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Some Problems Involved in the Study of Storm Surges

by

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Commerce-Weather Bureau, Washington, D. C.

SOME PROBLEMS INVOLVED IN THE STUDY OF STORM SURGES

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ABSTRACT

The various forces which affect the height of the sea and the response of the sea to these forces are reviewed. An attempt to clarify the interactions among the astronomical, climatological, and meteorological forces involved, reveals that the response to any given force varies from one part of the sea to another, and that a complete separation of the effects produced by the various forces is impossible in the present state of knowledge.

Some case studies of the "storm surge", the effect of a storm on sea level, are presented. A first approximation to the storm surge is obtained by subtracting from the observed sea level accurate predictions of the astronomical and climatological effects on sea level made by a suitable tide machine. The resulting curves give clear indication of a reaction between the normal tides and the storm surge, but this method of treating the data gives a much clearer picture of the effects of the storm than can be obtained by studying only the observed sea level data.

INTRODUCTION

More than half of the fatalities in hurricanes and other tropical storms have been drownings - either in floods from excessive rainfall or in tidal waves coming in from the sea. A large fraction of the property loss has been due to the same causes, yet only a small fraction of the research effort devoted to the study of hurricanes has been spent on these problems.

The lack of research on the problem of tidal waves or storm surges may be explained in part by the difficulty in obtaining quantitative data concerning the past storms, and in part by the difficulty of formulating any reasonably comprehensive theory of the development of these storm surges.

In spite of these difficulties, several meteorologists, oceanographers, and mathematicians, and practical-minded men with little special interest in any of these fields have studied the problem from time to time. The best known of these studies in the United States is that of Cline [2]. Much of the research on storm surges has never been formally published, largely because the people performing the work in relative isolation have not been satisfied with the results. Much of the material which has been published contains a number of questionable statements, mainly in the nature of over-simplification of those parts of the problem lying outside the authors' primary fields of interest. Most of the unpublished reports and a few of the published ones also display a lack of understanding of the real meaning of the technical concepts used by one or more of the scientific disciplines concerned in this problem.

After the tremendous losses in the northeastern United States due to hurricanes in 1954, Congress directed both the U. S. Army Corps of Engineers and the Weather Bureau to conduct an intensified study of the causes, behavior, and methods of forecasting of these storms. A large fraction of the available funds are to be spent in studying methods of protection against inundations from the sea. Among the protective measures to be considered is the development of an adequate forecasting and warning service.

This program is not yet sufficiently advanced to permit us to outline reliable techniques for forecasting storm surges. However, the first step in developing an adequate forecasting system is to obtain a clear statement of the physical problem we wish to solve. This requires an examination of the changes in sea level produced by several storms and of the principal factors which are believed to be important in determining the sea level as a function of time and space.

Figure 1 shows the hourly observed sea level at several Coast and Geodetic Survey Tide Stations on

August 27 through September 2, 1954 associated with hurricane Carol. The large dots on the curves, indicate interpolated values based on information other than the record from a recording tide gage. The dashed line extending across the maregrams shows the approximate time at which the storm was nearest the station. The solid line on the map in the left hand part of the figure shows the path of the storm. The enlarged dots along this line indicate the position of the storm center at the date and time shown. The tide records are matched with the geographic position of the gage by means of capital letters. The vertical scale of the maregrams is given on an insert near the center of the chart. It is seen here that the major source of variability at most stations is the normal semi-diurnal tide.

Figure 2 is a plot of the hourly difference between the observed and predicted tides at the same stations. The same convention as described above is used in identifying the stations and storm track. These curves are presented here in order to focus attention on the problem being discussed. The details of these curves are discussed in a later section of the paper.

The storm surge is defined, for the purposes of this paper, as the short-period rise or fall of sea level produced by a hurricane or other meteorological disturbance. Although it is recognized that ground swell and wind-driven waves having periods of less than one minute are an important part of the hurricane problem, they will not be considered in any fundamental way in this paper.

With this brief description of the problem being considered, we shall proceed to a discussion of the physical phenomena affecting sea level and then to a more detailed discussion of actual cases.

NATURE OF THE PROBLEM

The level of the sea at any point is affected by:

(1) the gravitational attraction of the sun and moon
(2) the atmospheric pressure at that point relative to the mean pressure over the entire ocean (the inverted barometric effect)
(3) variations in the density of the sea water
(4) natural oscillations of the sea.

In shallow water near the coast, the following additional factors are important:

(5) the piling-up of water by the wind (setup)
(6) the transport of water by waves and swell
(7) the shoaling of waves formed in deeper water
(8) natural oscillations of the shelf water.

Still other factors become important inside harbors and estuaries:

(9) convergence or divergence of waves from the sea
(10) rainfall and runoff
(11) wind setup within the estuary
(12) natural oscillations within the estuary.

The observed sea level results from a combination of all of these effects and perhaps others which are neglected here. Forecasters and other meteorologists are interested primarily in the changes in sea level produced by unusually high winds and tight pressure gradients. These will be referred to below as "storm surges." However, the public for whom we forecast, is interested primarily in how high the water will rise, or how low it will fall. The practical importance of any given storm surge will be greater if it occurs at the time of an already high natural tide, than if it coincides with the normal low tide. Moreover, any observations which we may use to check our theories will give us only the combined effects of all factors which affect sea level.

Thus, it is necessary to have some understanding of all of the factors which influence sea level before we can proceed very far with our understanding of the ones in which we are interested. The present unsatisfactory state of storm surge research in the Americas is due more to the difficulty of separating these various effects than to any other cause.

THE GRAVITATIONAL ATTRACTION OF THE SUN AND MOON

The most universal and best understood of the various factors which affect the sea level is the gravitational attraction of the sun and the moon. The facts which must be considered in explaining these forces are the rotation of the earth, the rotation of the moon around the earth, the rotation of both around the sun, the variable inclination of the plane of the moon's orbit with the plane of the earth's equator and with the plane of the earth's orbit around the sun, and the variable distances between the earth and the moon and the sun. All of these variables are periodic in time, and so are their interactions. Thus, it is quite natural that the various tide predicting agencies should seek to express the tide as the sum of a harmonic series of the form:

