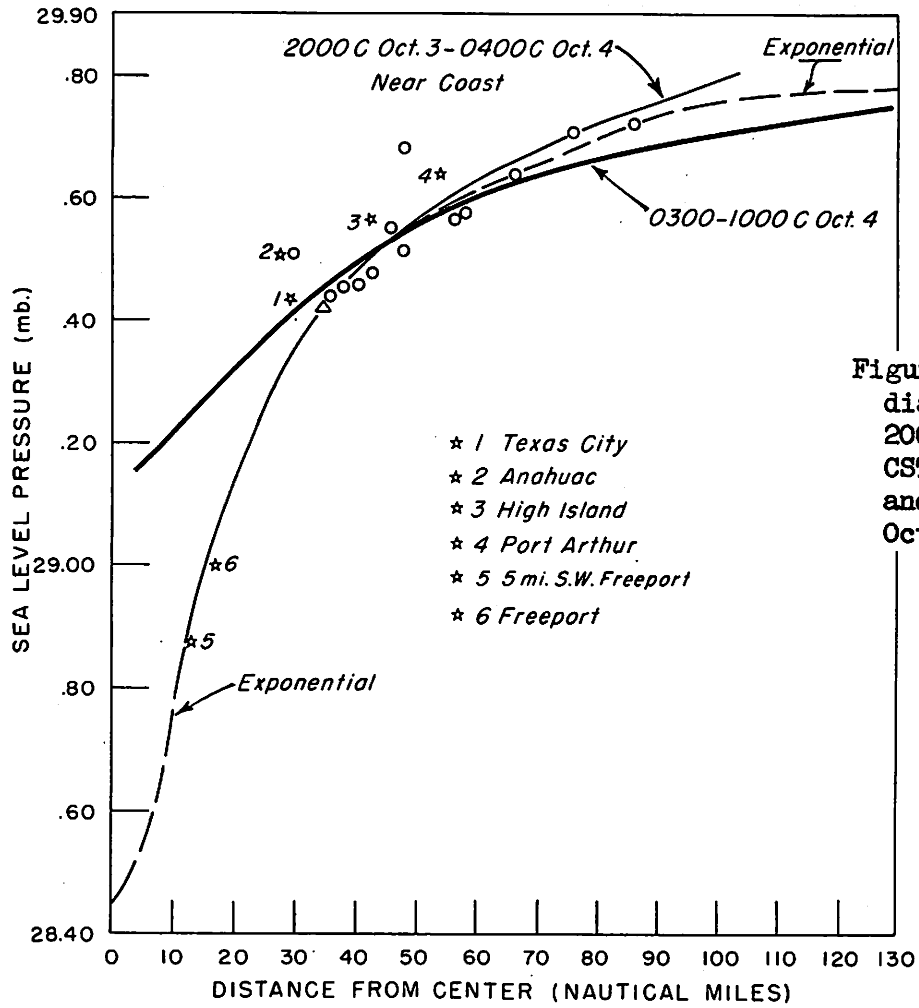


Figure 11-3. Average radial pressure profiles, 2000 CST, October 3-0400 CST, October 4, 1949, and 0300 CST-1000 CST, October 4, 1949.

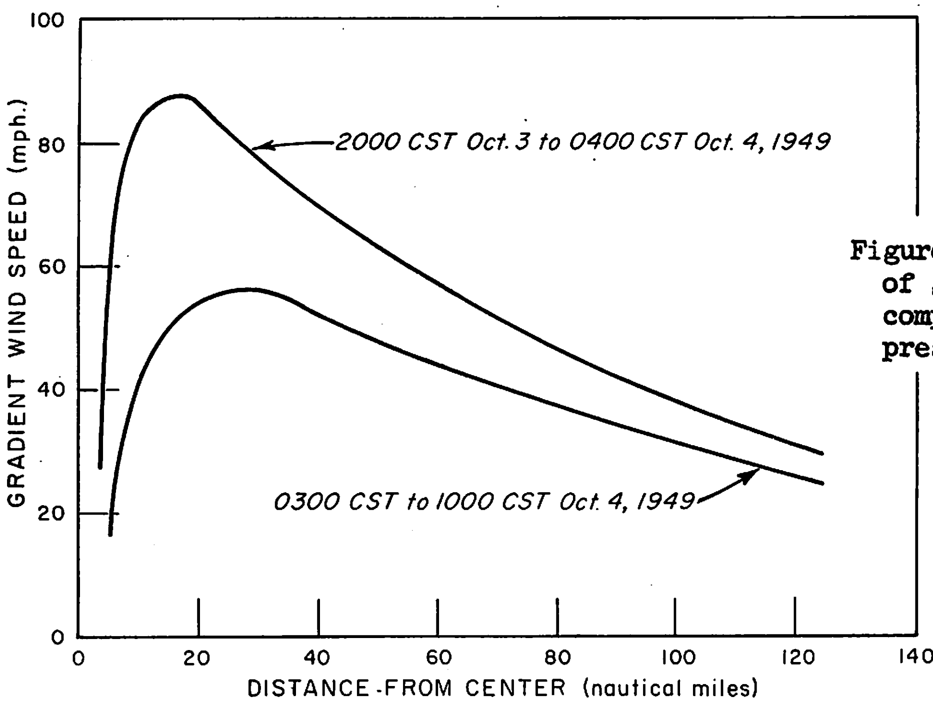


Figure 11-4. A comparison of gradient-wind speeds computed from composite pressure profiles.

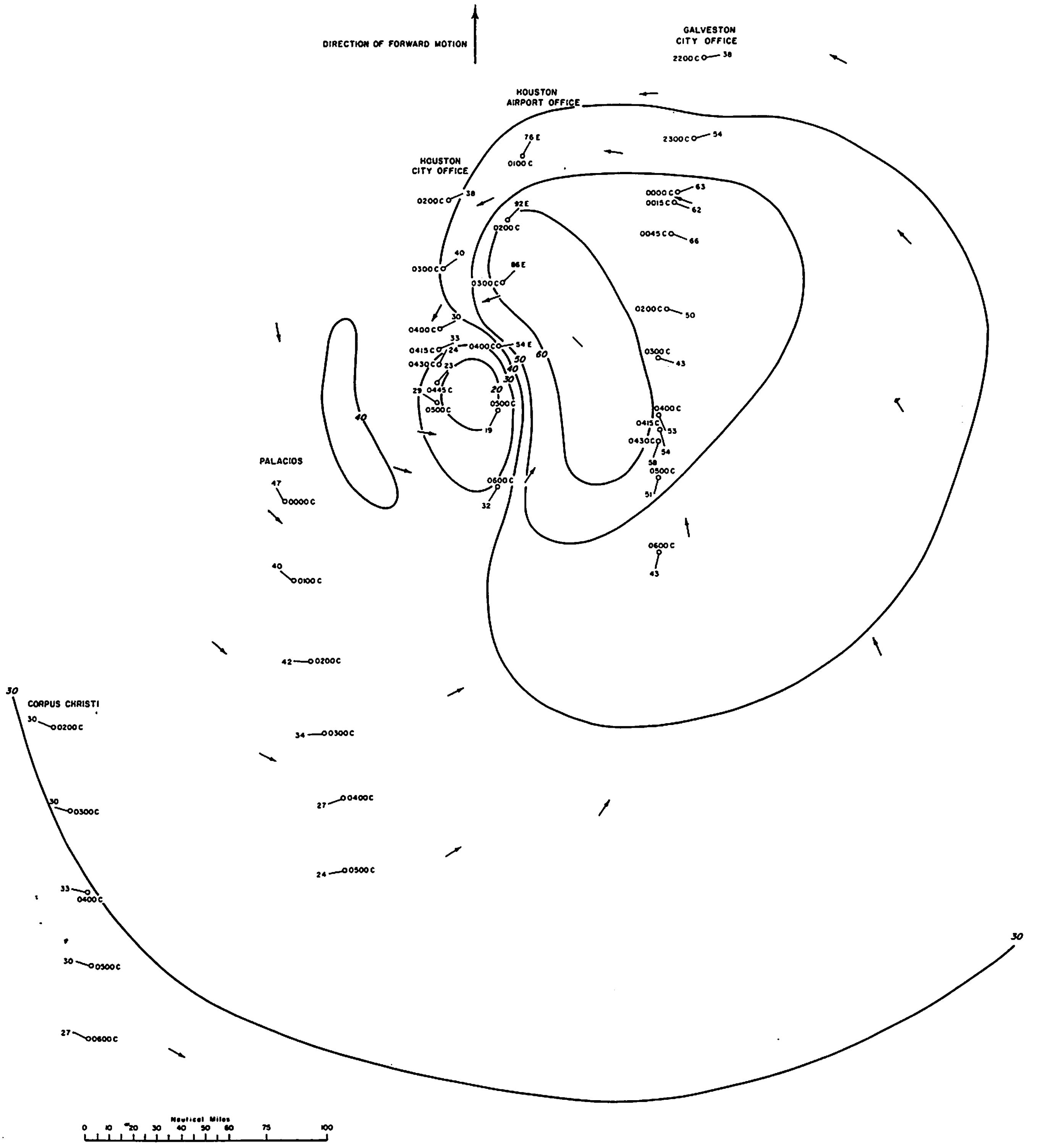


Figure 11-5. Composite wind-speed and direction pattern, 0300 to 0500 CST, October 4, 1949. Speeds in m.p.h. adjusted to 30 feet over water.

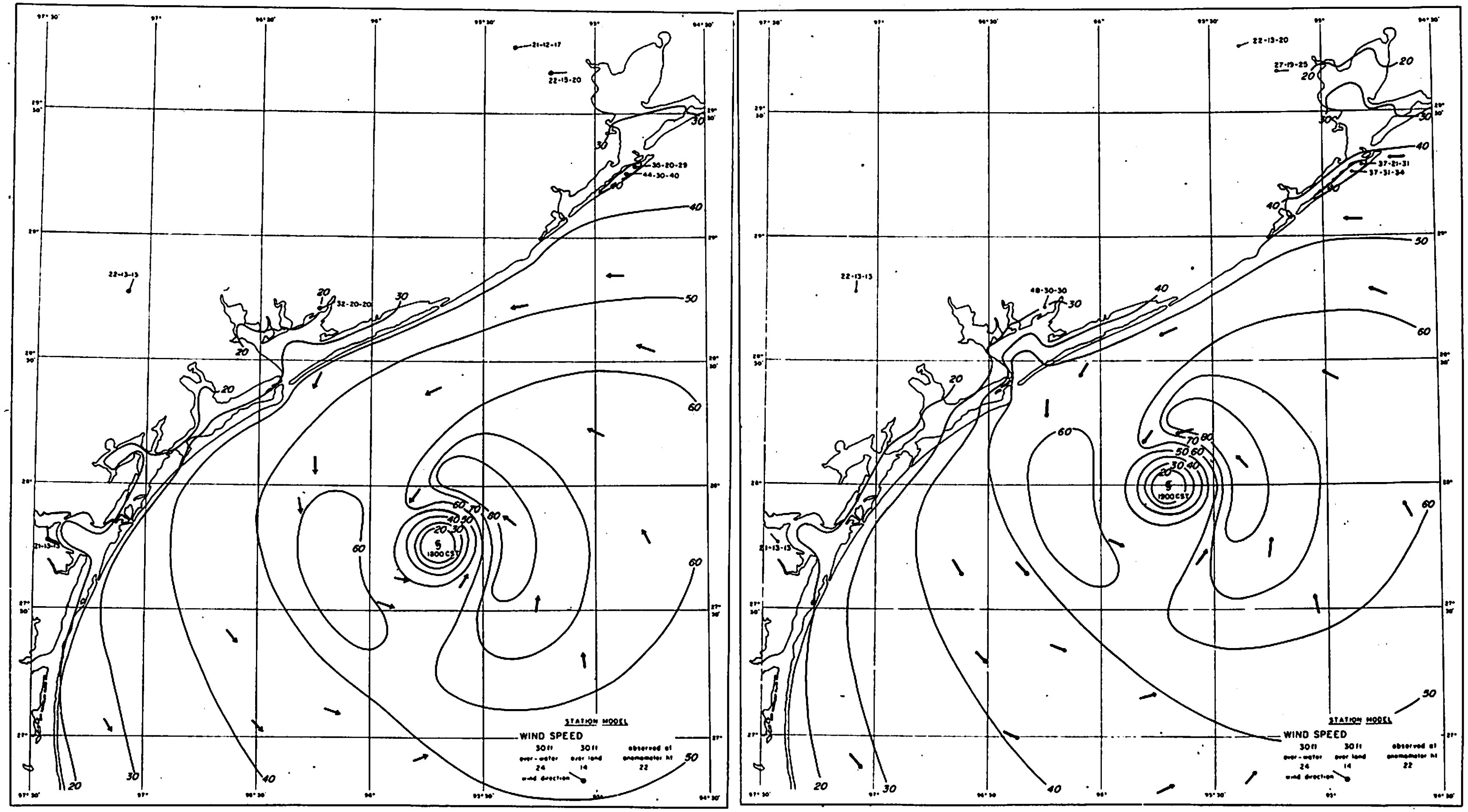


Figure 11-6a, Wind speeds and directions, October 3, 1949, 1800 and 1900 CST.

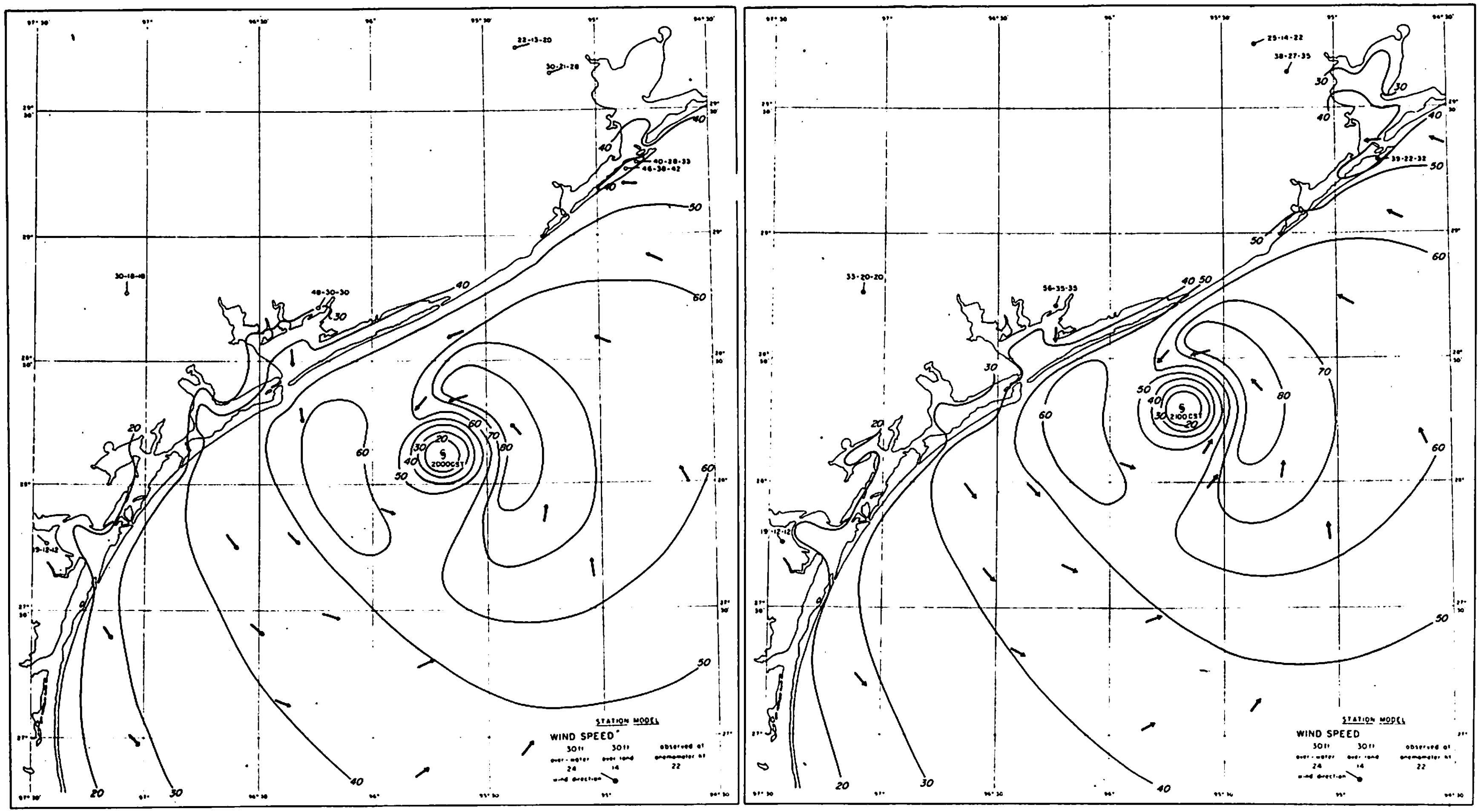


Figure 11-6b. Wind speeds and directions, October 3, 1949, 2000 and 2100 CST.

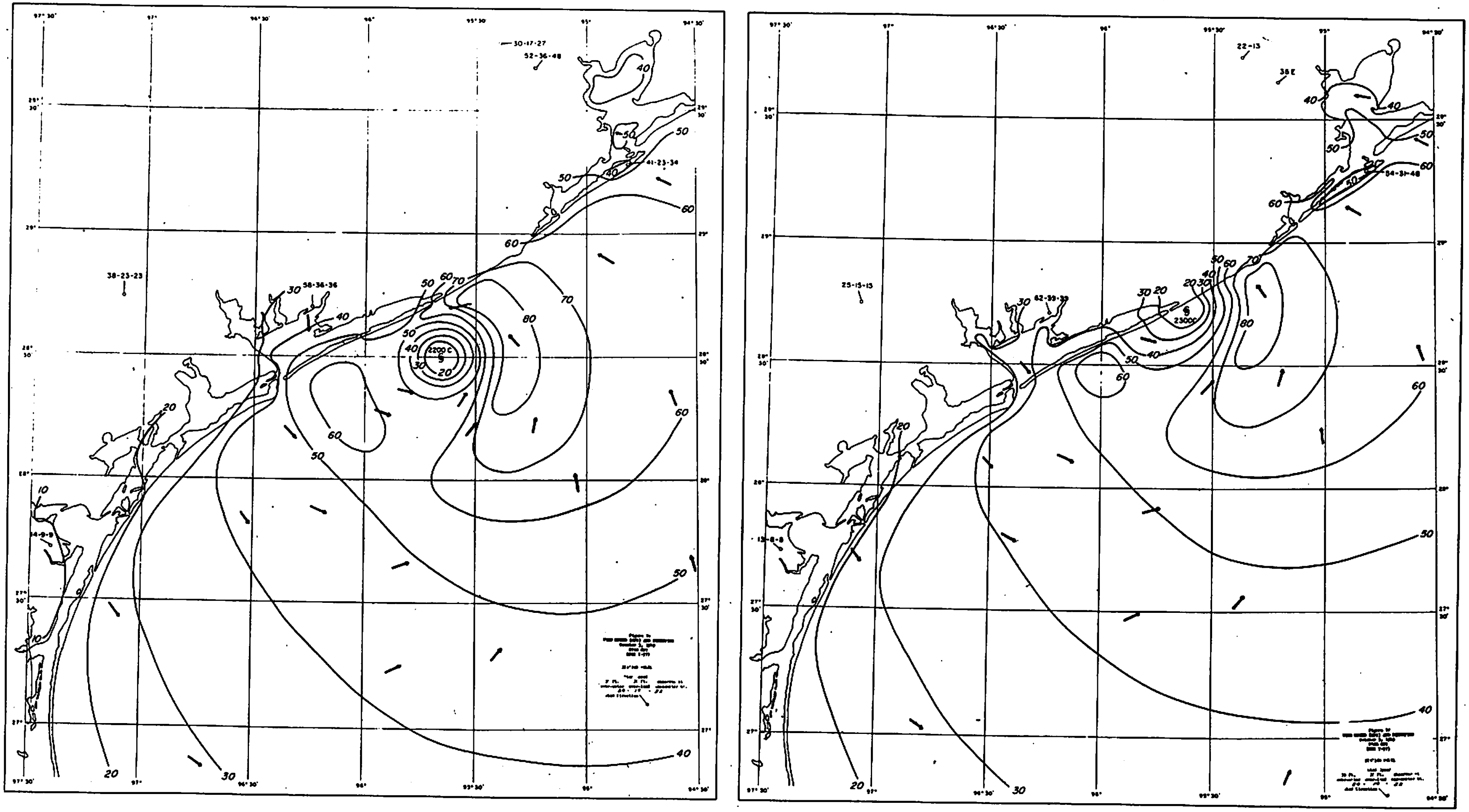


Figure 11-6c. Wind speeds and directions, October 3, 1949,2200 and 2300 CST.

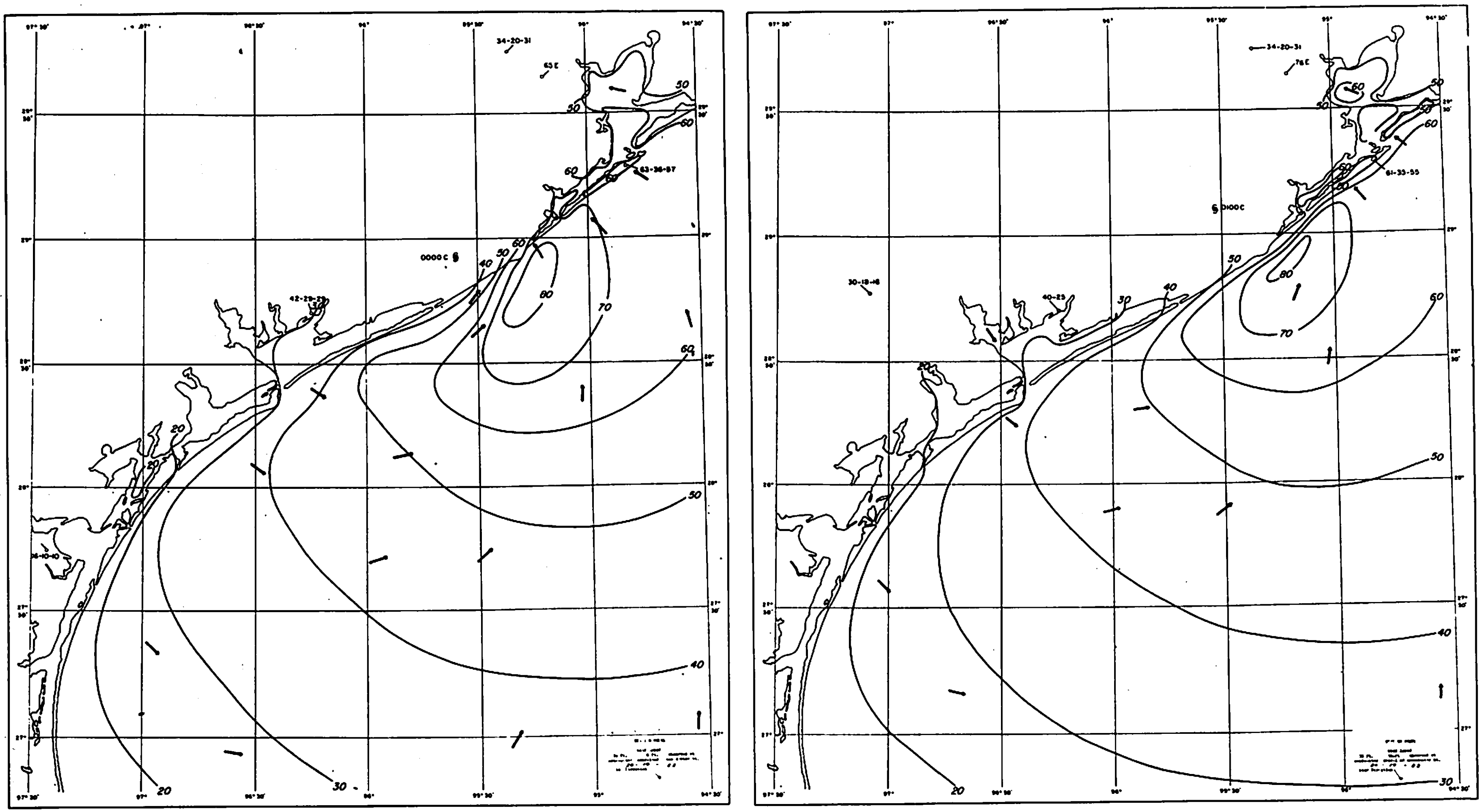


Figure 11-6d. Wind speeds and directions, October 4, 1949, 0000 and 0100 CST.

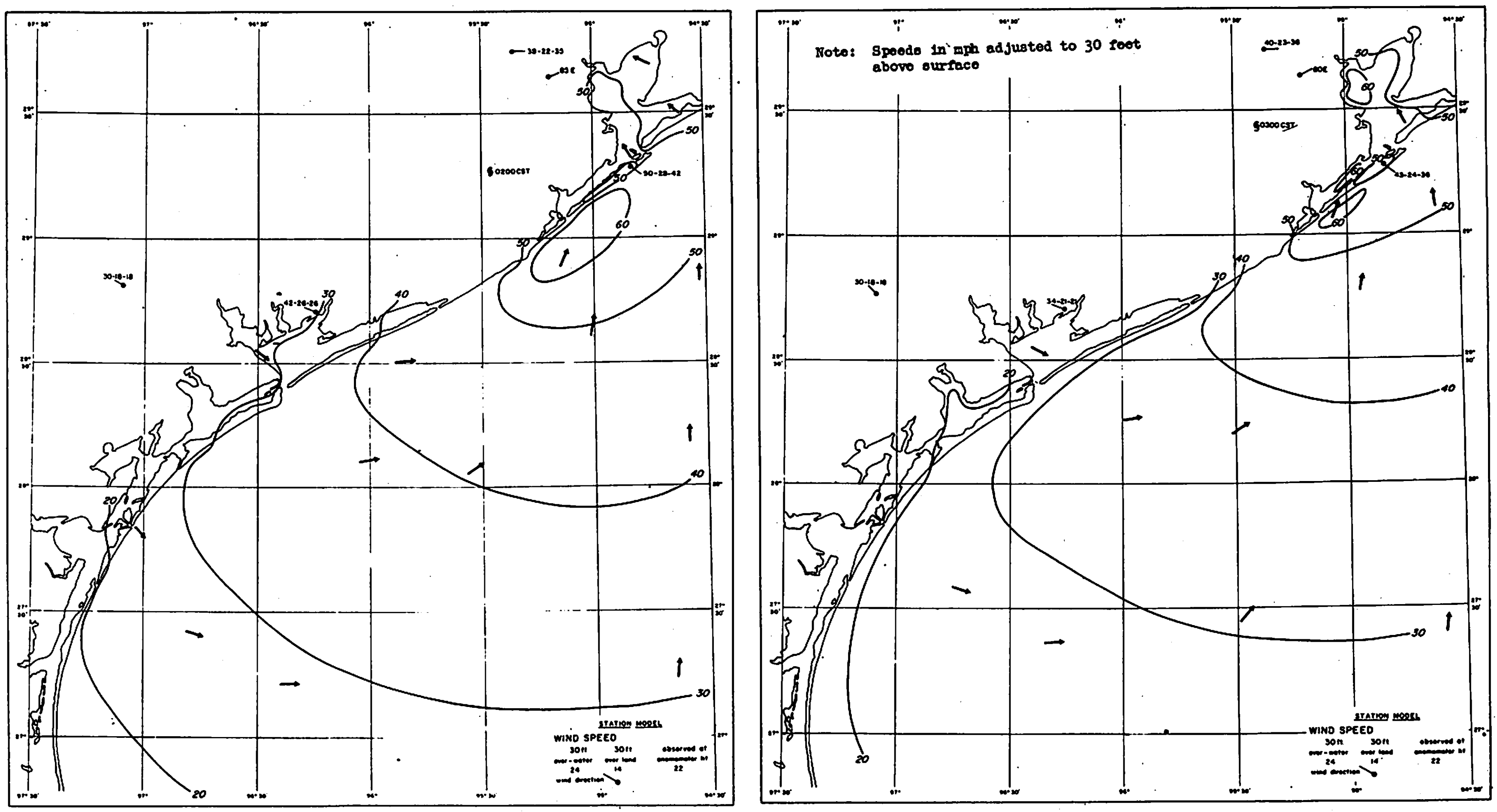


Figure 11-6e. Wind speeds and directions, October 4, 1949, 0200 and 0300 CST.

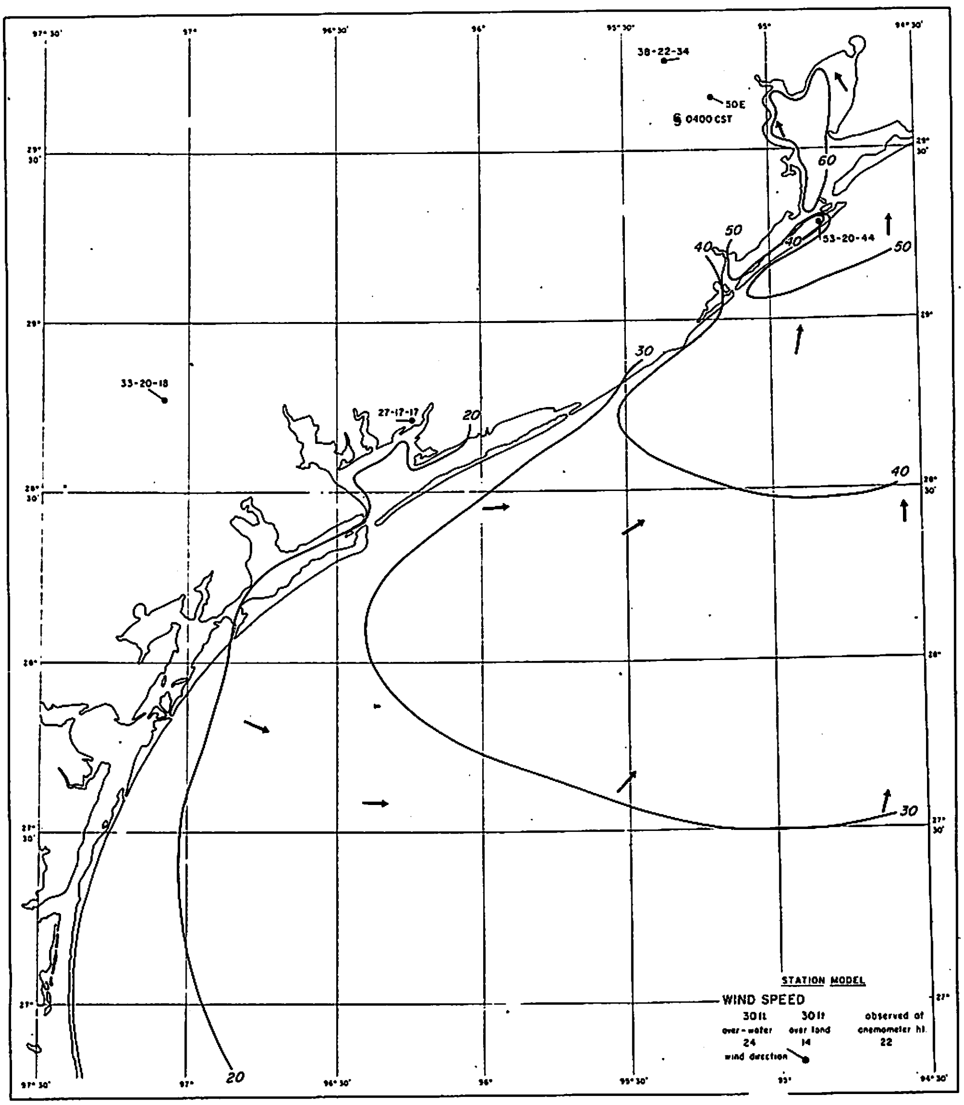


Figure 11-6f. Wind speeds and directions, October 4, 1949, 0400 CST.

period to the gradient winds of the second period at the same distance from the storm center. The isotachs for the composite wind speed pattern (fig. 11-2) were drawn to the adjusted data. The effects of filling that occurred after the storm had been inland for more than 3 hours are incorporated into the composite wind speed and direction pattern for the period from 0300 to 0500 CST, October 3 in figure 11-5.

WIND DIRECTION

Since pressure distribution around the hurricane was not symmetrical, a standard wind-deflection angle around the center of the storm was not used. In order to reconstruct the wind direction in all quadrants of the hurricane, a pressure pattern (not shown) was constructed and wind-direction arrows were drawn across the tangent to the isobar at a 25° angle from 10 miles beyond the radius of maximum winds and at a 20° angle within the radius of maximum wind, with a transition zone between. These directional arrows showed good agreement with observed winds at coastal stations as shown in figure 11-2.

HOURLY ISOTACH CHARTS

Figure 11-6 shows isotach patterns over the Gulf from 1800 CST October 3 through 0400 CST October 4, 1949. For charts up to 0100 CST October 4, the composite wind speed and direction pattern (fig. 11-2) was overlaid on charts of the Texas coast and centered at selected positions of the storm center with the forward portion aligned with the direction of forward motion of the storm. The isotachs along the coast were adjusted to off-land and off-water speeds. The composite wind speed pattern in figure 11-5 was used in a similar manner to draw isotachs over the Gulf for the period from 0300 CST to 0400 CST October 4. The isotachs for the 0200 CST October 4 chart were interpolated between the two patterns (figs. 11-2 and 11-5).

Table 11-1. - Parameters of October 3, 1949 hurricane at the Texas coast

P_o,	Central pressure (in.), 28.45	
P_n,	Asymptotic pressure (in.), 29.95	
V_{gx},	Maximum gradient wind (m.p.h.), 78	
R,	Radius of maximum winds (n. mi.), Computed	15
	Observed	20
c,	4-hr. average forward speed at the coast (kt.), 11	

12. HURRICANE HAZEL OF OCTOBER 15, 1954, IN THE ATLANTIC

INTRODUCTION

Hurricane Hazel was the most intense storm of record to strike the Carolina section of the Atlantic Coast. Property and crop losses totaled more than $250,000,000 in the United States and more than half of this total occurred in North Carolina. Wind-driven tides devastated the area along the immediate ocean front from Pawley's Island, S. C. to Cape Fear, N. C. In the remainder of South Carolina, most damage along the ocean front was also caused by wind-driven water. The history of hurricane Hazel spanned a period of about 17 days, during which it covered thousands of miles from the Tropics to the Arctic [37].

A more detailed discussion is given of the analysis of the surface winds and pressures in this hurricane than for the storms discussed in other sections because of its significance as one of the most intensive and destructive storms in recent years to strike the Atlantic Coast and also to present the evidence for an unusual feature of the hurricane; its deepening just prior to moving inland over the Carolina coast.

BASIC DATA

Periods of data concentration. Over the area from Haiti to the Carolinas, two intervals were selected for wind speed determination. Data from all sources were sufficient to warrant a more detailed pressure and wind analysis on October 13 near Great Inagua Island where reconnaissance planes penetrated the eye and made several low-level observations near the eye and through the zone of maximum winds. The second period with considerable data near the center occurred when the hurricane was near the Carolina coast.

TRACK

Over the ocean. A track of the storm center from the vicinity of Haiti through the southeastern United States is shown in figure 12-1. Two kinds of track are shown. The over-ocean part of the storm track, as shown here, is based primarily on naval aircraft reconnaissance observations, mostly radar fixes. The track was determined after some smoothing of the reconnaissance-determined positions. The last indicated turn to the left before landfall may have been associated with the friction differential between the part of the hurricane over land and the part over water, as described for hurricane Connie, Diane, and Ione of 1955 by Dunn, Davis, and Moore [38].

Over land. The portion of the track shown in figure 12-1 over the continental United States is based primarily on pressure observations and is therefore a minimum pressure track. It was positioned by methods described in section 1.

Separation of centers. The storm track shown in figure 12-1 shows a discontinuity at the coast of approximately 14 n. mi. As the hurricane was approaching the coast, positions reported by observers aboard reconnaissance planes became more irregular. Consequently, the reconnaissance track shown in the vicinity of the coast is the result of considerable smoothing. Considering navigational errors and smoothing, there appears to be a possible error in track positioning over the ocean on the order of 5 to 10 miles. The center of wind symmetry could not be determined, so the assumption was made that it was coincident with the reconnaissance center. This would

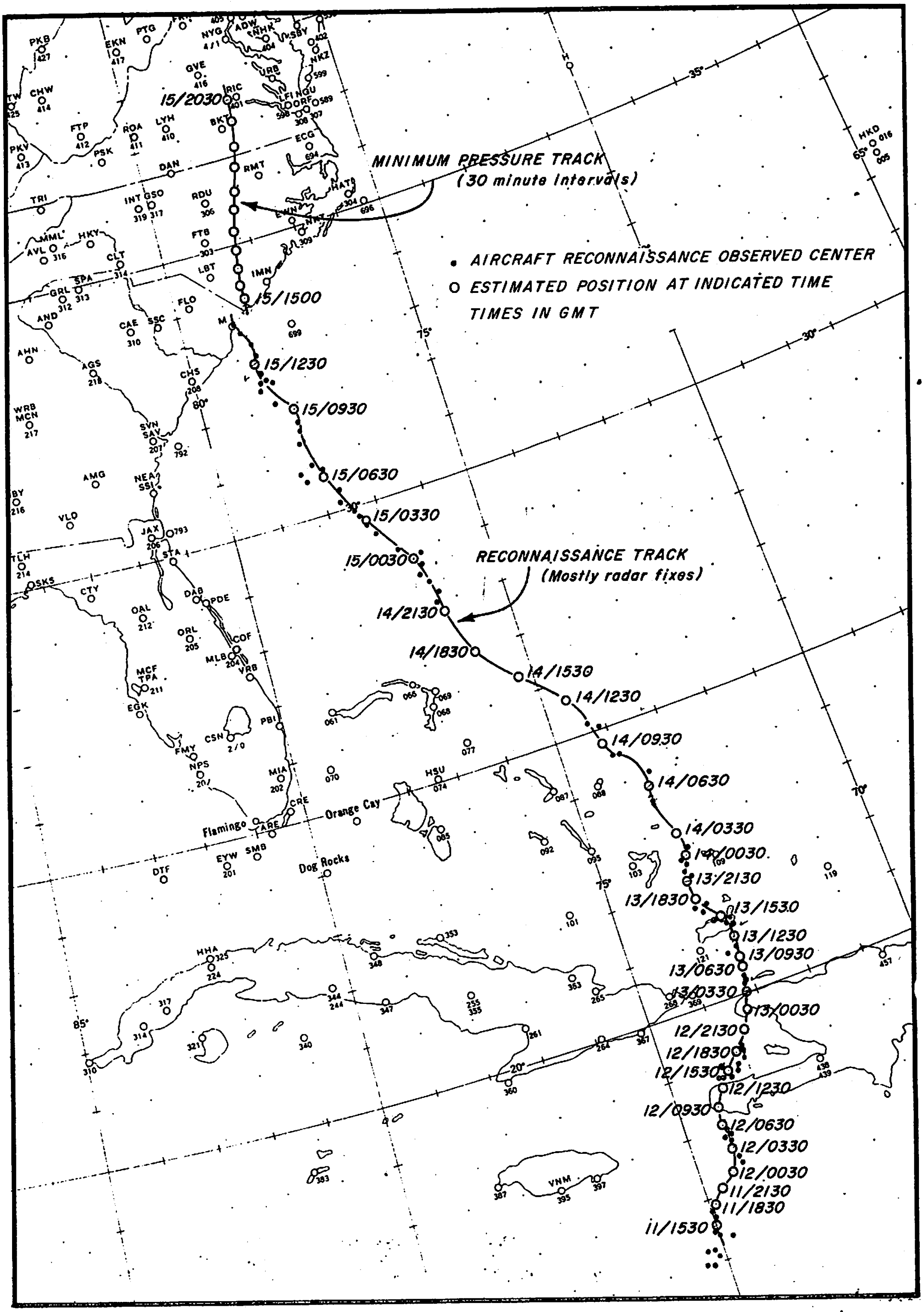


Figure 12-1. Partial track, Hurricane Hazel, October 11-15, 1954.

likely be a reasonable approximation since the wind eye is usually inside the limits of the radar eye.

Oscillations. Oscillations are clearly evident on the hurricane track chart (fig. 12-1). According to Yeh /39/ in his theoretical discussion of oscillations in hurricane tracks, the period of oscillation is less as the storm intensity decreases and the size increases. In hurricane Hazel, the period of oscillation was approximately 24 hours on October 12 and 13. During the first 12 hours of the 14th, the period had decreased to about 6 hours. After midday on the 14th, the period increased to about 10 hours. Considerable deepening and increase in size occurred between October 13 and landfall at about 1500 GMT on the 15th. Possibly there is a relation between the short period of oscillation on the 14th and the increased maximum wind speed due to deepening of the storm center and the increased period thereafter until landfall and the increasing over-all size of the storm.

PRESSURE ON OCTOBER 13, 1954

Data. Several aircraft reconnaissance observations, together with ship observations, were available on the 13th near Great Inagua Island. In this area there were two penetrations of the hurricane's eye within a period of about 5 hours on the 13th.

Central pressure. Reported minimum pressure in the eye was 972 mb. at 1615 GMT and 974 mb. at 2136 GMT. The observations were made by different reconnaissance flights. An average of the two minimum pressure observations, 973 mb. (28.73 in.), was selected as the central pressure (P_o).

Pressure profile. Since there were insufficient data in each of the several directions from the center to determine a family of profiles for those directions, all the available data were plotted on a single graph and a curve of pressure profile was fitted to the data by eye (not shown). From the selected central pressure and two selected points along this pressure profile, values of the asymptotic pressure (P_n) and radius to region of maximum winds (R) were computed from the formula (1-1). The resulting parameters are shown in table 12-1, part A. Using these parameters a curve of pressure versus distance from the center was plotted for the data as computed by formula (1-1) and is shown in figure 12-2.

Asymptotic pressure comparison. Weather maps were examined as a check on the computed value of P_n. By averaging the pressures at points in the various directions at which the curvature of the isobars changed from cyclonic to anticyclonic, an average observed P_n was determined to be 29.97 in. Since this value was of the general order of magnitude of the computed value and was subject to some error due to the asymmetry of the outer isobar patterns, the computed P_n was allowed to stand.

Center of reference. The unusually large scatter of pressure data on the pressure-profile graph (fig. 12-2) is due to use of the reconnaissance track from which to scale distances. The reconnaissance track was probably displaced from the minimum pressure track, but data were insufficient to determine the displacement. As a result, fitting a curve to the data in figure 12-2 is less exact than for many other similar graphs.

PRESSURE AT LANDFALL ON OCTOBER 15, 1954

The hurricane maintained a circular isobaric field during most of its last few days over the ocean, but as it approached the coast it became more elongated. The trend toward elongation continued during the northward overland stage as the hurricane began to take on extratropical characteristics.