$$h = \bar{h} + \sum_{n=1}^{M} B_n \cos(A_n t + D_n) \qquad (1)$$

where

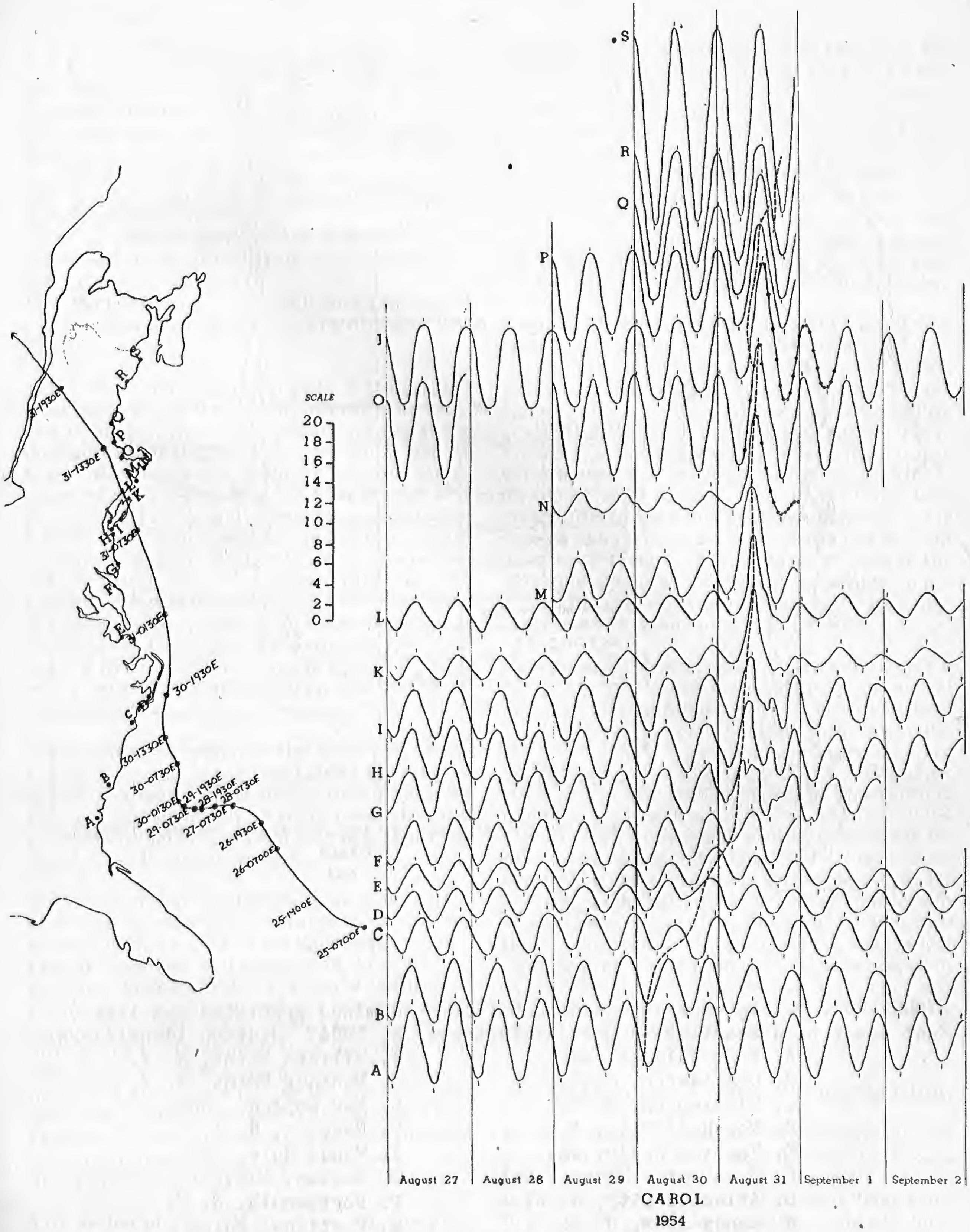

FIGURE 1. - Hourly observed sea level, east coast tide stations, August 27-September 2, 1954. See legend to figure 2 for station identification.

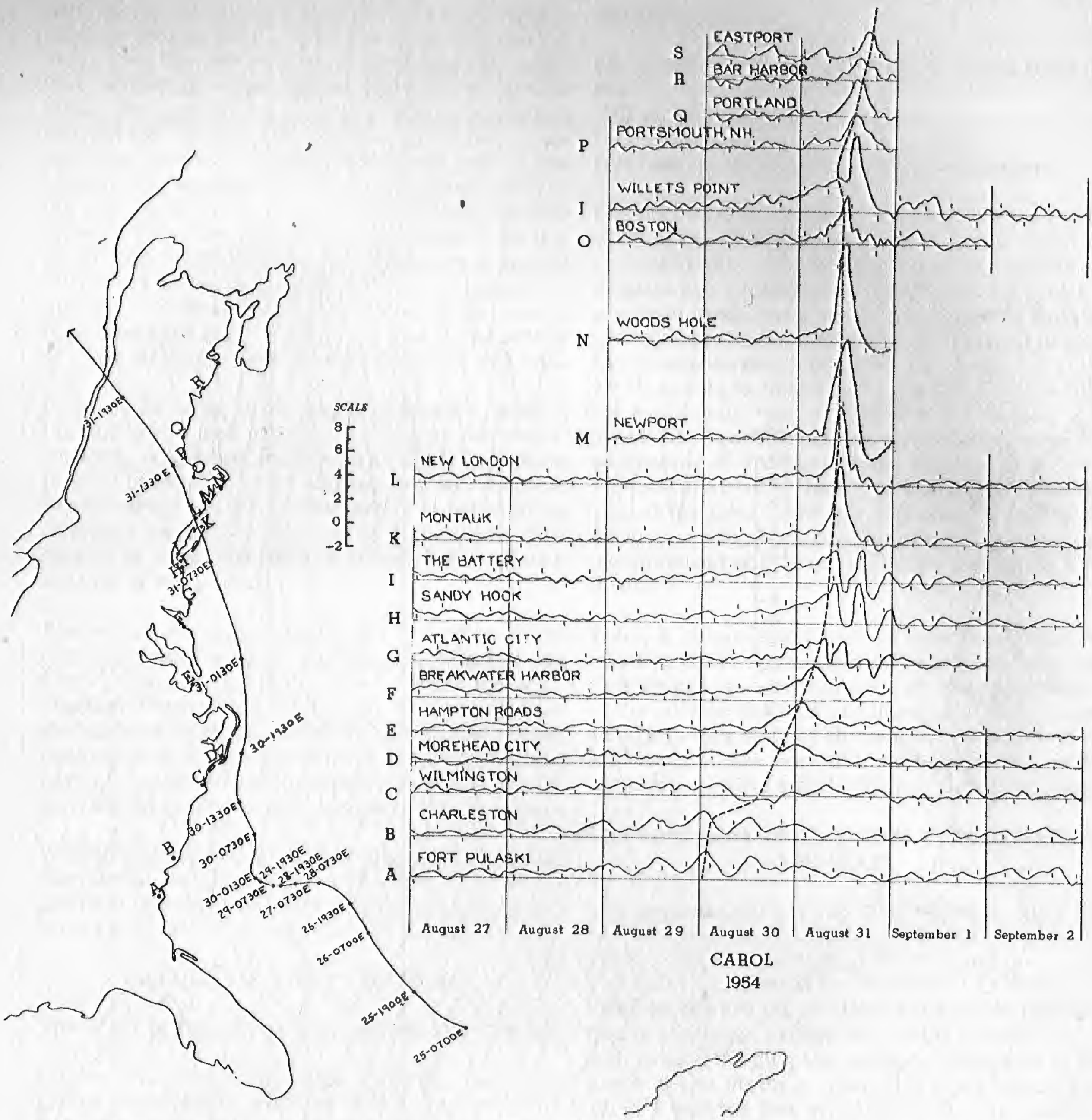

FIGURE 2. - Hourly storm surge height (observed minus predicted sea level). East coast tide stations, August 27-September 2, 1954. Station identifiers:

A. Fort Pulaski, Ga.
B. Charleston, S. C.
C. Wilmington, N. C.
D. Morehead City, N. C.
E. Hampton Roads, Va.
F. Breakwater Harbor, Del.
G. Atlantic City, N. J.
H. Sandy Hook, N. J.
I. The Battery, New York City
J. Willets Point, N. Y.
K. Montauk Point, N. Y.
L. New London, Conn.
M. Newport, R. I.
N. Woods Hole, Mass.
O. Boston, Mass.
P. Portsmouth, N. H.
Q. Portland, Maine
R. Bar Harbor, Maine
S. Eastport, Maine

h is the predicted sea level at any time
$\bar{h}$ is the mean sea level measured from any arbitrary base line
B_n is the amplitude of the n'th constituent of the tide (determined from observations and modified by theory)
A_n is the speed of the n'th constituent of the tide, usually expressed as degrees per hour (360 degrees per period of the constituent).
D_n is the phase displacement or epoch of the n'th constituent (determined in part from theory and in part from observations)
M is the total number of constituents considered.
t is the time, usually expressed in hours since 0000 January 1.

The most prominent constituents of the tides at most locations are those having periods between 12 and 13 hours. Next most prominent are those constituents having periods between 24 and 28 hours. However, longer periods of approximately 2 weeks, 4 weeks, 6 months, 12 months, and 18.5 years as well as shorter periods of approximately 6 hours and 3 hours must be considered at many locations in order to obtain satisfactory predictions. The periods in excess of a year affect only the amplitudes B_n and the epochs D_n of the constituents due to the moon, and have no affect on the constituents due to the sun. This effect is taken into account by changing the value of B_n and D_n from year to year, by an amount determined from the astronomical theory.

It should be mentioned here that these long-period cycles (in excess of one year) affect the range of the tide, not the mean sea level. The astronomical cycles of approximately 19 years cause the mean low water datum to vary from year to year but they do not affect the mean sea level.

The theory, which is satisfactory for a description of the forces involved, is unable to predict the manner in which seas of variable depth and irregular coastline will respond to these forces. However, in general, the periods of the induced motion are the same or related in some simple way to the periods of the applied forces. Therefore, in practical tide predictions the periods to be considered are determined from astronomical theory but amplitudes B_n and the epochs D_n are determined from an analysis of the observed data. Theoretical considerations are employed to modify these parameters, however, to take into account the astronomical periods in excess of one year.

True meteorological cycles of one day, one year, one-half a day, one-half a year, and so forth, are well known. Since the variation of atmospheric pressure, wind stress, and to a slight extent temperature, affect the sea level, the empirically determined parameters B_n and D_n represent the influence of the climatological as well as the astronomical effects on the sea. Thus, the predicted or "normal" tide includes both astronomical and climatological effects and no satisfactory means of completely separating these has been found. However, it is generally believed that the astronomical influences are predominant in determining the coefficients for constituents having periods of less than six months and that the meteorological factors are most prominent in determining the coefficients for the annual and semi-annual constituents.

Equation (1) gives only the departure of the sea level from its mean or average position. However, the mean sea level itself changes from day to day, month to month, and year to year. Figure 3 from Marmer [14] shows the daily sea level variations at six Atlantic coast stations for October 1947. Figure 4, also from Marmer, shows the monthly variation in mean sea level for the years 1946-47 for the same six stations. Pattullo et al. [20] have shown that the variation in the temperature of the upper 100 meters or so of the ocean can account for a large fraction of this change. Some of the variation is undoubtedly due to variations in the general circulation of the surface winds and variations in atmospheric pressure.

Even the annual mean sea level varies from year to year. Figure 5 shows the variation of the annual mean sea level at Atlantic and Gulf coast locations, as obtained from records of the U. S. Coast and Geodetic Survey. There is a general trend toward rising sea level at the rate of about .011 foot or about .33 cm. per year (Disney [4]). The cause of this rise has been ascribed to an increase in the volume of the ocean due to melting of the polar ice caps, to increasing mean temperature of the oceans, to a sinking of the land due to various causes, and to variation in the wind patterns leading to more onshore winds (DeVeaux [3]). However, the important thing to note here is that the mean sea level, which we have been accustomed to consider as constant in most meteorological problems, varies in a way which is important in studying the meteorological effects on the level of the sea.

THE EFFECTS OF ATMOSPHERIC PRESSURE

If the atmospheric pressure were constant all over the oceans, it would not affect the level of the sea. If the pressure at a point were to remain constant in time, but the pressure were to vary from place to place, the laws of hydrostatics would call for a plane of constant pressure at some level below the surface of the sea and the sea level would be raised in regions of low pressure and depressed in regions of high pressure.