Data. With the exception of eye positions, little detailed information on the hurricane was available from October 13 until the storm approached the Carolina coast. Since a determination of the over-water wind speed was to be made for all quadrants of the storm, it was desirable to obtain pressure profiles for each quadrant and thereby compute a theoretical comparative wind. The hurricane became quite asymmetrical with respect to pressure, wind, and temperature, and began to fill rapidly within a short time after landfall. As a result, observations representative of off-shore conditions were only available from a few ships and from the various land stations on the north side of the storm before landfall as the hurricane approached and on the east and west sides of the storm at landfall.

Pressure profile. Pressures for the east and west halves were compared, but unique profiles could not be identified with any reliability. All of the pressure data for October 15 are shown on figure 12-3, which represents a mean radial pressure profile at approximately the time of landfall. A curve was drawn by eye through the data (dashed line, fig. 12-3) and an exponential profile, defined by formula (1-1), was then fitted (dash-dot line, fig. 12-3). An extrapolation inward along the exponential curve resulted in a value of 27.66 inches for the central pressure.

Modified exponential equation. The profile defined by formula (1-1) appeared to fit the data for the inner 50 n. mi. of the storm but was considerably in error for the outer portion of the storm. For example, the value computed for the asymptotic pressure from the exponential curve using formula (1-1) was 29.32 in., while the observed asymptotic pressure from weather maps (by the same method as for the 13th) was determined independently by two analysts to be 29.79 and 29.81 in. The plan was to compute winds from the pressure gradient to supplement the observed wind data. Determining the pressure gradient by measurement of the slope of the tangent to the visually-fitted curve was found to be subject to wide individual error. Since it was necessary to smooth the pressure gradients, it was concluded that a more refined process of smoothing could be carried out by fitting a special formula to the pressure profile. Formula (1-1) was modified by adding a fourth arbitrary dimensionless constant:

$$\frac{P - P_o}{P_n - P_o} = e^{-(R/r)^b} \qquad (12\text{-}1)$$

where P is the pressure at radius r, P_n is the asymptotic pressure, R the radius of maximum winds, P_o the central pressure, and b a constant. R and b were evaluated from a pair of points on the visually-fitted pressure profile (marked A and B on fig. 12-3), the observed P_n of 29.81 in., and the previously computed central pressure of 27.66 in. The computed radius to the region of maximum winds was determined to be 21.3 n. mi., and b to be 0.826. The exponential profile defined by points A and B, P_n, P_o, and formula (12-1) is represented by the solid line in figure 12-3.

Central pressure. The central pressure of 27.66 in. at landfall was considerably lower than that observed by reconnaissance 2 days earlier. Because of the marked deepening indicated, a careful examination was made of the evidence. When the center was at the coast, a pressure of 27.70 in. was observed at Tilgham Point, Little River Inlet, N. C., by a fishing boat, Judy Ninda /40_/. It was estimated that this observation, reported to have been in the eye of the hurricane, was made 4 miles from the point of minimum pressure. The aneroid barometer from the Judy Ninda was compared at Wilmington, N. C., and found to be reasonably accurate /40_/. Another pressure observation of 27.90 in. was observed at Holden Beach Bridge, N. C. /40_/, 10 miles from the pressure center. This pronounced decrease in central pressure has also been substantiated qualitatively by the decrease in pressure at various distances from the center. A comparison of figure 12-2 with figure 12-3 illustrates this. For example, at 100 miles from the center on October 13 the pressure on the average radial pressure-profile curve (fig. 12-2) is 29.65 in., while 29.28 in. or 0.37 in. less, is shown at the same distance from the center on figure 12-3. Miller /41_/computed central pressure for several hurricanes in testing the validity of computed eye soundings and procedures for estimating the minimum surface pressures. Using hurricane Hazel as an independent test of the process, he calculated a minimum pressure of 937 mb. (27.67 in.). The evidence of the pressure observations in and near the eye at the coast, the general decrease in pressure some distance from the center from the 13th to landfall on the 15th, and the value computed by Miller all support the estimated value of 27.66 in. for the central pressure.

Central pressure variation. The central pressure was observed by reconnaissance on five occasions from October 6 through the 13th and was computed at landfall on the 15th. Figure 12-4 shows the variation of central pressure with time during the storm's movement over the ocean and for 3 hours after the center crossed the coast.

WIND SPEED ON OCTOBER 13, 1954

Data. Since data were too limited and scattered to make an analysis of the winds on all sides of the storm, all observations were combined in a radial profile of the wind speed. No ship report was nearer than 60 miles to the center. In the course of penetrating the center, reconnaissance planes crossed the zone of maximum winds several times. Wind speeds are plotted on figure 12-5 according to distance from the radar center at the time of the wind observation without regard to quadrant. The reconnaissance

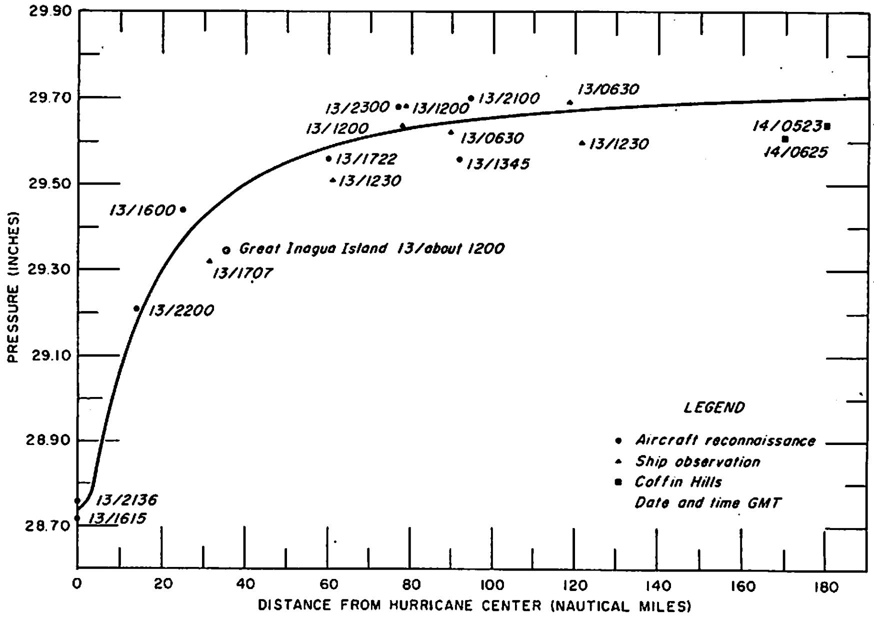


Figure 12-2. Radial pressure profile, Hurricane Hazel, October 13, 1954, about 1900 GMT.

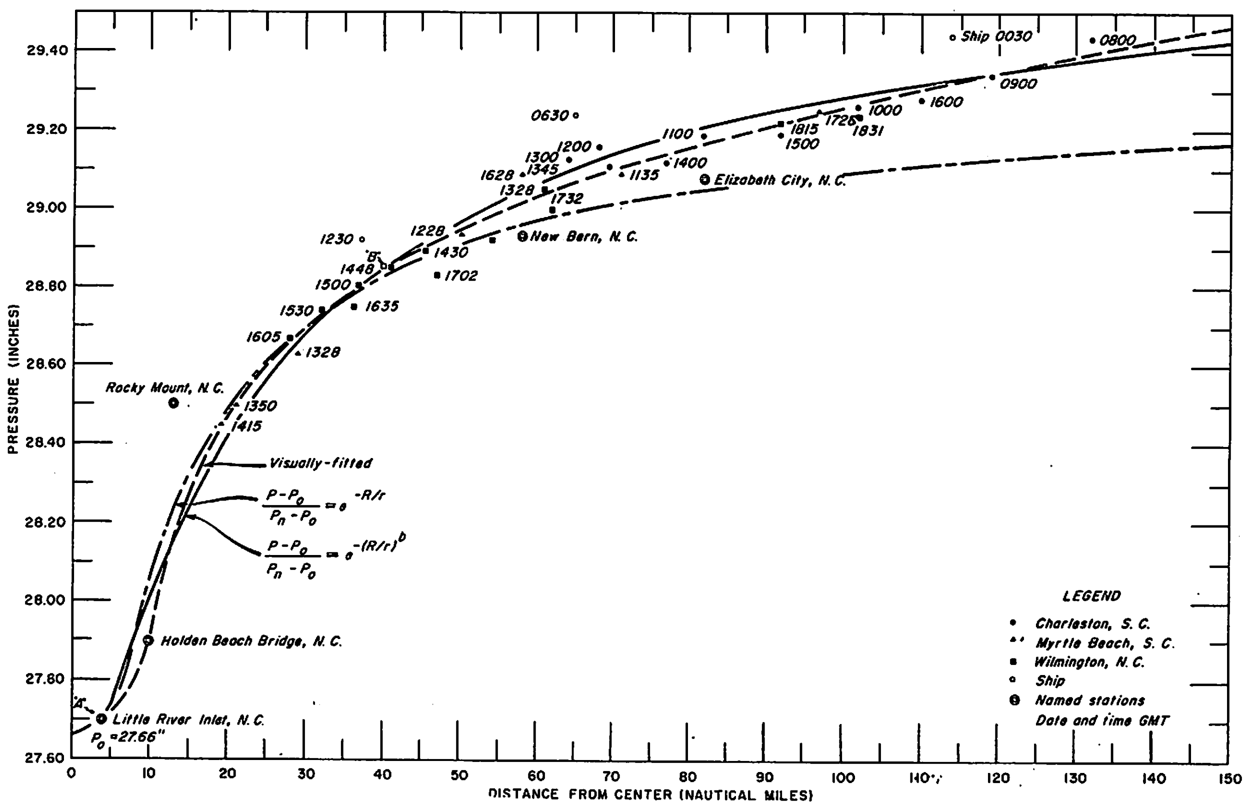


Figure 12-3. Radial pressure profile, Hurricane Hazel, October 15, 1954, about 1500 GMT (landfall).

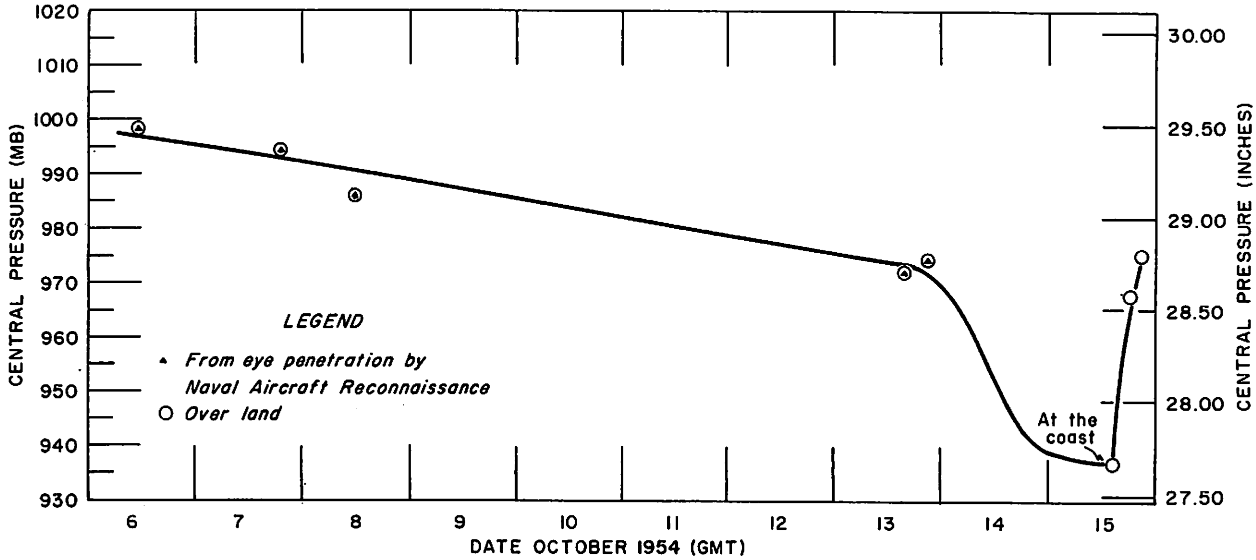


Figure 12-4. Variation of central pressure with time, Hurricane Hazel, October 6-15, 1954.

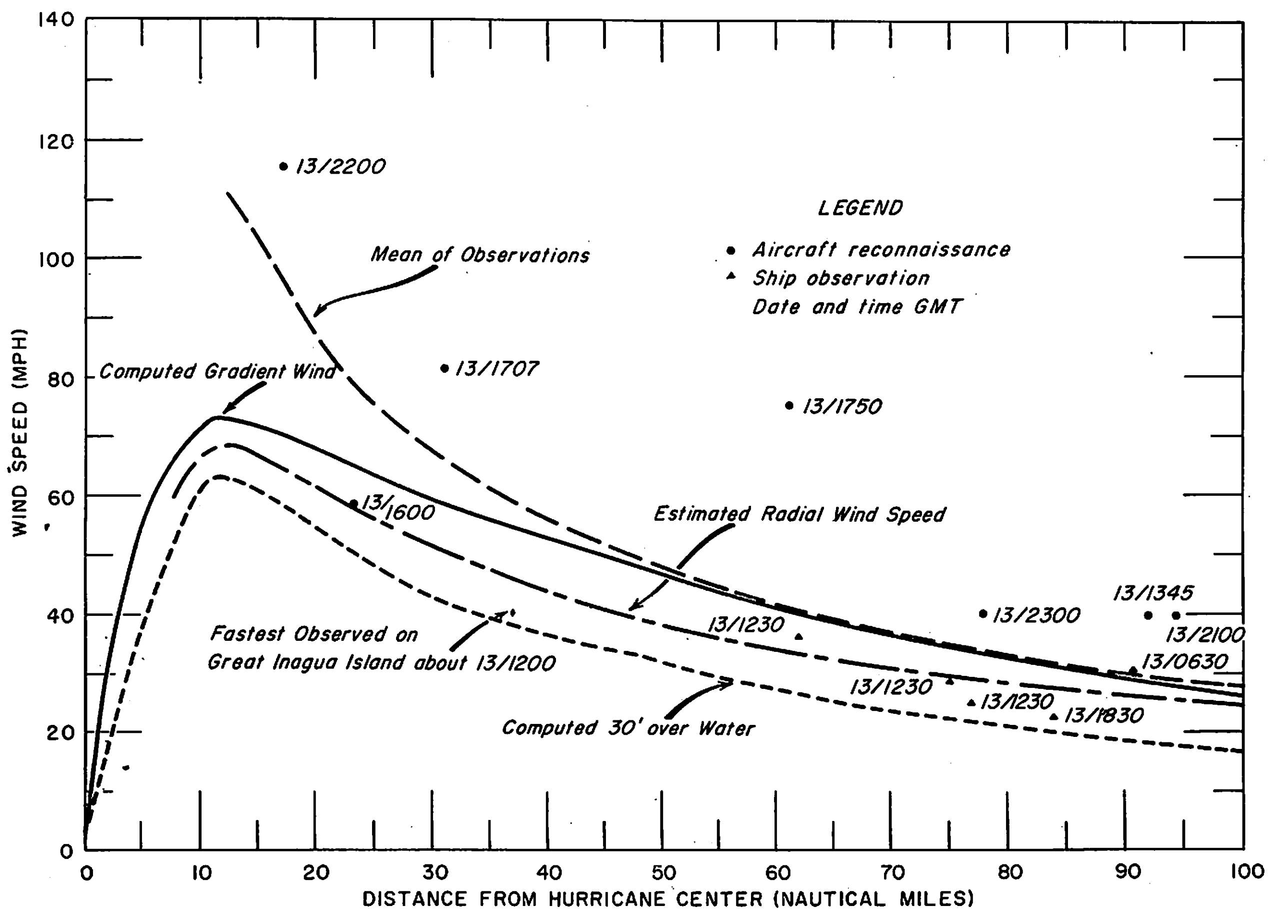


Figure 12-5. Radial profiles of wind speeds, Hurricane Hazel, October 13, 1954, about 1900 GMT.

observations were "spot winds," which were visually obtained primarily by observing the state of the sea. A dashed line on figure 12-5 shows the approximate unadjusted mean of all direct observations.

The gradient wind profile in figure 12-5 was computed from figure 12-2; this was in turn reduced to the "computed 30-ft. over-water" profile by Chapter I procedure. Considerable difference may be noted between the computed 30 ft. over-water winds and the mean of the observations. For example, at 15 miles from the center the computed value is 60 m.p.h. and the observations indicate a speed of 103 m.p.h. or about twice the computed value.

Great Inagua Island observation. Considerable weight is given to the report from Great Inagua Island. Quoting from Climatological Data National Summary /40 /, "After passing through the Windward Channel the hurricane moved northward and passed directly over the Island of Great Inagua and between Mayaguana and Acklin Islands, and passed a short distance east of the remainder of the Bahamas. A minimum pressure of 29.34 inches and a maximum wind of only 40 m.p.h. were reported at Great Inagua Island." This report appears to be from Matthew Town, which is the only listed reporting station at Great Inagua Island. Matthew Town was 37 n. mi. from the center when the storm was closest to the station. A minimum pressure of 29.34 in. is comparable to the average shown by the pressure profile in figure 12-2. The records indicate that the exposure of the anemometer at Matthew Town is good, and the anemometer height such that the observed speeds are comparable to 30-ft. over-water speeds.

Conclusion on wind speed. Beyond 60 miles from the center there is a more reasonable agreement between ship and reconnaissance wind speed observations than between reconnaissance and Great Inagua Island or computed speeds near the center, but all speeds observed by reconnaissance are higher than ship observations. Brooks and Brooks /42 / in a study of the accuracy of wind speed estimates from ships showed that the estimated speeds correspond to those measured in 60 percent of the cases; 28 percent were underestimated and 12 percent overestimated. Considering this evidence, most weight was given to observations from ships and Great Inagua Island in determining the likely average radial wind-speed profile. The Great Inagua wind observation was made on the left side of the hurricane where the lower wind speeds are usually found. An average speed about 10 percent over the Great Inagua observation was therefore used as the estimated average speed at that distance from the center. The curve labeled "estimated average wind speed" depicts what are subjectively considered to be the most probable values of the mean speeds at 30 ft. It is thus assumed that the reconnaissance reported surface speeds are from about 40 percent to 90 percent too high.

WIND SPEEDS AT LANDFALL ON OCTOBER 15

Data. Wind speeds and direction at selected stations were plotted relative to the center at the time of the observation, figure 12-6. These were the 10-minute-average wind speeds at half-hour intervals within the period from 0630 to 1830 GMT at the Weather Bureau Airport Station, Wilmington, N. C.; Weather Bureau Office, Charleston, S.C.; Weather Bureau Airport

Station, Savannah, Ga.; the airway observations at Myrtle Beach, S. C.; Frying Pan Shoals Lightship, and miscellaneous ships. The speeds were adjusted to a common 30-ft. over-water frictional surface. Speeds observed after the center entered the coast were also adjusted upward for filling of the storm after landfall.

Computed wind speeds. Wind speed observations were absent in the portion of the storm between the Wilmington and Myrtle Beach observations during the period of this analysis (0630 to 1830 GMT). For a general guide as to the magnitude of the average maximum wind speed in this part of the storm, wind speeds were computed from the radial pressure profile (fig. 12-3). Equation (12-1) was solved for the pressure gradient by differentiating P with respect to r:

$$\frac{dP}{dr} = \frac{bR^b}{r^{b+1}} (P_n - P_o)e^{-(R/r)^b} \qquad (12\text{-}2)$$

Substituting in the general formula for the cyclostrophic wind

$$\frac{V_c^2}{r} = \frac{1}{\rho}\frac{dP}{dr} \qquad (12\text{-}3$$

we obtained for the cyclostrophic wind

$$V_c^2 = \frac{b}{\rho}\left(\frac{R}{r}\right)^b (P_n - P_o)e^{-(R/r)^b} \qquad (12\text{-}4)$$

where ρ is the air density. The reduction to gradient wind (V_g) was approximated from the formula $V_c - V_g = .173\ r$, which is discussed in /4/. The over-water wind at 30 ft. was determined by applying empirical factors to the gradient wind measured at a known distance from the storm center, (fig. 1-3). Average maximum wind speeds were computed to be: cyclostrophic, 97 m.p.h.; gradient, 94 m.p.h.; and 30-ft. over-water, 81 m.p.h. The values of 27.66 in. for central pressure, 29.81 in. for asymptotic pressure, 1.175×10^{-3} gm. per cc. for air density, 21.3 n. mi. for radius to region of maximum winds, and 0.826 for the constant, b, were used.

Smoothing. Considerable smoothing was employed in fitting the isotachs to the data (fig. 12-6). Smoothing was desirable because: 1) several types of wind speed data are represented, 2) the data from which the isotachs were drawn represented a period of approximately 10 hours, so that the pattern is one integrated over the period, 3) most of the observations were at land stations, necessitating adjustments both to a common height and to the common frictional surface of "over water" where many approximations were necessary, and 4) wind speeds observed after 1500 GMT were in a filling hurricane requiring an upward adjustment to make them comparable to earlier observed speeds. Computed wind speeds were used only as a general guide in estimating the winds in the zone of maximum winds where observations were absent. The considerable asymmetry which was observed in speeds outside the zone of

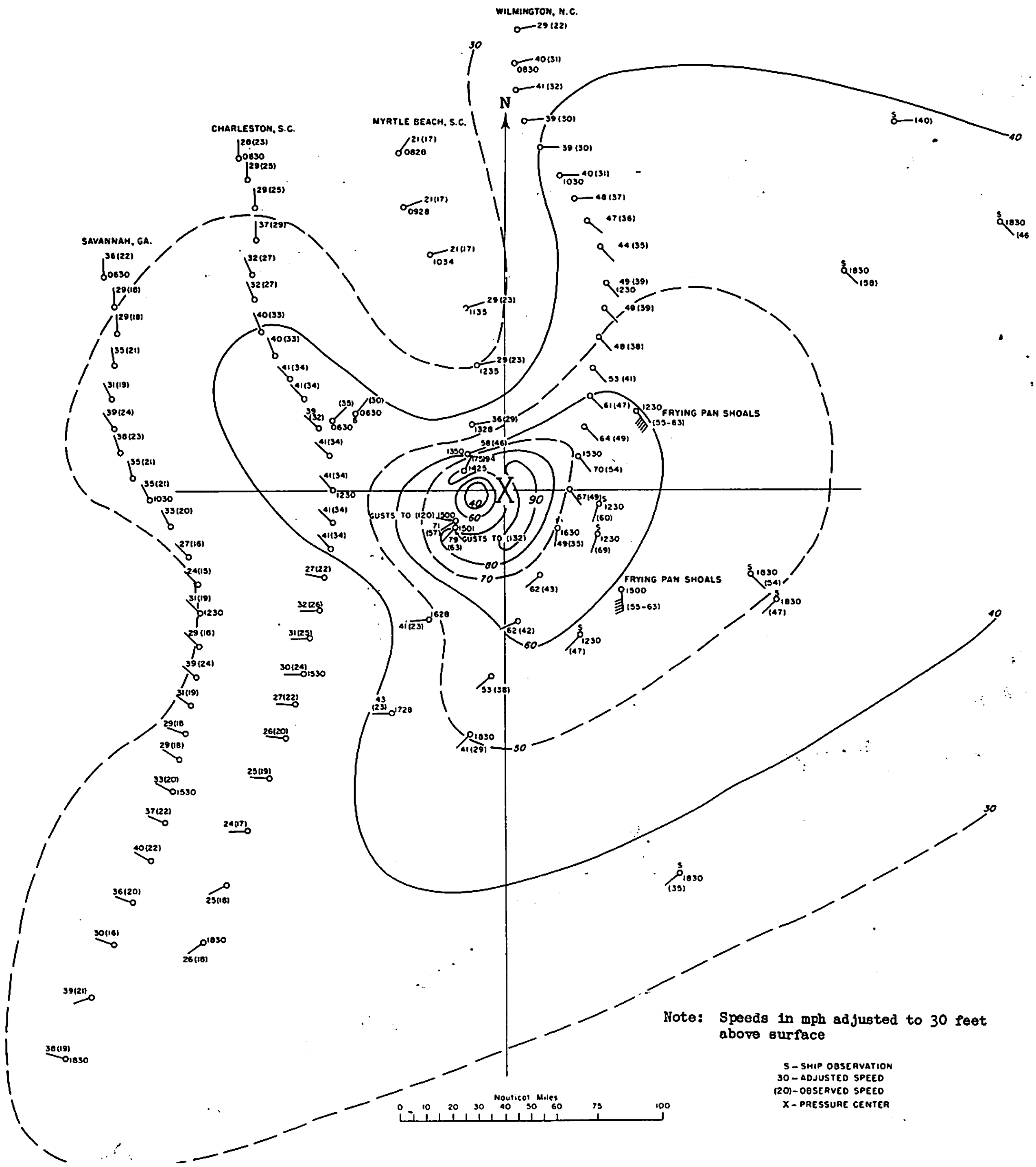


Figure 12-6. Speculative wind speeds, Hurricane Hazel, October 15, 1954, adjusted to 1500 GMT, intensity.

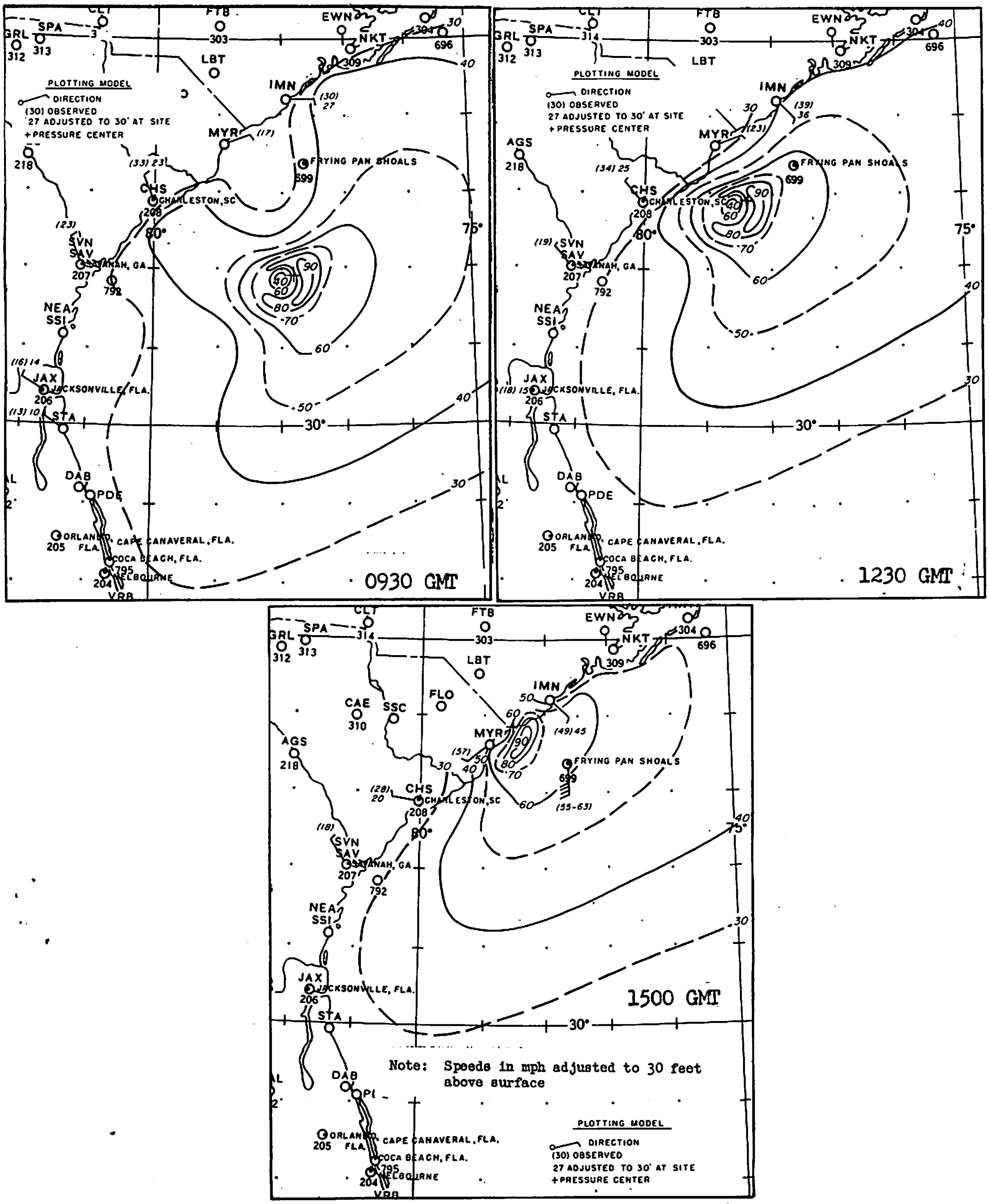


Figure 12-7. Wind speeds, Hurricane Hazel, October 15, 1954, 0930-1500 GMT.

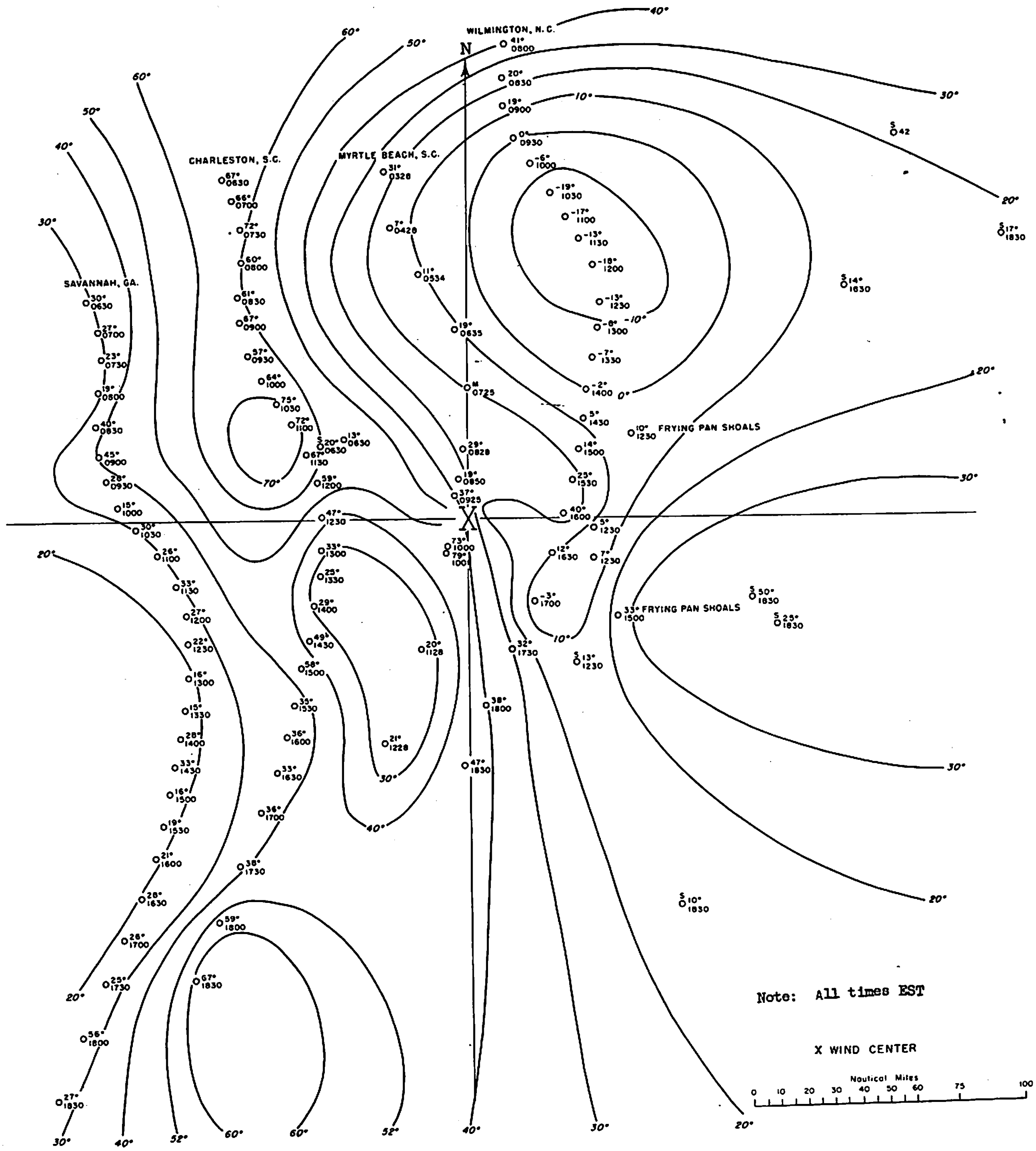


Figure 12-8. Wind deflection angles, Hurricane Hazel, October 15, 1954, about 1500 GMT (landfall).

maximum winds was carried inward to the pattern near the center. Consideration was given to unofficial estimates of high wind speed at the coast [40]. Figure 12-6 shows the speculative 30-ft. over-water wind speed and direction pattern at about landfall on October 15, 1954. In figure 12-7 are the final wind-speed patterns at 0930, 1230, and 1500 GMT positioned on the track. These patterns are reproductions of the speculative wind-speed pattern (fig. 12-6) with appropriate modification of the speeds near the shore.

WIND DIRECTION

A composite wind deflection angle pattern was prepared (fig. 12-8) by plotting all available deflection angles on a chart relative to the wind center and drawing isopleths of deflection angle. Because of the scatter of the data, considerable smoothing was employed.

The deflection angle pattern shown in figure 12-8 is based, primarily, on observations taken at land stations where differences in frictional surfaces cause variation in individual station deflection angles. The time variation is also reflected in the deflection angles. Despite the variation and the necessary smoothing, the deflection angle pattern in figure 12-8 is considered to be useful for quantitative application in describing the wind directions from about 9 hours before landfall until 3 hours after landfall. It may be used in conjunction with figures 12-6 and 12-7.

Table 12-1. - Parameters of October 15, 1954, hurricane in the Atlantic

	Part A. Near Great Inagua Island, October 13, 1954	
P_o,	Central pressure (in.), 28.73	
P_n,	Asymptotic pressure (in.), 29.77	
R,	Radius of maximum winds (n. mi.), Computed	12

	Part B. At the Carolina Coast, October 15, 1954	
P_o,	Central pressure (in.), 27.66	
P_n,	Asymptotic pressure (in.), 29.81	
R,	Radius of maximum winds (n. mi.), Computed	18
	Observed	36
	Isotach patterns based on 21	
c,	4-hr. average forward speed at the coast (kt.), 26	

13. HURRICANE HAZEL OF OCTOBER 15, 1954, IN THE CHESAPEAKE BAY AREA

INTRODUCTION

After landfall, hurricane Hazel accelerated northward, reaching forward speeds near 60 m.p.h. as it moved along Chesapeake Bay. (The hurricane before landfall is described in section 12.) Damage in the Norfolk area was estimated at $3,500,000. Marine damage in Chesapeake Bay was high; many small craft were sunk or damaged; piers were demolished and private docks were swept away in the tidewater areas. In the Maryland section of the Bay, the highest tides were reported variously from 3 to 7 feet above mean low water. At Baltimore, the highest tide recorded was 6 feet above mean sea level. Several observation stations along the path of the storm set new wind speed records /37/. These included Norfolk and Richmond, Va., Washington National Airport, WBAS, Binghamton, N. Y., and WBO New York, N. Y.

As the hurricane moved northward over the eastern United States, it acquired extratropical characteristics, and by the time it was nearest to Chesapeake Bay, it had become quite asymmetrical with respect to temperature, pressure, and wind.

TRACK

The approximate locations of the storm center are shown in figure 12-1.

SEA LEVEL PRESSURE

The pressure distribution over the Chesapeake Bay area for times corresponding to isotach charts is shown by the sea-level isobars superimposed on the isotach charts in figure 13-1. After landfall at 0955 EST, the central pressure (28.80 in.) increased at the rate of 0.167 in. per hour for a period of 6 hours and 50 minutes.

ISOTACH CHARTS

Isotachs are shown in figure 13-1 in the Chesapeake Bay area at 3-hourly intervals. The first isotach chart is for 0800 EST when the center was still over the Atlantic and about 270 n. mi. southsouthwest of Richmond, Va. The isotach patterns were constructed directly from adjusted wind speed data.

FORWARD SPEED

Forward speed of storm is considered in some surge models. The hurricane moved at an accelerated rate after landfall. Average rates of forward speed over the intervals between times of the isotach charts are shown in table 13-1.

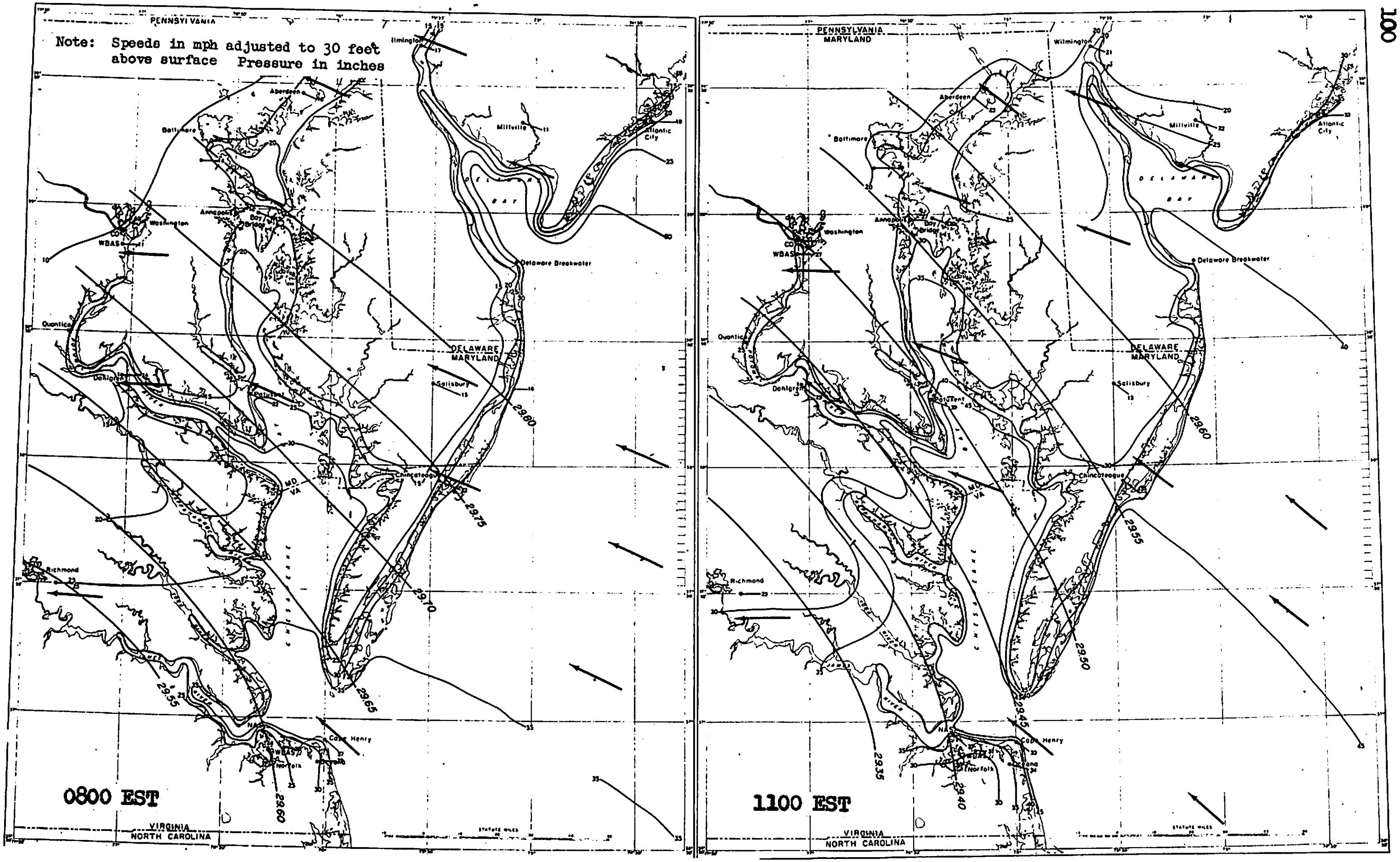


Figure 13-1a. Wind speed, direction, and sea-level pressure distribution, Hurricane Hazel, October 15, 1954, 0800 and 1100 EST.

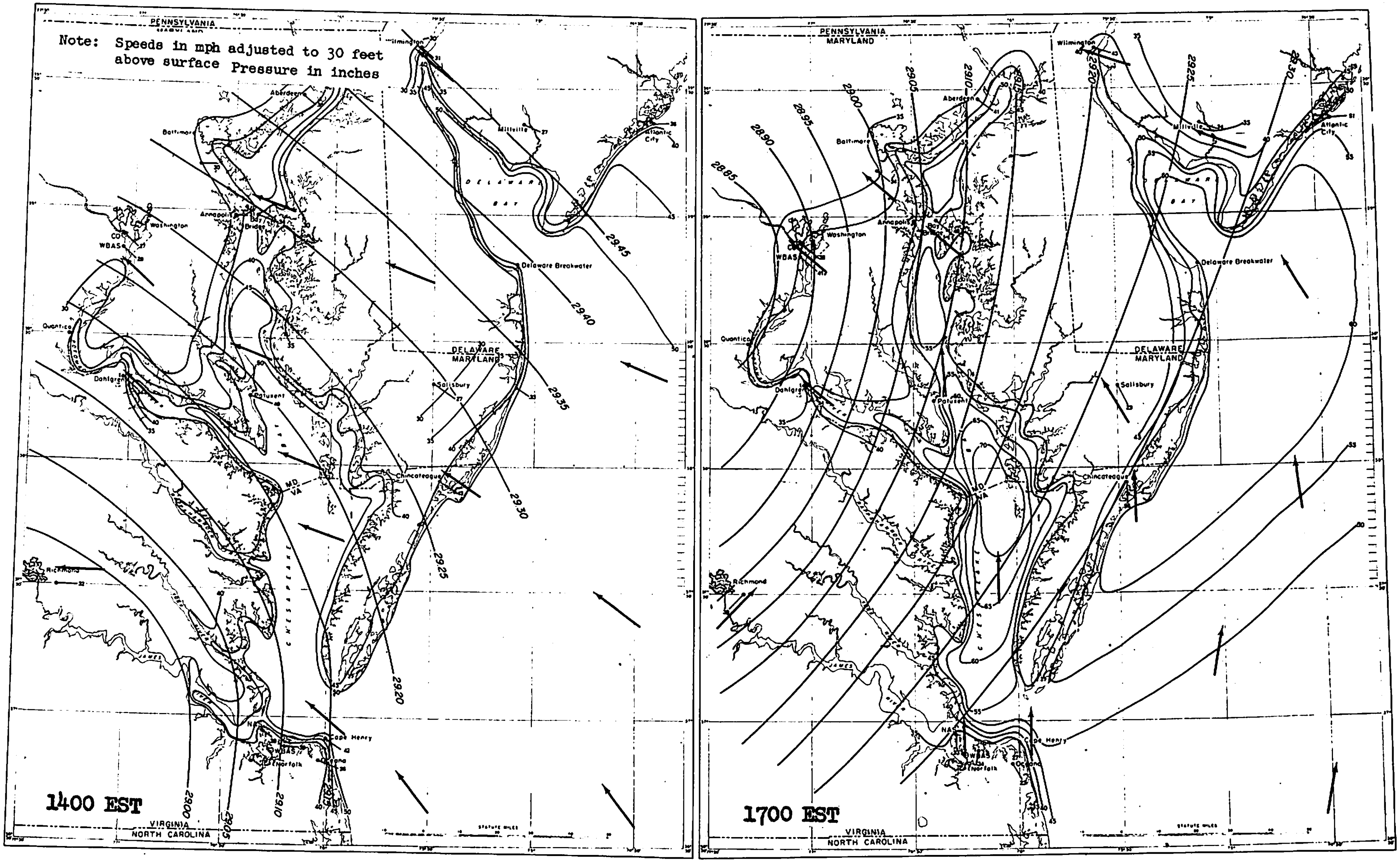


Figure 13-1b. Wind speed, direction, and sea-level pressure distribution, Hurricane Hazel, October 15, 1954, 1400 and 1700 EST.