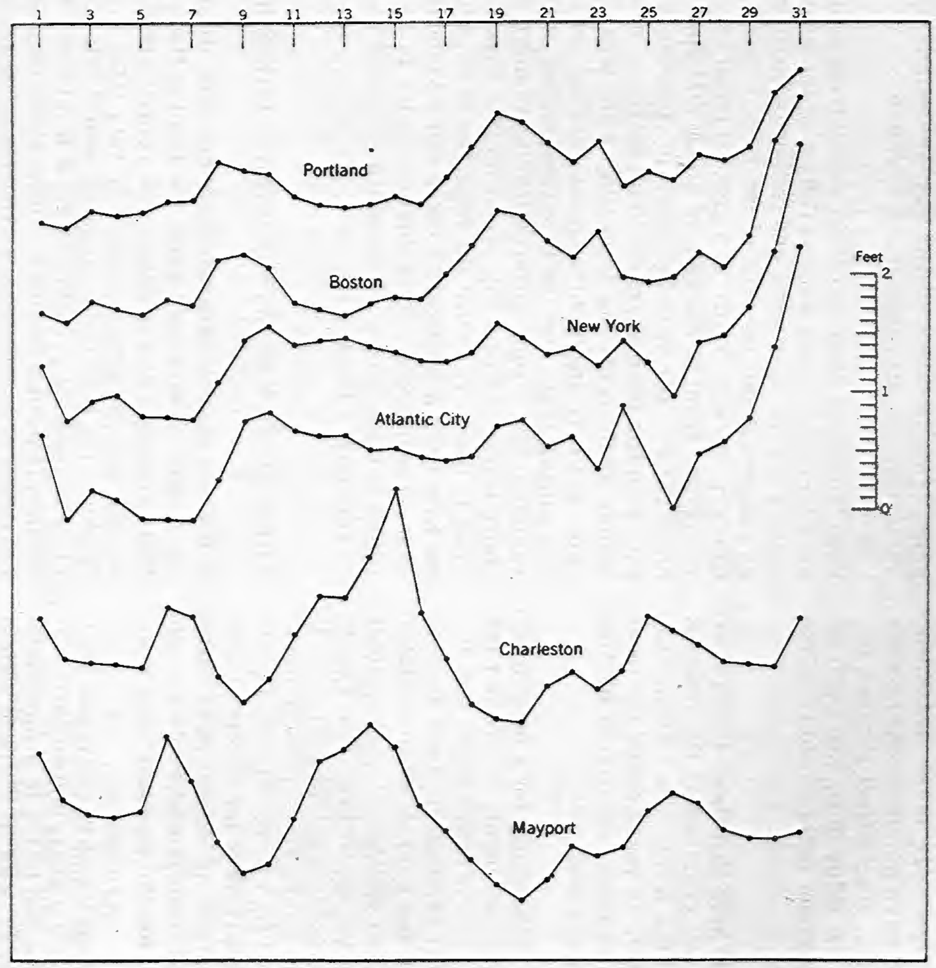

FIGURE 3. - Daily sea level at six Atlantic coast stations, October 1947. From Marmer [14]

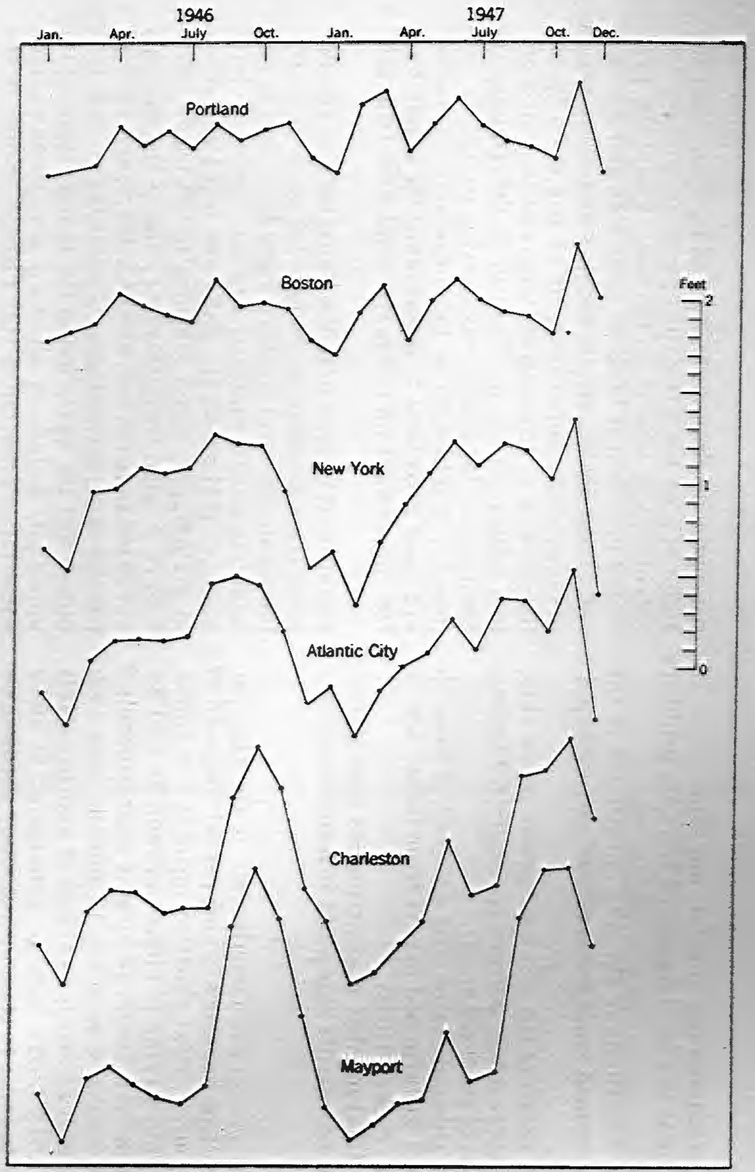

FIGURE 4. - Monthly sea level at six Atlantic coast stations, 1946-47. From Marmer [14]

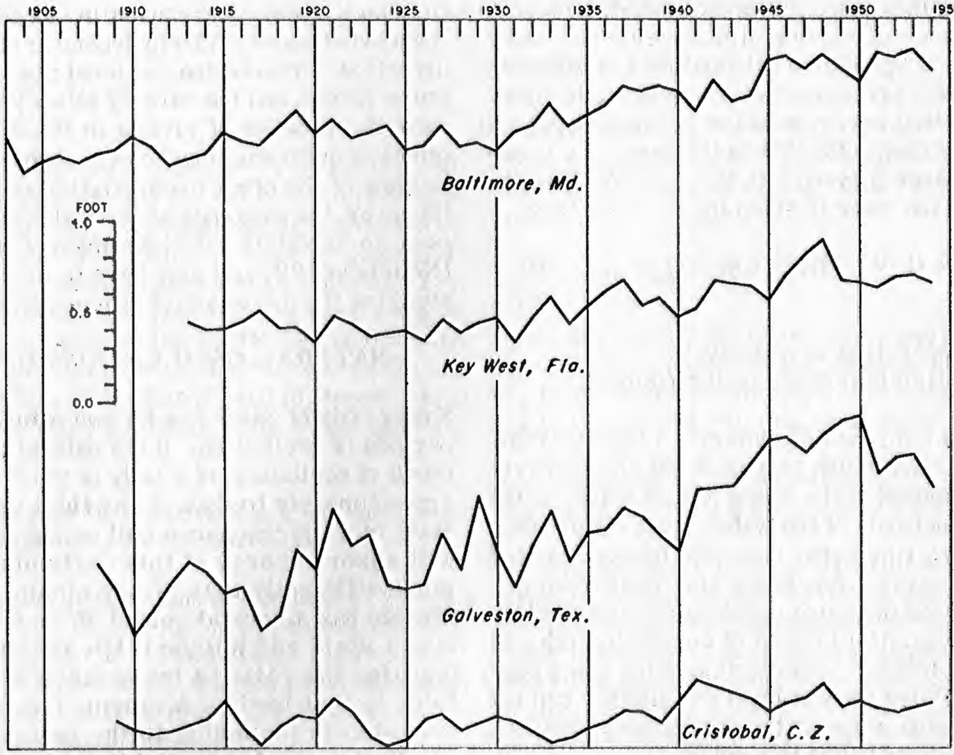

FIGURE 5. - Annual mean sea level at east coast and Gulf of Mexico stations.