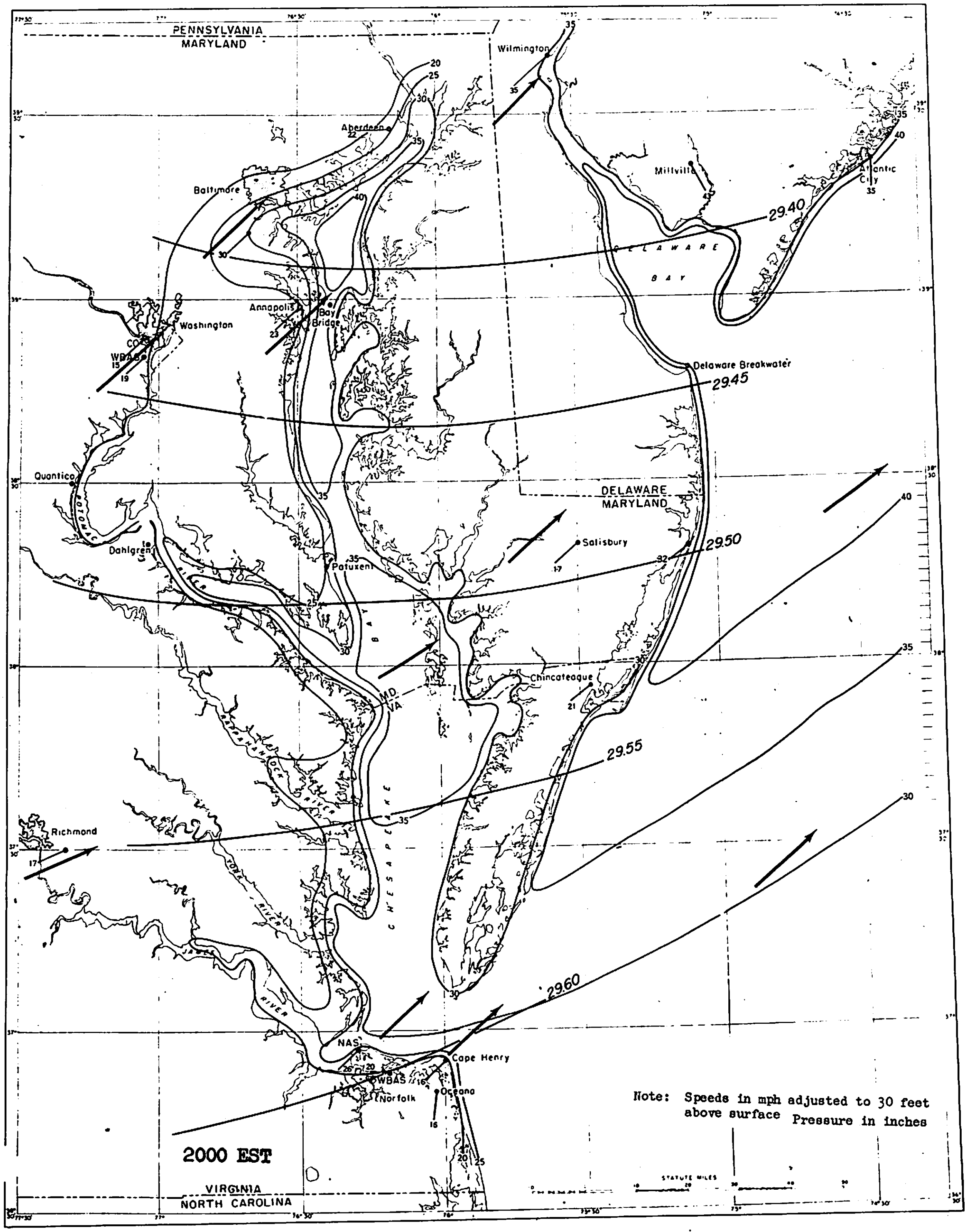


Figure 13-1c. Wind speed, direction, and sea-level pressure distribution, Hurricane Hazel, October 15, 1954, 2000 EST.

Table 13-1. - Forward speeds of hurricane Hazel, October 15, 1954

Interval (EST)	Average Speed (knots)
0800 to 1100	23.0
1100 to 1400	40.0
1400 to 1700	55.3
1700 to 2000	57.3
0800 to 2000	44.0

14. HURRICANE OF SEPTEMBER 23-24, 1956 IN THE GULF OF MEXICO

INTRODUCTION

Hurricane Flossy caused high water to flood the area in Louisiana from the Mississippi Sound to Orleans Parish and the Mississippi Levees. The Gentilly Section of New Orleans was flooded when water from Lake Pontchartrain poured over the sea wall /43 7.

TRACK

The track, with hourly positions of the center, is shown in figure 14-1. The storm moved off the Yucatan Peninsula into the Gulf of Mexico on September 22. It continued to move northward across the Gulf during the 23d and recurved to the northeast just off the Louisiana coast. The center crossed the Mississippi River Delta between Buras and Burrwood, La., between 0300 and 0600 CST September 24 and moved inland near Valparaiso, Fla., about 1700 CST September 24.

PRESSURE

Central pressure. The storm deepened slowly as it moved northward across the Gulf of Mexico. At about 1600 CST, September 23, when the storm was centered 130 n. mi. south of New Orleans, La., a reconnaissance flight reported a central pressure of 29.06 in. The central pressure early on the morning of the 24th, at the time the hurricane center crossed the Mississippi Delta, was computed to be near 28.80 in., by the method described in section 1. This value was based on the minimum pressure of 29.03 in. reported at Burrwood as the center passed 17 n. mi. to the north of the station, and a pressure observation of 28.94 in. from a ship that passed within the eye of the storm about 0900 CST september 24. Later on the 24th, aircraft reconnaissance reported a minimum pressure of 28.76 in. when the storm was centered just off Pensacola, Fla. At 1725 CST, when the center was crossing the coast, a dredge within the eye at Destin, Fla., also observed a minimum pressure of 28.76 in.

Asymmetry of the pressure field. The pressure distribution around the hurricane was asymmetrical. The strongest pressure gradient, near the center but beyond the radius of maximum wind, was in the forward sector. The pressure gradient was weakest south of the center. In the right sector of the storm, at a distance of 100 miles from the center and beyond, the pressure gradient was greater than the gradients that occurred at this distance in the other directions (fig. 14-2). The proximity of the subtropical High to the northeast probably contributed to the larger pressure gradient in this sector at a distance from the center.

Pressure profiles. Figure 14-2 shows pressure profiles in the forward sector of the storm at 1830 CST September 23, using the reconnaissance observation of 29.06 in. at 1600 CST as the minimum pressure, and for the period from 0000 CST to 0940 CST September 24 when the storm had deepened and developed hurricane force winds. Beyond 35 miles from the center, the two visually-fitted curves correspond well to pressure profiles derived from the exponential formula (1-1) indicated by dashed lines. Ships' observations of pressure in each quadrant for the period from 1200 CST September 23 to 0000 CST September 24 when the storm was moving north to northeastward are plotted in figure 14-2 to indicate the difference in the pressure distribution in the right sector from the distribution in the forward sector. Observations at Burrwood and New Orleans are also plotted on the chart. A curve has been visually fitted to the observations in the right sector to indicate the probable average slope of the pressure profile in that sector.

WIND

Composite wind speed chart. A composite wind speed chart for 1200 CST September 23 to 1230 CST September 24 was constructed by the usual procedures from ship observations (unadjusted), wind speeds observed at coastal stations adjusted to 30-ft. over-water values, and wind speed profiles computed from pressure profiles in the forward sector of the storm, figure 14-3. In constructing the isotachs, extra weight was given to the observations made at 0000 CST September 24 and later. Considerable smoothing was necessary in analyzing the ship reports because large variations in speed were frequently reported within a small area. These variations may have resulted from squalls in the area which affected only part of the ships, from observers overestimating or underestimating the wind speed, differences in the actual times of the observations, and transmittal errors.

Maximum isotachs. The maximum isotachs in the right side of the storm were based largely on the autographic wind-speed records at Burrwood, La. In the left sector, where the data were lacking, the maximum isotachs are based on 30-ft. over-water speeds computed from pressures (fig. 14-4). The 0000-0930 CST September 24 mean pressure profile in the forward sector (fig. 14-2) was used to compute gradient wind speeds that were reduced to the 30-ft. over-water speeds.

Wind speed distribution. The composite wind speed pattern (fig. 14-3) is quite asymmetrical. Speeds are considerably higher at about 100 miles

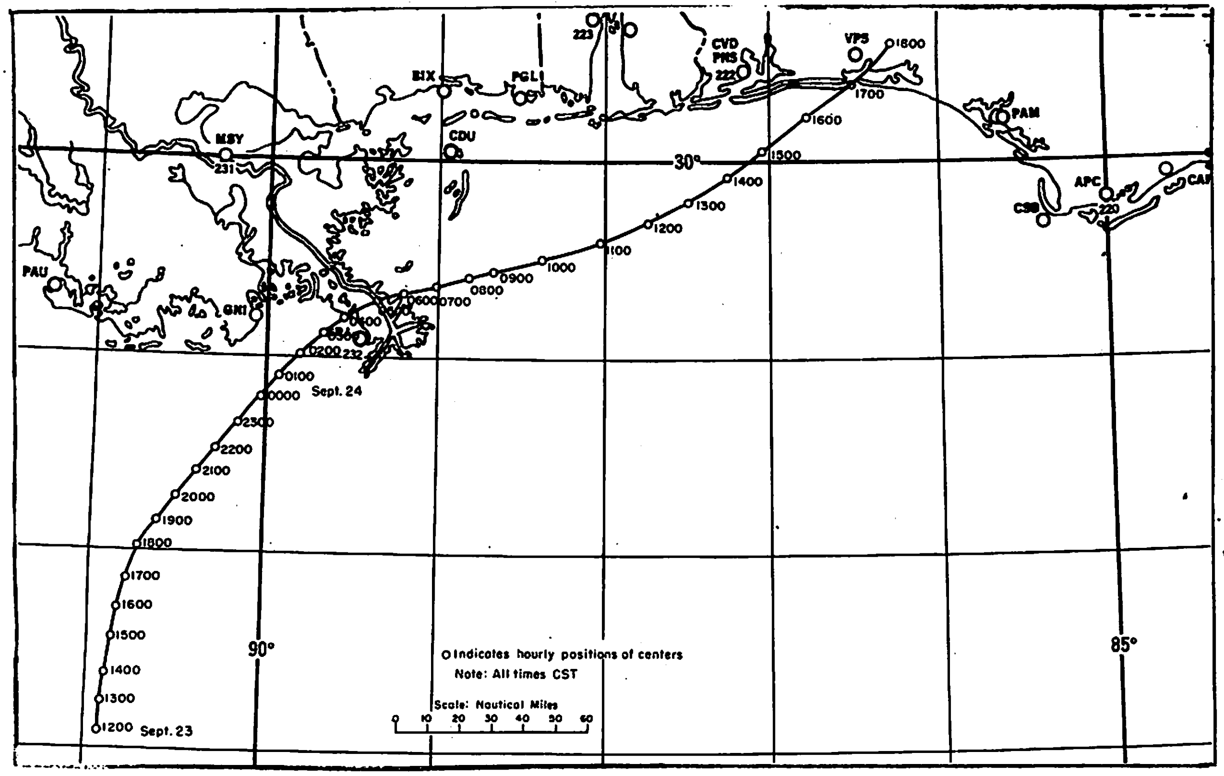


Figure 14-1. Track of Hurricane Flossy, September 23-24, 1956.

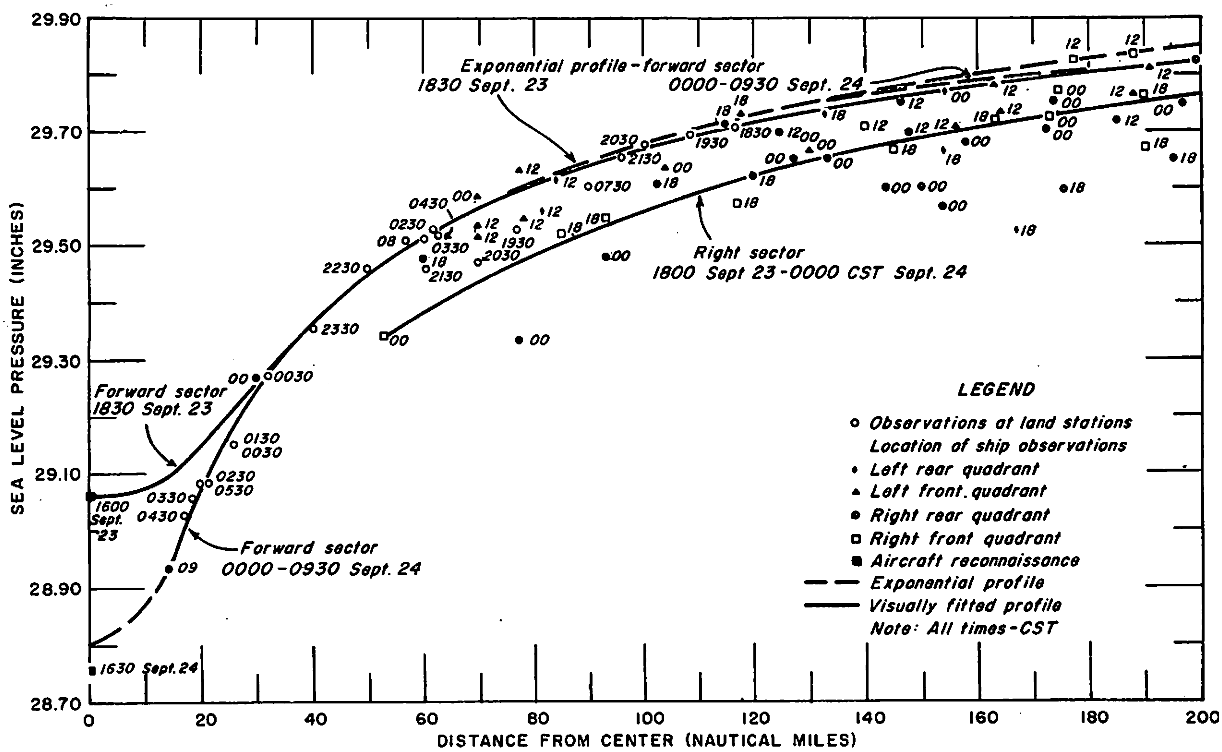


Figure 14-2. Pressure profiles in the forward and right sectors of Hurricane Flossy, September 23-24, 1956.

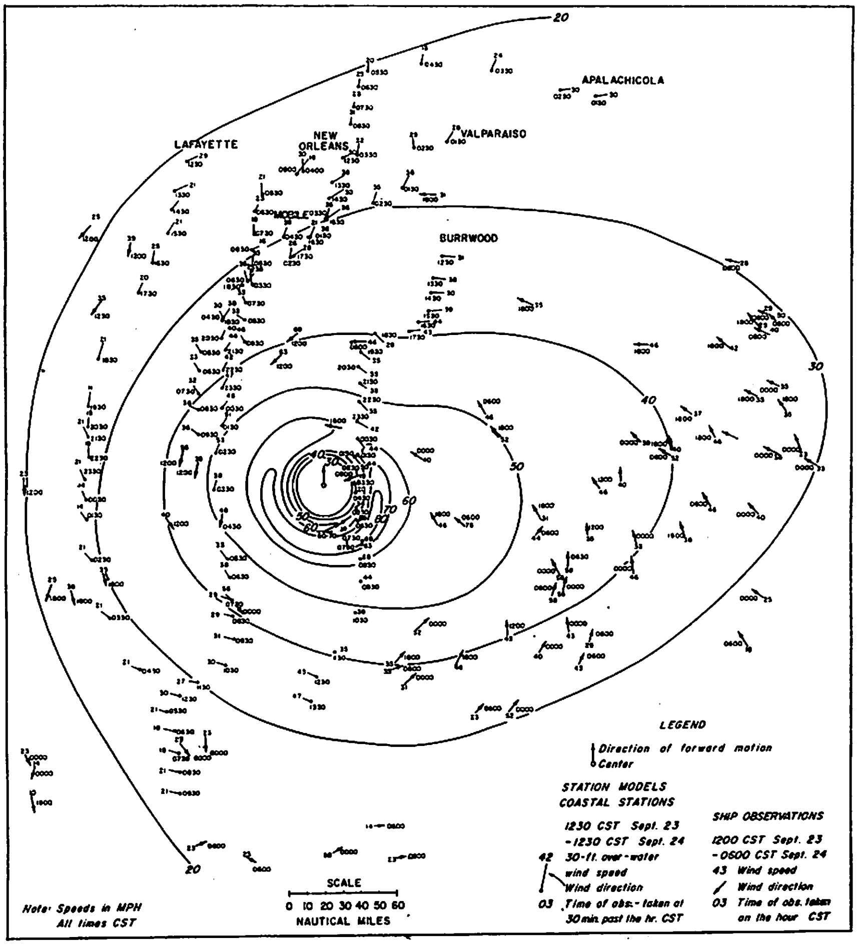


Figure 14-3. Composite wind speed pattern, Hurricane Flossy, 1230 CST, September 23 to 1230 CST, September 24, 1956.

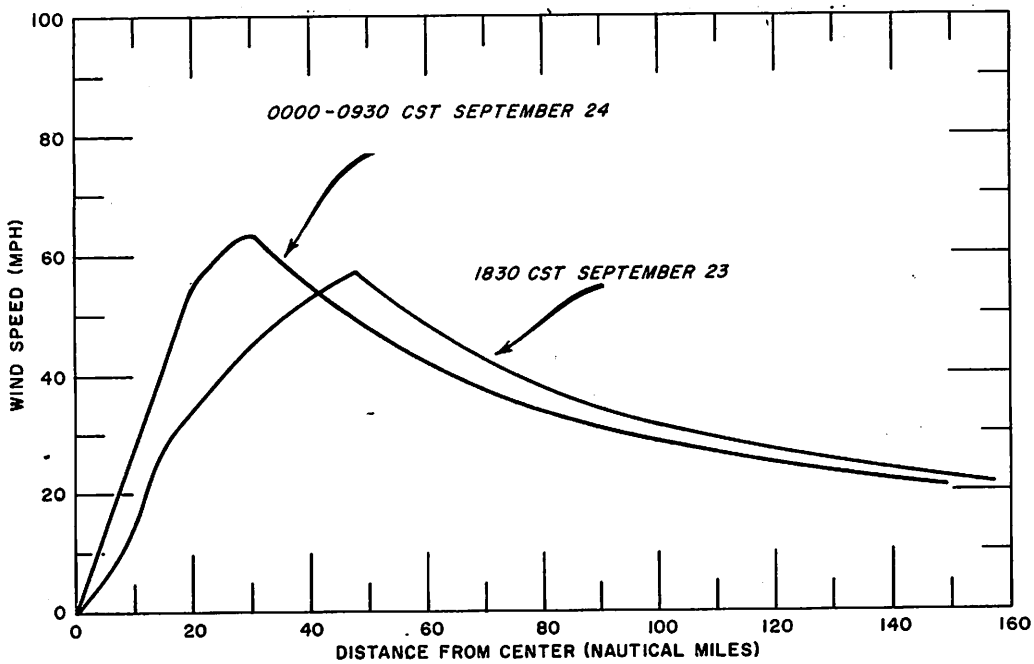


Figure 14-4. Computed 30-ft. over-water wind-speed profiles, forward sector, Hurricane Flossy, September 23-24, 1956.

from the center in the right sector than for the same distance in other directions. An inspection of weather charts for the period suggests that the storm circulation in this sector was reinforced by the subtropical High. Both the stronger pressure gradient and the larger radius of curvature of air parcels in the right sector would lead to higher wind speeds.

DEFLECTION ANGLE

A composite wind-deflection-angle pattern over open water was prepared from a plot of deflection angles from ship reports at 1200 and 1800 CST September 23, 0000 and 0600 CST September 24, and from reports from Burrwood, La., from 1800 CST September 23 to 0200 CST September 24 (fig. 14-5). The chart is aligned to the north. Near the radius of maximum wind, deflection angles of 20 degrees were assumed because of a limited number of reports. The deflection-angle chart is not applicable north of 29°30'N. just off the Mississippi, Alabama, and northwestern Florida coasts. Deflection angles in that portion of the storm were near 90 degrees.

ISOTACH CHARTS

Construction. Isotach charts at 3-hourly intervals were constructed for the period from 1830 CST September 23 to 1230 CST September 24 (fig. 14-6). Where observations were available, isotachs were drawn to the observed speeds. This analysis was then compared to the composite wind speed pattern (fig. 14-3) for consistency and for aid in constructing the isotachs where there were no observations. The wind speed profile computed from the pressure profile at 1830 CST September 23 in the forward sector of the storm (fig. 14-4) was used to construct the isotachs near the radius of maximum winds at that time. The isotach pattern at 2130 CST September 23 was interpolated between the 1830 CST pattern and the 0030 CST September 24 pattern. At 0330 and 0930 CST September 24, when few or no ship observations were available, the composite wind speed chart, adjusted for coastal observations and for continuity with adjacent patterns, was used to construct the isotach pattern over the Gulf.

Wind direction. Wind directions south of 29° 30'N. are determined from the deflection-angle chart (fig. 14-5). Wind directions in the Gulf north of 29°30'N. were determined by streamline analysis of observed wind directions. These derived wind directions are indicated by heavy arrows on the isotach charts.

Observation times. Observations at coastal stations were taken on the half hour and ship observations were made on the hour. The position of the hurricane center is indicated at the half hour on the isotach charts, figure 14-6. This difference between the time of the ship observation and the chart time caused the ship observations plotted on the isotach chart to be displaced about 5 miles from the center (the average forward speed of the storm was 10 knots). Because of the few observations near the center, this displacement is not considered significant. All data shown in the composite chart and the pressure profiles were plotted relative to the distance of the observation point from the center at the time of observation.

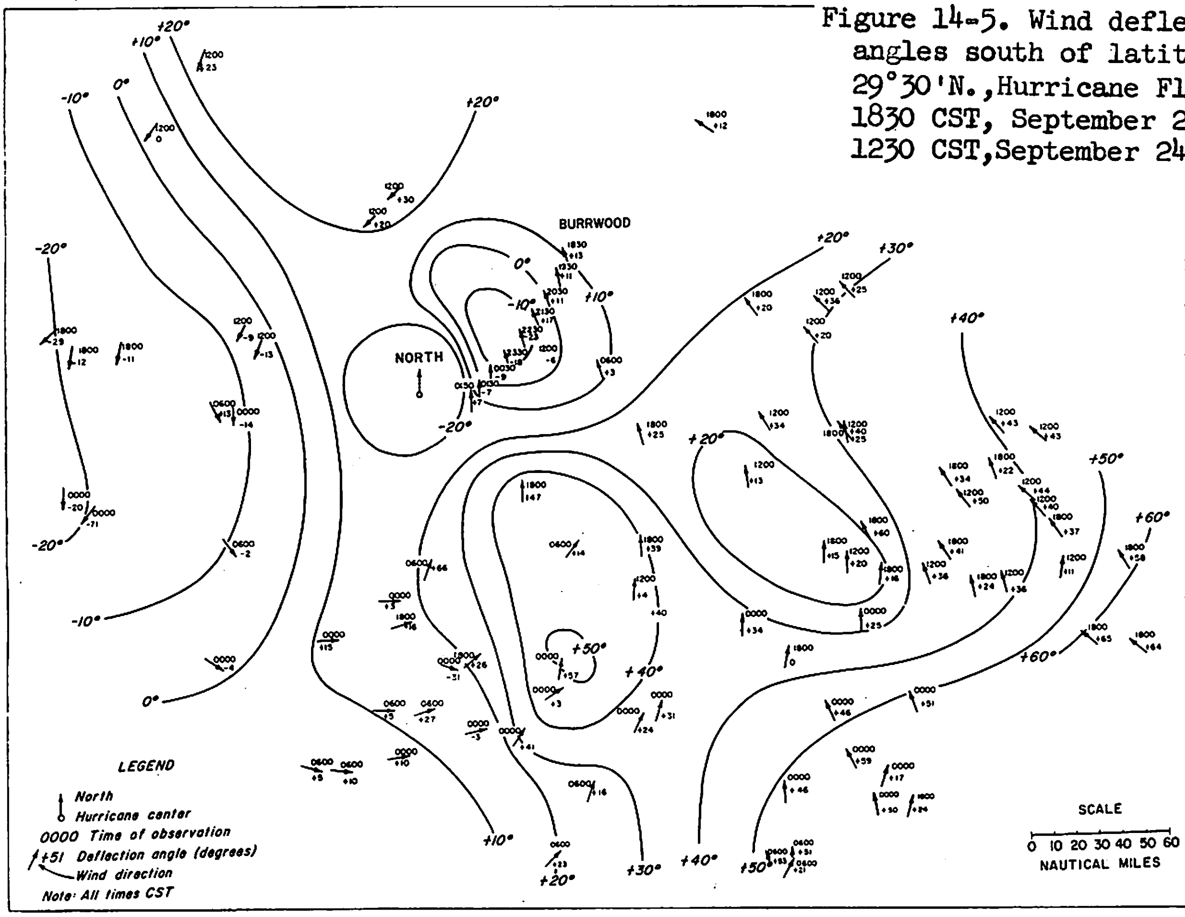


Figure 14-5. Wind deflection angles south of latitude 29°30'N., Hurricane Flossy, 1830 CST, September 23 to 1230 CST, September 24, 1956.

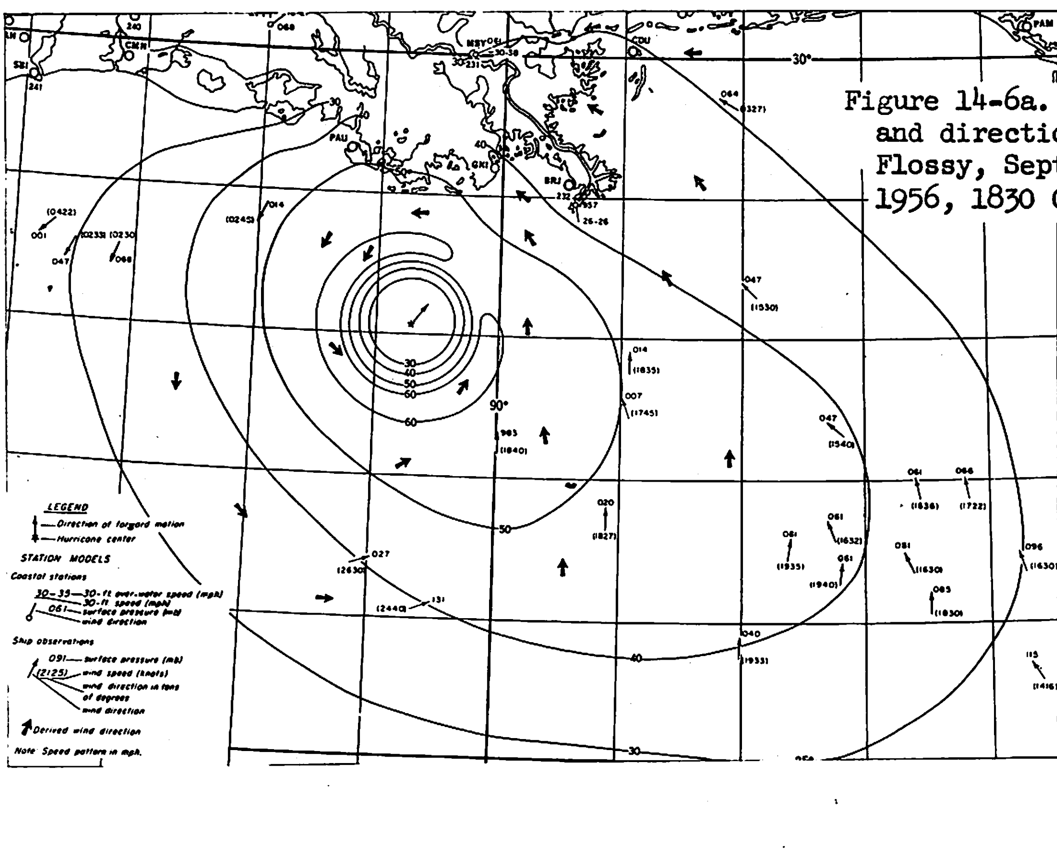


Figure 14-6a. Wind speeds and directions, Hurricane Flossy, September 23, 1956, 1830 CST.

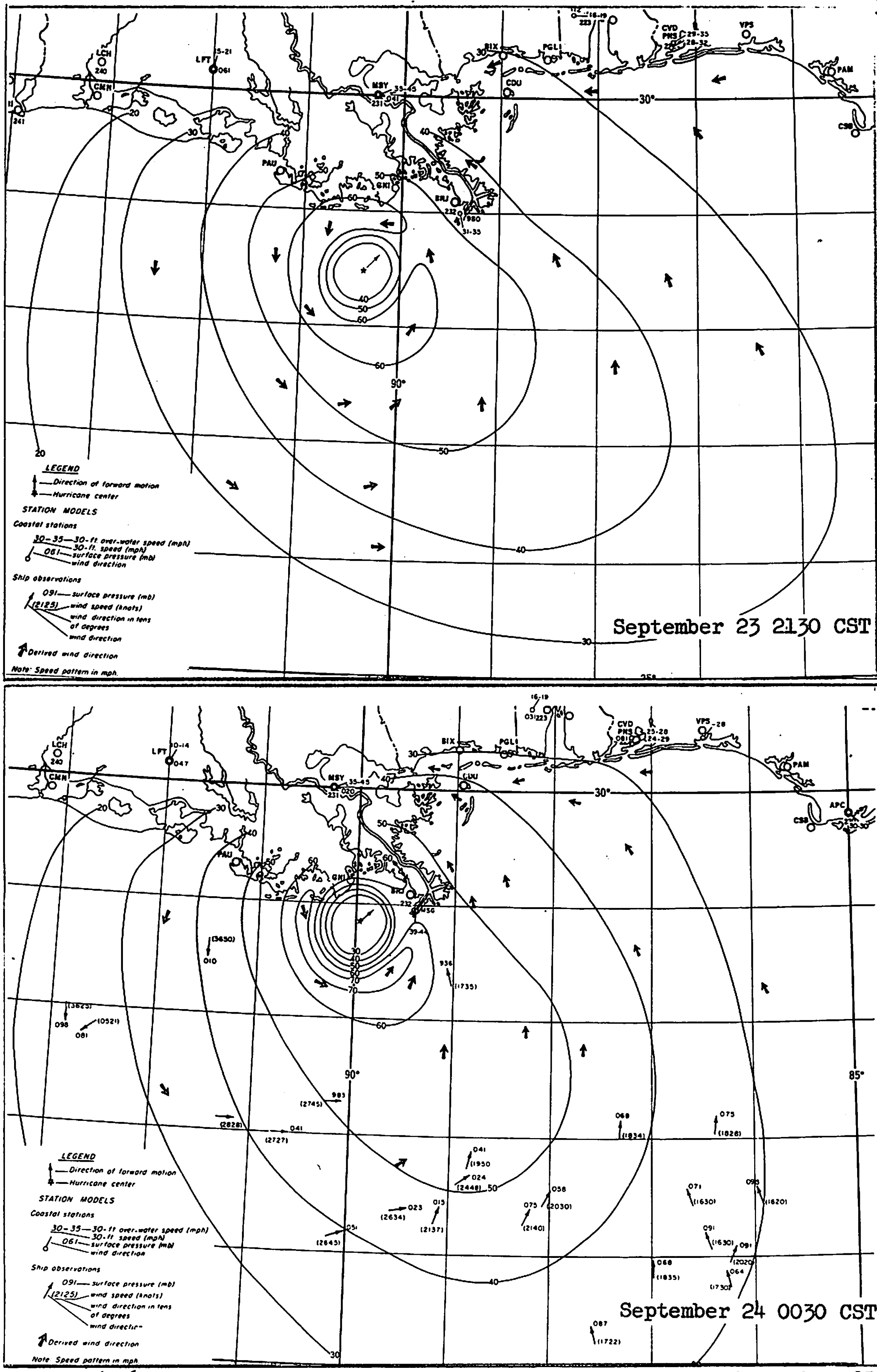


Figure 14-6b. Wind speeds and directions, Hurricane Flossy, September 23, 1956, 2130 CST, and September 24, 1956, 0030 CST.

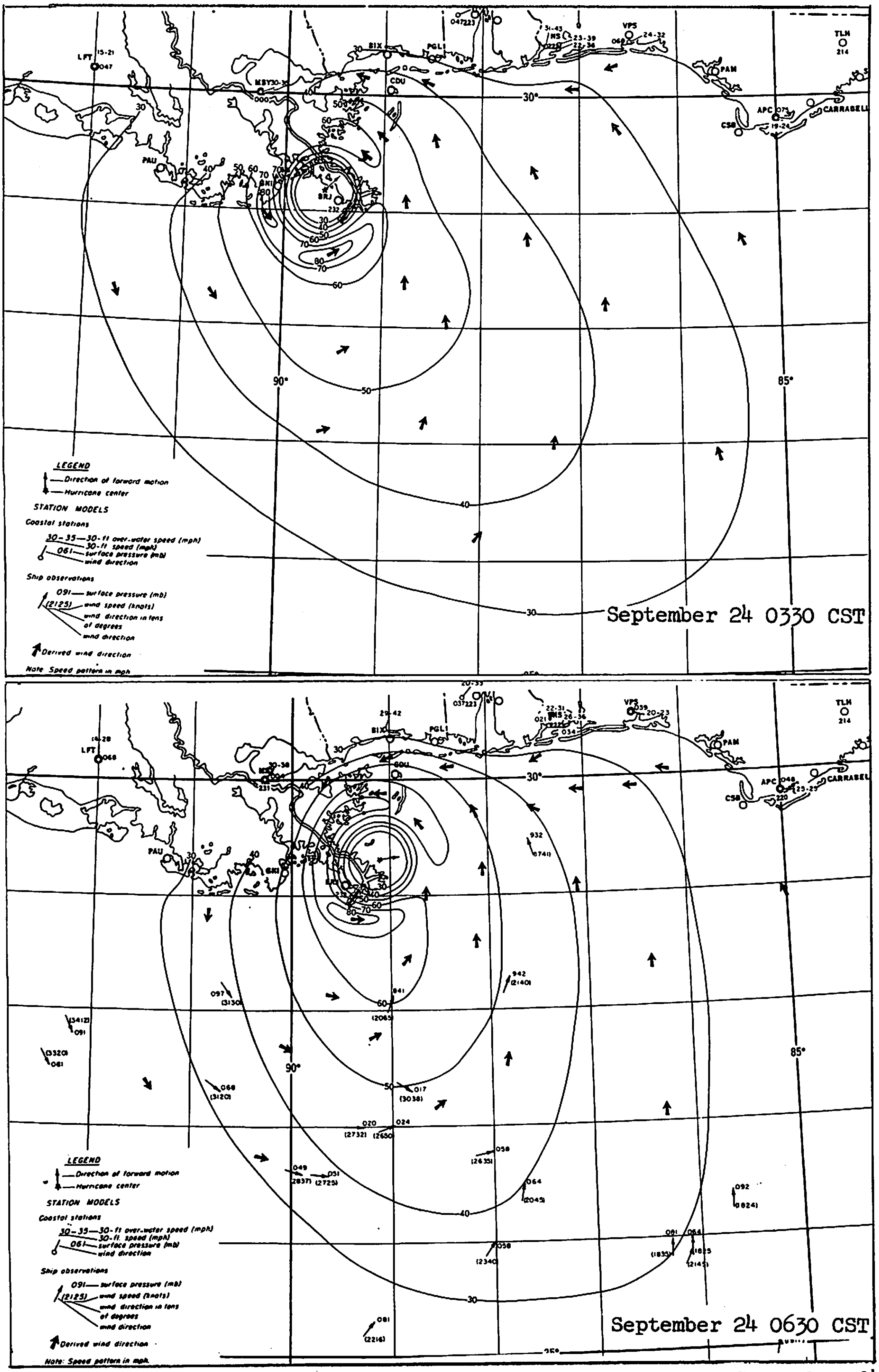


Figure 14-6c. Wind speeds and directions, Hurricane Flossy, September 24, 1956, 0330 and 0630 CST.

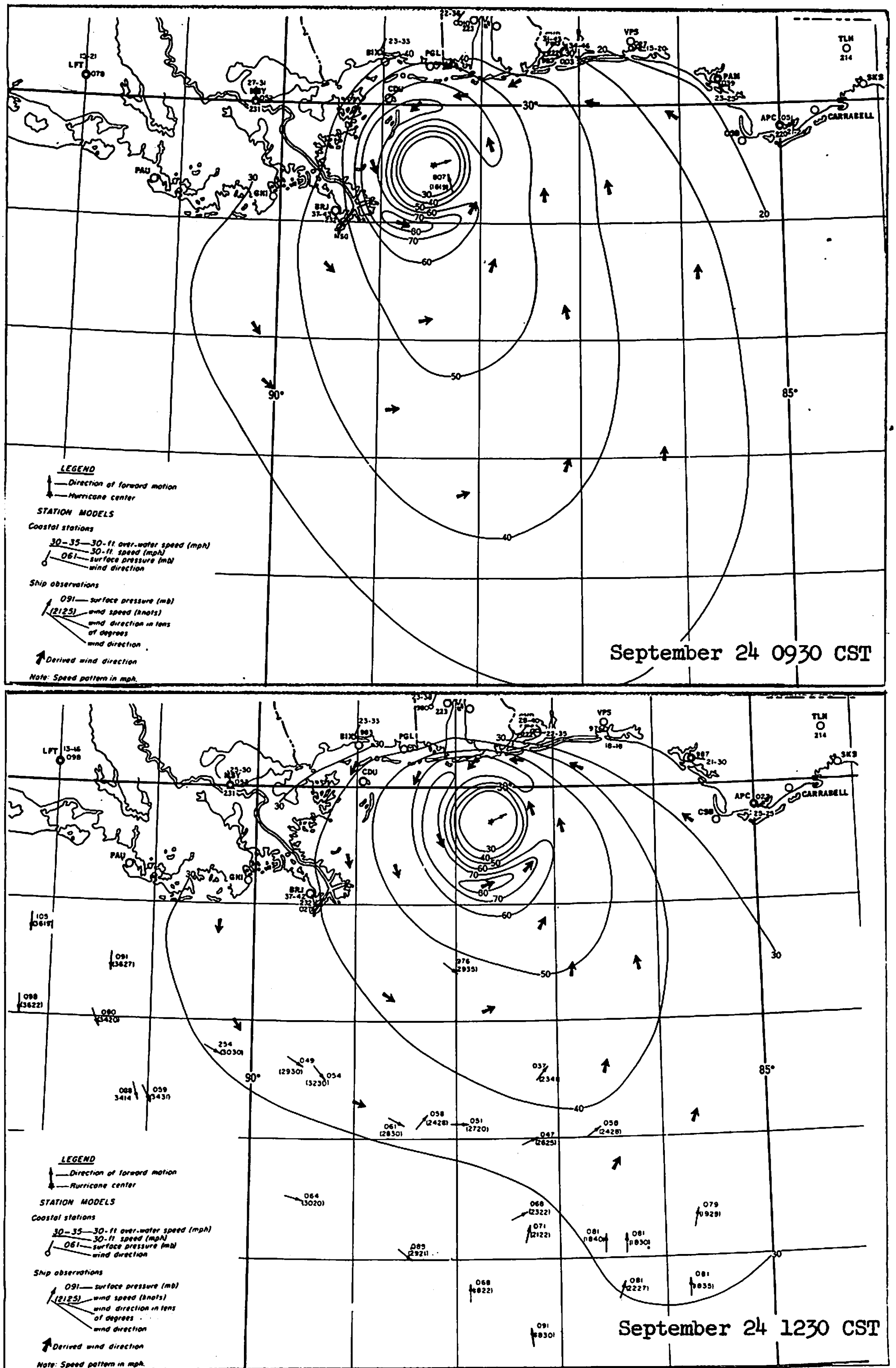


Figure 14-6d. Wind speeds and directions, Hurricane Flossy, September 24, 1956, 0930 and 1230 CST.

Table 14-1. - Parameters of the September 24, 1956 hurricane near Burrwood, La.

P_o,	Central pressure (in.), 28.80
P_n,	Asymptotic pressure (in.), 29.97
V_{gx},	Maximum gradient wind (m.p.h.), 74
R,	Radius of maximum winds (n. mi.), Computed 30, Observed 22
	Isotach pattern based on computed R
c,	4-hr. average forward speed at the coast (kt.), 10

15. HURRICANE AUDREY OF JUNE 27, 1957, NEAR THE LOUISIANA COAST

INTRODUCTION

Hurricane Audrey of June 27, 1957, one of the most destructive June hurricanes of record, moved inland near the Texas-Louisiana border causing disastrous storm tides along the coast. Greatest destruction from tides and winds extended from Sabine Lake, Tex., to Cote Blanche Bay, La. The death toll in this area is estimated at about 400 and damage at $150,000,000 /45_7. An estimated 4500 homes were destroyed or severely damaged; 95 percent of the homes in Cameron and lower Vermilion Parish were in this category. One hundred thousand additional homes suffered varying lesser damage. Structural damage was widespread in an area 70 miles eastward from the center and inland for 100 miles. A large acreage of rice was inundated by salt water and losses were suffered by other crops. Forty to fifty thousand head of cattle perished, mostly by drowning /44_7.