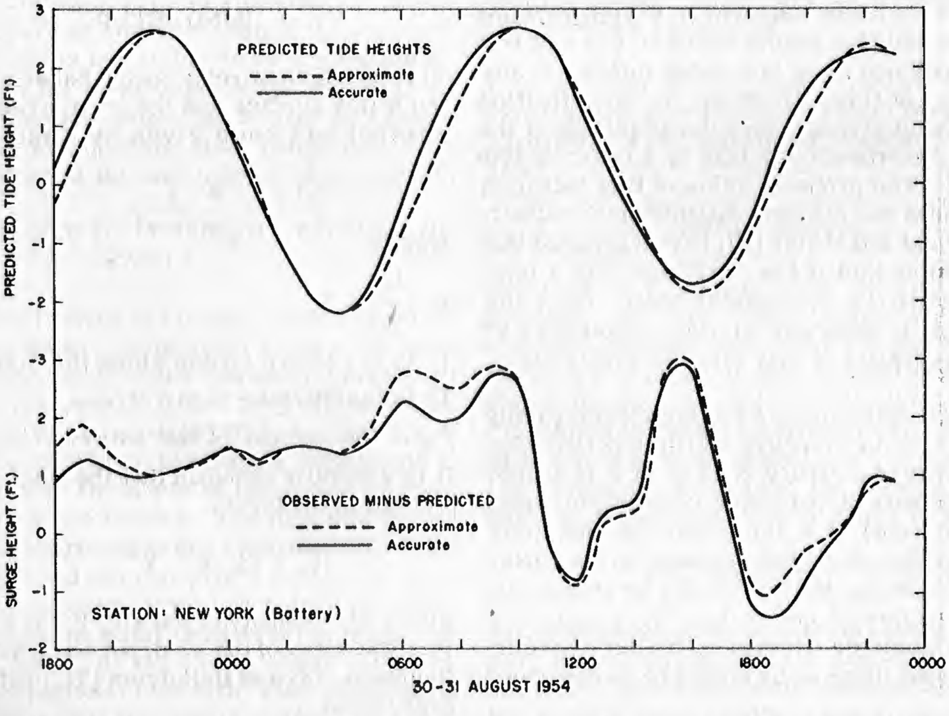

Figure 6. - Exact and approximate predictions of normal tide and the resulting computed storm surge height. Battery Station, New York City, August 30-31, 1954.

The problem is made more complicated, however, by the presence of moving atmospheric pressure disturbances. Proudman [21] and [22] in studying the effects of a pressure disturbance moving over an infinitely long narrow canal of constant depth and width showed that if P(x-Vt) is the form of a pressure disturbance moving with the speed V, then the amplitude of the wave is given by

$$h = (1-V^2/gH)^{-1}\,P(x-Vt) \qquad (2)$$

where
g is the acceleration of gravity,
H is the equilibrium depth of the field.

Here we see evidence of dynamic amplification. If V^2 should tend to gH, that is if the atmospheric disturbance moved at the speed of long waves in the canal, the amplitude of the water level disturbance would be many times that indicated for an inverted water barometer. Arakawa and Yoshitake [1] have considered the same problem for an infinitely large two dimensional ocean of constant depth and have found a dynamic amplification of the same type, but they found that the sea level disturbance can not take on the same shape as the atmospheric disturbances if this disturbance is moving.

Actually there are no infinitely long canals or infinitely large oceans of constant depth to consider, but if either theory is expanded to account for the finite size of the basin, the term $(1-V^2/gH)$ remains although the additive terms serve to prevent the actual disturbance from becoming infinite in any finite interval of time. However, the amplification due to this term may increase the amplitude of the water level disturbance in a lake by a factor of five (Harris [6]). The probable value of this factor in real hurricanes has not been satisfactorily evaluated, but Redfield and Miller [23] have suggested that it may be important if the hurricane has a long trajectory over the continental shelf. Over the open ocean gH is generally so much larger than V^2 that the importance of this term is negligible.

The pressure deficiency in the hurricane rarely exceeds 3 inches of mercury (Willett [27]). The specific gravity of mercury is 13.6. If it is assumed that the density of sea water is unity (this must be the lower limit), it is found that the maximum equilibrium effect of the low pressure in the center of a hurricane on the sea level would be an increase of about 40 inches or one meter. However, this may be increased or decreased by the dynamic effect described above or by others to be described below.

VARIATIONS IN THE DENSITY OF SEA WATER

The effect of the annual variation in water temperature on the annual variation in sea level has been mentioned above. The hydrostatic effect is in the direction of raising the sea level where the temperature is high and the salinity is low, as is the case near the mouths of rivers in flood stage. This effect is quite small and can probably be neglected in view of the other uncertainties of the problem. However, the existence of vertical density gradients is quite important in the dynamics of ocean currents (Neumann[19]), and may have to be considered in studying the dynamics of storm surges.

NATURAL OSCILLATIONS OF THE SEA

Every body of water has its own natural modes and periods of oscillation. If the natural period of any mode of oscillation of a body of water corresponds approximately to that of any tidal constituent, a state of near resonance will occur and the water will absorb energy of this particular frequency more efficiently than of any other. The Gulf of Mexico has a natural period of approximately 24 hours (Reid and Wilson [24]), and this probably explains the relative importance of the diurnal tides in that basin. A storm, too, may have a period corresponding to the natural period of oscillation of a basin, and in this case the storm surges in this basin, whether the result of wind or pressure gradients, will be greater than for storms with other periods.

WIND SETUP

The equilibrium relationship between the slope of the water surface and the wind stress in a closed channel has been given by Keulegan [11] as

$$\frac{\partial h}{\partial x} = \frac{n\,\tau_s}{\rho_w\, g\,(H+h)} \qquad (3)$$

where

$$n = \frac{\tau_0}{\tau_s} + 1$$

τ_0 is the shear stress along the bottom
τ_s is the surface shear stress
ρ_w is the density of the water.

It is generally assumed that the wind stress can be written in the form

$$\tau_s = \rho_a\,\gamma^2\,V^2 \qquad (4)$$

where ρ_a = density of the air, γ^2 is a constant, and V is the speed of the wind, but some writers, notably Neumann [18] and Hellström [7], prefer to use the expression

$$\tau_s = \rho_a\,AV^{\alpha} \qquad (5)$$

where A and α are constants. Munk [16] recently suggested that the proper expression may well be of the form:

$$\tau_s = C_1 V^2 + C_2 V^3 \qquad (6)$$

where C_1 and C_2 are constants. The agreement between equations (3) and (4) and laboratory data is excellent (Keulegan [11]), and the agreement with data from natural closed basins such as Lake Erie and Lake Okeechobee is good (Keulegan [12], Saville [25]). Neumann [18] reports good results in relating the setup in the Baltic Sea to the wind stress over the sea by combining equations (3) and (5), with $\alpha = 3/2$. Hellström [7] and [8] reports good agreement for other basins by using other values of α.