Hurricane Audrey was first reported as a tropical depression in the Bay of Campeche on June 24, 1957. The storm increased to hurricane intensity on the 25th and then moved northward, the center crossing the Louisiana coast at about 0830 CST June 27 midway between Sabine, Tex., and Cameron, La. The storm began recurving to the northeast about the time it passed inland.

TRACK

The smoothed track of the hurricane center is shown in figure 15-1. Over the Gulf of Mexico, hourly positions of the storm center along the track were determined largely from aircraft reconnaissance reports and land-based radar reports. Over land, the hourly positions were determined from reports of calms and from radar eye reports. Reports of minimum pressure and wind shifts were also used in positioning the track.

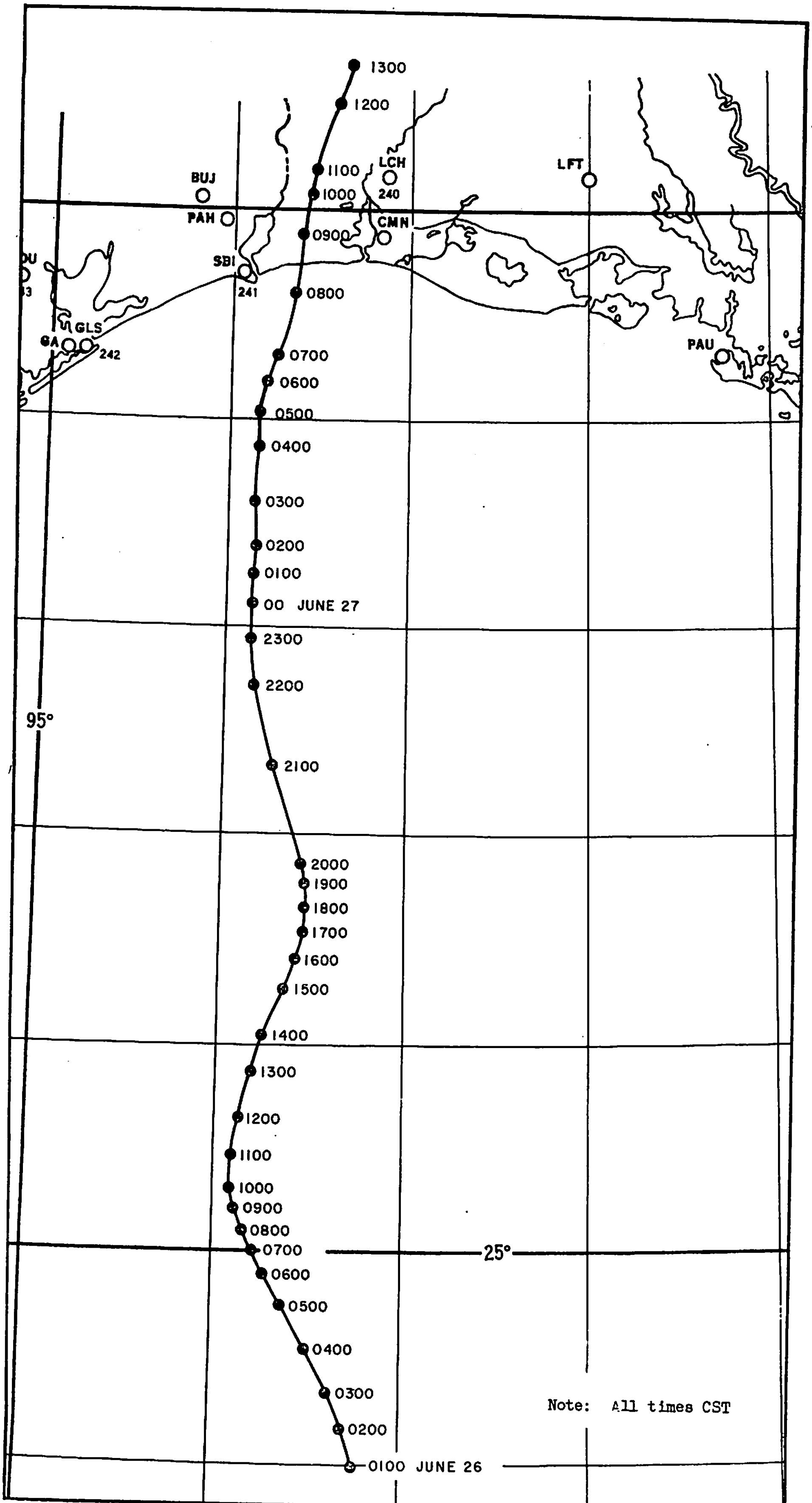


Figure 15-1. Partial track of Hurricane Audrey, June 26-27, 1957.

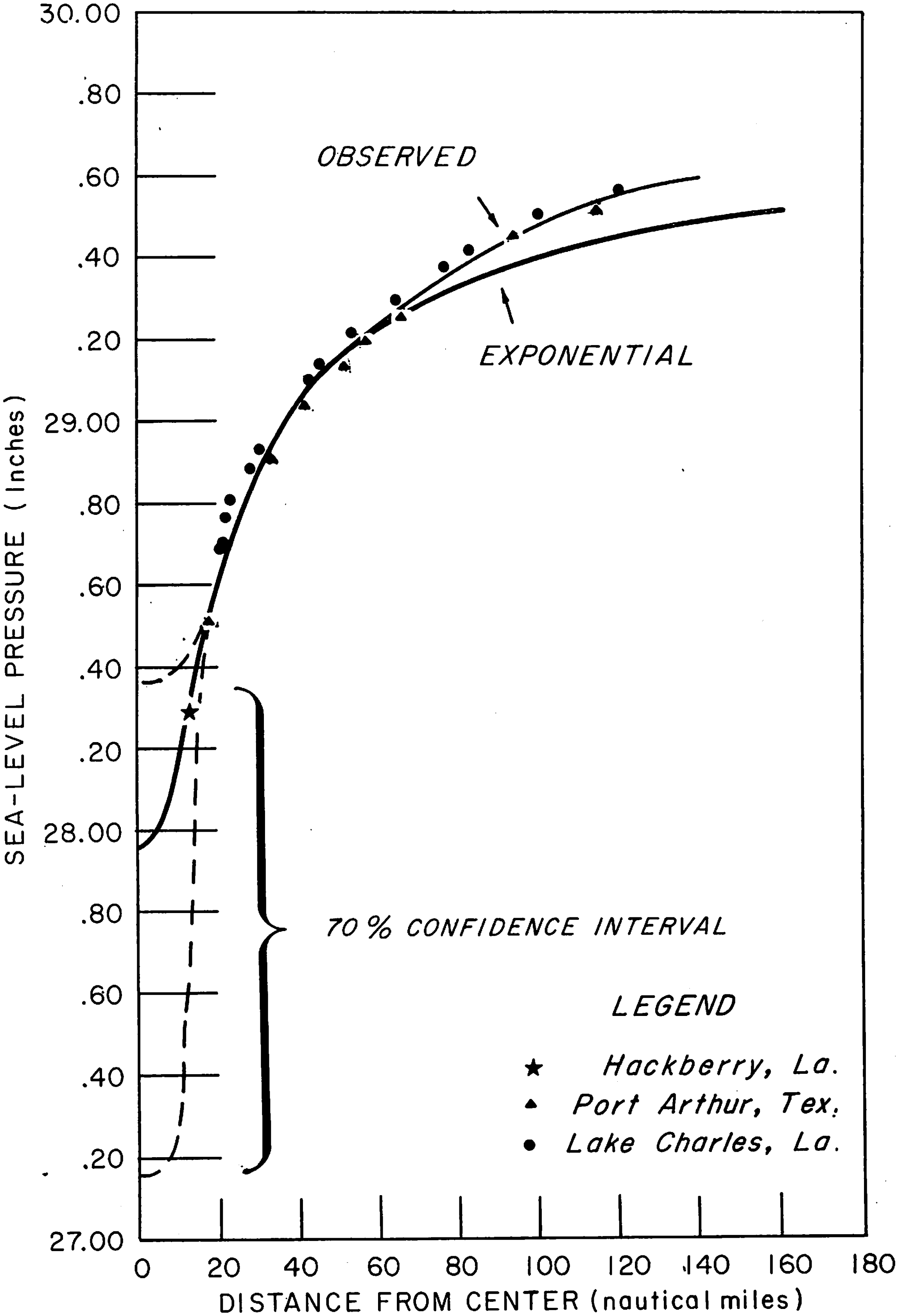


Figure 15-2. Radial pressure profiles, Hurricane Audrey, about 0830 CST, June 27, 1957.

PRESSURE

There was no observation of the minimum pressure in the hurricane at the time the center moved inland. An indication of the central pressure at the coast was obtained by constructing an average sea level pressure profile for the hurricane (fig. 15-2) and using formula (1-1).

The lowest observed pressure in the hurricane, 28.30 in. at Hackberry, La., 12 n. mi. from the pressure center, was used as the innermost point of the visually-fitted profile when computing the exponential curve. The minimum observed pressure at Port Arthur, Tex., 28.52 in., 17 n. mi. from the pressure center, also fell on the exponential curve. Pressure distribution around Audrey as a whole was asymmetrical, but it was most nearly symmetrical within 60 n. mi. of the center. The exponential profile, shown as the heavy line in figure 15-2, was fitted to the visually-fitted profile of the symmetrical part of the hurricane. Beyond 60 n. mi. from the center, where the asymmetry was greater, the exponential curve departs from the visually-fitted curve.

A 70 percent confidence interval about the central pressure as extrapolated from the pressure observation nearest the pressure center can be read from figure 18 of /4/. This chart indicates that, assuming the observed pressure observations are placed the correct distance from the storm center, there is a 70 percent probability that the true central pressure in hurricane Audrey lies between 27.15 in. and 28.35 in. This range is shown by the dashed lines in figure 15-2.

COMPOSITE WIND PATTERN

Time periods for observation. A composite over-water wind speed chart for the hurricane when it was off the Texas-Louisiana coast was constructed using observations of wind velocities from ships during the period from 1500 CST June 26 to 1800 CST June 27 and hourly observations from Weather Bureau stations near the coast for the period from 1800 CST June 26 through 1800 CST June 27 (fig. 15-3). These periods of time were selected in order to obtain observations in all quadrants of the hurricane as it passed over the coast.

Wind reports. Wind reports made by the U. S. Coast Guard Stations at Sabine, Tex., and Cameron, La., were also plotted on the chart. However, since the values plotted on the chart represent sustained wind speeds, the peak gusts reported by four Continental Oil Co. oil barge tenders adrift off the coast southeast of Cameron were not plotted on the composite observation chart.

Adjustments for intensity changes off the coast. No adjustments were made to the observed wind speeds for the effects of deepening or filling as the storm center approached the coast, because the data near the center were too limited to indicate the details of any changes in the central pressure and there were no marked changes over the outer portion of the storm where

Figure 15-3. Surface wind speeds and directions relative to wind center, Hurricane Audrey, 1800 CST, June 26 to 1800 CST, June 27, 1957.

data were available to serve as a guide to the time or amount of change of intensity of the storm.

Adjustments for filling after landfall of center. The wind speeds observed after the storm center had been over land and filling had occurred were adjusted upward to assumed corresponding values before landfall. The adjustments were made by dividing the various wind values over land by the appropriate ratio from table 1-1. The time selected for landfall of the center was 0900 CST June 27.

Isotach pattern. In order to check the consistency of the observations, independent composite isotach analyses of the ship and adjusted land reports were prepared. The two analyses agreed very well in most areas. The final analysis (fig. 15-4) was made after combining the two analyses and comparing the resulting isotach patterns with the distribution of winds in the hurricane as reported by aircraft reconnaissance.

RADIUS OF MAXIMUM WINDS

A radius of maximum winds of 19 n. mi. was computed using formula (1-1). This value is supported by observed data. Neither Lake Charles, La., nor Port Arthur, Tex., which lay approximately 19 n. mi. to the right and left of the track of the storm center, respectively, reported a lull in the wind as the center passed closest to the station. Their peak winds occurred about the time the center passed closest to the station (fig. 15-3). This would indicate that they lay at or outside of the radius of maximum winds. The wind eye at the coast was less than 15 mi. in diameter. The U. S. Coast Guard Station at Sabine, Tex., 15 n. mi. west of the track, reported a decrease in the winds as the center passed by, and at Cameron, about 20 n. mi. to the east of the track, the Coast Guard reported that there was no decrease in speed. Therefore it is reasonable to assume that the average radius of maximum winds was within the area defined by the minimum distance of Lake Charles and Port Arthur from the center and the limits of the wind eye.

ISOTACH CHARTS

Isotach charts are shown in figure 15-5 for 0000 CST June 27, when the storm was still over the Gulf, for 0600 CST June 27 when the center was nearer the coast, for 0800 CST when the center was at the coast, and for 1300 CST June 27 when the center had moved inland. For the first three charts it was assumed that no appreciable filling or deepening occurred from 0000 CST June 27 until after the storm center crossed the coast. The composite wind speed pattern (fig. 15-4) was superimposed on charts of the Gulf with the front sector of the pattern aligned in the direction of forward motion. The isotachs along the coast were adjusted for the greater frictional effects. To construct the isotachs off the coast at 1300 CST, when the storm had been inland for several hours, a new composite wind speed pattern was constructed for that portion of the storm remaining over water by the method previously described under Composite wind pattern, using observations from 1300 to 1800 CST, unadjusted for the effects of filling.

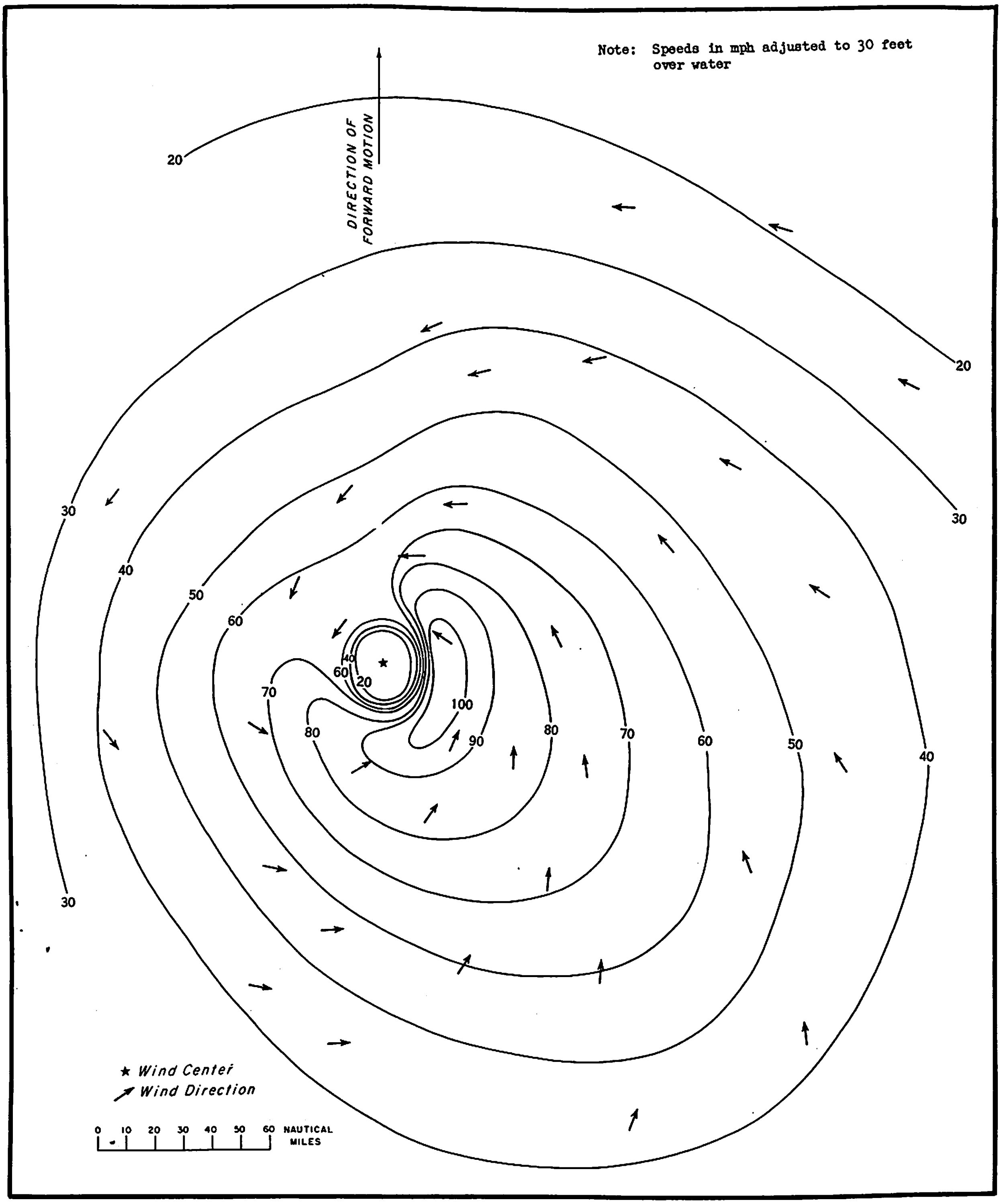


Figure 15-4. Composite wind-speed pattern near Texas-Louisiana coast, Hurricane Audrey, June 27, 1957.

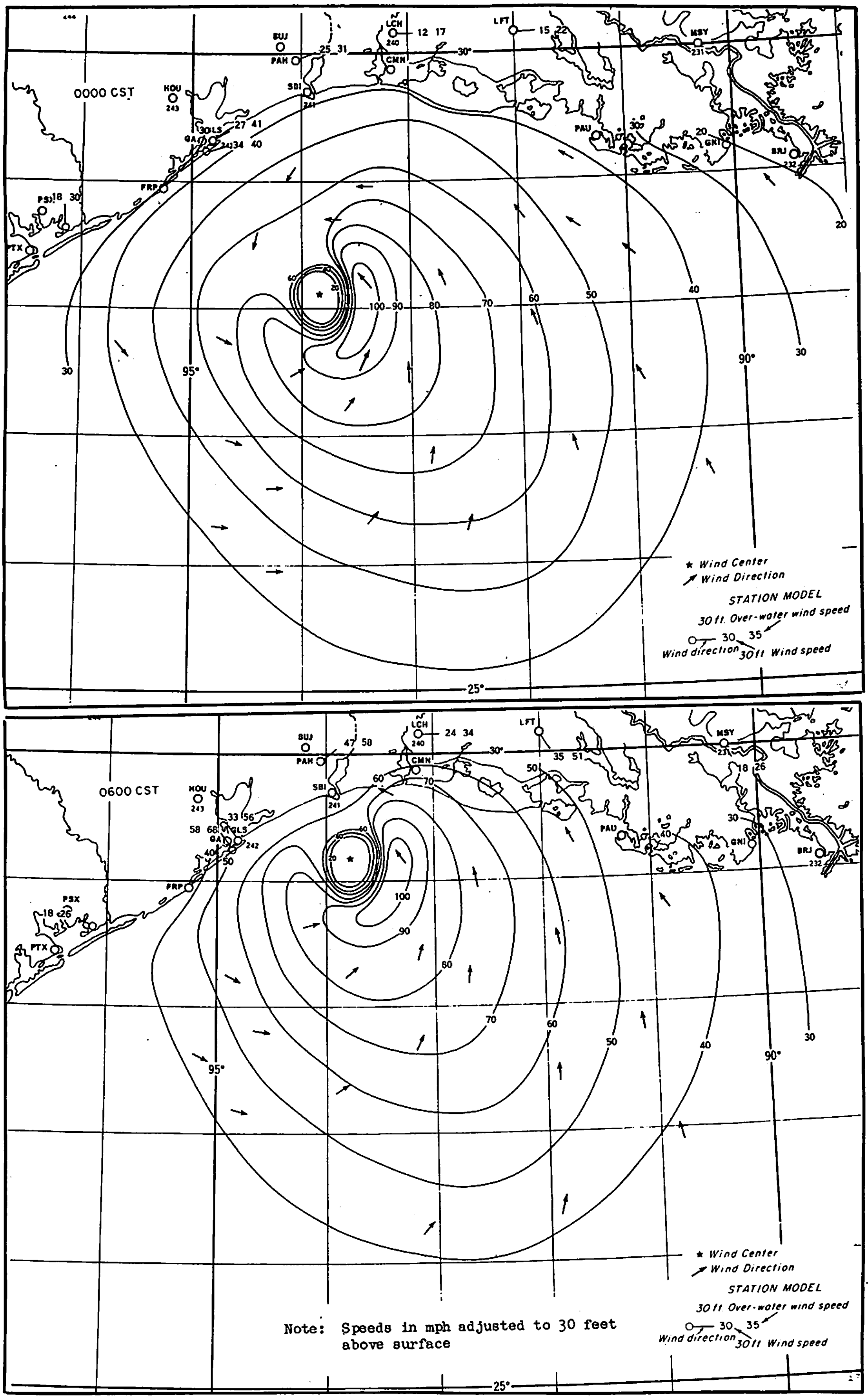


Figure 15-5a. Wind speeds and directions, Hurricane Audrey, 0000 and 0600 CST, June 27, 1957.

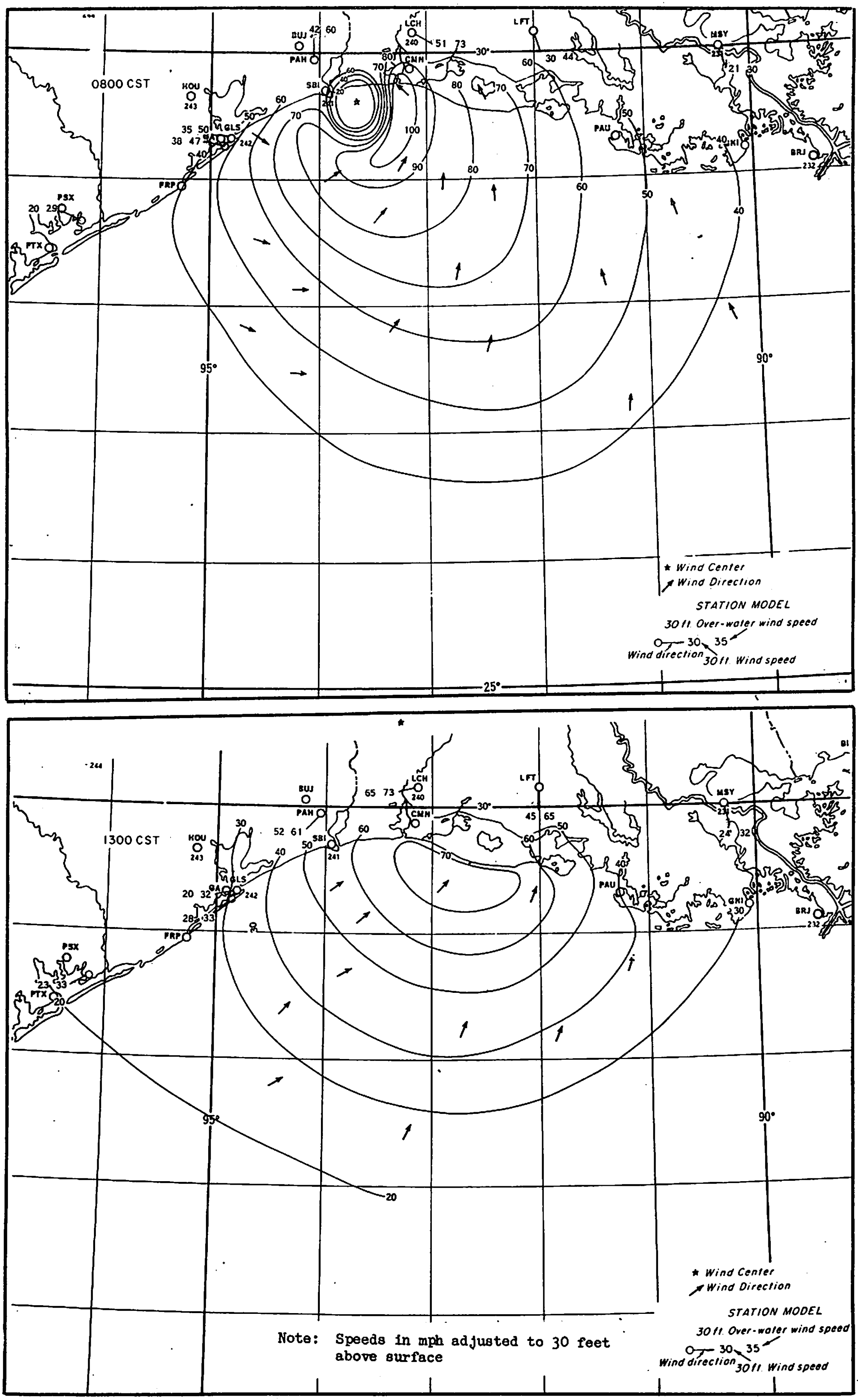


Figure 15-5b. Wind speeds and directions, Hurricane Audrey, 0800 and 1300 CST, June 27, 1957.

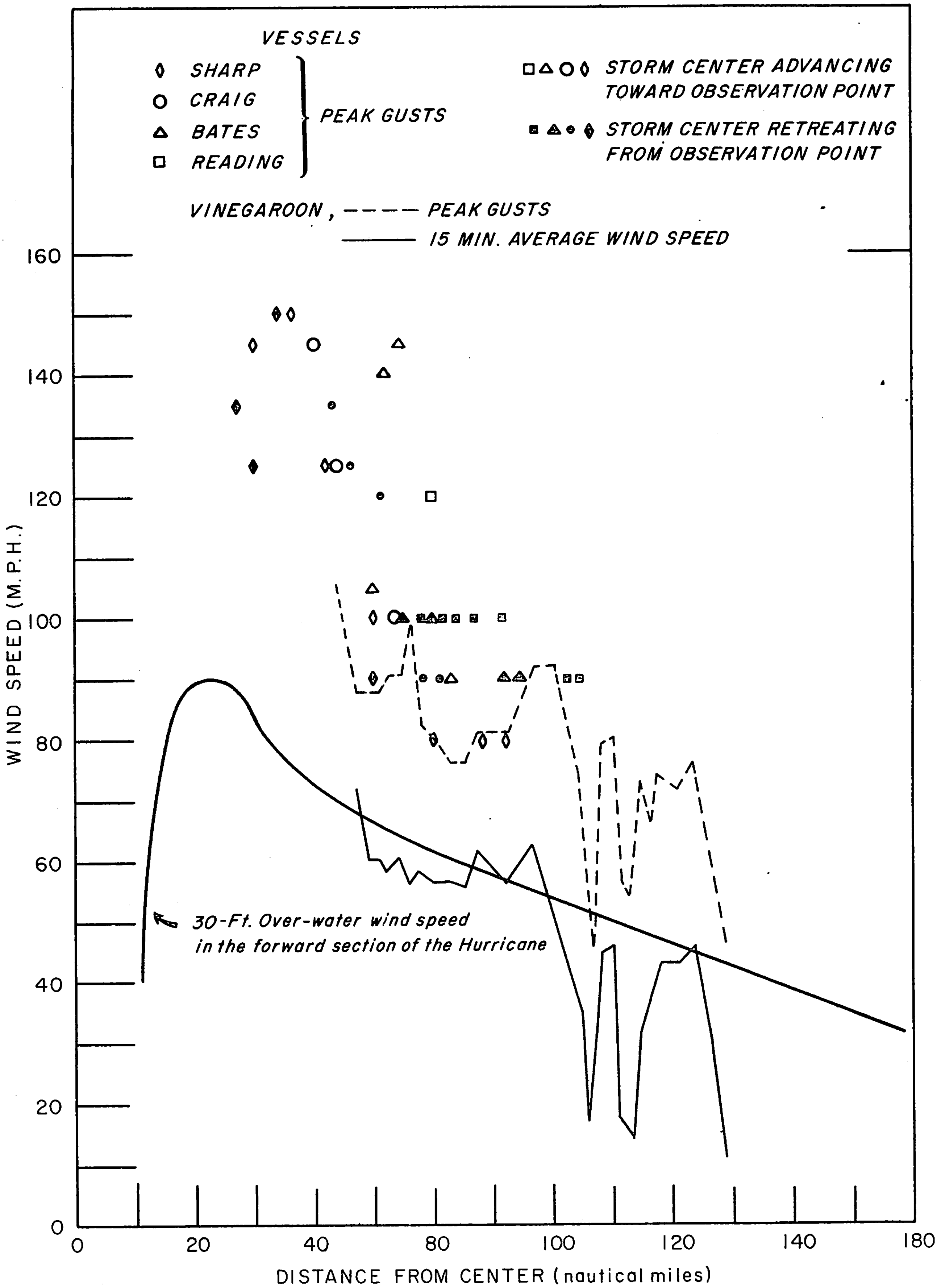


Figure 15-6. Peak gusts versus sustained winds, right sector, Hurricane Audrey, June 27, 1957.

WIND DIRECTION

Wind directions in the storm are shown by the short arrows on the composite wind speed and direction pattern, figure 15-4. Since the hurricane was not symmetrical, a standard wind-deflection angle across circles around the center as used for some other hurricanes was not appropriate. A composite pressure pattern for the storm at the coast (not shown) was drawn by adding the pressure values to wind observations in the composite plot of the coastal stations used for the wind-speed analysis and then drawing isobars to these pressure values. The majority of the ship reports showed good agreement with directional arrows drawn at 25° to the tangent to the isobars, so this deflection angle (cross-isobar) was used over the whole storm. By 1500 CST June 27, after the storm center had moved over land, the isobar pattern changed, becoming elongated to the west instead of to the south. This change, and the recurvature of the hurricane to the northeast, gave an apparent increase in the deflection angle relative to storm center on the composite observation chart (fig. 15-3) for those observations that were made in the left rear quadrant after 1200 CST June 27. However, ship observations of wind directions made at 1200 CST and later that were compared to pressure analyses of the storm made at these times, indicate that the wind in the portion of the storm over water was still blowing across the isobars at a deflection angle of approximately 25°.

A COMPARISON OF PEAK GUSTS WITH SUSTAINED WIND SPEEDS

A comparison of peak gusts with sustained wind speeds was made in order to evaluate unusually high speeds reported from four oil barge tenders and to find an empirical relationship between sustained over-water speeds and over-water peak gust speeds. The tenders adrift southeast of Cameron during the hurricane logged wind speeds up to 150 m.p.h. which were reported to be peak gusts. A comparison of these reports was made with the average wind speed and peak gusts recorded in the same area by the oil drill barge, _Vinegaroon_, and with the wind speed profile from the right forward sector of the composite wind speed pattern, (fig. 15-4). That sector of the storm was selected for comparison because the _Vinegaroon_ record and the majority of the gusts reported by the tenders occurred while the vessels were in that sector. The wind speeds were plotted at the distance of the observations from the hurricane center (fig. 15-6). At the same distance from the storm center, the speeds reported by the tenders are compared with the peak gust speeds recorded by the _Vinegaroon_. For sustained winds of 50 m.p.h. or higher, the peak gusts near the center of the storm averaged 40 to 50 percent more than the sustained winds. Speeds reported from the oil barge tender are comparable to reported peak gusts on the _Vinegaroon_. It is confirmed that the tender's wind speeds were peak gust speeds and are compatible with figure 15-4 as drawn.

Observations. A chart showing the estimated courses and hourly positions of four tenders, the _Sharpe_, _Bates_, _Reading_, and _Craig_, and extracts from the logs of the vessels, covering a period of time from 0230 CST to 1830 CST June 27, were prepared by the Continental Oil Co. The tenders were equipped with Bendix-Friez selsyn type anemometers located 65 feet above the water. The oil drill barge, Vinegaroon, was equipped with a Bendix Aerovane recording anemometer. A copy of the Vinegaroon wind speed record was obtained for the period from early morning of June 26 to 0600 CST June 27 when the record ended. The barge was located at approximately 29°38'N., 93°05'W. during this period. The average wind speed for 15-minute intervals and the peak gusts for each interval were read from the Vinegaroon trace from 2300 CST June 26 until the record ended.

Table 15-1. - Parameters of June 27, 1957 hurricane at Louisiana coast

P_o,	Central pressure (in.), 27.95*
P_n,	Asymptotic pressure (in.), Computed 29.70* Observed 29.75**
R,	Radius of maximum wind (n. mi.), Computed 19* Observed 16-19#
##V_{gx},	Average maximum gradient wind (m.p.h.), 95
c,	4-hr average forward speed at the coast (kt.), 14
	At U. S. Wildlife Service Station, Hackberry, La.
P_a,	Lowest observed pressure on land (in.), 28.30
r_a,	Minimum distance from station storm track (n. mi.), 12

* Computed with the exponential formula
** Observed on weather charts
\# Estimated from miscellaneous wind observations
\#\# The computed maximum gradient wind represents an average speed at the radius of maximum wind. Because of the asymmetry of the pressure field of this hurricane the highest observed winds adjusted to 30-ft. over-water winds are greater than the average maximum gradient wind. The average of the wind speeds read at eight points around the center at the radius of maximum winds (fig. 16-2) is 82 m.p.h. This value is equivalent to the average maximum gradient wind speed, 95 m.p.h., reduced to 30-ft. over-water speed using the factor of 86.5 percent taken from figure 1-3.

Chapter III

WINDS ASSOCIATED WITH SELECTED EXTRATROPICAL STORMS ALONG THE ATLANTIC COAST

16. STORM OF NOVEMBER 25, 1950, OFF THE NEW JERSEY COAST

INTRODUCTION

Rapid intensification of a small Low which was centered over western North Carolina and Virginia at 1930 EST November 24, 1950, caused one of the most destructive storms of record in the Northeast. The path of the storm's pressure center remained well inland moving northward through Pennsylvania and then westward into Ohio during the 25th. Gale force winds from an easterly and northeasterly direction persisted over an extensive portion of the Atlantic Coast. The high winds did not reach the speeds that occurred in the hurricanes of 1944 and 1938, but they were of longer duration. The strong onshore winds caused excessively high tides with the highest tides of record occurring at some places in New York Harbor and the western end of the south shore of Long Island. Great destruction was caused by the wind and waves. La Guardia Airport on Long Island was flooded, damage in New Jersey amounted to near $30,000,000, and the storm caused 32 deaths. In New York State damage was estimated at $20,000,000 and 32 persons lost their lives.

WIND SPEEDS AND PRESSURE DISTRIBUTION

Isotachs and isobars at 6-hour intervals for the period from 0730 EST November 24 through 0130 EST November 26, 1950, are shown in figure 16-1 as solid lines, and dashed lines, respectively. The map times correspond to times of regular 6-hourly weather observations. Isotachs were determined from the regular 6-hourly ship observations, from observations from land stations along the coast, and from estimates of wind speed using the general pressure pattern.

The strongest winds shown southeast of Nantucket on the first map, at 0730 EST November 24, and on the 1330 EST map off the New Jersey and Long Island coast were associated with a strong pressure gradient between a High centered over Labrador and a trough of low pressure centered over the Great Lakes, with a secondary Low center over North Carolina. As the pressure gradient between the High over Labrador and the secondary Low intensified between 0730 EST November 24 and 0730 EST November 25, wind speeds increased off the Atlantic coast. Two areas of wind speed maximum appeared on the next four maps (1930 EST November 24 through 1330 EST November 25). The southern maximum off the coast of the Carolinas occurred along a cold front extending southward from the Low center. The maximum off the New Jersey coast and New York Harbor was associated with the strong pressure gradient between the High over Labrador and the Low to the west and a warm front extending from the Low east-southeastward just south of New York City. The Low was centered over Ohio by 1930 EST November 25. The highest winds off the coast at 1930 EST November 25 and 0130 EST November 26 were north and east of the cold front which extended from the Low over Ohio eastward through New York and then southeastward over the Ocean.

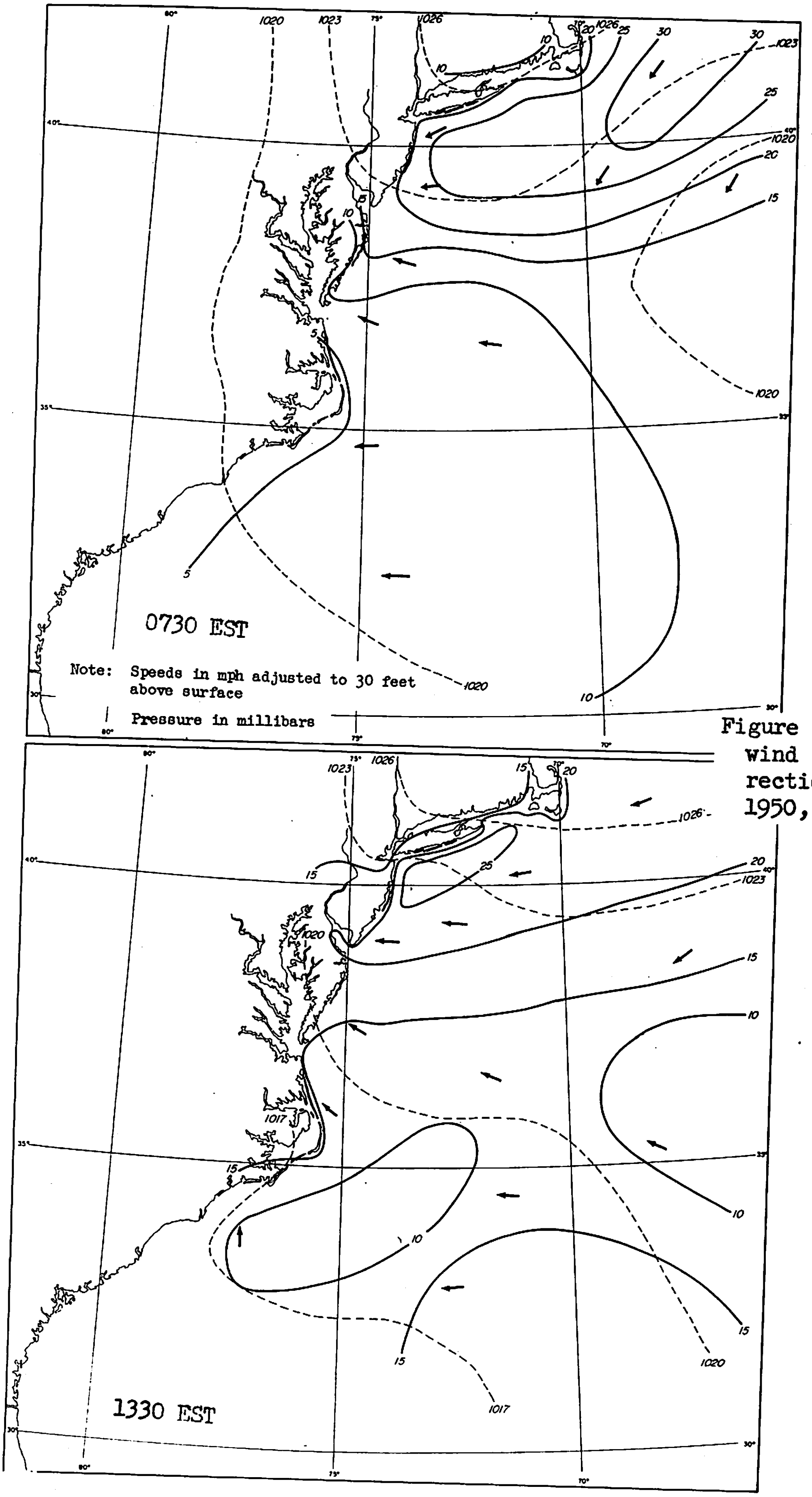


Figure 16-1a. Pressure, wind speeds, and directions, November 24, 1950, 0730 and 1330 EST.

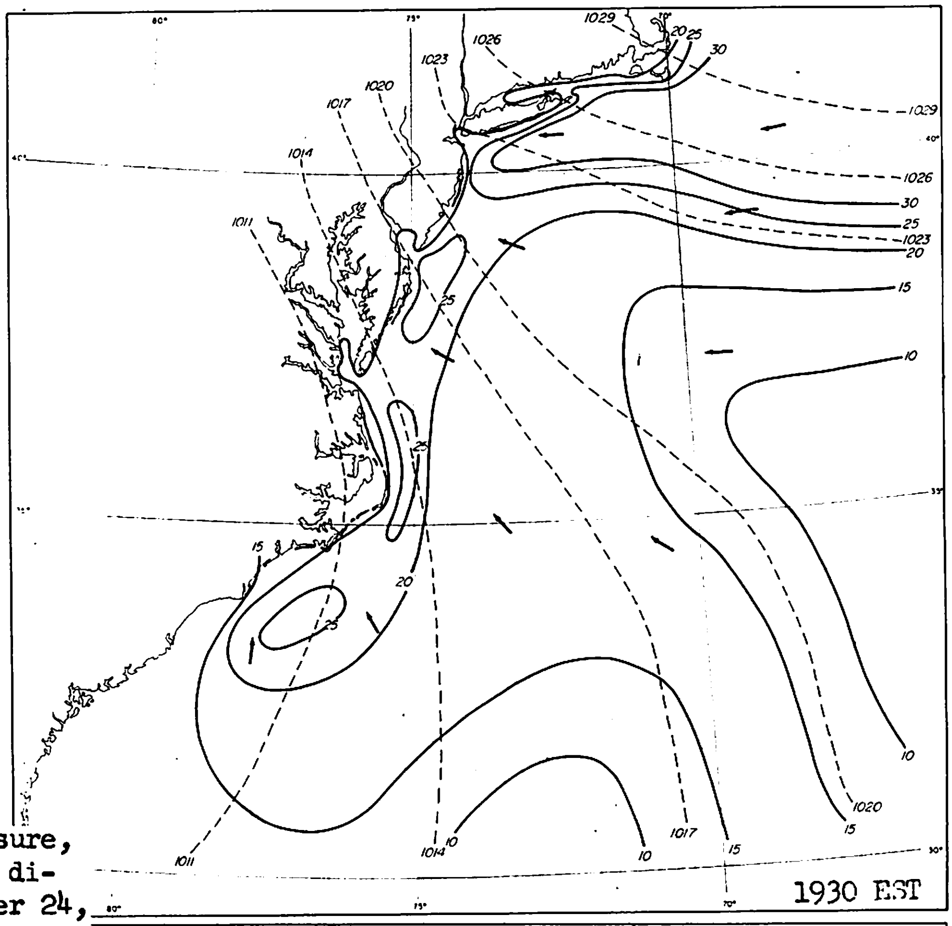
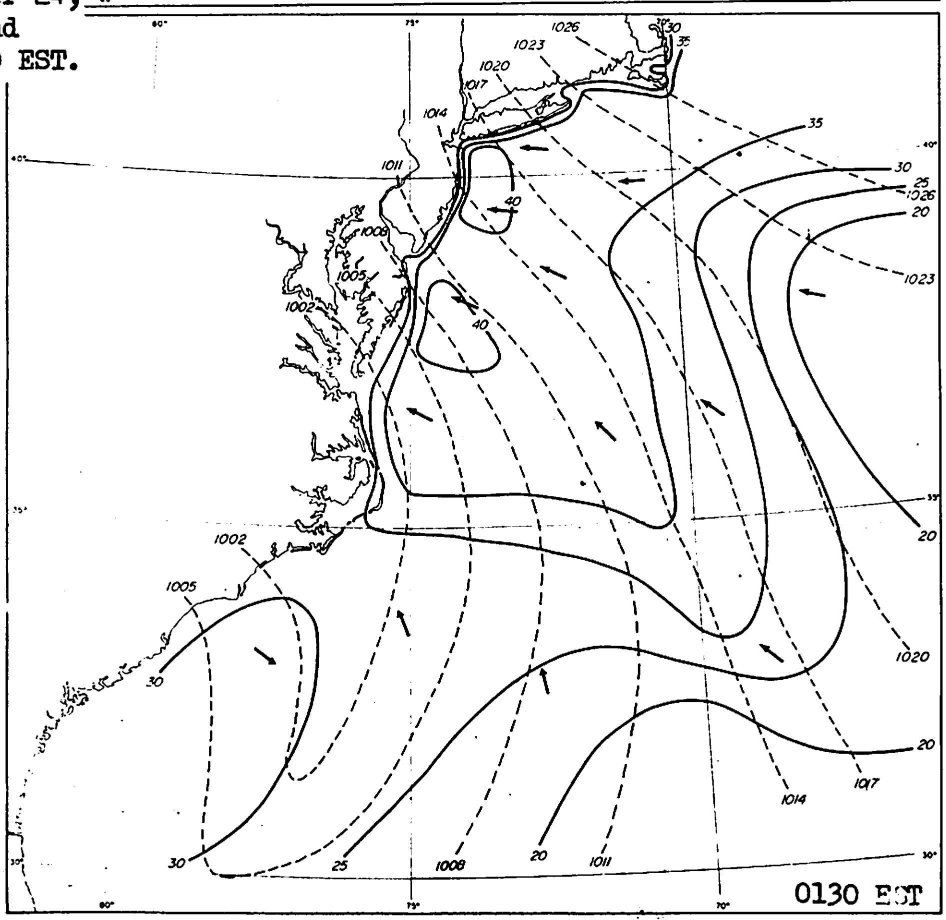


Figure 16-1b. Pressure, wind speeds, and directions, November 24, 1950, 1930 EST and November 25, 0130 EST.