The available data do not permit a clear distinction between the values of these expressions.

The applicability of equations of this kind to the wind setup along open coasts has not been established. A recent study in the United States (Miller [15]) indicated that equation (5) may be preferable and that the best value of α may vary from place to place along the coastline.

It should be noted here that all writers agree that the setup is inversely proportional to the undisturbed depth of the water. Hence a given wind stress will produce a greater disturbance in sea level if it occurs at low tide than if it occurs at high tide. This is not likely to be important in areas in which the mean depth of the sea is great compared to the tidal range, but it must be considered in areas in which the tidal range is a substantial fraction of the mean depth of the water.

THE TRANSPORT OF WATER BY WAVES AND SWELL

The irrotational waves of elementary theory do not transport any water. Some other theoretical wave forms however, such as the Gerstner Trochoidal wave (Lamb [13], p. 421), do carry water in the direction of wave propagation. This is also true of natural waves, particularly when the wavelength is long compared to the depth of the water through which the waves are moving. The long swells sent out ahead of a hurricane carry a considerable mass of water shoreward and may produce a rise of one to two feet in the mean sea level long before the hurricane approaches the coast (Willett [27]). This rise in sea level, known as the "forerunner", may be a substantial fraction of the total rise in sea level due to the storm. Examples of this effect are shown below.

SHOALING OF WAVES FORMED IN DEEP WATER

It is well known that the amplitude of a wave tends to increase as the wave moves into a region of decreasing depth. Several theories have been advanced to account for this effect quantitatively. The most quoted is known as Green's Law, (Lamb [13], p. 274) which states that

$$h_s/h_d = (H_d/H_s)^{1/4} \qquad (7)$$

where

h_s is the amplitude of the wave near the shore
h_d is the amplitude of the wave in deep water
H_s is the equilibrium depth near the shore
H_d is the equilibrium depth in deep water.

This is based on the assumption that the relative change in depth $\frac{\Delta H}{H}$ within a distance L, (where L is the wavelength of the disturbance) is small. This equation obviously cannot hold after the wave has passed the normal shoreline. However, it does give some indication of the amount of dynamic amplification to be expected from this cause. The amplitude of the tsunami of April 1, 1946, has been estimated as two feet in open water (Kaplan [10]). The height of the disturbance above mean low water on the island of Hilo, Hawaii varied from 10 to 25 feet and values of 20 feet were common. The tsunami occurred at the approximate time of low water, so that the quoted values are approximate heights above normal tide level.

It is possible that an amplification of this type explains the unusually high storm surge in Ciudad Trujillo in 1930 and in the Yucatan Peninsula in 1955.

SHELF SEICHES

Not only is it possible for an entire basin to oscillate with some natural frequency, but if these is a sudden increase in depth (as along a continental shelf) it is possible to have oscillations between the shore and the edge of the shelf. These have been discussed in detail by Hidaka [9]. Redfield and Miller [23] have suggested that the resurgences of the storm surges along the New Jersey coast (see fig. 2) may be due to shelf seiches.

ESTUARIAN EFFECTS

Any disturbance in sea level, once formed, is propagated throughout the sea according to the equations of motion for the ocean without regard to the mechanism by which it was formed, excepting for the possible nullification or reinforcement by the creation of some new water level disturbance. The tides in harbors and rivers and in many seas are largely due to the propagation of the normal tides from the ocean as ordinary gravity waves into these arms of the ocean. A storm surge likewise may be propagated as an ordinary gravity wave into a narrow channel opening into the ocean. An example of this can be seen in figure 2. The maximum storm surge at Willets Point, "J", occurred four hours after the center of the hurricane passed. This is because the surge observed at Willets Point, at the western end of Long Island Sound, was formed in the open ocean and traveled westward through the Sound as a gravity wave.

If the estuary has a wide mouth and becomes progressively narrower toward its head, the equation of continuity requires a convergence of stream lines, and the amplitude of the wave at the head of the estuary will be many times the amplitude at the mouth. On the other hand, if the mouth of the bay is narrow and the internal area is large the amplitude of the disturbance will decrease rapidly with distance from the open ocean.

An estuary may also have its own natural modes and periods of oscillation, and resonance between these and the disturbances on the open ocean is not uncommon. The large tides of the Bay of Fundy are caused in part by convergence and in part by resonance, for the natural period of the Bay is near that of the semi-diurnal tidal constituents (Sverdrup, Johnson, and Fleming [26], p. 562.)

In the case of storm surges there is also a possibility that the sea level inside an estuary or tidal river will be increased due to the run-off of excessive rainfall accompanying the storm. Water level disturbances inside an estuary or land-locked sound may also be produced by the transport of water from one part of the basin to another due to the high winds associated with a storm. This effect may act to increase or to nullify the effect of the storm surge created over the open sea and impinging on the mouth of the estuary. The increase in water level on the downwind side of Lake Okeechobee due to this cause has exceeded 19 feet (Saville [25]).

SEPARATION OF NORMAL AND METEOROLOGICAL TIDES

The above discussion of the causes of sea level variations shows that we must deal with the interaction of many complicated phenomena whose effects cannot be easily separated. Nevertheless, we must achieve some degree of separation if we are to make any quantitative study of storm surges. To the first approximation, at least, the storm surge may be defined as the difference between the observed and predicted sea levels - the predicted sea levels being those predicted on the basis of tidal theory and including both the astronomical and climatological terms.

Accurate predictions generally require the summation of 20 to 30 terms of equation (1), and are generally practicable only if one has access to a tide prediction machine such as that operated by the U. S. Coast and Geodetic Survey and similar agencies in other countries. These tide predicting agencies generally publish tables giving the time of high and low water and the height of the sea level above some specified datum at high and low water. To a first approximation, the tide at intermediate times can be obtained by connecting successive highs and lows by means of sine curves. A method of graphically constructing such a curve is given in each edition of the tide tables published by the Coast and Geodetic Survey. This method is probably accurate enough for most purposes at most locations near the sea. However, its applicability to storm surge research needs to be critically examined. In figure 6 the solid line in the upper part of the figure gives the predicted tide at the Battery station, New York Harbor, for the period 1800 EST August 30 through 2300 EST August 31, as reconstructed from hourly values of the complete tide equation. The dashed line gives the result of graphically connecting the highs and lows by means of sine curves. It can be seen that differences of 0.7 ft. or about 14 percent of the tidal range may occur between the two curves. The importance of this difference in studying storm surges can be determined from the lower two curves. The solid curve gives the difference between the observed tides and the more accurate prediction and the dashed curve gives the difference between the observed and the approximate predicted values. At the point of maximum difference between these two curves, the more accurate prediction gives a storm surge amplitude of 2.0 feet. This occurred near the height of the disturbance. The approximate prediction gives 2.7 feet, or an error of about 35 percent of the true surge amplitude. This type of accuracy may be satisfactory for operational use, but for research purposes something more is to be desired.

Short-period oscillations can be removed or greatly reduced by computing running averages of the hourly sea level; Doodson and Warburg [5] have published a set of weighting factors which reduce the amplitude of the normal tidal constituents about 98 percent. This procedure is satisfactory if one's purpose is to determine the variation of mean sea level over a period of days. However, this method is not satisfactory for studying storm surges, for if any part of the storm surge can be expressed as a series of cosines having the same period as any constituent of the normal tide, this portion of the storm tide will be eliminated by this averaging

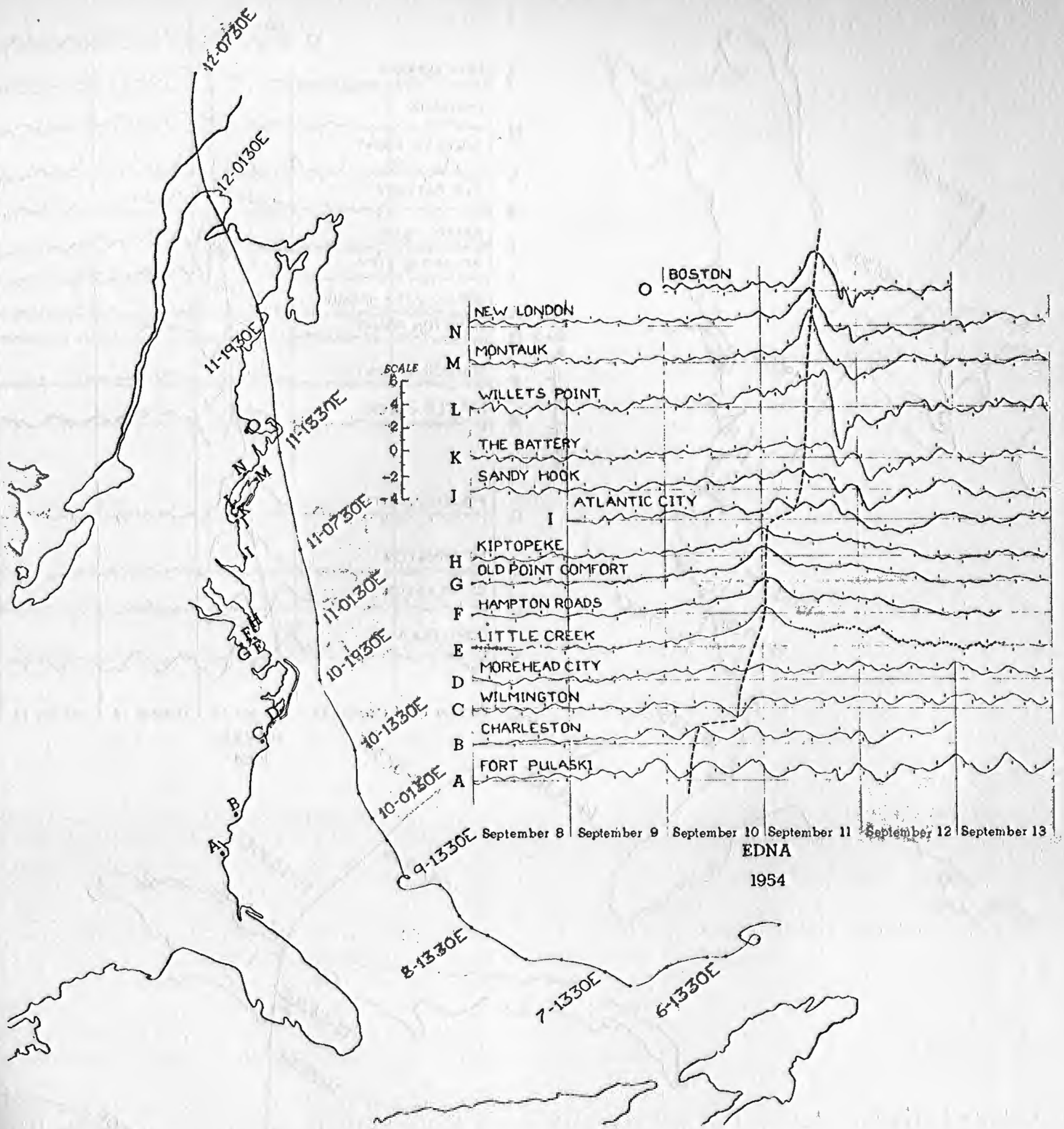

FIGURE 7. - Hourly storm surge height, hurricane Edna, September 8-13, 1954.