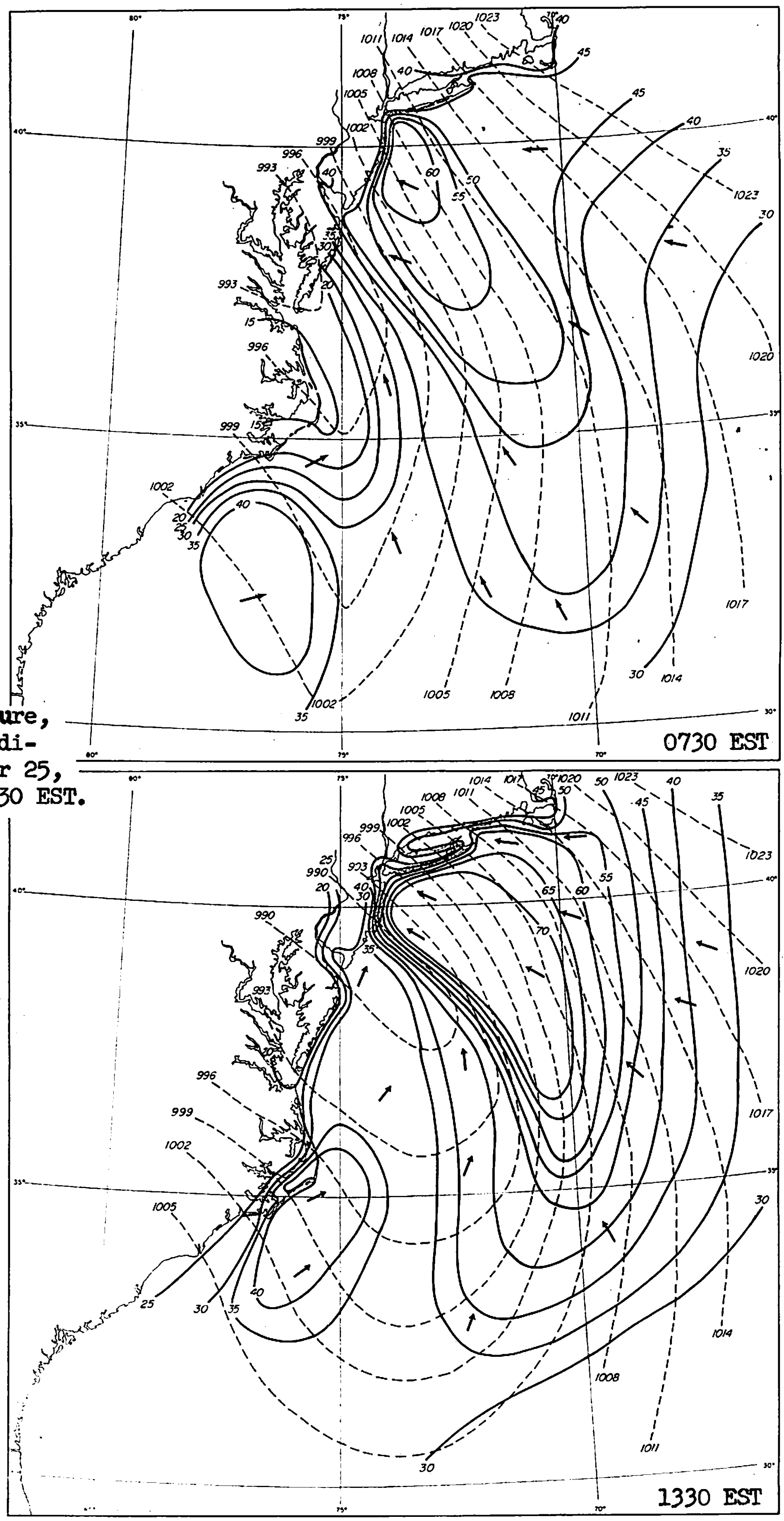


Figure 16-1c. Pressure, wind speeds, and directions, November 25, 1950, 0730 and 1330 EST.

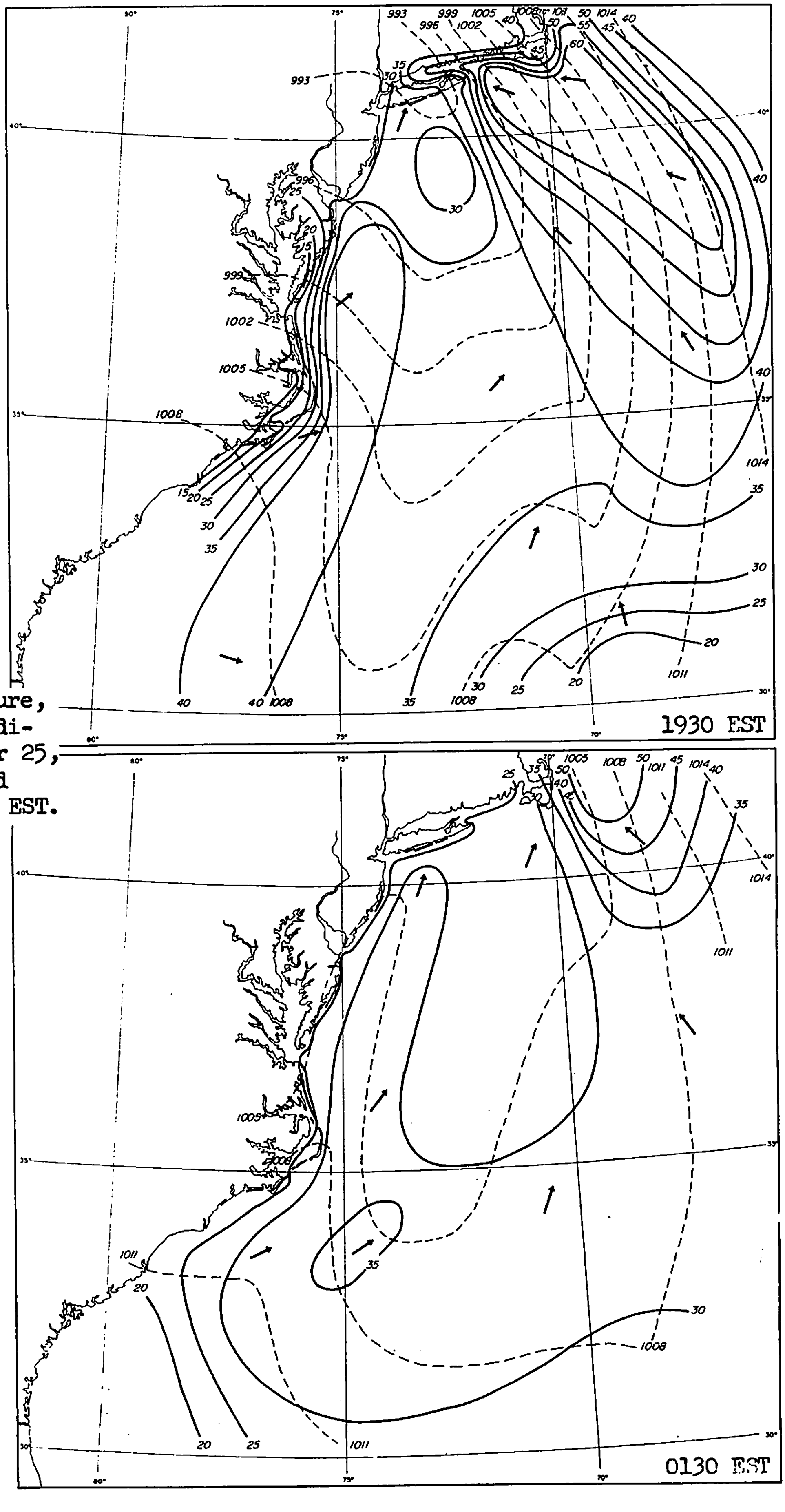


Figure 16-1d. Pressure, wind speeds, and directions, November 25, 1950, 1930 EST and November 26, 0130 EST.

17. STORM OF NOVEMBER 6-7, 1953, OFF THE NEW JERSEY COAST

INTRODUCTION

The near-coincidence of the time of passage of the northeaster of November 6-7, 1953, and predicted astronomical high tide resulted in record and near-record tides in New York Harbor and along the New Jersey coast from Mansaquan Inlet to and beyond Raritan Bay. Highest storm tides of modern record occurred in New York Harbor at the Battery (1920 to 1956) and Fort Hamilton (1900 to 1956). Extensive damage from flooding and wave action occurred along the water front in these areas. Storm damage from New Jersey to New England was estimated at $75,000,000 /46/.

Cyclogenesis was occurring over the Gulf of Mexico on November 5, 1953, along a cold front on the south side of a pronounced cold High. By 0130 EST November 6 the Low which had developed was centered off the coast of Georgia. Its direction of movement, by this time, shown in figure 17-1, had become northeast. During the next 24 hours it intensified more rapidly and moved northward, and at 0130 EST November 7 the storm was located about 60 miles off the New Jersey coast. This center moved over land at about 0730 EST November 7 and by 1330 EST was well inland over southern New York. During the next 12 hours the storm moved northwestward into the Great Lakes area.

As the Low moved northward along the Atlantic Coast and deepened on the 6th, the High over the Great Lakes reoriented itself into a ridge extending eastward into New England while maintaining its strength. A strong pressure gradient was set up between the High and the Low which resulted in high winds along the middle Atlantic and New England coast. Strong northeasterly winds persisted off the New Jersey and Long Island coasts throughout November 6 and the early morning of November 7 when the winds shifted to southerly and diminished.

WIND SPEED AND PRESSURE DISTRIBUTION

Figure 17-2 shows wind speed and pressure patterns at 6-hour intervals from 0730 EST on November 6 through 1330 EST on November 7, 1953. Isotach patterns were determined by the same methods described in section 16. At 0730 EST November 6 a wind speed maximum appeared north of the storm center located off Hatteras, N. C. As the Low moved northward and intensified, the speeds in this area increased. At 0130 EST November 7, the Low was centered about 60 miles off the New Jersey coast and a wind speed maximum was located off the New Jersey and Long Island coasts north of the Low center and the warm front which extended eastward from the center. Another maximum was located south and southwest of the Low center. Wind speeds over the ocean off Long Island and New York Harbor had decreased by 0730 EST November 7 as the wind shifted with passage of the warm front across the area. A wind speed maximum still remained off the New Jersey coast south of the Low center. By 1330 EST November 7 the Low center was well inland over southern New York. Highest winds were then off the New England coast, but a lesser wind speed maximum was still located off the New Jersey and Long Island coasts until 1930 EST November 7.

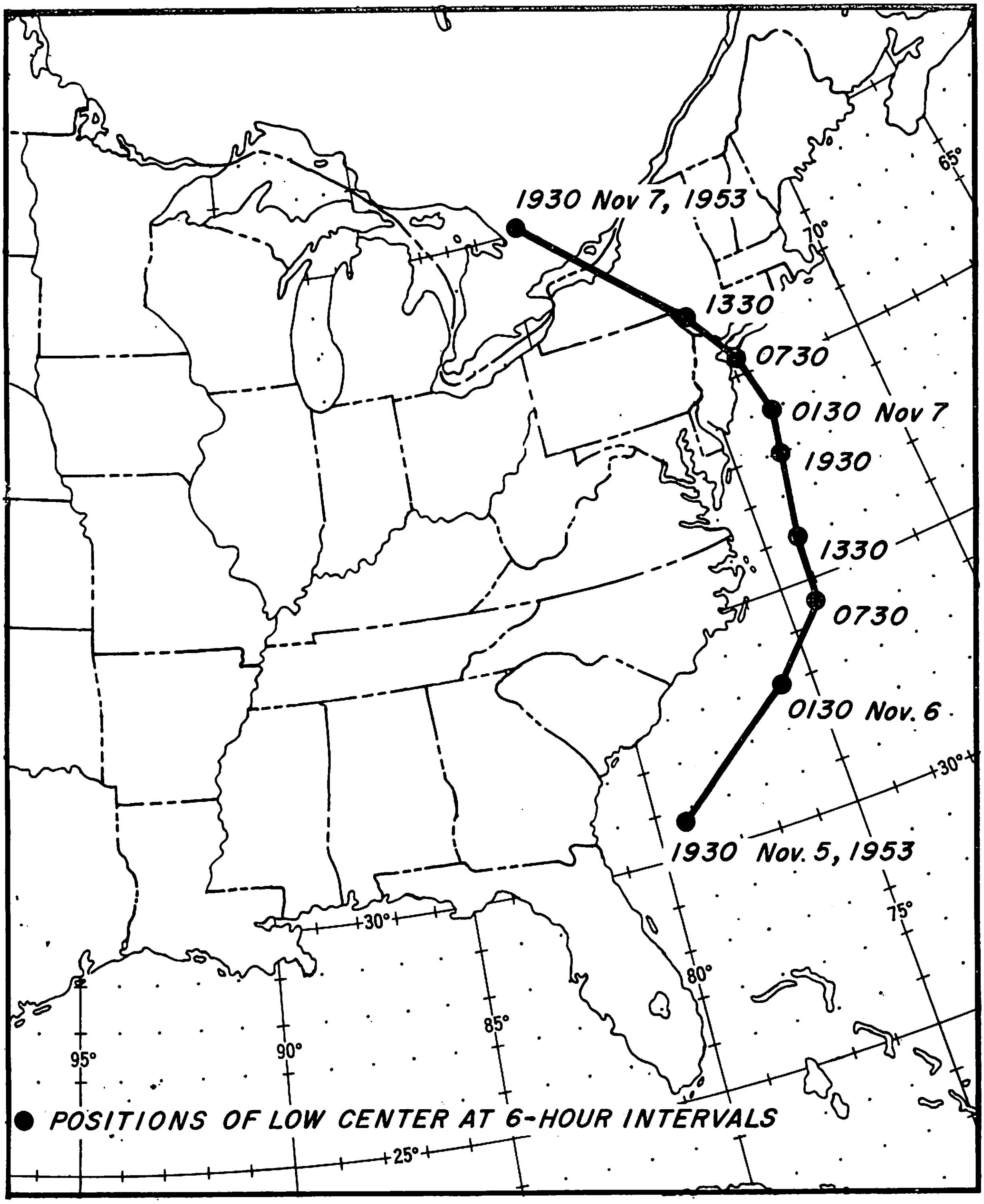


Figure 17-1. Track of pressure center, storm of November 6-7, 1953.

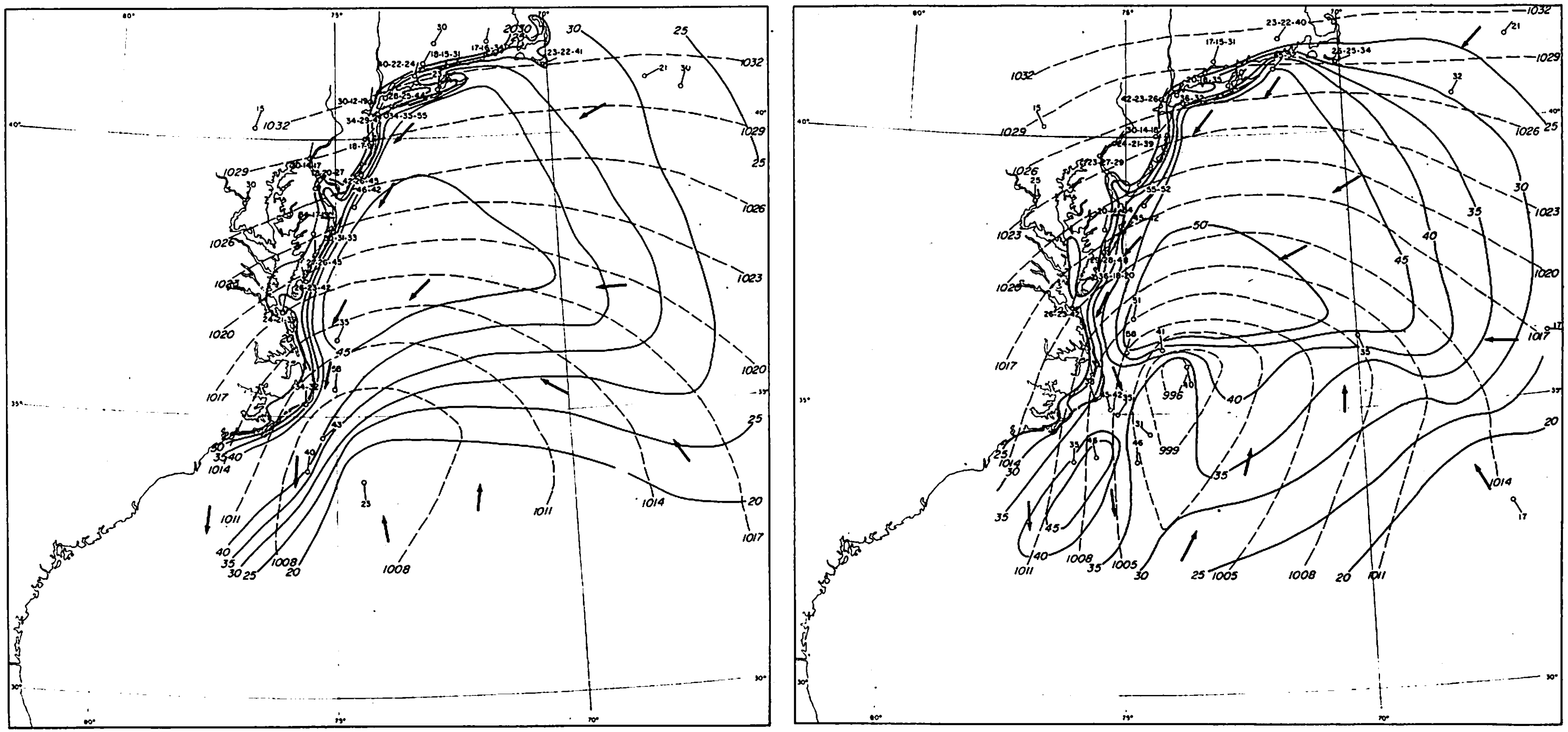


Figure 17-2a. Pressure, wind speeds, and directions, November 6, 1953, 0730 and 1330 EST.

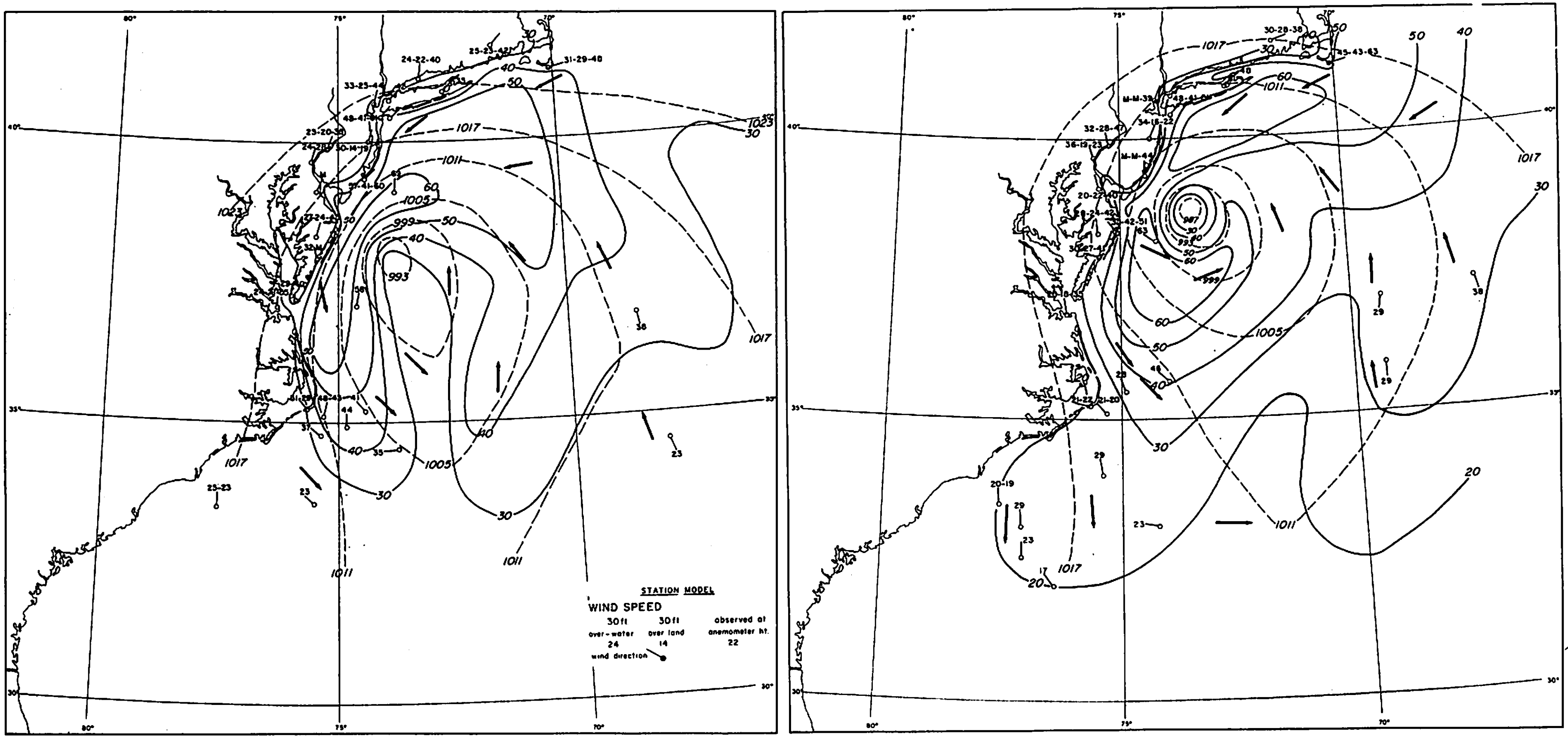


Figure 17-2b. Pressure, wind speeds, and directions, November 6, 1953, 1930 EST and November 7, 0130 EST.

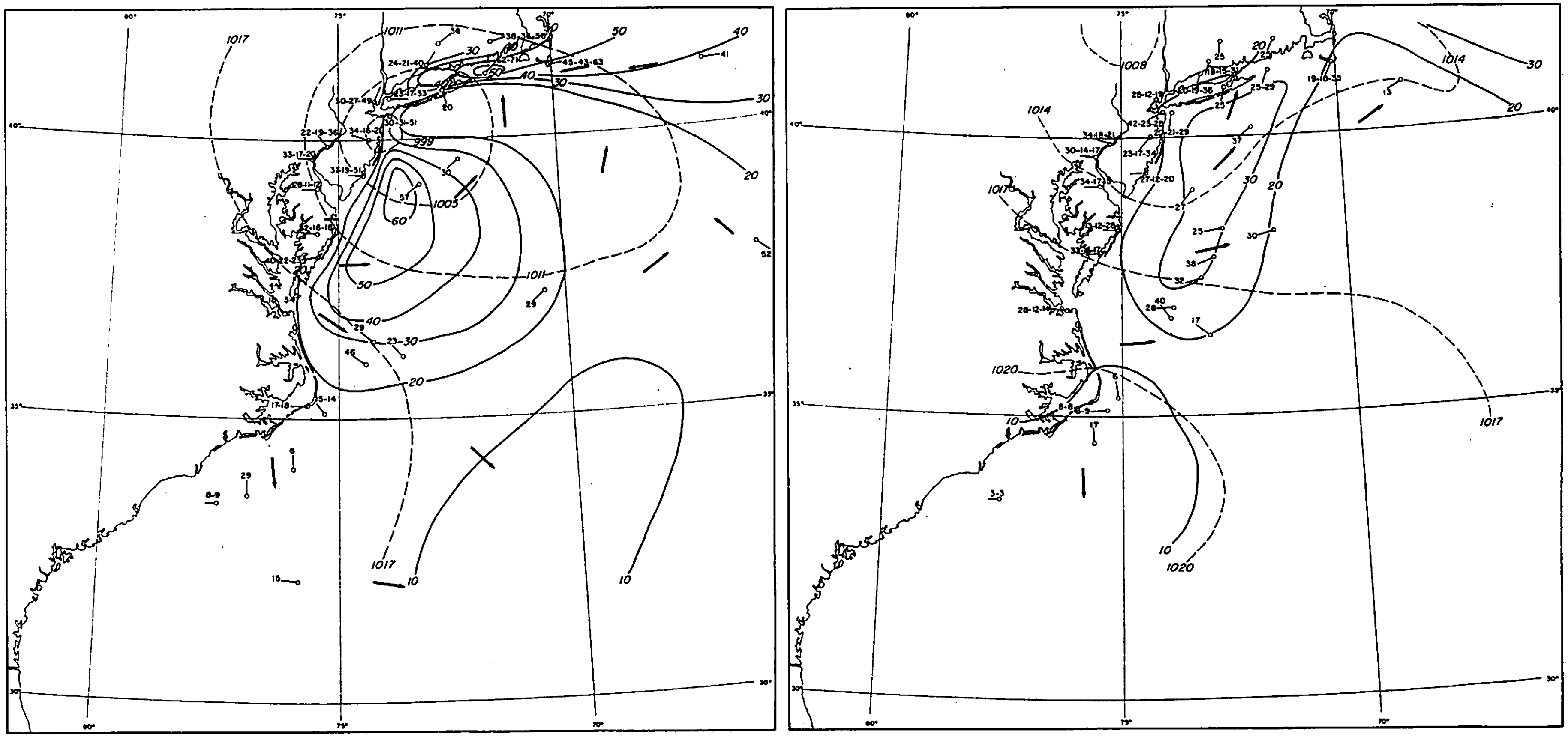


Figure 17-2c. Pressure, wind speed, and directions, November 7, 1953, 0730 and 1330 EST.

18. STORM OF APRIL 11-12, 1956, OFF THE MID-ATLANTIC COAST

INTRODUCTION

The extratropical storm of April 11-12, 1956, along the east coast of the United States, is of considerable interest because of the unusually high storm-tide heights along the northern Virginia and southern Maryland coasts. Hampton Roads, Va., had the highest tide, 4.6 ft. above predicted astronomical tide, since the hurricane of 1936. At Portsmouth, Va., the storm tide was 7.9 ft. above mean low water or 4.6 ft. above predicted astronomical tide. Several city blocks in Norfolk were inundated, and two large ships were grounded due to the gale winds and high tides /47/.

As a low-pressure area moved through the southern United States, a second Low formed in the Gulf of Mexico. The two Lows moved northeastward at variable speeds but continued to move more or less together. The nearness of the two centers, their orientation and paths, caused winds from the east and north to prevail over Norfolk and vicinity for nearly 14 hours. The extremely strong pressure gradient was the principal cause of the strong easterly winds /48/.

TRACK

The tracks of the two Lows are shown in figure 18-1. The "A" position was the dominant Low at 0730 and 1330 EST on April 11. At 1930 EST of April 11 the two Lows appeared to be of about equal intensity. The "B" position was the dominant Low at 0730 EST on April 12.

WIND SPEED AND PRESSURE DISTRIBUTION

Figure 18-2 shows isotach patterns (solid lines) derived from observed wind speeds from ships and land stations and pressure patterns (dashed lines) at 6-hour intervals for the period from 0730 EST April 11 to 0730 EST April 12. There are two areas of wind speed maximum in each of the figures. The high wind speeds in the northern section of the chart are associated with the two low pressure centers. The maximum in the southern sector of the charts is more closely associated with a cold front that extends southward from one of the centers.

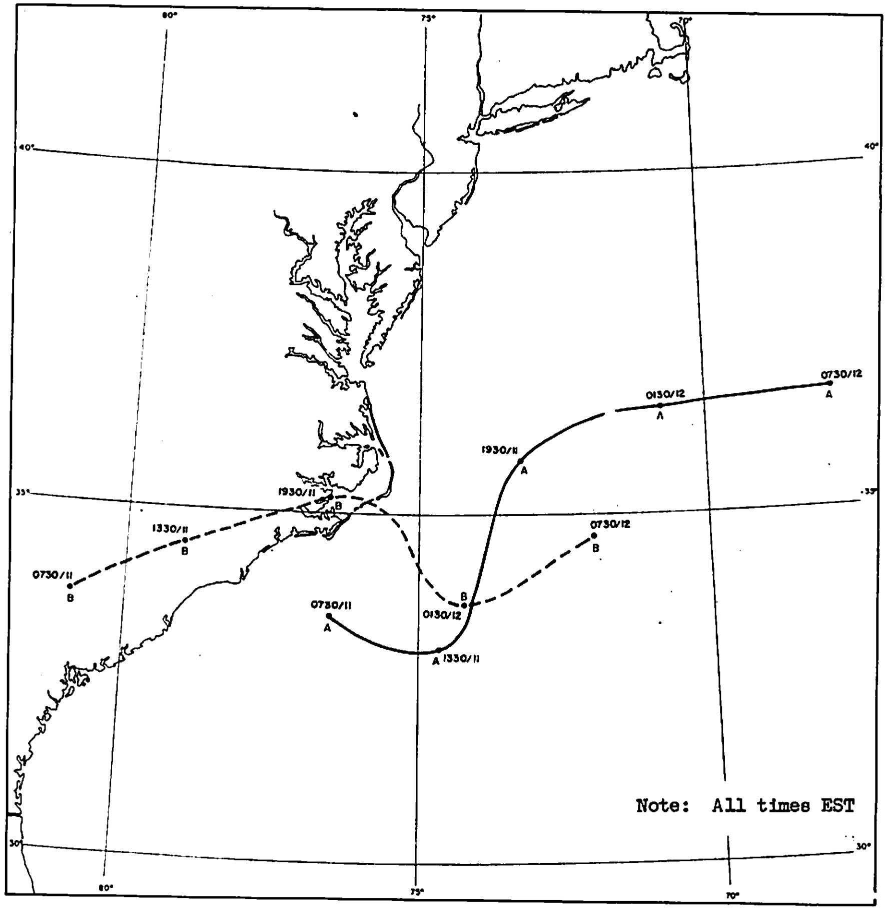


Figure 18-1. Track of pressure centers, storm of April 11-12, 1956.

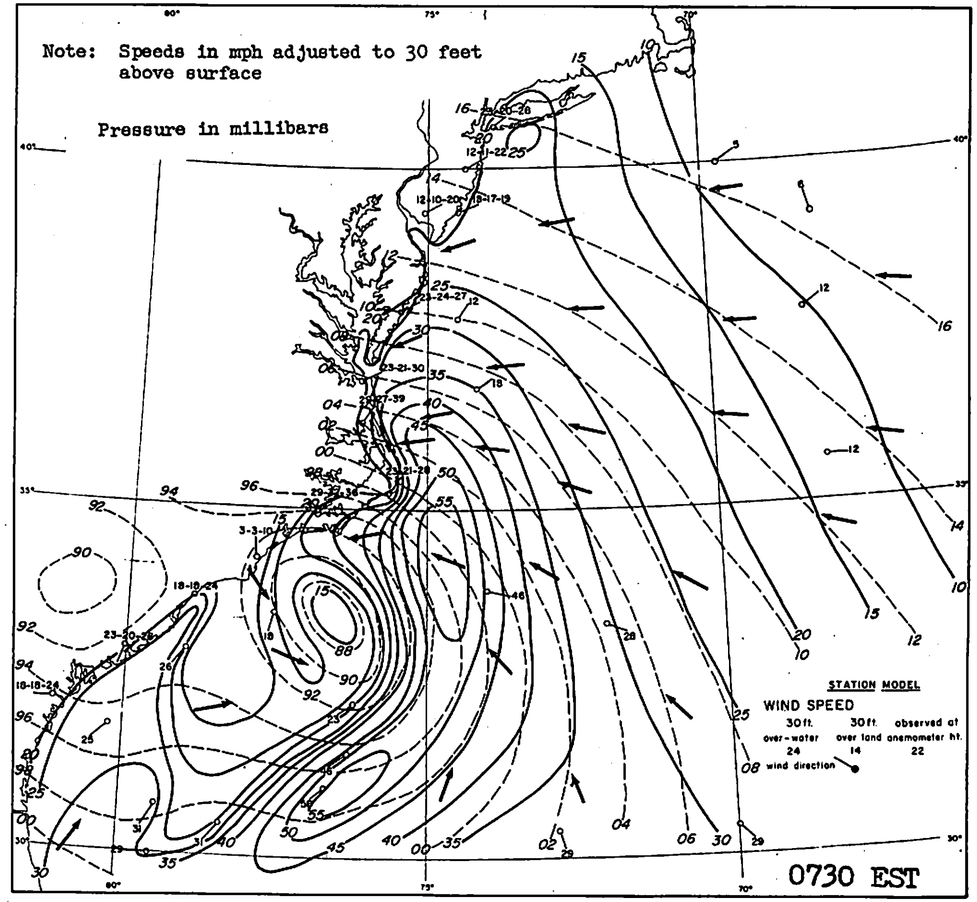


Figure 18-2a. Pressure, wind speeds, and directions, April 11, 1956, 0730 EST.

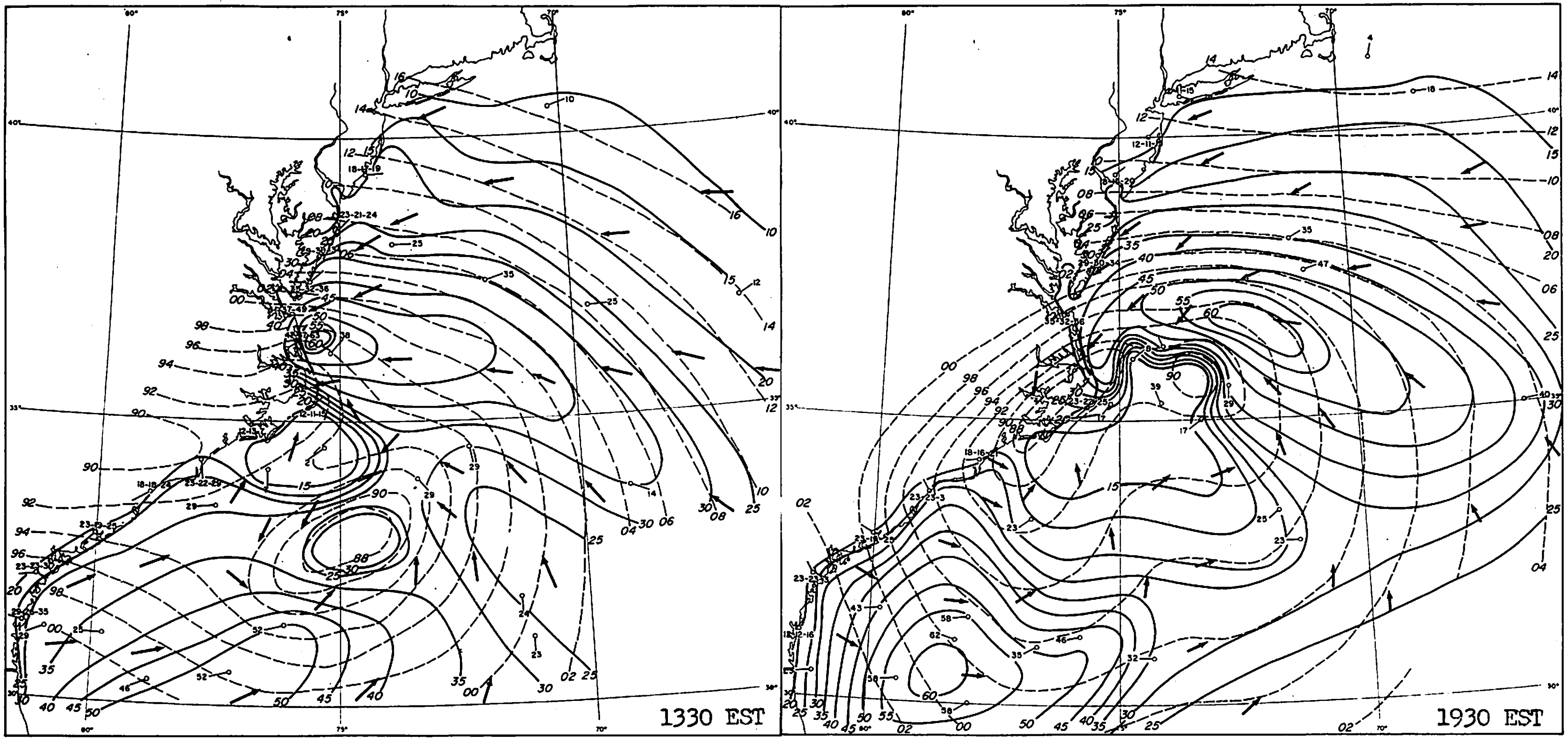


Figure 18-2b. Pressure, wind speeds, and directions, April 11, 1956, 1330 and 1930 EST.

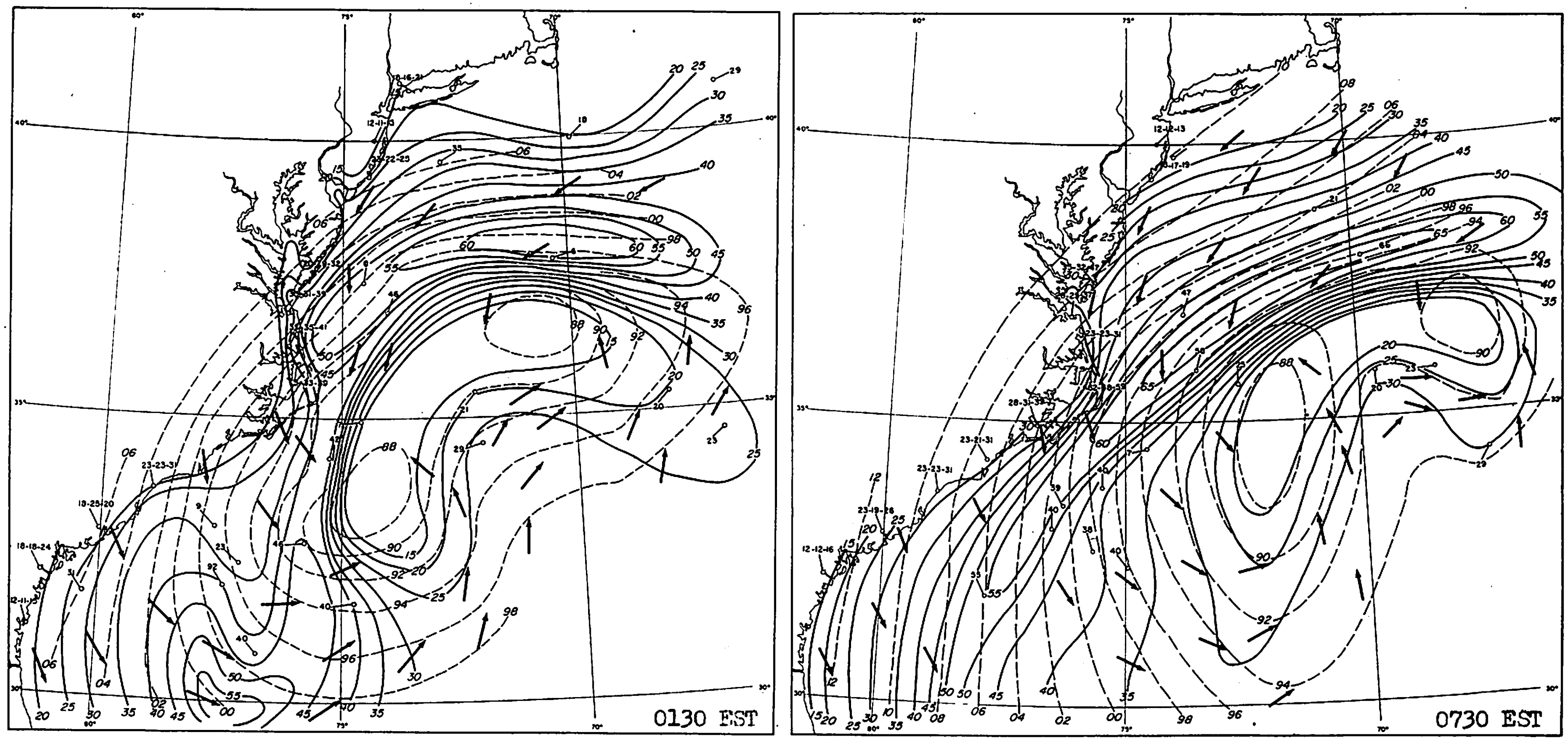


Figure 18-2c. Pressure, wind speeds, and directions, April 12, 1956, 0130 and 0730 EST.

Chapter IV

INVESTIGATION OF LOCAL WIND RELATIONS

19. A COMPARISON OF NANTUCKET ISLAND WIND SPEEDS WITH OPEN-WATER WINDS

PURPOSE

The 89 percent ratio of off-water to over-water wind speeds determined at Lake Okeechobee /4/ has been used consistently in the wind analyses of hurricanes in this report to adjust an over-water to an off-water wind speed at a coast or vice versa. The primary purpose of the investigation described in this article was to ascertain whether the 89 percent ratio was generally applicable or was due to some local idiosyncrasy at Lake Okeechobee. In the absence of a satisfactory physical explanation the 11 percent reduction on a flat shore seemed large. A secondary purpose was to obtain calibration factors to adjust wind speeds at the Nantucket Weather Bureau Office in hurricanes that affected the island to the corresponding speed over open water.

DATA

At about the time of the United States entry into World War I, several offshore lightships were commissioned as cooperative weather observation stations. These were equipped with anemometers and wind speed recorders. These recorders were similar to the triple register, except that they recorded only wind speeds (on W.B. Form 1015). Such records from Nantucket Shoals Lightship are available from August 17, 1916, through April 30, 1918, with a few breaks. The existence of this autographic wind speed record from a stationary ship gives an unusual opportunity for comparison of winds over land with winds over the sea.

During 1916-1918 the Nantucket Weather Bureau Office was at 41°17'N., 70°06'W. in the town of Nantucket on the north side of Nantucket Island. The standard 4-cup Robinson anemometer was mounted 90 ft. above the ground on a steel storm-warning display tower behind the Weather Bureau Office. It is assumed that the Nantucket Shoals Lightship had an identical anemometer. The anemometer height was recorded to be 24 ft. above the sea. The position of the ship was 40°37'N., 69°37'W., 49 n. mi. south-southeast of the Nantucket Weather Bureau Office. Location of Nantucket WBO is shown on the map in figure 19-1.

PLOTTING PROCEDURE

The passage of wind in 6 hours was read from the original sheets from the recorders for the Nantucket Weather Bureau Office and for Nantucket Shoals Lightship for the two winter periods November 1 to December 10, 1916, and January 19, 1918 through April 30, 1918 (December 11-31, 1916, and January 1-18, 1918, missing for Nantucket Shoals Lightship). These values had been entered on the margin of the original sheets (anemometer corrections were not applied). The mean wind direction to 16 points at Nantucket for each 6-hour period was estimated by eye from the triple-register sheet. If the average wind direction

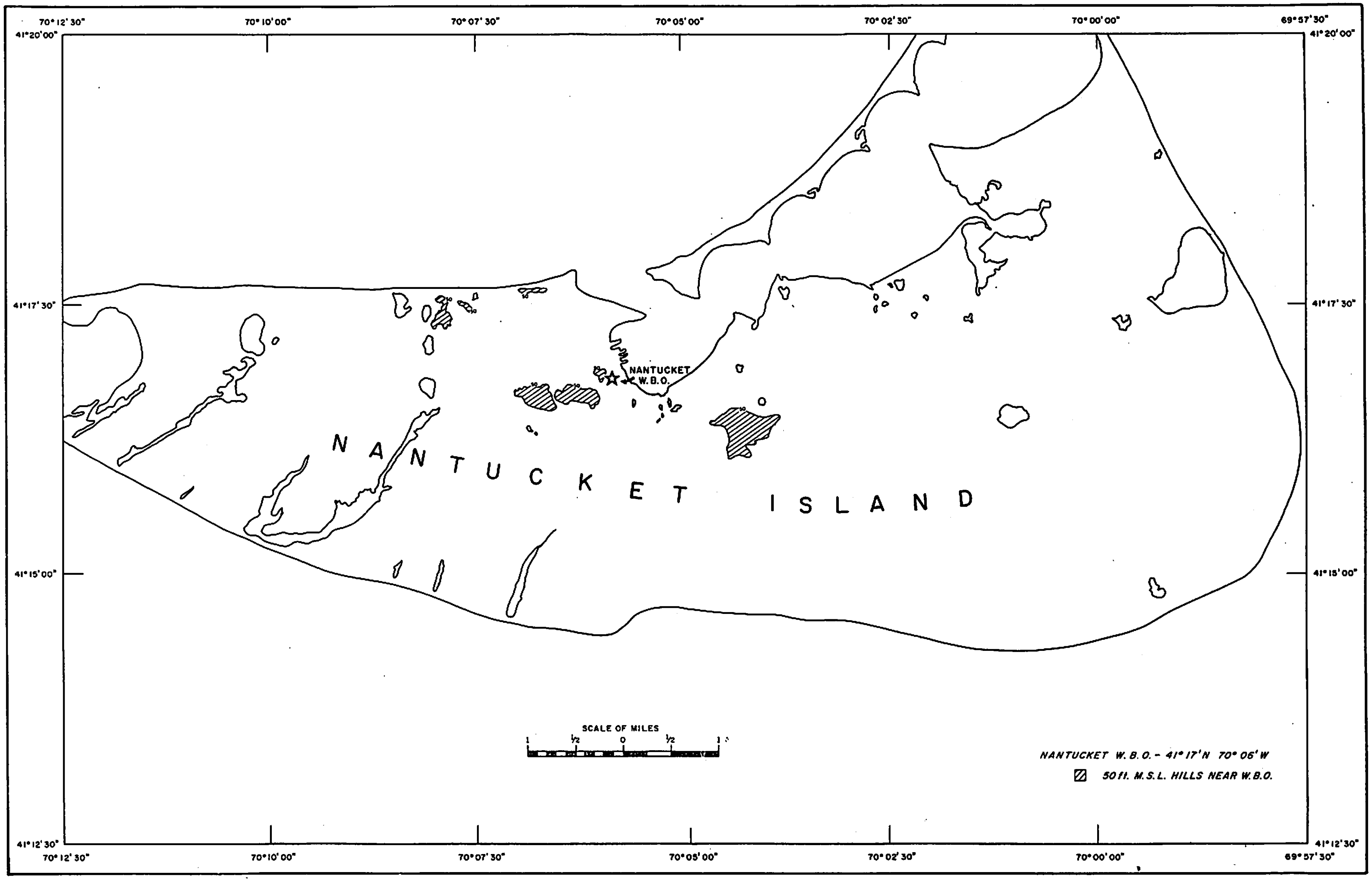


Figure 19-1. Location of Nantucket Weather Bureau Office on Nantucket Island.

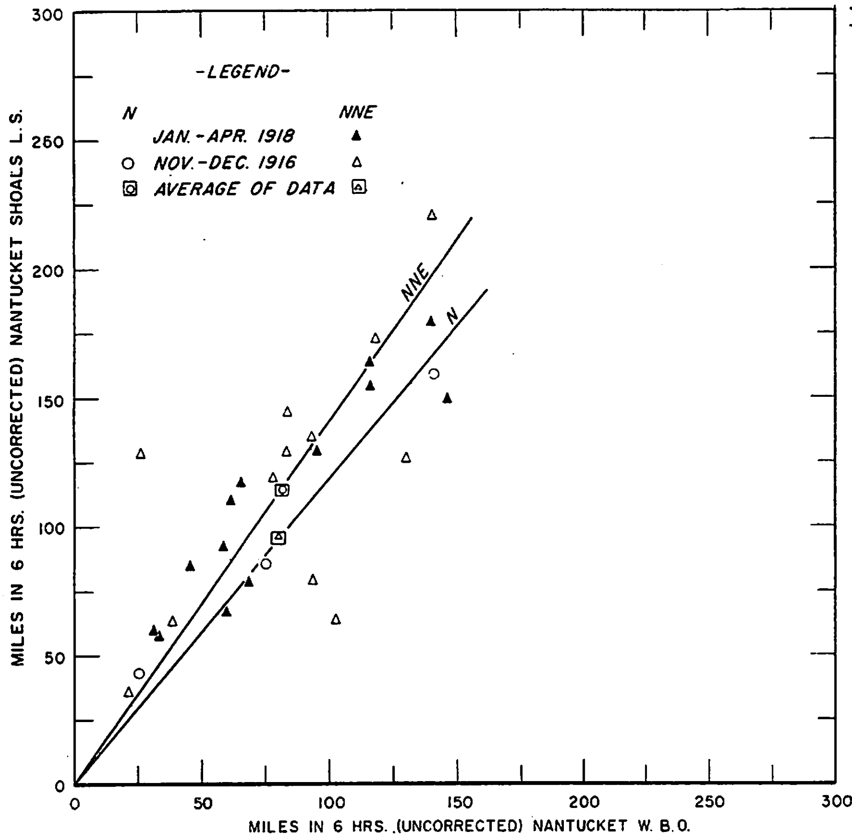


Figure 19-2. North and north-northeast wind speed, Nantucket WBO versus Nantucket Shoals Lightship.

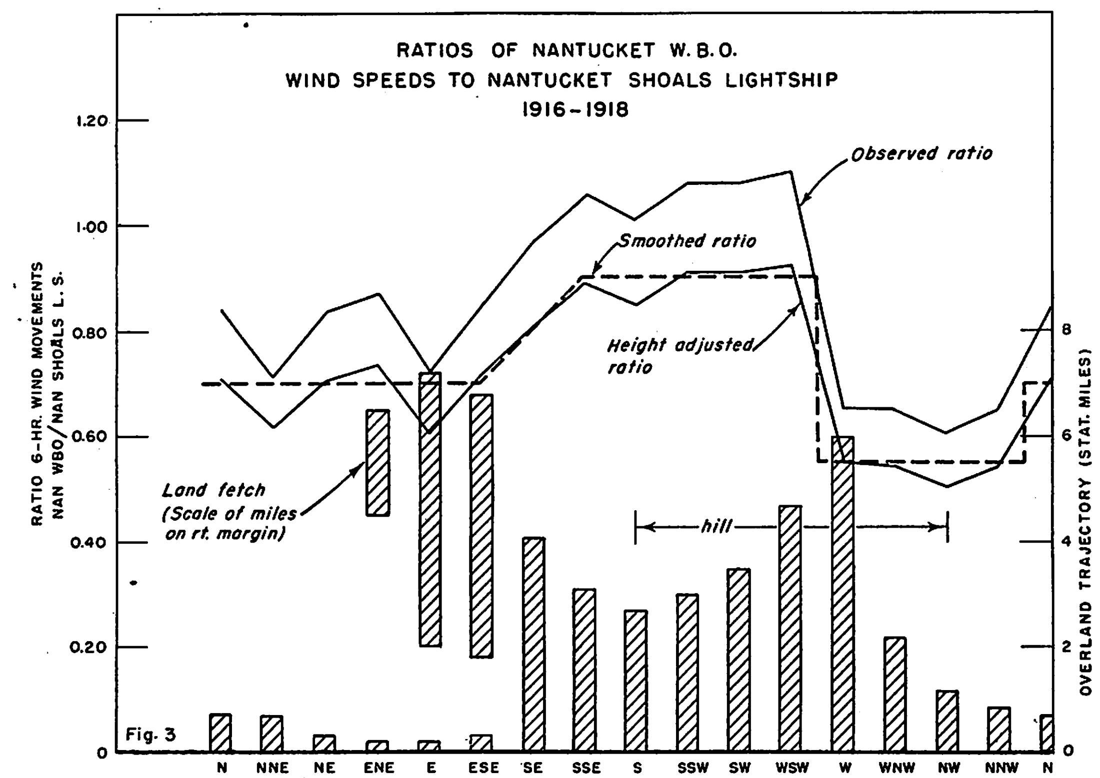


Figure 19-3. Ratios of Nantucket Weather Bureau Office wind speeds to Nantucket Shoals Lightship, 1916 to 1918.

was not immediately apparent, the direction was recorded as "mixed". The 6-hour wind movements at one station were then plotted against the simultaneous 6-hour movements at the other station, separately for different wind directions (illustrated for north and north-northeast in fig. 19-2) and separately for the 1916 and 1918 periods. Speeds for "mixed" directions were not plotted. Inspection of the plots showed no significant time trend from 1916 to 1918, as might be occasioned by inadequate anemometer maintenance at the ship, and therefore the data for the two years were lumped together for the remainder of the analysis.

WIND SPEED RATIOS

Inspection of the plots also showed an obvious and significant difference in the ratio of the wind speed at one station to wind speed at the other for different wind directions. Another characteristic of the plots was that straight lines through the origin appeared to fit the data about as well as any other kind of curve. Therefore, lines of relationship for each wind direction were obtained by computing a mean point and connecting this point and the origin with a straight line.

Surprisingly, the result showed that wind speed from southerly directions at Nantucket was relatively higher in comparison with that at the ship than wind speed from northerly directions which had a much shorter fetch over land. The ratios for the various directions are listed in table 19-1 and portrayed graphically in figure 19-3. The fetch over land in reaching the Weather Bureau Office anemometer from each direction is shown graphically by the bars at the lower portion of figure 19-3. The bars represent land at the indicated number of miles from the WBO. Gaps in the bars indicate that there is an over-water fetch between the two over-land fetches for the particular direction and show the extent of the over-water fetch.

BIAS FROM SYNOPTIC SITUATIONS

The passage, from time to time, of a northeaster closer to Nantucket Shoals Lightship than to Nantucket would be expected to produce higher winds at the ship than at the island, irrespective of any frictional differences. The magnitude of this bias in the data was investigated. Weather maps from the Northern Hemisphere 40-year synoptic series were examined on dates of northeast and east-northeast winds at Nantucket. Synoptic situations between the once-a-day maps were interpolated subjectively for intermediate 6-hour periods. Storm tracks in the Monthly Weather Review, which showed twice-a-day positions of Low centers, were also consulted. The instances of east or east-northeast winds were separated into "cyclonic" and "anticyclonic" classes, depending on the curvature of the sea level isobars at Nantucket. It was assumed that when the isobars at Nantucket were cyclonic most likely a Low center would lie closer to Nantucket Shoals Lightship and that there would be a bias for higher winds at the Lightship. It was also assumed that when isobars were straight or anticyclonic at Nantucket a general broad wind belt situation prevailed in which there would be little bias in the wind speed at the two stations. The mean ratios of Nantucket WBO to Lightship winds for cyclonic or anticyclonic are shown in table 19-2. According to the ratios there is an appreciable, but not large, bias. The mean bias for all the northeast and east-northeast comparisons is about 3 percent. This bias is probably real, but it is also apparent that it is much too small to explain the difference in ratios between northerly winds and southerly winds (fig. 19-3 and table 19-1).

A test for the presence of bias of this type for other wind directions was not made. Review of pressure patterns on weather maps lead to the conclusion that northeast was the wind direction class most likely to be biased and that it was unlikely that the bias for any other direction would be as high.

LOCAL EFFECTS

By "local effects" is meant the effects of topography and obstructions within a few yards up to perhaps a mile of the anemometer. At Nantucket there is an obvious local effect in several directions. First is the marked difference from a ratio of .925 for west-southwest to 0.55 for west (table 19-1). This presumably is due to the effect of a hill near the anemometer influencing the wind stream in some way that cannot be ascertained from inspection of the Geological Survey Quadrangle Map. Another local effect seems to be that the land to the south of the anemometer is contoured in such a fashion that it speeds up the wind at the anemometer by an aerodynamic effect rather than slowing it down. Note in figure 19-3 that from south-southeast through west-southwest the wind speed at the Nantucket anemometer is greater than that over the open sea at the Lightship, even after a trajectory of 3 to 4 miles over land. This, of course, is due in part to the greater height of the Nantucket anemometer.

CONCLUSIONS

1. The area downwind from an anemometer can have an appreciable effect on the wind speed at the anemometer. This is shown by the relatively lower northerly winds at the Nantucket WBO as compared with southerly winds and open-water winds.

2. The above leads to the conclusion that off-water winds can be appreciably weaker than corresponding winds over open water. This confirms a conclusion of Lake Okeechobee studies.

3. Winds blowing across an island of the dimensions of 3 to 6 miles may under some circumstances be as strong on the lee side as on the windward side. A land surface may be contoured in such a way, it appears, that it will speed up the wind at an anemometer downwind rather than obstructing it.

4. A calibration for the Nantucket Weather Bureau Office wind speed by directions to adjust to over-water winds was obtained. The smoothed value shown by the dashed line in figure 19-3 was used in analysis of the September 1944 New England hurricane (section 8).

FURTHER REMARKS

It was assumed throughout this study that wind speeds at the Lightship are not biased by wind direction. This seems reasonable but is not absolutely certain. If the ship was always anchored in exactly the same way with two anchors which prevented the ship from turning in the wind, any shipboard obstruction to the anemometer would be reflected in reduced wind speeds for a particular direction. It seems doubtful, however, that this could account for the major differences of the ratios in figure 19-3.

Table 19-1. - Ratios of wind speed at Nantucket W.B.O. to wind speed at Nantucket Shoals Lightship. 1916-1918

Direction at Nantucket WBO	No. of 6-hour periods compared	Ratio WBO/LS	Height adjusted ratio	Smoothed height adjusted ratio
N	3	0.845	0.71	0.70
NNE	25	0.71	0.61	0.70
NE	36	0.84	0.705	0.70
ENE	16	0.875	0.735	0.70
E	5	0.72	0.605	0.70
ESE	4	0.85	0.715	0.70
SE	14	0.97	0.815	0.80
SSE	9	1.06	0.89	0.90
S	3	1.01	0.85	0.90
SSW	15	1.08	0.91	0.90
SW	54	1.08	0.91	0.90
WSW	37	1.10	0.925	0.90
W	16	0.655	0.55	0.55
WNW	56	0.65	0.545	0.55
NW	28	0.605	0.51	0.55
NNW	33	0.65	0.54	0.55

Notes: Ratios based on 6-hour wind movements, uncorrected. The height-adjusted ratio is 0.86 of the unadjusted ratio. This adjusts Nantucket WBO from 90 feet to 30 feet and the Lightship from 24 feet to 30 feet.

Table 19-2. - Synoptic bias in wind movement ratios, NE and ENE winds

	Ratio
"Cyclonic", average WBO to LS Wind (15 cases)	0.908
"Anticyclonic", average WBO to LS Wind (24 cases)	0.977
Bias of "cyclonic" cases (assuming "anticyclonic" not biased)	1.08
Average bias for 24 cases, cyclonic and anticyclonic	1.03

WBO: Nantucket WBO
LS: Nantucket Shoals Lightship

20. A COMPARISON OF WIND SPEEDS AT THE WASHINGTON NATIONAL AIRPORT AND THE U. S. WEATHER BUREAU CENTRAL OFFICE

PURPOSE

An appraisal of U. S. Weather Bureau Central Office wind observations was made during the process of analyzing the wind over the Chesapeake Bay for the August 1933 hurricane (section 6). The Central Office downtown site was the only station in the Washington, D. C. area operating a triple register in 1933. It was assumed that the downtown wind speeds were less than would be observed in open country at the same anemometer height. To determine the validity of this assumption and the degree of reduction, a comparison of the Central Office wind speeds with the more exposed anemometers at the Washington National Airport was carried out.

COMPARISON

In order to use the 1933 Central Office wind speeds as an index of speed over a more standard friction surface such as "over-water", an adjustment factor was required. This was obtained from a comparison of the Washington National Airport (WBAS) and the Central Office (CO) wind speeds for later years when triple registers were operated at both stations. The comparison was made by plotting a graph of simultaneously observed 1-hour average wind in the higher wind speed range at each site for each of eight compass points (fig. 20-1 as example of north wind). Only cases with the same direction at the two stations were plotted. A straight line passing from the origin to the mean point of the data was judged to be a sufficiently accurate representation of the relationship between the two sites. The relation of wind speed at the Airport and Central Office sites was expressed as a ratio of $\frac{\text{WBAS speed}}{\text{CO speed}}$ for each direction. A graphic representation was made of the

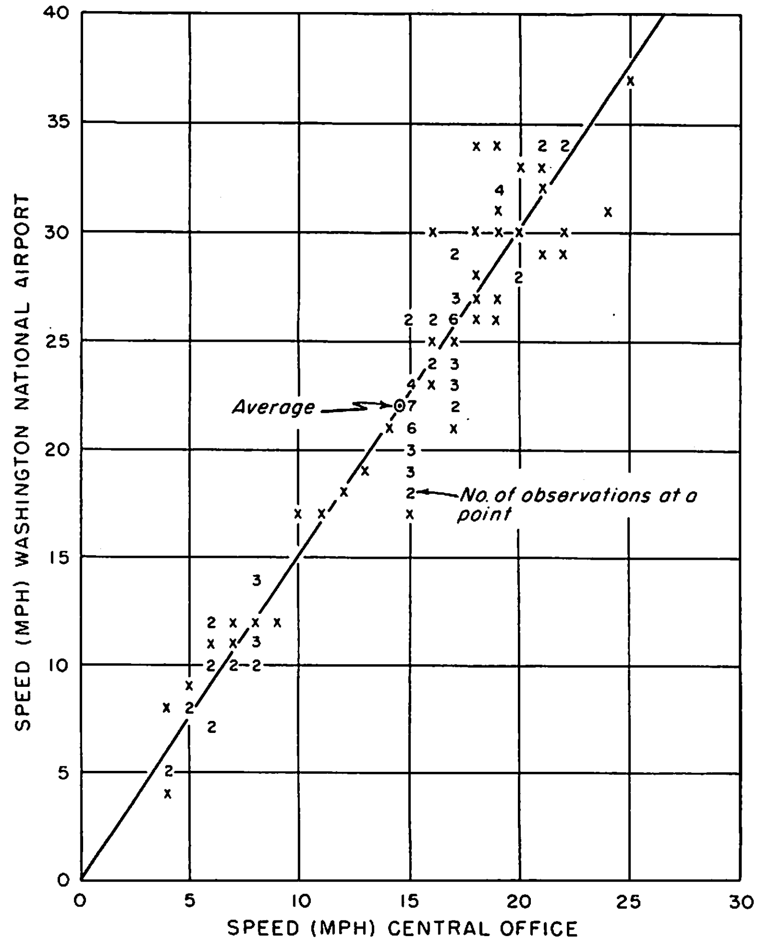


Figure 20-1. One-hour-average north wind at Washington National Airport versus Weather Bureau Central Office.

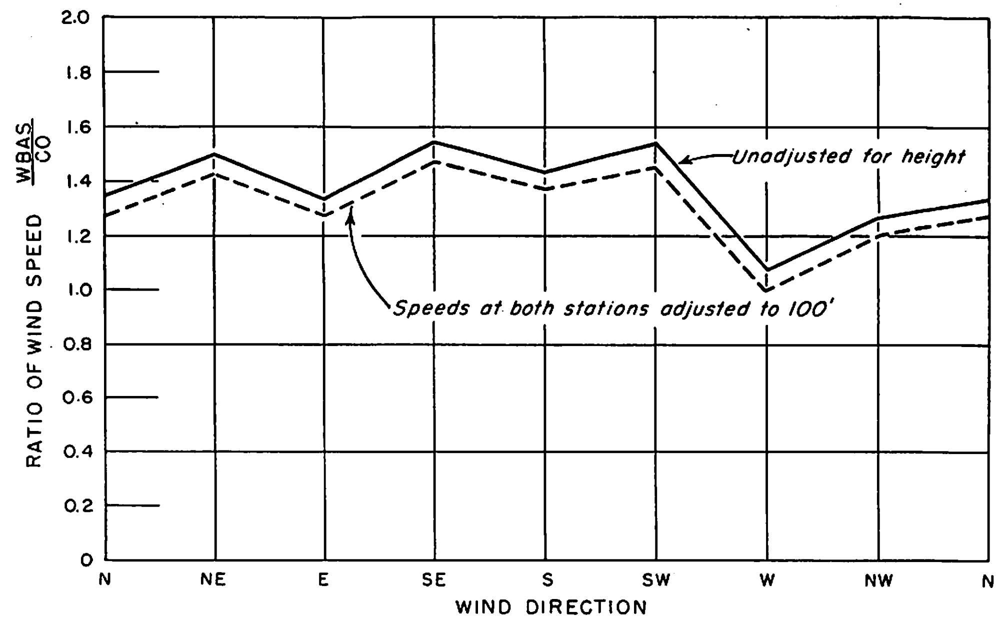


Figure 20-2. Variation with direction of ratio of Washington National Airport wind speed to Weather Bureau Central Office wind speed.

ratios of speeds as observed and of speeds reduced to a common 100-ft. level, which was the Central Office anemometer height above ground (fig. 20-2). The Airport 115-ft. speeds were reduced to 100 ft. with the aid of the graph in figure 1-1.

The two stations can be related by

$$\frac{\text{WBAS observed wind speed}}{\text{Gradient-level wind speed}} = a \qquad (20\text{-}1)$$

$$\frac{\text{CO observed wind speed}}{\text{Gradient-level wind speed}} = b \qquad (20\text{-}2)$$

If we assume that the gradient-level wind speed is the same at both stations, then

$$\frac{\text{WBAS observed wind speed}}{\text{CO observed wind speed}} = \frac{a}{b} \qquad (20\text{-}3)$$

By selecting a value of either a or b from the wind reduction graph (fig. 1-1), we may determine the other by using the observed comparative speed ratio and equation (20-3). Other things being equal, the ratios of observed to gradient-level wind speed are inversely proportional to surface roughness. The Central Office site is quite rough due to city buildings but appears uniform in most directions. A tentative ratio of Central Office to gradient-level winds, b, was selected as an anchor point. Gradient-level speeds were only assumed values and were not determined from any type of measurement. Variations of the ratio, WBAS to CO, with direction therefore depended primarily on the WBAS exposure. The exposure at the WBAS is shown schematically in figure 20-3. Table 20-1 shows the assumed ratios of observed speed to gradient-wind speed at the two sites with a brief description of the frictional characteristics affecting the wind from various directions. The ratios were determined after a consideration of the various frictional surfaces and the wind reduction graph (fig. 1-1). The ratios of observed speed to gradient-wind speed from table 20-1 are shown graphically for easy comparison in figure 20-4. The primary purpose of this graph is not to show the ratio of the surface wind speed to the gradient-level wind but rather the comparative speeds over the differing frictional surfaces.

CONCLUSION

The Washington National Airport has the more openly exposed anemometer. Because of its location on the shore of the Potomac River in a slight valley, a different fraction of the gradient-level wind speed is measured for each direction. Some part of off-water speed is measured when wind is from the northeast around through east and southeast, whereas winds from other directions are from land (fig. 20-3). Hills up to about 160 feet rise to the east, southeast (across the river), west, and southwest of the Airport. The Airport east wind speed is lower (figs. 20-2 and 20-4) probably due to the 160-ft. ridge east of the Potomac, the relatively short over-water fetch, and

Table 20-1. - Ratio of observed speed to gradient wind speed at the Central Office and the Washington National Airport

Direction	Ratio CO Observed / Gradient Wind		Ratio WBAS Observed / Gradient Wind	
N	.46	Rough surface, about same as NE, E, SE, S, and NW	.62	Smooth surface with some off-water effects
NE	.46	Rough surface, probably slight damming from hospital	.68	Off-water effects of wind across Potomac River and down Anacostia River
E	.46	Rough surface, about same as N	.62	Off-water effects from short fetch across river, hills beyond river probably reduce speed
SE	.46	Rough surface, about same as N	.72	Off-water effects, longest over-water fetch
S	.46	Rough surface, about same as N	.66	Some off-water effects, combination smooth water and rough tree-lined shore surface
SW	.39	Hospital shields anemometer	.61	Land trajectory, variable surface
W	.52	Off-water effects from Potomac River and channeling down Potomac Valley	.56	Rising ground to west, irregular surface
NW	.46	Rough surface, about same as N	.58	Similar to west, off-land winds

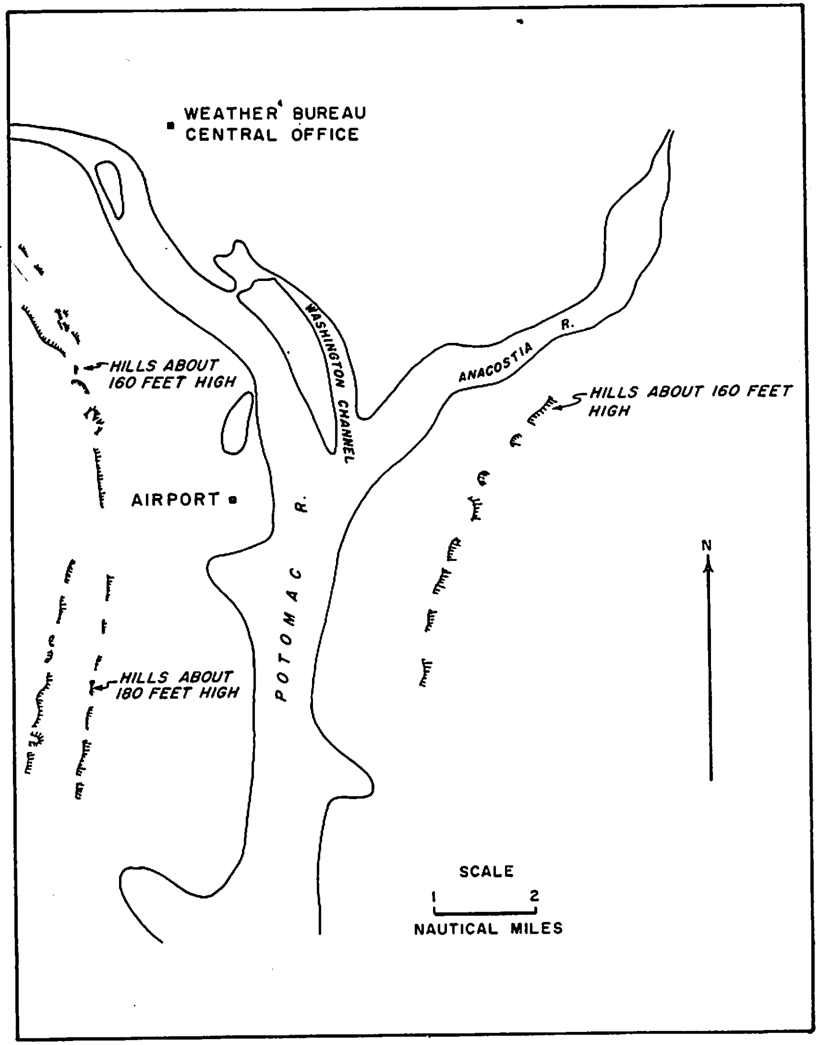


Figure 20-3. Schematic map of Washington area.

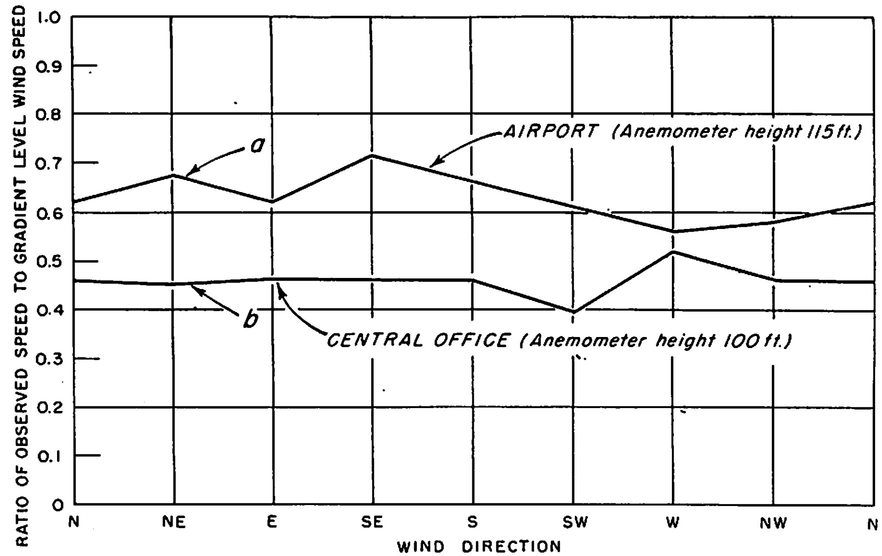


Figure 20-4. Observed gradient-wind speed, Washington National Airport and Weather Bureau Central Office.

the roughness of the terrain downwind from the anemometer.

At the Central Office site, the 100-ft. wind speed is reduced by surrounding buildings. The southwest wind speed is further reduced by the adjacent hospital building (located there since 1917). The increased west wind speed is probably due to the air blowing off the Potomac River. Speed reduction caused by buildings for other directions appears fairly uniform with observed speeds averaging about 45 percent of gradient-wind speed. The observed Central Office wind speed for all directions except southwest and west is about representative of 100-ft. wind over a relatively rough surface.

This comparison made it feasible to use the Weather Bureau Central Office observed wind speed as an index of speed over an assumed standard friction surface. Empirical relations of 30-ft. wind to gradient wind /4/ were applied to the ratios determined in this comparison to estimate the 30-ft. over-water wind speed during the 1933 hurricane (section 6).

21. A COMPARISON OF THE WINDS AT THE CHESAPEAKE BAY BRIDGE, BALTIMORE, AND ANNAPOLIS

(and variation of wind speed with length of over-water fetch)

THE PROBLEM

In synthesizing the various wind patterns for tropical and extratropical storms shown in this report, the need arose for a better understanding of wind accelerations due to variations in the underlying friction surface when there was a change from land to water or vice versa. In addition to the relation of over-water speeds to off-water and off-land speeds, determined empirically at Lake Okeechobee during the 1949 hurricane /4/, a quantitative determination was needed of wind speed for air blowing from land to water at any given distance from the shore.

The State of Maryland, in cooperation with the Baltimore Weather Bureau Airport Station (Friendship), has maintained an anemometer on the Chesapeake Bay Bridge since about 1953. The record from this instrument, together with the observations from Friendship Airport and the Annapolis Naval Air Facility, during several strong wind situations afforded a basis for comparison of winds over some of the various friction surfaces.

THE OBJECTIVES

It was decided to attempt several determinations from an analysis of the data. The several objectives were as follows: 1) Determine a ratio of over-land wind speed to over-water wind speed; 2) Verify the off-water to over-water wind-speed ratio as determined at Lake Okeechobee, Fla., /4/; 3) Determine empirical method(s) for computing offshore wind speeds over water at various distances from shore; 4) Determine a height-reduction factor for wind speeds (not accomplished); 5) Determine a method for computing 30-ft. wind speeds over the Chesapeake Bay for the various directions based on the observed speeds at Baltimore or Annapolis.

STATION DESCRIPTIONS

The stations were close enough together so that, for any large-scale disturbance, they were all under the same general wind regime. The relative station positions are shown in figure 21-1.

The anemometer at the Baltimore Airport site is 133 feet above the ground, mounted above the Administration Building. The airport is surrounded by more or less uniform rolling terrain in all directions and is in a slight bowl. Some of the surrounding terrain at a distance of two or three miles is approximately as high as the anemometer. There appeared to be no particular obstruction from any one direction so the underlying frictional surface was assumed to be the same for all directions. Wind observations were taken from triple-register records.

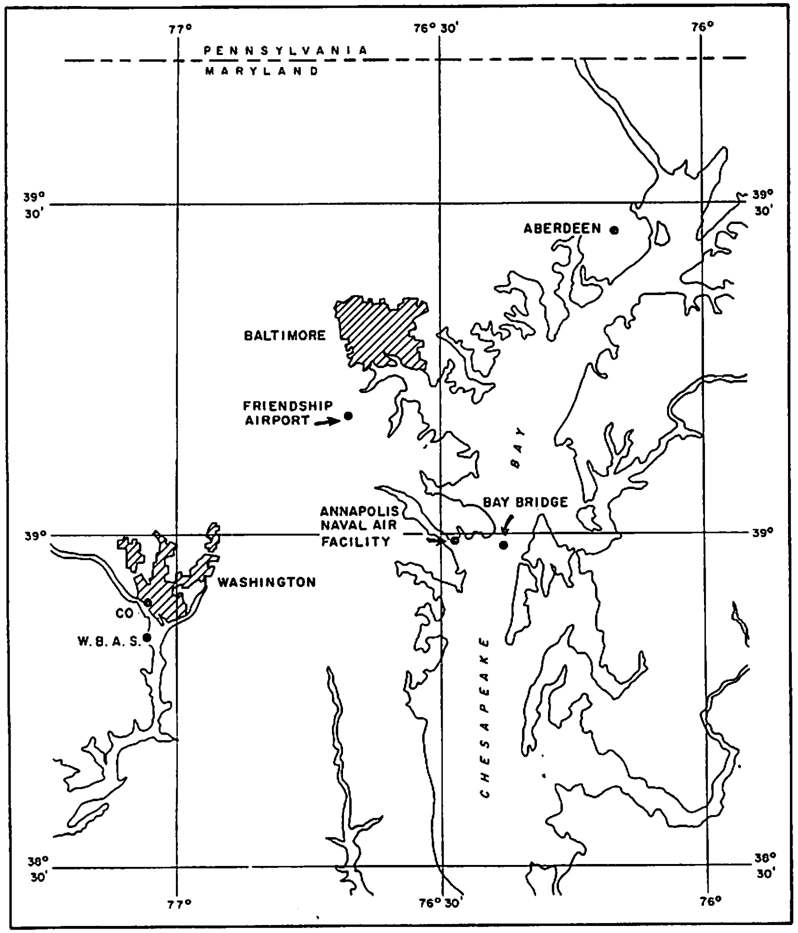


Figure 21-1. Location of Baltimore Friendship Airport, Chesapeake Bay Bridge, and the Annapolis Naval Air Facility Stations.

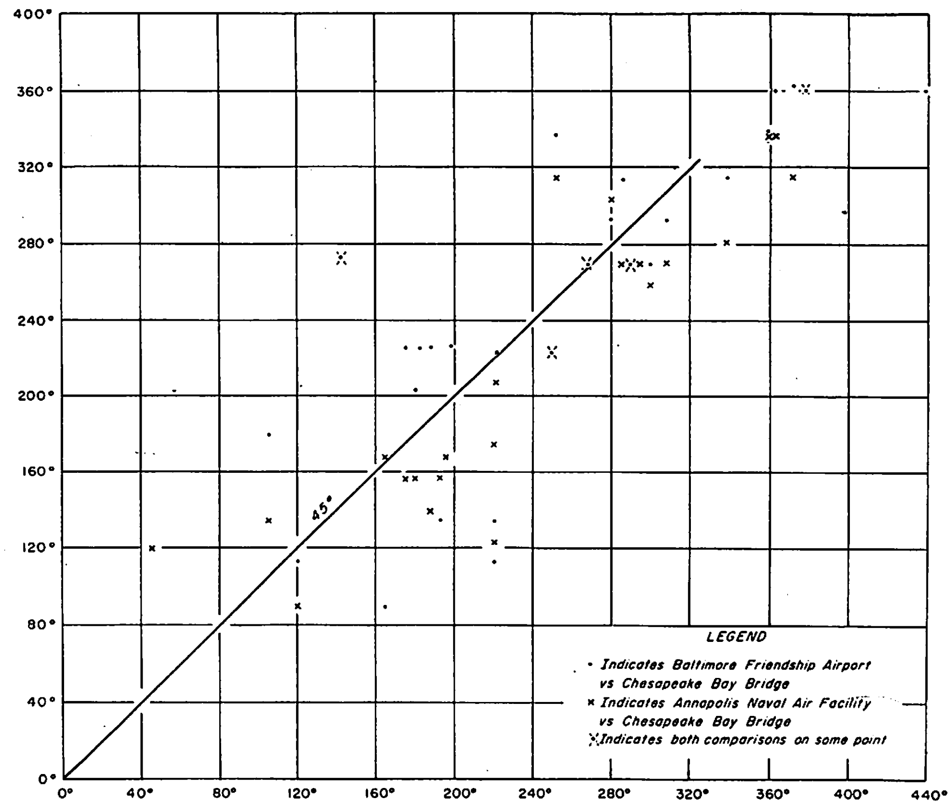


Figure 21-2. Comparison of wind directions 1500 EST, October 1 to 31, 1954.

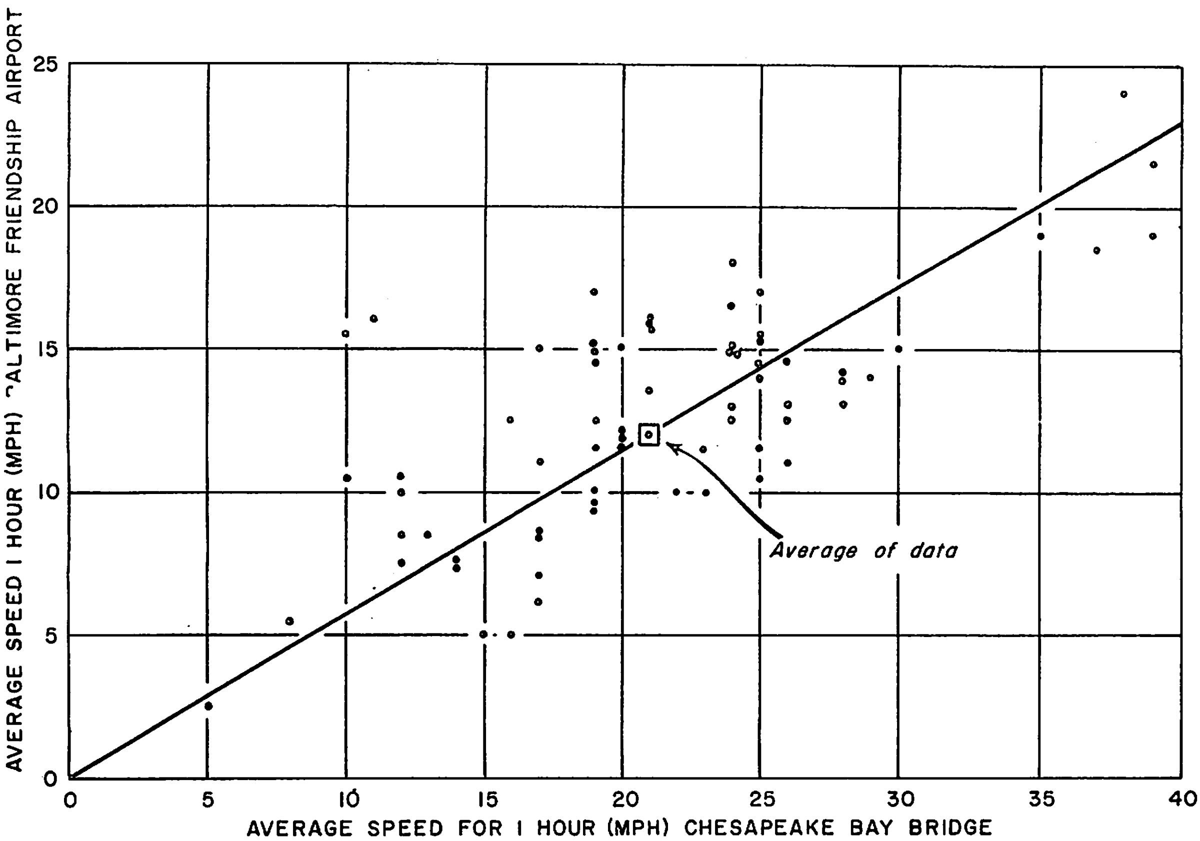


Figure 21-3. Observed one-hour-average north-wind speed and straight line analysis.

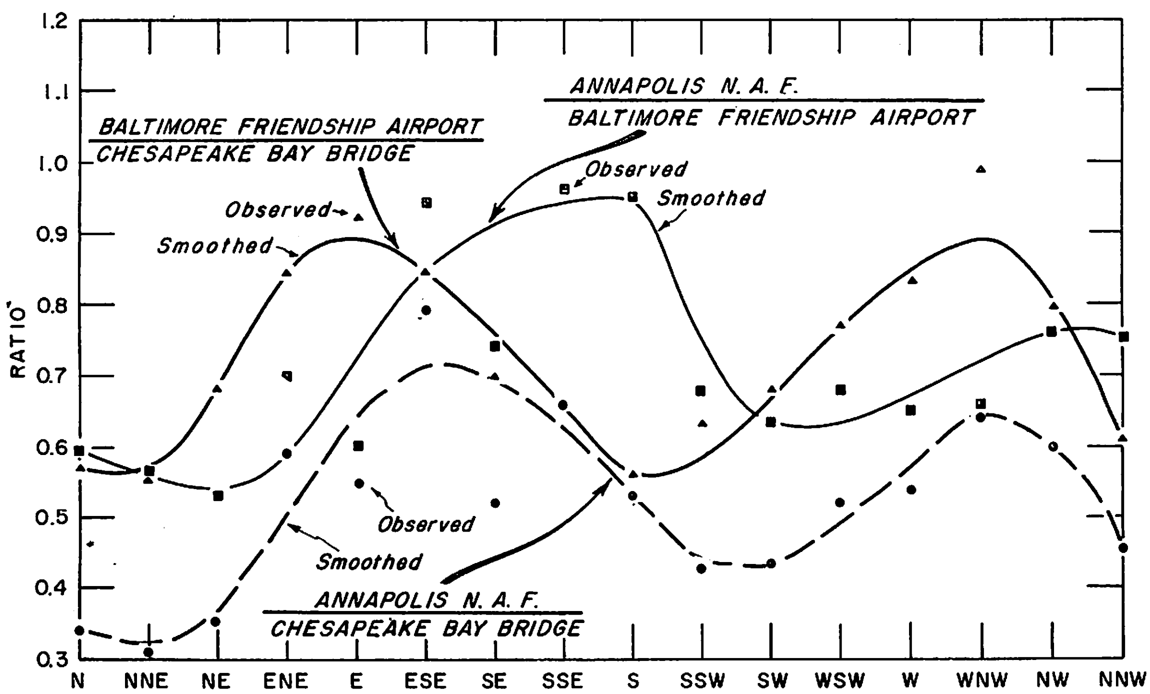


Figure 21-4. Ratios of observed wind speeds by directions: Baltimore Friendship Airport, Annapolis Naval Air Facility, and Chesapeake Bay Bridge.

On the Chesapeake Bay Bridge a Friez Aerovane anemometer and Esterline-Angus recorder are located on the main span approximately 226 feet above the water surface, 14,125 feet from the eastern shore and 8,917 feet from the western shore. The anemometer is secured several feet above the bridge structure where it measures an unobstructed wind speed from most directions. Some narrow portions of the bridge structure rise a few feet above the anemometer a few hundred feet to the west-northwest and east-southeast and possibly reduce the wind slightly in these directions, though no reduction could be detected.

WIND DIRECTION

To ascertain any bias in observed directions for the three stations, the directions observed at one time each day during the month of October 1954 (during which there was one period of unusually strong winds) at both Annapolis and Baltimore were plotted against the observed directions at the Bay Bridge site. Figure 21-2 shows an analysis of these data. No bias is evident and therefore at a given time wind speeds at the three stations may be compared using any one station direction to determine the direction category.

SPEED RATIOS

One-hour average wind speeds at the three stations were tabulated and simultaneous values plotted against each other over several periods which were prior to, coincident with, and after periods of strong winds in hurricanes or extratropical storms. The data were stratified by directions at the Bay Bridge, to 16 points. In each of the 32 graphs, a straight line from the origin through the mean point of the data seemed to be a sufficiently accurate and simple representation of the relationship between the station wind speeds.

A sample plot is illustrated in figure 21-3 where the speeds at Baltimore are plotted against the Bay Bridge speeds for the north direction. The wind-speed comparisons are shown as ratios in table 21-1. Ratios of Annapolis speed to Baltimore speed were obtained mathematically from the first two ratios. Since data for some directions are not as plentiful as for others, the data from table 21-1 have been smoothed and presented graphically on figure 21-4. These values were derived by visually fitting a smooth curve through the observed ratios, giving greatest weight to the ratios based on the most data.

REDUCTION TO 30 FEET

Mutually consistent reduction factors to 30 ft. were estimated by applying figure 1-1 and working through the gradient wind with formulas 20-1, 20-2, and 20-3, in the same manner as for Washington. The constant (0.54) was selected as the factor for reducing the Baltimore speeds to 30 feet. The reduction factors for other stations varied with the frictional surface, which was a function of direction, table 21-2. The ratios of 30-ft. wind speed for the 3 stations are shown in figure 21-5.

Table 21-1. - Comparison of wind speeds at Baltimore Friendship Airport, Annapolis Naval Air Facility, and Chesapeake Bay Bridge

Direction	Baltimore No.	Baltimore Highest Speed (m.p.h.)	Baltimore Mean (m.p.h.)	Annapolis No.	Annapolis Highest Speed (m.p.h.)	Annapolis Mean (m.p.h.)	Bay Bridge No.	Bay Bridge Highest Speed (m.p.h.)	Bay Bridge Mean (m.p.h.)	Ratio of Means: Baltimore-Bay Bridge	Ratio of Means: Annapolis-Bay Bridge*	Ratio of Means: Annapolis-Baltimore
N	70	24	12.0	70	17	7.1	70	39	21.0	0.57	0.34	0.60
NNE	49	18	10.9	49	13	6.1	49	38	19.7	0.55	0.31	0.56
NE	20	25	11.2	15	10	4.5	20	36	16.4	0.68	0.36	0.53
ENE	15	17	10.7	10	7	5.0	15	19	12.8	0.84	0.59	0.70
E	17	24	10.3	9	6	5.0	17	23	11.2	0.92	0.55	0.60
ESE	26	38	16.0	20	32	15.0	26	47	19.0	0.84	0.79	0.94
SE	14	18	12.5	9	15	6.9	14	26	17.5	0.70	0.52	0.74
SSE	41	31	12.5	21	18	9.7	41	34	18.0	0.69	0.66	0.96
S	94	26	9.0	80	20	8.2	94	36	16.0	0.56	0.53	0.95
SSW	76	23	11.1	59	16	7.7	76	38	16.8	0.63	0.43	0.68
SW	71	23	8.3	62	14	5.3	71	25	12.1	0.68	0.43	0.63
WSW	52	20	10.0	42	17	7.0	52	22	13.0	0.77	0.52	0.68
W	35	15	11.0	34	20	7.0	35	22	13.0	0.83	0.54	0.65
WNW	55	26	12.9	53	21	9.0	55	29	13.1	0.99	0.65	0.66
NW	39	22	11.0	39	17	8.4	39	22	14.1	0.79	0.60	0.76
NNW	50	20	10.6	41	17	8.0	50	30	17.3	0.61	0.46	0.75

*Average ratio of coincidentally observed speeds excludes the Chesapeake Bay Bridge observation during times of missing observations at Annapolis. (The number is listed under Annapolis.)

Table 21-2.-Ratios for reduction of anemometer height winds to 30-ft. speeds

Direction	Baltimore Friendship Airport	Chesapeake Bay Bridge	Annapolis Naval Air Facility
N	0.54	0.90	0.65
NNE	0.54	0.90	0.65
NE	0.54	0.81	0.65
ENE	0.54	0.71	0.65
E	0.54	0.69	0.70
ESE	0.54	0.70	0.75
SE	0.54	0.75	0.83
SSE	0.54	0.83	0.77
S	0.54	0.90	0.72
SSW	0.54	0.90	0.72
SW	0.54	0.81	0.69
WSW	0.54	0.74	0.65
W	0.54	0.70	0.65
WNW	0.54	0.70	0.70
NW	0.54	0.70	0.70
NNW	0.54	0.80	0.70

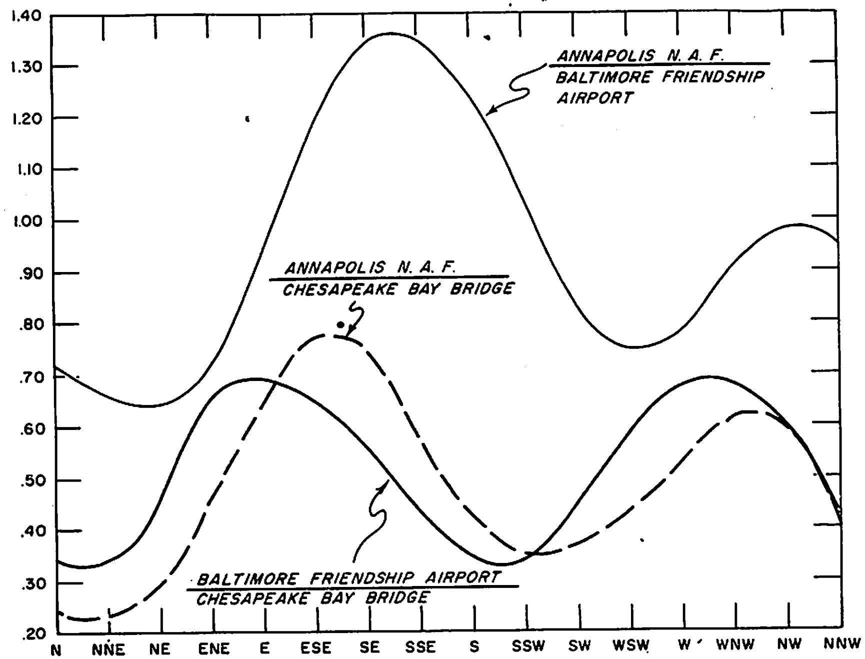


Figure 21-5. Ratios of wind speeds adjusted to 30 ft. by directions.

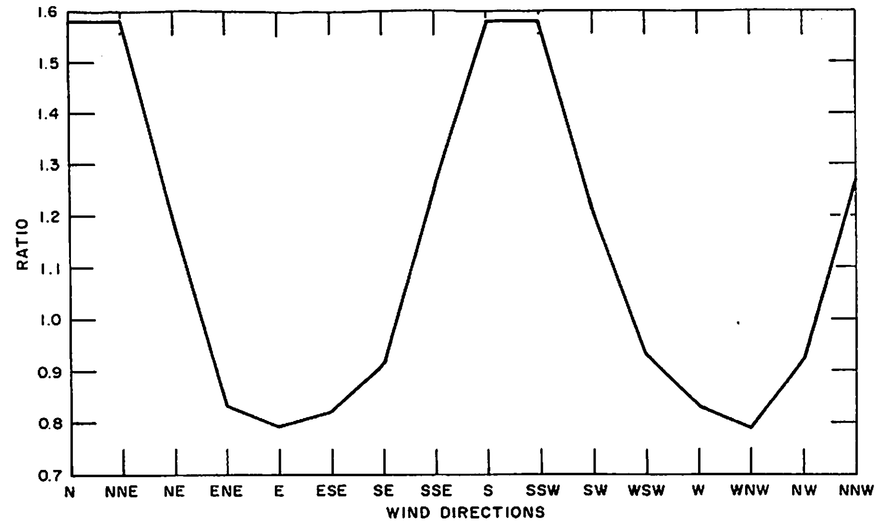


Figure 21-6. Ratios of 30-ft. wind speed at Chesapeake Bay Bridge to observed speed at Baltimore Friendship Airport (one-hour **average**).

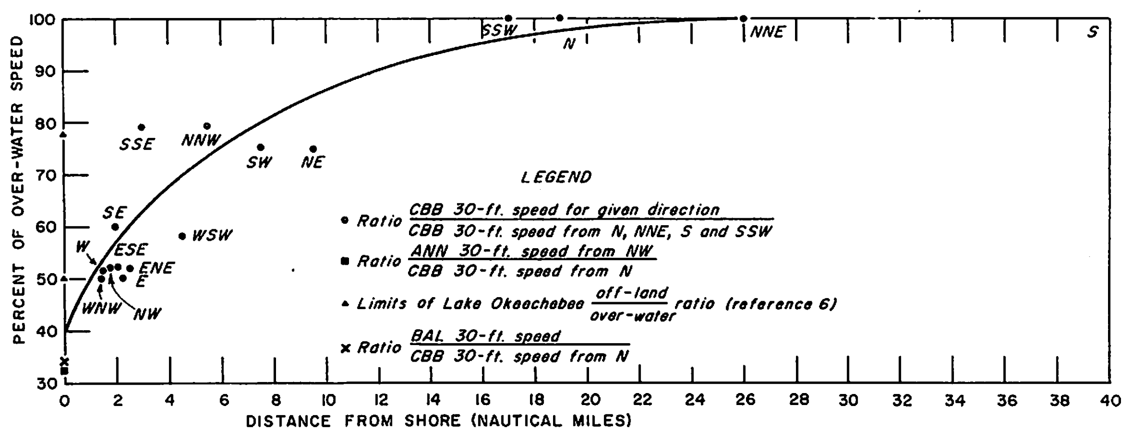


Figure 21-7. Increase of offshore wind speed with distance from shore.

COMPARISON WITH LAKE OKEECHOBEE FACTORS

Any over-land to over-water wind speed ratio will be primarily a function of the land anemometer exposure. Baltimore Friendship Airport speeds vs. Chesapeake Bay Bridge for the most exposed directions at the bridge, north and south, reduced to 30 feet (not a precise procedure), gives an over-land to over-water 30-ft. wind speed ratio of 34 percent (figure 21-5). This is about the same as the off-land to over-water ratio at Lake Okeechobee in the lower speed range, figure 1-2.

A comparison of off-water to over-water wind speeds at Lake Okeechobee /4/ gave an average ratio of 89 percent. Winds are off-water at Annapolis from the south-southeast. Comparing wind speeds at Annapolis from the south-southeast with the Chesapeake Bay Bridge winds from south, both reduced to 30 feet, gives a ratio of 45 percent. (Winds from different directions were compared by multiplying ratios ANN/BAL and BAL/CBB where BAL speed is unity for all directions.)

There are two possible explanations for the considerably lower ratio of 45 percent compared to the 89 percent Lake Okeechobee ratio: 1) At Annapolis there is a gradual rise in elevation landward from the anemometer, and the terrain is moderately rough and covered with trees offering a greater degree of friction than occurred around Lake Okeechobee. 2) There may have been an error introduced in reducing the anemometer height winds to 30 feet. The differences are significant and suggest that an off-water to over-water speed ratio is inversely proportional to the land roughness downwind with a value of 89 percent as the upper limit.

ESTIMATING CHESAPEAKE BAY 30-FT. WINDS FROM BALTIMORE FRIENDSHIP AIRPORT OBSERVED WINDS

Failure of the anemometer on the Chesapeake Bay Bridge during the period when Hurricane Hazel was nearby made it necessary to reconstruct the winds over the Bay for the hours after the anemometer failure from estimates based on nearby stations (see section 13). The wind speeds at Baltimore Airport were adjusted according to empirical factors to determine wind speeds over the north end of the Bay. Another use for a relationship between Baltimore observed speeds and Chesapeake Bay Bridge 30-ft. winds would be in forecasting Bay winds on a routine basis for shipping interests in the Bay. Synoptic observations over the open Bay are rare. However, a most likely 30-ft. speed in the Bay Bridge area can be computed from the Baltimore observed speeds when a large-scale disturbance is over the area. From the forecasting standpoint this would be an acceptable substitute for actual observations over the Bay and quite dependable because the Baltimore wind speed observations are readily available.

The mean ratio of one-hour average 30-ft. wind speed at the Chesapeake Bay Bridge site to one-hour average observed speed at Baltimore Friendship Airport was computed by combining ratios from figures 21-4 and 21-5 and is shown in figure 21-6. The predicted speed in the vicinity of the Bay Bridge is equal to the Baltimore Airport observed speed times the plotted ratio from figure 21-6 for the Airport directions. Since the width of Chesapeake Bay is quite variable, speeds for other places in the Bay must be estimated from air parcel trajectories and computed Bay Bridge speeds. Winds blowing across the Bay would be proportionately stronger near the center in most other sections of the Bay because the Bridge is over one of the narrowest portions of the Bay.

VARIATION OF WIND SPEEDS WITH OVER-WATER DISTANCE

Parcels of air at low levels will accelerate on the average on passing from a land surface to a water surface. The rates of acceleration were necessary in synthesis of cyclone winds over water surface, but adjacent to land areas. Determinations of acceleration rates are discussed below from an empirical standpoint.

Off-land to over-water speed ratio. In order to determine this the speed at the shore is used as a starting value. As an indication of this value, several bits of information are available: 1) The ratio of off-land to over-water speeds in the Lake Okeechobee studies /4/ ranged from 50 percent to 78 percent and were in direct proportion to wind speed; 2) In the Chesapeake Bay wind study, off-land winds at the Annapolis site were about 33 percent of over-water speeds as the latter were observed at the Bay Bridge; 3) The ratio of Baltimore Friendship Airport 30-ft. wind speed to the Bay Bridge was 34 percent; 4) Wide variations in the off-land to over-water speed ratio were observed in the Lake Okeechobee data /6/ indicating that this is a more uncertain ratio. The evidence suggests that the off-land to over-water wind speed ratio is a function of the shoreline roughness and may vary from near 33 percent at a poorer exposed site to near 80 percent when the terrain near the shore line is smooth.

Speed variation with over-water distance. The speeds at the Bay Bridge site vary with direction. This variation is a function of over-water fetch. Figure 21-7 shows a plot of the ratios of Chesapeake Bay Bridge 30-ft. wind speeds for each direction to the Bay Bridge 30-ft. wind speed from four selected directions along the length of the bay. These ratios were obtained by working through figure 21-6, assuming that the wind exposure for Friendship Airport is the same for all directions. The abscissa in diagram 21-7 is the distance of the bridge anemometer from shore for each wind direction. The curve through the data in figure 21-7 may be interpreted as the ratio of wind speed blowing from land at a given distance from shore to over-water wind speed. The speeds at the Bridge for wind directions which are across the Bay are probably reduced by both shores and are therefore underestimates of the speeds at those distances from shore for a wide body of water. The wind speed of an air parcel moving from land to water depends on the off-land wind speed, which was shown to be a function of the terrain near the shore. This variation with off-land wind speed is less pronounced with increased distance from shore.

22. A COMPARISON OF WIND SPEEDS AT THE WEATHER BUREAU OFFICE AND AIRPORT STATION, NEW ORLEANS, LA.

PURPOSE

This study was made to determine, for use in analyzing the 1915 and 1947 hurricanes (sections 5 and 9), the relationship between wind observations at the New Orleans Weather Bureau Office, where the anemometer is located on the roof of the Post Office Building, and the Airport Station at Moisant International Airport, which has a more favorable anemometer exposure, and to determine if the ratio of the Weather Bureau Office speed to open water speed determined from 1947 data was applicable in 1915.

In studying the 1947 hurricane, it became evident that the wind speeds at the Weather Bureau Office were considerably reduced by frictional effects. The September 1947 Monthly Meteorological Summary for New Orleans /49_7 states: "The maximum wind velocity on the 19th recorded at the City Office and shown hereon is inaccurate and unreliable because of eddies and other malformations of the wind flow caused by obstructions from higher buildings nearby." In the description of the station location in the Local Climatological Data for 1952 for New Orleans /50_7 it is further noted, "Wind velocities and directions are adversely affected by the taller buildings to the west and north."

COMPARISON OF DAILY AVERAGE WIND SPEEDS

Situations were chosen during the period from September 1950 through December 1954 when high winds other than those associated with hurricanes prevailed over the area and when there was little pressure-gradient change over the 10 miles between the two places. Daily average wind speeds as recorded on Weather Bureau Form 1001C (Local Climatological Data) for the two stations were plotted against each other separately by directions for those days when the airport daily average was 15 mph or more. The daily average wind speed and direction at the airport is found by averaging the 24 record observations of one-minute average wind speeds and at the city office by averaging the prevailing direction and wind speed observed each hour on the triple-register chart.

The corresponding mean speeds and ratios are listed in table 22-1. Directions with fewer than four observations are omitted.

Table 22-1. - A comparison of the mean daily average wind speeds at New Orleans Weather Bureau Office (WBO) and Weather Bureau Airport Station (WBAS)

Direction At WBAS	No. of Cases		Mean Speed at WBAS (m.p.h.)	Mean Speed at WBO (m.p.h.)	Ratio of WBO to WBAS
N	36		18.9	10.4	.55
NNE	15		18.1	10.5	.58
NE	10		16.5	10.2	.62
ENE	9		17.3	11.4	.66
SSE	8		17.0	10.6	.62
S	16		17.3	10.7	.62
SSW	7		17.0	9.8	.58
WNW	4		16.4	10.0	.61
NW	7		16.6	10.5	.63
NNW	20		17.8	10.4	.58
Total cases	132	Mean	17.8	10.5	.605

The wind speeds at the City Office were consistently lower than the speeds at the airport (about 0.6 of the airport speed) although the anemometer is located 85 feet above the ground at the City Office and 53 feet above the ground at the airport. There was no significant directional difference in the ratio. This indicates that there was considerable obstruction to wind flow at the City Office in all directions reducing the effective height of its anemometer. If wind observations at both stations had been adjusted to the same height without considering the differences in topographical effects, the difference between the adjusted speeds would have been even greater than the difference between the observed speeds.

COMPARISON OF AVERAGE HOURLY WIND SPEED FOR A DAY WITH HIGH WIND SPEEDS

Average hourly speeds at the two stations were compared for a day when winds at the airport were 20 m.p.h. or more for a period of 14 hours, April 29, 1953. Average hourly wind speeds and directions for the City Office were taken from the triple-register chart. The wind direction for the Airport Station was taken from the observations on Weather Bureau Form 1130 and the average hourly wind speed was read from the gust recorder chart.

The ratio of the mean hourly wind speed between the two stations for this day differed little from the ratio of the mean daily average wind speeds from the same directions. The ratio of the mean hourly wind speed at the City Office to the mean hourly wind speed at the Airport Station was 0.63. Southerly winds prevailed during the day, varying from west-southwest through south-southeast. The mean daily average wind speed ratio with a south-southeast wind at the airport is 0.62 and with a south-southwest wind at the airport, 0.58.

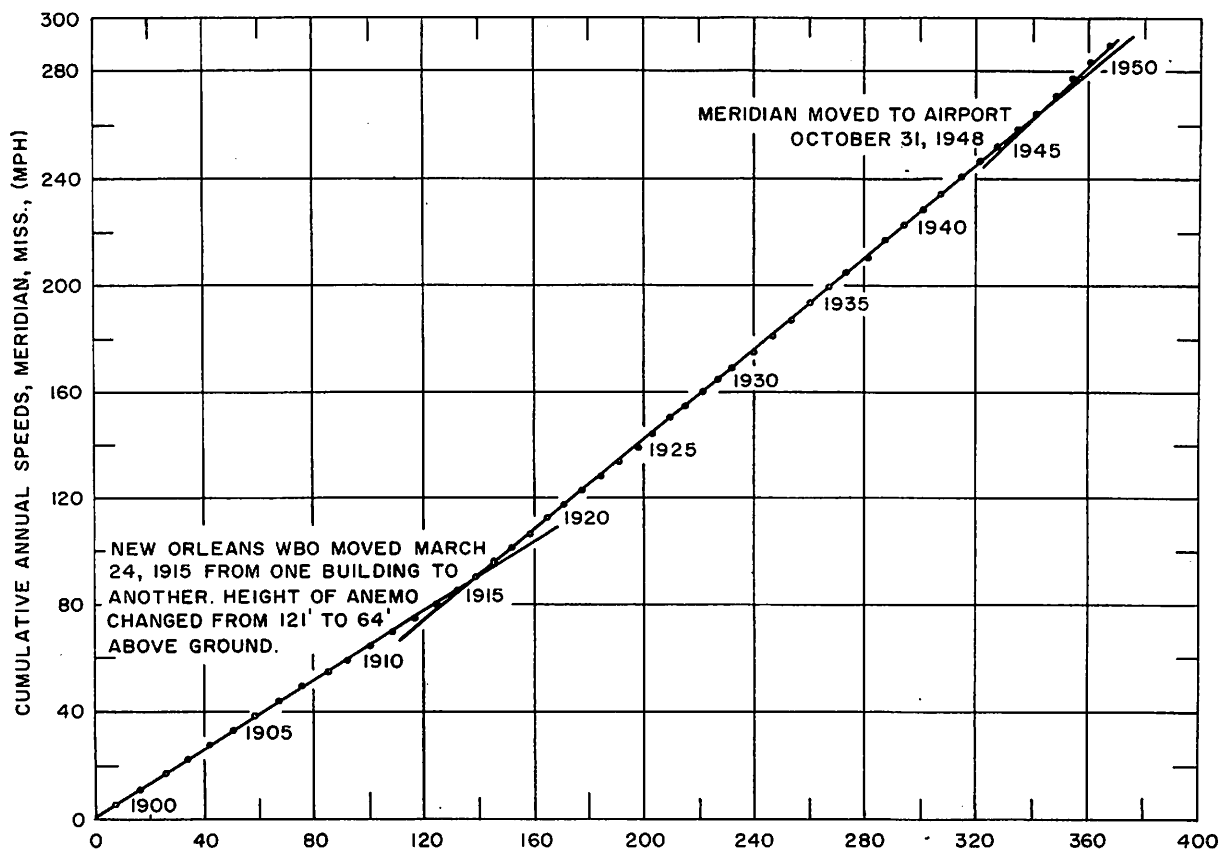


Figure 22-1. Cumulative annual wind speed comparison, Weather Bureau Office, New Orleans, La., versus Meridian, Mississippi.

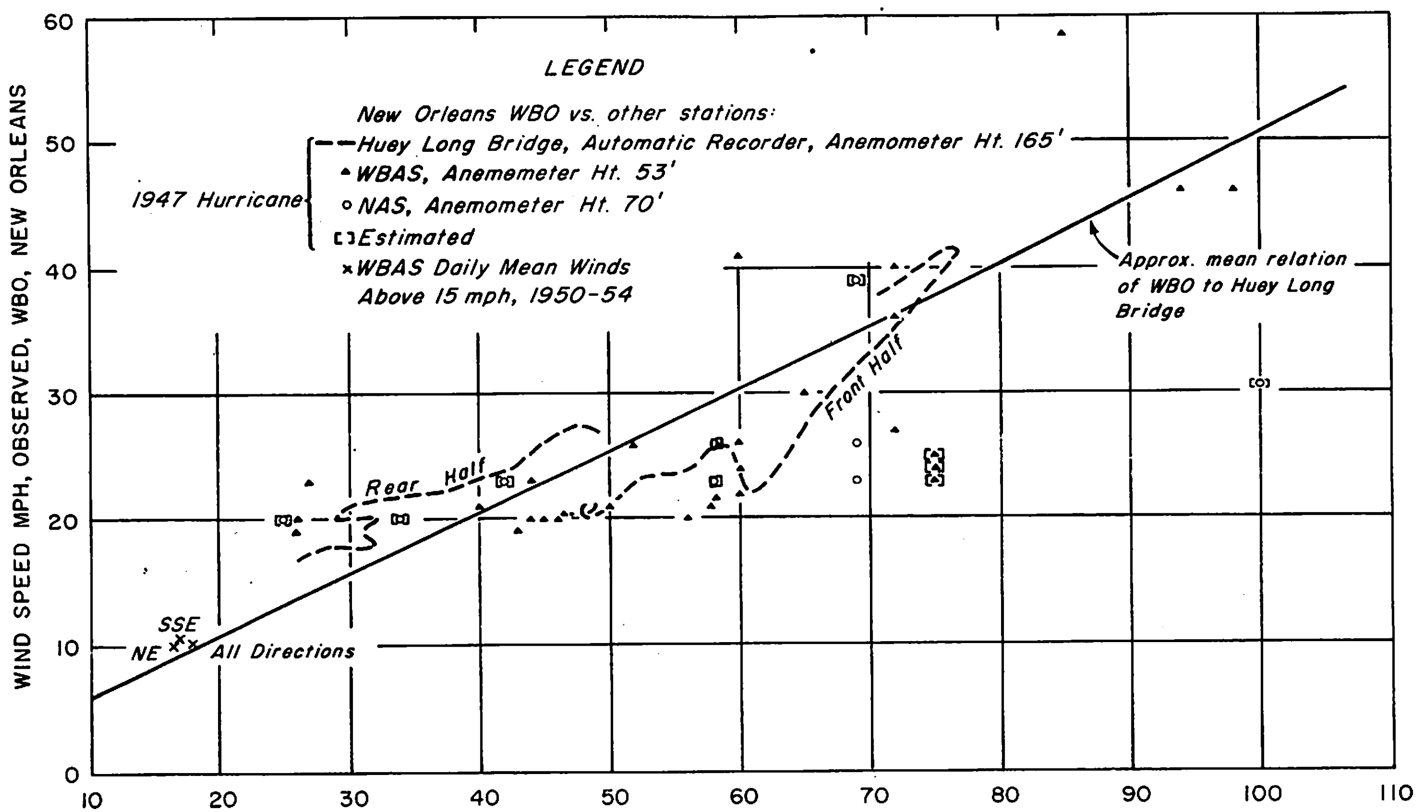


Figure 22-2. Comparison of observed speeds at WBO, New Orleans, La., with nearby stations during Hurricane of September 19, 1947.

WIND SPEED VARIATIONS AT NEW ORLEANS OVER THE YEARS

The New Orleans Weather Bureau Office has not changed location since March 1915 so that speed comparisons for later years could be considered a valid indication of the 1915 conditions. As a check on possible changes in wind speed due to environmental changes (such as the construction of buildings) at the WBO site between 1915 and more recent years, the accumulated mean annual wind speeds at the WBO from 1900 to 1950 were plotted against the same variable for Meridian, Miss. (fig. 22-1). It appears that there was a change associated with the moving of the New Orleans WBO in 1915, but there has been no appreciable change since that time. The anemometer height had been changed only one foot at Meridian and moved one block prior to 1948 when the Meridian station was moved to the Airport. As a result of this comparison, it is concluded that ratios of New Orleans WBO speeds to open water speeds determined from 1947 data are applicable to 1915 data.

COMPARISON OF NEW ORLEANS WBO WIND SPEED WITH OTHER SITES DURING THE HURRICANE OF SEPTEMBER 19, 1947

For a comparison during the 1947 hurricane, the New Orleans WBO speeds were plotted against speeds at the Moisant Weather Bureau Airport Station, the New Orleans Naval Air Station, and the Huey P. Long Bridge. The fact that the stations would be in different parts of the hurricane at a particular time was taken into account by constructing profiles of speed against distance from the storm center for each station and then plotting, against each other, speeds at each station at equal distances from the storm center. The winds at Huey P. Long Bridge, where the anemometer is at 165 feet, are perhaps 5 percent (using fig. 1-1) in excess of equivalent speeds at 30 feet over Lake Pontchartrain. The Naval Air Station speeds were from the direction of the lake in this comparison and are comparable to off-water speeds. The Moisant Airport speeds required upward adjustment of perhaps 5 or 10 percent to over-water speeds. The data from Huey P. Long Bridge and the New Orleans WBO were given the most weight in the comparison, as only these stations had automatic wind-registering equipment. The mean ratio of speeds at Huey P. Long Bridge to those at New Orleans WBO in the 1947 hurricane was 1.97 to 1 (by eye, in fig. 22-2).

ACKNOWLEDGMENTS

The authors appreciate the many contributions of Vance A. Myers who furnished general guidance together with many worthy suggestions as to the content of this report. Appreciation is also expressed to Lillian K. Rubin for critical reading of the manuscript and suggestions for improving clarity and consistency, to Walter S. Spuhler for supplying charts for section 18, to Cora G. Ludwig and Edna L. Grooms for the considerable amount of clerical assistance, to Elizabeth J. Weiss for editorial advice, and to Edward E. Edstrom, Nicholas A. Aspiotis, Roger D. Burchfield, Mae J. Hughes, Lalah B. Kohl, Donald D. Kastner, James L. Keister, and James V. Villarejo for their aid in data processing. Drafting was done by Caroll W. Gardner, Vivian M. Campbell, and Clare S. Gladden.

REFERENCES

1. C.L. Mitchell, "West Indian Hurricanes and other Tropical Cyclones of the North Atlantic Ocean," Monthly Weather Review, Supplement No. 24, 1924.

2. G. W. Cry, William H. Haggard, Hugh H. White, "North Atlantic Tropical Cyclones." U. S. Weather Bureau, Technical Paper No. 36, 1959.

3. José A. Colón, "A Study of Hurricane Tracks for Forecasting Purposes." Monthly Weather Review, vol. 81, No. 3, Mar. 1953, pp. 53-66.

4. Hydrometeorological Section, U. S. Weather Bureau, "Characteristics of United States Hurricanes Pertinent to Levee Design for Lake Okeechobee, Florida," Hydrometeorological Report No. 32, 1954.

5. U. S. Weather Bureau, "Survey of Meteorological Factors Pertinent to Reduction of Loss of Life and Property in Hurricane Situations." National Hurricane Research Project Report No. 5, Mar. 1957.

6. Vance A. Myers and Elizabeth S. Jordan, "Winds and Pressures over the Sea in the Hurricane of September 1938," Monthly Weather Review, vol. 84, No. 7, July 1956, pp. 261-270.

7. I. M. Cline, Tropical Cyclones, 3d Ed. revised, MacMill and Co., New York, 1951.

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

9. Hydrometeorological Section, U. S. Weather Bureau, "Analysis and Synthesis of Hurricane Wind Pattern Over Lake Okeechobee, Florida," Hydrometeorological Report No. 31, 1954.

10. L. A. Hughes, "On the Low-Level Wind Structure of Tropical Storms," Journal of Meteorology, vol. 9, No. 6, Dec. 1952, pp. 422-428.

11. Leon Sherman, "On the Wind Asymmetry of Hurricanes," Journal of Meteorology, vol. 13, No. 5, Oct. 1956, pp. 500-503.

12. U. S. Weather Bureau, Climatological Data, Maryland and Delaware Section, vol. XXXVIII, No. 8, Aug. 1933.

13. Abraham S. Kussman, Report on the Hurricane of September 3, 1821, Weather Bureau Office, New York, N. Y. Unpublished, October 1957.

14. William C. Redfield, "Remarks on the Prevailing Storm of the Atlantic Coast, of North American States," American Journal of Science and Arts, vol. XX, July 1831.

15. New Orleans Times-Democrat, Oct. 5, 1893.

16. New Orleans Times-Democrat, Oct. 6, 1893.

17. Daily Register, Mobile, Alabama, Oct. 7, 1893.

18. Daily Register, Mobile, Alabama, Oct. 3, 1893.

19. U. S. Weather Bureau, "Characteristics of the Weather for October, 1893," Monthly Weather Review, vol. 21, No. 10, Oct. 1893, p. 272.

20. U. S. Army, Corps of Engineers, "Hurricane Problems along Coastal Louisiana," Appraisal Report, New Orleans District, November 1956.

21. H. C. Frankenfield, "The Tropical Storm of August 10, 1915," Monthly Weather Review, vol. 43, No. 8, Aug. 1915, p. 410.

22. Isaac M. Cline, "The Tropical Hurricane of September 29, 1915 in Louisiana," Monthly Weather Review, vol. 43, No. 9, Sept. 1915.

23. William Malkin, "Filling and Intensity Changes in Hurricanes Over Land," National Hurricane Research Project Report No. 34, Nov. 1959.

24. U. S. Weather Bureau, Climatological Data, Virginia Section vol. XLIII, No. 8, Aug. 1933.

25. U. S. Weather Bureau, Climatological Data, New Jersey Section, vol. XXXVIII, No. 8, Aug. 1933.

26. I. R. Tannehill, "Hurricane of September 16 to 22, 1938," Monthly Weather Review, vo. 66, No. 9, Sept. 1938.

27. C. H. Pierce, "The Meteorological History of the New England Hurricane of September 21, 1938," Monthly Weather Review, vol 67, No. 8, Aug. 1939, pp. 237-285.

28. C. F. Brooks, "Hurricanes into New England, Meteorology of the Storm of September 21, 1938," The Smithsonian Report for 1939, Smithsonian Institution, Washington, D. C., pp. 241-251.

29. Corps of Engineers, U. S. Army, Supplemental Report on Hurricane of September 21, 1938, and its Effect on the Coastal Region, U. S. Engineer Office, Providence, R. I., June 1939.

30. H. C. Sumner, "The North Atlantic Hurricane of September 8-16, 1944," Monthly Weather Review, vol. 72, No. 9, Sept. 1944, p. 187.

31. I. R. Tannehill, Hurricanes, 9th ed., Princeton University Press, 1956, p. 237.

32. Harry Wexler, "The Structure of the September, 1944 Hurricane off Cape Henry, Virginia," Bulletin of the American Meteorological Society, vol. 26, No. 5, May 1945, p. 156.

33. F. B. Wood, "A Flight into the September 1944 Hurricane off Cape Henry, Virginia," Bulletin of the American Meteorological Society, vol. 26, No. 5, May 1945, pp. 153-156.

34. H. C. Sumner, "North Atlantic Hurricanes and Tropical Disturbances of 1947," Monthly Weather Review, vol. 75, No. 12, Dec. 1947.

35. Richmond T. Zoch, "North Atlantic Hurricanes and Tropical Disturbances of 1949," Monthly Weather Review, vol. 77, No. 12, Dec. 1949, p. 339.

36. Richmond T. Zoch, "North Atlantic Hurricanes and Tropical Disturbances of 1949," Monthly Weather Review, vol. 77, No. 12, Dec. 1949, p. 341.

37. U. S. Weather Bureau, Climatological Data, National Summary, vol. 5, No. 10, Oct. 1954.

38. Gordon E. Dunn, Walter R. Davis, and Paul L. Moore, "Hurricanes of 1955," Monthly Weather Review, vol. 83, No. 12, Dec. 1955, pp. 315-326.

39. Tu Cheng Yeh, "The Motion of Tropical Storms Under the Influence of a Superimposed Southerly Current," Journal of Meteorology, vol. 7, No. 2, Apr. 1950, pp. 108-113.

40. U. S. Weather Bureau, Climatological Data, National Summary, vol. 5, No. 13, 1954.

41. B. I. Miller, "On the Maximum Intensity of Hurricanes," National Hurricane Research Project Report No. 14, Dec. 1957.

42. Charles F. Brooks and Eleanor S. Brooks, The Accuracy of Wind Speed Estimates at Sea, Unpublished, 1957.

43. U. S. Weather Bureau, Climatological Data, National Summary, vol. 7 No. 9, Sept. 1956.

44. U. S. Weather Bureau, Weekly Weather and Crop Bulletin, National Summary, vol. XLIV, No. 26a, July 1, 1957.

45. U. S. Weather Bureau, Climatological Data, Louisiana, vol LXII, No. 6, June 1957, p. 72.

46. U. S. Weather Bureau, Climatological Data, New York, vol. LXV, No. 11, Nov. 1953.

47. U. S. Weather Bureau, Climatological Data, Virginia, vol. LXVI, No. 4, Apr. 1956, p. 38.

48. Henry R. McQueen and William A. Rammer, "The Unusual Movement of the Gulf of Mexico Cyclone, April 10-13, 1956," Monthly Weather Review, vol. 84, No. 4, Apr. 1956, pp. 166-178.

49. U. S. Weather Bureau, Monthly Meteorological Summary, New Orleans Sept. 1947.

50. U. S. Weather Bureau, Local Climatological Data New Orleans, 1952.

51. M. E. Smith and I. Singer, "Hurricane Winds at Brookhaven National Laboratory," paper delivered at New York Meeting of American Meteorological Society, Jan. 23, 1956.

APPENDIX A

WIND SPEED AND DIRECTION DATA

Included here are wind speed and direction data that were used in computing wind patterns in Chapters II and III and not shown in figures or text of those chapters.

HURRICANE OF SEPTEMBER 8, 1900

Station: Galveston, Tex.

Anemometer height above ground: 88 ft.

15-min. avg. for period ending at Time (CST)	Wind direction (degree)	Observed speed (m.p.h.)	15-min. avg. for period ending at Time (CST)	Wind direction (degree)	Observed speed (m.p.h.)
1215	006	24	1530	027	34
1230	360	27	1545	021	34
1245	360	26	1600	021	36
1300	003	27	1615	015	35
1315	012	28	1630	027	34
1330	006	29	1645	024	37
1345	015	28	1700	039	40
1400	021	30	1715	030	41
1415	009	27	1730	024	46
1430	018	28	1745	030	50
1445	024	28	1800	042	52
1500	012	31	1815	-	52
1515	015	34	(instrument failure)		

HURRICANE OF AUGUST 17, 1915

Station: Galveston, Tex.

Anemometer height above ground: 114 ft.

15-min. avg. for period ending at Time (CST)	Wind direction	observed speed (m.p.h.)	30-ft. over-water speed (m.p.h.)	15-min. avg. for period ending at Time (CST)	Wind direction	observed speed (m.p.h.)	30-ft. over-water speed (m.p.h.)
8/16/15				8/16/15			
1415	NNE	35	39	2200	ENE	60	67
1430	NNE	35	39	2215	ENE	59	66
1445	NNE	38	43	2230	ENE	52	64
1500	NNE	40	45	2245	ENE	59	66
1515	NNE	44	49	2300	E	56	63
1530	NNE	50	56	2315	E	55	62
1545	NNE	47	53	2330	E	51	57
1600	NNE	47	53	2345	E	54	61
1615	NNE	44	49	0000	E	50	56
1630	NNE	45	51	0015	E	53	59
1645	NNE	44	49	0030	E	54	61
1700	NNE	41	46	0045	E	60	67
1715	NNE	44	49	0100	E	61	68
1730	NNE	41	46	0115	E	61	68
1745	NNE	41	46	0130	E	60	67
1800	NE	41	46	0145	E	62	70
1815	NE	46	52	0200	E	65	73
1830	NE	49	55	0215	E	67	70
1845	NE	50	56	0230	E	62	70
1900	NE	50	56	0245	E	64	72
1915	NE	50	56	0300	E	60	67
1930	NE	49	55	0315	E	60	67
1945	NE	51	57	0330	E	61	68
2000	NE	45	51	0345	E	53	60
2015	NE	44	49	0400	E	54	61
2030	NE	50	56	0415	E	53	60
2045	NE	50	56	0430	E	50	56
2100	NE	50	56	0445	E	46	52
2115	NE	51	57	0500	E	49	55
2130	NE	54	61	0515	E	50	56
2145	ENE	56	63	0530	E	43	48
				0545	E	42	47

HURRICANE OF AUGUST 17, 1915

Station: Houston, Tex.

Anemometer height above ground: 122 ft.

15-min. avg. for period ending at Time (CST)	Wind direction	Observed speed (m.p.h.)	30-ft. over-water speed (m.p.h.)	15-min. avg. for period ending at Time (CST)	Wind direction	Observed speed (m.p.h.)	30-ft. over-water speed (m.p.h.)
8/16/15				8/16/15			
1615	NNE	26	34	0130	ENE	30	39
1630	NNE	24	31	0200	ENE	34	44
1700	NNE	25	32	0230	E	37	48
1730	NNE	25	32	0300	ENE	39	51
1800	NNE	26	34	0330	ENE	43	56
1830	NNE	29	38	0400	E	47	61
1900	NNE	30	39	0430	E	57	74
1930	NNE	31	40	0500	ESE	63	82
2000	NNE	32	42	0530	SE	60	78
2030	NNE	30	39	0600	SE	-	-
2100	NNE	35	45	0630	SE	54	70
2130	NNE	40	52	0700	SE	45	58
2200	NNE	34	44	0730	SE	43	56
2230	NE	37	48	0800	SSE	35	45
2300	NE	39	51	0830	SSE	35	45
2330	NE	38	49	0900	SSE	32	42
2400	NE	38	49	0930	SSE	32	42
0300	NE	37	48	1000	SSE	32	42
0100	NE	44	57	1030	SSE	30	39

HURRICANE OF AUGUST 17, 1915

Station: Corpus Christi, Tex.

Anemometer height above ground: 77 ft.

10-min. avg. for period ending at Time (CST)	Wind direction	Observed speed (m.p.h.)	30-ft. over-water speed (m.p.h.)
8/17/15			
0000	NNW	23	27
0100	NNW	24	29
0200	NW	24	29
0300	NNW	16	20
0400	NNW	16	19
0500	NNW	17	21

HURRICANE OF SEPTEMBER 29, 1915

Station: New Orleans, La.			Station: Burrwood, La.		
Anemometer height above ground: 85 ft.			Anemometer height above ground: 33 ft.		
10-min. avg. for period ending at Time (CST)	Wind direction	Observed speed (m.p.h.)	10-min. avg. for period ending at Time (CST)	Wind direction	Observed speed (m.p.h.)
1100	NE	34	1100	ESE	65
1200	NE	32	1200	ESE	62
1300	NE	38	1300		65
1400	E	39	1400	SSE	61
1500	E	40	1500		60
1600	E	40	1550		
1700	SE	47	1600	SSE	82
1750	center passed		1700		81
1800	SE	49	1750		
1900	SE	33	1800	SW	73
2000	SW	27	1900	SSW	60
2100	SW	23	2000	WSW	49
2200	SW	19	2100	S	40
2300	SW	22	2200	S	35
			2300		

Station: Ship Ceiba, New Orleans, La.

Time (CST)	Wind direction	Beaufort Force
1400		7
1500	E by N	7-8
1600	E	8
1700	E by S	9-10
1800	ESE	11
1900	SE by E	11
2000	SE	11-10
2100	SE	10

HURRICANE OF AUGUST 23, 1933, IN THE CHESAPEAKE BAY AREA

Station: Richmond, Va.

Anemometer height above ground: 52 ft.

10-min. avg. for period ending at Time (EST)	Wind direction (deg.)	Observed speed (m.p.h.)	30-ft. over-water speed (m.p.h.)
01	048	17	21
03	052	21	27
05	046	25	31
07	045	29	37
09	039	33	43
11	030	26	33
13	010	24	30
15	318	19	24
17	295	23	29
19	270	24	30
21	270	21	27
23	262	20	24

Station: Washington, D. C.

Anemometer height above ground: 85 ft.

10-min. avg. for period ending at Time (EST)	Wind direction (deg.)	Observed speed (m.p.h.)	30-ft. over-water speed (m.p.h.)
01	050	14	23
03	050	15	24
05	045	18	29
07	046	21	36
09	040	27	46
11	045	30	50
13	050	25	43
15	068	23	39
17	075	23	40
19	088	15	23
21	198	11	19
23	216	13	23

Station: Cape Henry, Va.
Anemometer height above ground: 54 ft.

Time (EST)	Wind direction (deg.)	Observed speed (m.p.h.)	30-ft. over-water speed (m.p.h.)
01	046	54	70
03	045	59	77
05	046	57	74
07	048	53	69
09	090	46	60
11	149	27	36
13	202	27	36
15	210	21	27
17	220	21	27
19	230	18	23
21	215	17	21
23	216	17	21

Station: Norfolk, Va.
Anemometer height above ground: 205 ft.

Time (EST)	Wind direction (deg.)	Observed speed (m.p.h.)	30-ft. over-water speed (m.p.h.)
01	044	41	44
03	042	48	50
05	042	48	50
07	045	57	60
09	060	20	21
11	182	26	27
13	186	37	39
15	210	32	34
17	220	31	33
19	220	29	30
21	210	29	30
23	185	24	25

Station: Atlantic City, N. J.
Anemometer height above ground: 172 ft.

Time (EST)	Wind direction (deg.)	Observed speed (m.p.h.)	30-ft. over-water speed (m.p.h.)
01	050	37	43
03	052	38	44
05	050	43	47
07	055	51	59
09	058	53	60
11	072	57	66
13	088	52	60
15	108	54	63
17	132	50	59
19	134	50	59
21	138	50	59
23	142	51	59

Station: Baltimore, Md.
Anemometer height above ground: 215 ft.

Time (EST)	Wind direction (deg.)	Observed speed (m.p.h.)	30-ft. over-water speed (m.p.h.)
01	005	17	19
03	355	19	20
05	359	20	20
07	036	27	29
09	036	37	39
11	040	33	36
13	046	37	39
15	050	42	44
17	060	37	39
19	074	32	34
21	116	42	77
23	154	34	61

HURRICANE OF AUGUST 23, 1933, IN THE CHESAPEAKE BAY AREA

Station: Delaware Breakwater

Anemometer height above ground: 68 ft.

10-min. avg. for period ending at Time (EST)	Wind direction (deg.)	Observed speed (m.p.h.)	30-ft. over-water speed (m.p.h.)
01	045	31	40
03	045	31	40
05	044	39	50
07	044	44	57
09	084	46	60
11	090	40	51
13	095	41	53
15	130	41	53
17	135	41	53
19	178	39	50
21	180	36	46
23	180	32	41

Station: Quantico, Va.

Anemometer height above ground: 60 ft.

10-min. avg. for period ending at Time (EST)	Wind direction (deg.)	Observed speed (m.p.h)	30-ft over-water speed (m.p.h.)
01	N	13	16
02	N	16	20
03	N	17	21
04	N	18	23
05	N	18	23
06	N	20	26
07	N	24	30
08	N	26	33
09	N	28	36
10	N	29	37
11	N	31	39
12	N	35	44
13	NNE	30	37
14	NNE	30	37
15	NNE	32	40
16	N	32	40
17	N	29	37
18	N	18	23
19	WNW	12	16
20	SW	10	13
21	SW	11	14
22	SW	16	20
23	SSW	15	19
24	SSW	14	17

HURRICANE OF SEPTEMBER 14, 1944, IN THE NORTH ATLANTIC

Station: Fishers Island, N. Y.

Anemometer height above ground: 35 ft.

Time (EST)	Observed speed (m.p.h.)
1700	25
1725	26
1735	30
1745	30
1800	37
1825	35
1840	46
1855	48
1910	57
1925	55
1940	58
1945	61
2000	62
2005	65
2025	66
2035	67
2045	68
2100	78
2110	78
2125	65
2135	41
2145	17
2200	14
2210	32
2225	40
2235	41
2250	45
2325	51
2330	46
2335	42
2345	51
0005	45
0025	48
0030	43

Station: Point Judith, R. I.

Anemometer height above ground: 50 ft.

Time (EST)	Observed speed (m.p.h.)
1700	26
1745	28
1800	30
1830	34
1900	45
1930	50
2000	65
2030	75
2100	75
2130	75
2200	75
2230	70
2245	50
2330	55
0000	45
0030	40
0100	40
0130	38
0200	35
0230	35

HURRICANE OF SEPTEMBER 14, 1944, IN THE NORTH ATLANTIC

Station: Hatteras, N. C.		Station: Cape Henry, Va.	
Anemometer height above ground: 47 ft.		Anemometer height above ground: 54 ft.	
15-min, avg. for period ending at Time (EST)	Observed speed (m.p.h.)	15-min. avg. for period ending at Time (EST)	Observed speed (m.p.h.)
0415	29	0815	32
0430	31	0830	38
0445	33	0845	37
0500	34	0900	42
0515	38	0915	47
0530	45	0930	45
0545	42	0945	50
0600	42	1000	53
0615	38	1015	60
0630	50	1030	63
0645	54	1045	61
0700	56	1100	65
0715	56	1115	61
0730	56	1130	70
0745	42	1145	73
0800	42	1200	80
0815	48	1215	72
0830	50	1230	80
0845	63	1300	72
0900	65	1315	70
		1330	68
		1345	64
		1400	58
		1415	47
		1430	38
		1445	37
		1500	37
		1515	34
		1530	32
		1545	28
		1600	26
		1615	22
		1630	22
		1645	23
		1700	17
		1715	17
		1730	14

HURRICANE OF SEPTEMBER 14, 1944, IN THE NORTH ATLANTIC

Station: Block Island, N.Y.

Anemometer height above ground: 60 ft.

15-min. avg. for period ending at Time (EST)	Observed speed (m.p.h.)
1800	37
1815	43
1830	44
1845	47
1900	54
1915	54
1930	63
1945	63
2000	73
2015	77
2030	59
2045	70
2100	70
2115	70
2130	42
2145	77
2200	52
2215	40
2230	40
2245	47
2300	52
2315	44
2330	39
2345	44
2400	42
0015	38
0030	31
0045	25
0100	45
0115	42
0130	43
0145	41
0200	42

Station: Nantucket, Mass.

Anemometer height above ground: 63 ft.

10-min. avg. for period ending at Time (EST)	Observed speed (m.p.h.)
1800	23
1810	23
1820	23
1830	22
1840	27
1850	25
1900	28
1910	11
1920	29
1930	28
1940	28
1950	31
2000	30
2010	30
2020	33
2030	34
2040	36
2050	37
2100	37
2110	36
2120	36
2130	40
2140	38
2150	36
2200	39
2210	41
2220	45
2230	45
2240	42
2250	48
2300	45
2310	43
2320	47
2330	50
2340	50
2350	56
2400	50
2410	50
2420	57
2430	55
2440	48
2450	40
0100	56

HURRICANE OF SEPTEMBER 14, 1944, IN THE NORTH ATLANTIC

Station: Atlantic City, N. J.

Anemometer height above ground: 172 ft.

10-min. avg. for period ending at Time (EST)	Observed speed (m.p.h.)
1200	29
1210	52
1220	33
1230	35
1240	38
1250	36
1300	39
1310	41
1320	46
1330	47
1340	52
1350	50
1400	52
1410	55
1420	57
1430	58
1440	57
1450	65
1500	67
1510	66
1520	68
1530	70
1540	67
1550	75
1600	75
1610	73
1620	78
1630	79
1640	80
1650	77
1700	72
1710	71
1720	66
1730	65
1740	59
1750	65
1800	61
1810	61

Station: New York, N. Y.

Anemometer height above ground: 454 ft.

10-min. avg. for period ending at Time (EST	Observed speed (m.p.h.)
1630	17
1640	18
1650	19
1700	18
1710	22
1720	21
1730	21
1740	20
1750	18
1800	23
1810	27
1820	38
1830	41
1840	51
1850	50
1900	47
1920	56
1930	56
1940	57
1950	58
2000	54
2010	56
2020	56
2030	56
2040	53
2050	52
2100	49
2110	49
2120	46
2130	48
2140	47
2150	43
2200	38
2210	34
2220	33
2230	33
2240	31
2250	33
2300	30
2310	30
2320	32
2330	32
2340	26
2350	20
2400	18

HURRICANE OF SEPTEMBER 14, 1944, IN THE NORTH ATLANTIC

Station: Providence R. I.

Anemometer height above ground: 52 ft.

10-min. avg. for period ending at Time (EST)	Observed speed (m.p.h.)	10-min. avg. for period ending at Time (EST)	Observed speed (m.p.h.)
1800	15	2140	36
1810	15	2150	34
1820	18	2200	36
1830	20	2210	40
1840	22	2220	35
1850	22	2230	34
1900	20	2240	31
1910	20	2250	34
1920	22	2300	19
1930	21	2310	6
1940	23	2320	17
1950	27	2330	20
2000	26	2340	23
2010	28	2350	27
2020	30	2400	29
2030	33	2410	28
2040	32	2420	26
2050	34	2430	17
2100	29	2440	24
2110	30	2450	29
2120	29	0100	25
2130	30		

STORM OF NOVEMBER 25, 1950, OFF THE NEW JERSEY COAST

	Station: Chincoteague, Va.			Station: Ocean City, Md.		
	Anemometer height above ground: 35 ft.			Anemometer height above ground: 51 ft.		
Time (EST)	Wind direction	Observed speed (m.p.h.)	30-ft. over-water speed (m.p.h.)	Wind direction	Observed speed (m.p.h.)	30-ft. over-water speed (m.p.h.)
11/24/50						
0730	ESE	13	11	E	21	21
1330	ESE	21	21	E	13	13
1930	ESE	29	30	E	31	31
11/25/50						
0130				E	37	37
0730	SSW	25	27	E	42	42
1330	SW	13	26	SW	15	21
1930	SW	21	36	SW	29	42
	Station: Dover, Del.			Station: Lakehurst, N. J.		
	Anemometer height above ground: 25 ft.			Anemometer height above ground: 77 ft.		
11/24/50						
0730	E	15	21	NE	12	24
1330	SE	17	24	ENE	18	30
1930	ESE	15	21	E	21	31
11/25/50						
0130	ESE	23	27	E	31	41
0730	ESE	35	50	E	40	49
1330	SSW	26	46	E	35	44
1930	SW	26	46	SSW	25	37

STORM OF NOVEMBER 25, 1950, OFF THE NEW JERSEY COAST

	Station: Wilmington, N. C.			Station: Hatteras, N. C.		
	Anemometer height above ground: 43 ft.			Anemometer height above ground: 47 ft.		
Time (EST)	Wind direction	Observed speed (m.p.h.)	30-ft. over-water speed (m.p.h.)	Wind direction	Observed speed (m.p.h.)	30-ft. over-water speed (m.p.h.)
11/24/50						
0730		calm		NE	4	4
1330	SSE	10	10	SSE	14	14
1930	SE	8	15	N	6	5
11/25/50						
0130	NW	15	27	ESE	35	36
0730	WSW	16	30	SW	17	75
1330	W	11	24	WSW	40	40
1930	SW	10	23	WSW	26	28

	Station: WBAS, Norfolk, Va.			Station: Hog Island, Va.		
	Anemometer height above ground: 55 ft.			Anemometer height above ground: 47 ft.		
11/24/50						
0730	ESE	7	16			
1330	SE	16	30	SE	16	17
1930	ESE	19	31	SE	10	9
11/25/50						
0130	SSE	19	30	E	25	28
0730	SSE	6	15	E	20	20
1330	SSW	22	32	SW	10	11
1930	SW	20	31	SW	15	17

STORM OF NOVEMBER 25, 1950, OFF THE NEW JERSEY COAST

Time (EST)	Station: New York, N. Y. LaGuardia Field — Anemometer height above ground: 83 ft.			Station: Sandy Hook, N. J. — Anemometer height above ground: 98 ft.		
	Wind direction	Observed speed (m.p.h.)	30-ft. over-water speed (m.p.h.)	Wind direction	Observed speed (m.p.h.)	30-ft. over-water speed (m.p.h.)
11/24/50						
0730	NE	15	14	ENE	23	22
1330	NE	19	18	ENE	20	19
1930	E	20	30	E	32	31
11/25/50						
0130	ENE	26	36			
0730	E	52	59	E	48	46
1330	SE	50	56			
1930	SSW	24	36			

Time (EST)	Station: Bridgeport, Conn. — Anemometer height above ground: 48 ft.			Station: New Haven, Conn. — Anemometer height above ground: 42 ft.		
	Wind direction	Observed speed (m.p.h.)	30-ft. over-water speed (m.p.h.)	Wind direction	Observed speed (m.p.h.)	30-ft. over-water speed (m.p.h.)
11/24/50						
0730	E	13	13	NE	11	13
1330				NE	7	8
1930	E	21	21	E	14	16
11/25/50						
0130	E	25	28			
0730	E	45	45	ESE	39	41
1330	E	58	60	ESE	46	47
1930	E	44	46	ESE	50	52

STORM OF NOVEMBER 25, 1950, OFF THE NEW JERSEY COAST

	Station: Frying Pan Shoals Lightship			Station: Diamond Shoals Lightship		
	Anemometer height above ground: 65 ft.			Anemometer height above ground: 65 ft.		
Time (EST)	Wind direction	Observed speed (m.p.h.)	30-ft. over-water speed (m.p.h.)	Wind direction	Observed speed (m.p.h.)	30-ft. over-water speed (m.p.h.)
11/24/50						
0730	SE	8	7	E	25	23
1330	S	18	17	SSE	18	17
1930	SSW	37	34	SE	25	23
11/25/50						
0130	WNW	35	33	SE	38	35
0730	SW	41	38	WSW	15	14
1330	WSW	40	37	WSW	50	47
1930	W	28	26	WSW	35	33
	Station: Atlantic City, N. J.			Station: Ambrose Lightship		
	Anemometer height above ground: 172 ft.			Anemometer height above ground: 25 ft.		
11/24/50						
0730	E	21	25		25	26
1330	E	19	22		25	26
1930	E	19	22		39	40
11/25/50						
0130	E	42	39		46	47
0730	E	56	50		61	63
1330	SE	43	40		63	65
1930					39	40

STORM OF NOVEMBER 25, 1950, OFF THE NEW JERSEY COAST

SHIP DATA

Date	Local ship time	Lat. °W.	Long. °N.	Wind dir. (00-36)	Wind speed (kt.)
		CROWN TRADER			
25	0700	32.0	76.2	26	37
25	1300	31.6	76.7	26	44
25	1900	30.0	77.2	28	37
26	0100	29.8	77.6	29	18
		U.S.N.S. GENERAL W.C. LANGFITT			
25	0700	40.4	71.3	08	34
25	1300	40.4	71.0	08	34
25	1900	40.3	70.7	08	44
		U. S. TANKER GULFMEADOWS			
25	0700	32.7	77.2	25	37
25	1300	34.1	75.6	23	37
25	1900	35.3	74.7	23	37
		S. S. STELLA LYKENS			
25	1400	37.2	68.3	14	44
25	0800	37.2	67.5	23	21
		S. S. SANTA PAULA			
25	0730	36.0	72.7	14	44
25	1330	35.2	72.8	20	37
25	1900	34.5	72.9	25	44
26	0130	34.0	72.9	25	37
		AMERICAN S/S SEBIORNEY			
25	1300	34.4	75.7	23	30
		GENERAL R. H. BLATCHFORD			
25	1300	42.1	66.2	27	09
25	1900	41.1	67.3	08	30
26	0100	40.7	68.9	14	52

STORM OF NOVEMBER 25, 1950, OFF THE NEW JERSEY COAST

SHIP DATA

Date	Local ship time	Lat. °W.	Long. °N.	Wind Dir. (00-36)	Wind speed (kt.)
		PORTUGUESE M/S NOCALA			
25	0700	37.5	72.3	11	27
		AMERICAN TANKER S/S AMTANK			
24	1300	33.1	72.9	09	13
25	0100	36.3	74.0	11	18
		DANIEL PIERRE USA			
24	1200	31.5	76.8	14	11
		S/S BEATRICE--AMERICAN			
24	0800	34.8	71.8	01	02
24	1300	33.4	71.2	09	15
		S/S/ KATHRYN--U. S. Freighter			
25	1400	31.6	70.7	19	24
25	2000	33.2	71.3	20	30
26	0200	34.0	71.4	20	30
		S. S. SOUTH STAR C			
25	0800	38.0	66.5	09	37
25	1400	38.0	65.5	09	44
25	2000	38.2	66.1	09	44
		S/S ORIENTE--U. S. Freighter			
25	1300	37.9	74.2	24	44
		S/S CALUSA T-2 U.S.A.			
24	1300	35.5	75.1	11	10
24	1900	37.0	74.6	11	12
25	0100	38.4	74.2	09	18

STORM OF NOVEMBER 25, 1950, OFF THE NEW JERSEY COAST

SHIP DATA

Date	Local ship time	Lat. °W	Long. °N	Wind dir. (00-36)	Wind speed (kt.)
		S/S ESSO CHATTANOOGA-American Tanker			
25	0700	32.0	69.7	16	30
25	1300	30.3	69.4	17	30
		S/S FRANK A. MORGAN-U. S. Tanker			
25	0800	35.3	68.9	11	52
25	1500	35.9	67.8	14	52
25	1930	36.3	67.0	14	52
		U.S.A. S.S. ORIZABA			
25	0700	37.2	74.8	16	24
25	1300	38.3	74.6	18	24
		U.S.A. Tanker--ESSO ASHVILLE			
25	0700	28.5	68.0	09	24
25	1300	37.6	69.4	14	60
25	1900	37.2	70.4	12	68
26	0100	35.7	70.0	25	30
		U.S.A. Tanker--E.H. BLUM			
26	0100	37.3	73.7	23	30
26	1300	35.6	73.7	27	18
		U.S.N.S. GREENVILLE VICTORY			
24	0700	40.6	68.8	05	30
24	1300	40.5	71.1	09	18
		S.S. EXMINSTER			
24	1400	40.9	66.0	05	18
24	1900	40.6	68.5	06	18

STORM OF NOVEMBER 25, 1950, OFF THE NEW JERSEY COAST

SHIP DATA

Date	Local ship time	Lat. °W	Long. °N	Wind dir. (00-36)	Wind speed (kt.)
		S.S. SANTA LUISA			
25	0100	38.6	72.9	09	27
25	0700	37.3	73.9	14	30
25	1300	36.4	73.9	20	30
25	1900	35.4	73.8	25	30
26	0100	34.3	74.0	23	30
		SANTA CLARA--Passenger Freighter			
25	0130	38.6	73.3	11	25
25	0730	37.5	73.0	15	29
25	1330	36.7	72.9	18	35
25	1930	35.7	72.2	25	35
26	0130	34.5	72.5	25	30
		U.S.A. Export--S/S EXILONA			
24	1400	38.7	66.4	05	13
24	2000	39.3	68.8	09	09
25	0100	40.0	72.0	09	09
		QUEEN OF BERMUDA--British			
24	0700	34.3	75.3	09	05
24	1300	36.1	74.9	15	13
24	1900	37.9	74.4	07	13
25	0100	39.4	74.0	09	24
		PAN AMOCO--U.S. Tanker			
25	0700	33.2	69.1	14	35
25	1300	34.4	69.2	16	40
25	1300	37.8	69.2	23	40
		(SHIP NAME MISSING)			
24	0700	33.1	76.9	09	09
24	1300	34.4	75.6	13	09
24	1900	35.9	74.8	16	13
25	0100	37.1	74.1	09	18

STORM OF NOVEMBER 25, 1950 OFF THE NEW JERSEY COAST

SHIP DATA

Date	Local ship time	Lat. °W.	Long. °N.	Wind dir. (00-36)	Wind speed (kt.)
		S/S/ ESSO RALEIGH--American Tanker			
24	0700	36.7	72.8	09	05
24	1300	35.5	72.5	09	05
24	1900	34.0	72.0	12	18
25	0100	32.5	71.6	12	24
25	0700	31.0	71.2	16	24
25	1300	29.5	70.5	16	24
25	1900	28.1	70.5	20	13
26	0100	26.5	70.1	20	13

HURRICANE HAZEL IN CHESAPEAKE BAY AREA OCTOBER 15, 1954

	Station: Norfolk, Va. NAS	Station: Norfolk, Va. WBAS	
	Anemometer height above ground: 75 ft.	Anemometer height above ground: 78 ft.	
10-min. avg. for period ending at Time (EST)	Observed speed (m.p.h.)	Wind direction	Observed speed (m.p.h.)
0740		E	30
0750			
0080			
0810	36		
0820	35		
0830	35		
1040	38	E	40
1050	45		
1100	45		
1110	40		
1120	34		
1130	40		
1340	45	E	41
1350	51		
1400	57		
1410	45		
1420	50		
1430	47		
1640	51	SW	44
1650	45		
1700	45		
1710	45		
1720	45		
1730	44		

	Station: Atlantic City, N. J.		Station: Baltimore, Md.	
	Anemometer height above ground: 48 ft.		Anemometer height above ground: 133 ft.	
	Wind direction	Observed speed (m.p.h.)	Wind direction	Observed speed (m.p.h.)
1640	E	58	ESE	45
1650	E	58	ESE	50
1700	E	61	SE	50
1710	E	56	SE	48
1720	E	61	SE	58
1730	ESE	53	SE	50

HURRICANE HAZEL IN CHESAPEAKE BAY AREA OCTOBER 15, 1954

10-min. avg. for period ending at Time (EST)	Station: Atlantic, N. J. (cont.) — Anemometer height above ground: 48 ft. — Wind direction	Observed speed (m.p.h.)	Station: Baltimore, Md. (cont.) — Anemometer height above ground: 133 ft. — Wind direction	Observed speed (m.p.h.)
1940	SSE	50	W	33
1950	SSE	40	WSW	37
2000	S	40	WSW	40
2010	S	40	WSW	37
2020	S	46	WSW	32
2030	S	42	WSW	32
	Station: Cape Henry, Va. — Anemometer height above ground: 54 ft.		Station: Dahlgren, Va. — Anemometer height above ground: 31 ft.	
	(degrees)		(degrees)	
0740	135	39		
0750	135	35		
0800	135	39		
0810	135	36	175	16
0820	135	42	174	18
0830	135	40	169	18
1040	135	39	135	24
1050	135	39	135	24
1100	135	36	131	24
1110	135	39	135	24
1120	135	41	126	24
1130	135	41	135	24
1340	135	39	135	26
1350	135	37	135	32
1400	135	45	135	32
1410	135	45	135	29
1420	135	41	135	27
1430	135	42	135	28
1640	194	39	135	37
1650	198	34	135	34
1700	185	28	135	32
1710	189	30	153	29
1720	194	27	158	24
1730	212	27	171	29

HURRICANE HAZEL IN CHESAPEAKE BAY, OCTOBER 15, 1954

Station: Richmond, Va.

Anemometer height above ground: 67 ft.

10-min. avg. for period ending at Time (EST)	Wind direction	Observed speed (m.p.h.)
0810	ENE	25
0820	ENE	26
0830	E	25
1040	ESE	28
1050	ESE	27
1100	ESE	33
1110	ESE	31
1120	E	34
1130	E	29
1340	ESE	35
1350	ESE	31
1400	ESE	32
1410	ESE	32
1420	ESE	35
1430	ESE	41
1640	S	33
1650	SW	35
1700	WSW	36
1710	W	35
1720	SW	27
1730	SW	31

HURRICANE HAZEL IN CHESAPEAKE BAY AREA OCTOBER 15, 1954

	Station: Washington, D.C. WBAS		Station: Washington, D. C. CO	
	Anemometer height above ground: 131 ft.		Anemometer height above ground: 117 ft.	
10-min. avg. for period ending at Time (EST)	Wind direction	Observed speed (m.p.h.)	Wind direction	Observed speed (m.p.h.)
1040	ESE	34		
1050	ESE	34		
1100	ESE	30		
1110	ESE	34		
1120	ESE	31		
1130	ESE	34		
1340	ESE	38	SE	27
1350	SE	35	SE	23
1400	ESE	35	ESE	23
1410	ESE	36	SE	23
1420	SE	42	SE	23
1430	SE	37	SE	23
1440	SE	36	ESE	27
1640	SE	55	SE	34
1650	SE	56	SE	34
1700	SE	57	SE	34
1710	SSE	54	SE	32
1720	SE	50	SE	27
1730	SE	49	SE	23
1940			SW	20
1950			SW	18
2000			SW	14
2010			SW	12
2020			SW	12
2030			SW	13

HURRICANE HAZEL IN CHESAPEAKE BAY AREA OCTOBER 15, 1954

	Station: Annapolis, Md.		Station: Chincoteague, Va.	
	Anemometer height above ground: 83 ft.		Anemometer height above ground: 73 ft.	
10-min. avg. for period ending at Time (EST)	Wind direction	Observed speed (m.p.h.)	Wind direction	Observed speed (m.p.h.)
0800	ENE	14	ESE	25
1100	E	31	SE	42
1400	E	35	SE	53
1700	SE	53	S	65
2000	SW	28	SW	25
	Station: Patuxent R., Md.		Station: Aberdeen AFB, Md.	
	Anemometer height above ground: 85 ft.		Anemometer height above ground: 59 ft.	
0800	ESE	25	ESE	17
1100	ESE	45	SE	28
1400	ESE	55	SE	40
1700			SE	46
2000			W	25
	Station: Ocean City, Md.			
	Anemometer height above ground: 42 ft.			
0730	E	17		
1330	SE	37		
1930	SW	24		
	Station: Bay Bridge, Md.			
	Anemometer height above ground: 226 ft.			
0800	ESE	16		
1100	ESE	24		
1400	ESE	40		
1700	SE	58		

HURRICANE HAZEL IN CHESAPEAKE BAY AREA OCTOBER 15, 1954

Station: Millville, N. J.

Anemometer height above ground: 75 ft.

Time (EST)	Wind direction	Observed speed (m.p.h.)
0727	ESE	12
0827	ESE	14
1026	ESE	21
1126	ESE	22
1325	ESE	35
1425	ESE	29
1625	ESE	35
1726	ESE	46
1928	SSE	63
2028	SSW	40

Station: Wilmington, Del.

Anemometer height above ground: 34 ft.

Time (EST)	Wind direction	Observed speed (m.p.h.)
0726	E	12
0812	ESE	18
1025	ESE	20
1127	ESE	22
1328	SE	33
1426	ESE	32
1627	ESE	44
1727	SE	45
1925	SSW	44
2008	SW	35

Station: Salisbury, Md.

Anemometer height above ground: 51 ft.

Time (EST)	Wind direction	Observed speed (m.p.h.)
0725	ESE	12
0830	SE	18
1028	SE	15
1110	SE	15
1328	SE	30
1412	SE	30
1628	SSE	30
1715	SSE	25
1928	SW	20E
2028	SW	18E

Station: Oceana, Md.

Anemometer height above ground: 42 ft.

Time (EST)	Wind direction	Observed speed (m.p.h.)
0745	E	30
0828	ESE	32
1026	ESE	35
1128	ESE	40
1326	ESE	40
1427	ESE	38
1628	SSE	27
1726	S	23
1929	SSW	15
2028	SSW	18

APPENDIX B

Newspaper Accounts of Hurricane of September 3, 1821, at New York City

NEWSPAPER ACCOUNT NO. 1

From the American, New York, Tuesday Evening
September 4, 1821

DESTRUCTIVE GALE!

After three days of most welcome rain, the wind, about sun-set yesterday afternoon, blew a hurricane from East to ENE and occasioned in a short, space of time, (for it scarcely lasted more than two hours) an incredible amount of mischief. We have collected, as well as time would allow, a list of the disasters occasioned by it, but black as that list is, it falls short, we fear, of the extent of the evil.

We have often heard sailors tell of the wind breaking a spar like a pipe stem, but had no idea of it till last evening, when we saw the limbs of trees, as big as a man's body, broken with the facility of glass, and trees themselves, of the growth of half a century, uprooted in an instant by the force of the tempest.--The roads and fields, as well as some of our streets, are strewed with fallen trees, and the anticipations of the gardener and the fruiterer are vanished--not a bough now sustains its golden fruitage--all hurried to a premature fall. The force of the gale happened fortunately when the tide was nearly out--even then, the water was raised so suddenly as to inundate the lower part of the town.

NEWSPAPER ACCOUNT NO. 2

From the American, New York City
September 5, 1821

Mr. Editor--While accounts of the damages sustained by the storm of the 3d instant, in the loss of lives and property, or of distressing accidents, are accumulating from every quarter, it seems desirable, as a matter of philosophic speculation, to have also correct descriptions of its commencement, progress, and termination, in the order of time, at different and distant places in the Union, and on the coast, in order to know how far it extended. In the expectation of receiving similar descriptions from other places, through the medium of the public papers, I hasten to give a brief statement of its appearances in this City, which is chiefly extracted from a Register of the Barometer and Thermometer.

Sept. 3, 1821.--In the early part of the day, and at intervals till late in the afternoon, heavy showers, with steady breezes from the southeast. From 5 to 6 p.m. the wind and rain increasing, with every indication of a settled storm. From 6 to about 7:30 p.m. the wind from ESE, but varying to E and ENE accompanied with rain, blew with extreme violence. From 7:30 to

8 p.m. the wind had much abated. It then veered round to the SW and the clouds were swept away with astonishing quickness.

The rapid transition from the gloom and terrors of the tempest, to a delightful view of the blue and starry expansion above; of the moon diffusing her gentle radiance in the SW and of Jupiter and Saturn in the E, had a powerful tendency to recall to the imagination of the spectator the magnificient scene exhibited at the Creation, when the Almighty commanded the darkness to retire, and the lights of Heaven to appear.

For about two months past there has been a remarkable uniformity in the weight or pressure of the atmosphere. The barometer has generally ranged from about 29.9 to 30.1 inches, the mean being more than 30 inches. The highest observed was on the 9th of August, at 2 p.m. when it was 30.4 inches; the lowest till Sept. 3d, was on the 18th of July when at 6 a.m. it was 29.77 inches. The whole range of the Mercury in the barometer was, therefore .63 of an inch.

During the same period, the highest range in the thermometer, was on the 31st of July and 16th of August when at 2 p.m. it was 94°, properly in the shade. It must be excepted, however, that between 3 and 4 p.m., July 31st, it was 95°.

On the 16th of August at 3 p.m. the Mercury in a thermometer placed on the side of a building exposed to the sun, rose to 130°.

The lowest range of the thermometer observed in the same period was on the 22d of August, at 6 a.m. when it was 60°.

Hereunder are the observations of Sept. 3, 1821:

Thermometer	Degrees
At 6 a.m.	74
2 p.m.	79
6 p.m.	76
10 p.m.	72

Barometer	Inches
At 6 p.m.	30.13
2 p.m.	30.05

During and after the tempest.

Barometer	Inches	
At 6 p.m.	29.62	
7 p.m.	29.38	Falling
7:30 p.m.	29.34	
8:35 p.m.	29.53	
9 p.m.	29.64	Rising
10 p.m.	29.07	(29.70)

The whole difference between the highest, viz. at 6 a.m. 30.13, and the lowest, at 7:30 p.m., 29.34, is .69, or about 7/10 of an inch; which shows that the variation in the pressure or weight of the atmosphere on the third of September, only, was greater than it had been in two months before.

CIVIS.

NEWSPAPER ACCOUNT NO. 3

From the American, New York City
September 7, 1821

THE GALE

The following particulars of the damages sustained at Norfolk by the late violent gale, are given in the Beacon of the 4th. The storm commenced on Monday, at 10 a.m. and continued until 1 p.m., blowing a hurricane from the NE and NNW. The injury done in the town and its vicinity to buildings, enclosures, etc. is immense. The following are the most important particulars:-

The ground stories of all the warehouses on the wharves, and as high up as Wide Waterstreet, were entirely overflowed, and we learn that the damage sustained in sugar, flour and salt is very great, the amount of which, as of other damage inflicted by this awful visitation, it is impossible, at this time, to form even a conjecture.

NEWSPAPER ACCOUNT NO. 4

From the Mercantile Advertiser, New York
September 4, 1821

TREMENDOUS GALE

Yesterday from about 9 a.m., till evening, we had rain most of the time, with occasional heavy showers. The wind during most of the day was fresh from S to SE, but between 4 and 5 o'clock changed to NE, and began to blow a gale. At about 5, it became variable, blew unusually hard, and continued to increase in violence till about half past 7. Between 6 and 7 the gale was at its height, and more tremendous than ever before recollected. At this hour many vessels in the East River had broken adrift, and though it was then the hour for low water, the sea was forced in so as to overflow the wharves to the depth of about a foot. Much damage was apprehended and a general alarm prevailed. Chimnies /sic/ were blown down, many trees prostrated in the streets, and some buildings demolished. Fortunately, when the panic was greatest, the gale abated--the wind veered to WNW when it gradually subsided--and the water receded. Had the tide been flood, it is probable we should have experienced the greatest inundation ever known.

NEWSPAPER ACCOUNT NO. 5

From the Mercantile Advertiser, New York
September 5, 1821

THE GALE OF MONDAY

Yesterday morning, a more disastrous scene was presented than was anticipated from the accounts we gathered the night previous. Almost all the vessels in the East River are more or less injured and the wharves have sustained great damage. The water rose about ten feet above its usual height at that time of tide. It is most fortunate for the city, that the gale did not happen when the tide was on the flood in that case, the damage would inevitably have been incalculable. We hear of numerous disasters in every part of the town, but have not ascertained that any lives were lost in the city.

NEWSPAPER ACCOUNT NO. 6

From the Mercantile Advertiser, New York
September 7, 1821

THE GALE OF MONDAY

Having experienced such extensive havoc as has been described in this harbour, which is remarkably well protected from ravages by ordinary easterly gales, an anxiety was felt to know the fate of other places on the coast, few of which could have endured as well a gale so tremendous from that direction. There was some reason to believe, from the extreme violence of the hurricane here, and its short duration, it could not have been very extensive; and it turns out from the accounts received yesterday, that these conjectures were true. It will be seen by the letter from our correspondents at Boston, that no damage of consequence was sustained at that place; and the Baltimore papers of Tuesday do not even allude to any gale there. There is reason to hope that the gale was not so heavy at sea as was apprehended, and we are inclined to think we had the worst of it here. At Albany the gale was not spoken of in the papers.

NEWSPAPER ACCOUNT NO. 7

From The New York Evening Post, New York City
September 4, 1821

Tremendous gale.--From Saturday morning till 4 o'clock yesterday afternoon, we were visited with repeated and copious showers of rain, accompanied by some loud peals of thunder and lightning, and an extreme dense atmosphere; the wind during the time veered and shifted to almost every point of the compass, when about half past 4 o'clock yesterday afternoon it came out from about east, with all the violence and fury of a hurricane, and continued until about half past 8 o'clock last evening, throwing down chimnies /sic/, unroofing buildings, and prostrating trees in various directions. When the gale was at its height it presented a most awful spectacle. The falling of slate from the roofs of the buildings, and broken glass from the windows, made it unsafe for anyone to venture into the streets. Should the storm have extended with equal fury any distance along our seaboard, we fear for the destruction of lives and property it must have occasioned. The tide, although low water when the gale commenced, rose to an unusual height, overflowing all the wharves and filling the cellars of all the stores on the margin of the East and North Rivers. Great quantities of lumber, and other property on the wharves, have either been floated off or been damaged. The following are all the particulars we have been able to collect of the disasters and destruction to property in this city and its neighborhood.

NEWSPAPER ACCOUNT NO. 8

From The New York Evening Post, New York City
September 5, 1821

From the Philadelphia Gazette, Sept. 4

Great storm of rain and wind.--After a succession of genial showers on Sunday evening and yesterday morning, a storm of rain commenced about 1 o'clock, p.m. yesterday, accompanied with a high wind, which increased almost into a tornado during the afternoon. The wind was generally from N to NE during its greatest fury, but varied occasionally to almost every point of the compass.

NEWSPAPER ACCOUNT NO. 9

From The New York Evening Post, New York City
September 6, 1821

From the Bridgeport (Ct.) Farmer, Sept. 5

Tremendous Gale.--After two or three days of dull cloudy weather, with frequent heavy showers of rain, we were on Monday evening visited by the most dreadful hurricane which has been experienced for many years. The wind commenced blowing hard from the SE about 6 o'clock p.m. accompanied with rain, and continued to increase in violence until about 9 o'clock, when the tempest raged with a degree of fury the most awful and destructive. The storm continued with unabated force, till near 11 o'clock, when the wind hauled around to SW and gradually subsided. The effects of this afflicting visitation will be long seen and felt.

NEWSPAPER ACCOUNT NO. 10

From The Norfolk and Portsmouth Herald, Norfolk, Va.

Wednesday, September 5, 1821

TREMENDOUS STORM

Among the rest of our misfortunes, we are grieved to state that our town was on Monday visited by a storm, or rather tornado, far surpassing in violence and calamitous consequences, any that it has ever experienced within the remembrance of the oldest inhabitants. The best description we are prepared to give of it at this moment, can convey but an imperfect conception of its terrors.

The morning was dark and gloomy, and about six o'clock the black and lowering clouds began to discharge their watery contents, not in gentle showers, but literally in torrents. At ten o'clock the rain abated for a few minutes, as if to collect itself for a more copious discharge; for it presently set in again with increased violence, and the wind commenced blowing a heavy gale from NE which continued to increase to a most alarming height. From half past 11 till half past 12, so great was the fury of the elements, that they seemed to threaten a general demolition of everything within their reach. During that period the scene they presented was truly awful. The deafening roar of the storm, with the mingled crashing of windows and falling of chimneys--the rapid rise of the tide, threatening to inundate the town--the continuous cataracts of rain sweeping impetuously along, darkening the expanse of vision, and apparently confounding the heavens, earth and sea in a general chaos; together with now and then a glimpse, caught through the gloom, of shipping forced from their moorings, and driving with rapidity, as the mind might well conjecture in such circumstances, to inevitable destruction.--Even to those, if any there were, who could contemplate such a scene unappalled, it must have been painful to reflect on the widespread devastation which could not but be the result of this fearful "war of elements." About 12 o'clock the wind shifted round to NW but without abating its fury until half an hour after, when it ceased raining; the storm began to subside, and the water to recede. At four o'clock it changed to SW and the weather became calm and serene.

NEWSPAPER ACCOUNT NO. 11

From The Norfolk and Portsmouth Herald, Norfolk, Va.

September 5, 1821

A very considerable amount in merchandize /sic/, deposited in the lower stories of warehouses on the wharves has been either lost or damaged by the tide, which rose fully a foot higher than it has ever been known to be. ...