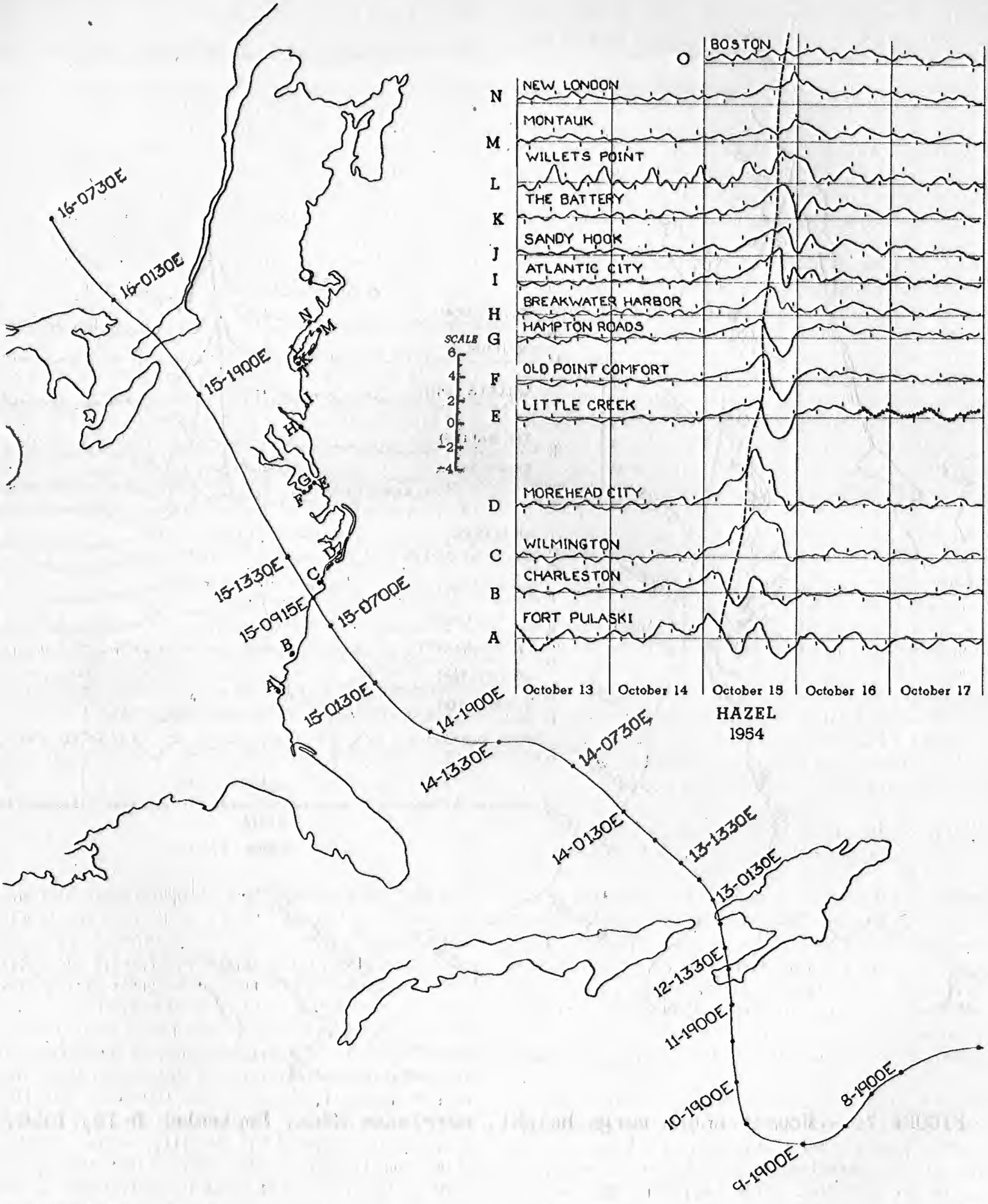

FIGURE 8. - Hourly storm surge height, hurricane Hazel, October 13-17, 1954.

procedure. It can be seen from figure 2 that periods, similar to the natural tidal periods, may be prominent in the storm surge produced by a hurricane.

OBSERVATIONS OF STORM SURGES

Figures 7 and 8 give the storm surge records associated with hurricane Edna, September 1954 and Hazel, October 1954, displayed in the same manner as for hurricane Carol in figure 2.

It can be seen from these three figures that periods similar to the tidal periods frequently remain in evidence after the predicted tide has been removed from the observations. This residue periodicity is particularly common in estuaries in shallow regions of the sea. The residue periodicity is evidence of interaction between the storm surge and normal tides, and shows that a more suitable method of separating the effects of the normal tide and wind stress may be required before a satisfactory solution to the storm surge problem can be found.

A few other points may be illustrated by these curves. An increase in the sea level by one to two feet from 12 to 24 hours in advance of the storm is in evidence at most stations. At Atlantic City, Sandy Hook, and the Battery this forerunner accounted for more than half of the total rise in sea level. At Fort Pulaski, Charleston, and Wilmington the forerunner generated before the storm turned northward is clearly in evidence, but the northerly, offshore winds which followed the nearest approach of the storm led to a decrease in the sea level at the time the storm was nearest these gages.

The prominent oscillations in the records for Atlantic City, Sandy Hook, and the Battery have been called resurgences by Redfield and Miller [23] and they have sought to explain them as oscillations of the shelf water. Munk et al. [17] would explain these oscillations as edge waves. These oscillations appear to be characteristic of the storm surges in this area, as they have occurred in a number of other storms. However, the data analyzed to date are not sufficient to determine which, if either, of these explanations is correct.

We are preparing charts similar to these for all storms which occurred along the east coast in recent years, and ultimately, we hope, for all hurricanes. Additional charts that have been prepared are contained in the Appendix. By studying these charts, we are developing a number of ideas concerning the manner in which these surges develop. The familiarity with the phenomenon gained by studying charts like these should lead within a year to some improvement in our intuitive forecasting procedures and within about two years to establishment of a sound scientific basis for forecasting these inundations.

VERIFICATION OF FORECASTS

The storm surge is considered as a temporary change in sea level; it should not be confused with the ordinary and more visible wind-driven waves and swells. The waves and swells, with a frequency normally greater than 5 to 12 per minute may reach amplitudes much greater than that of the storm surge, and may do tremendous damage near the shoreline, but they have a relatively short wavelength and cannot extend very far inland. However, the storm surge has a period measured in hours, and rarely goes through more than two or three significant cycles with a single storm. Usually one cycle is present. This disturbance has a wavelength of many miles and in low lying and swampy land it may penetrate several miles beyond the normal shoreline and produce flood damage in regions normally considered to be safe. From a public service as well as a scientific service point of view, the two phenomena must be considered separately. However, this is not always understood by laymen. It is not unusual to receive reports of tides as much as 8 to 12 feet above normal during the progress of a storm, and to learn later that these high values were obtained in exposed places by confusing wave height with surge height. Later, more careful studies may show that the surge height was no more than about 3 feet above the normal tide level. Most reports received from laymen must be evaluated very carefully before we can be sure they are reporting storm surge height and not wave height.

CONCLUSIONS

The hurricane surge is a complex phenomenon. It is difficult to separate the effects of the storm from those due to normal astronomical tides and wind-generated waves. There are too few quantitative data available to permit an adequate generalized description of the hurricane-generated surge. The data examined suggest that there is a systematic relation between the amplitude of the surge and the direction and distance of the storm from the observing point; the size, the intensity, and the speed of motion of the storm; as well as the local configuration of the shoreline in the vicinity of the observation. At the time of this writing we have analyzed a total of about ten hurricanes in the manner indicated here. Improvements in our method of analysis should permit the examination of a hundred storms within another year and by that time we hope to have developed a reasonably satisfactory system for forecasting these inundations.

ACKNOWLEDGMENTS

I would like to acknowledge the very extensive assistance given to me by the Tides and Currents Division of the U. S. Coast and Geodetic Survey, and by my associates in the Weather Bureau, Arthur Pore and C. V. Lindsay.

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APPENDIX

To supplement the charts of the main body of this paper the following groups of additional storm surge charts are presented;

1. Charts for four Atlantic Coast hurricanes (figs. 9-12).

2. Charts for two hurricanes in the Gulf of Mexico (figs. 13-14).

3. Charts for two Atlantic Coast extratropical storms (figs. 15-16).

4. Charts for seven Gulf of Mexico extratropical storms (figs. 17-23).

The storm surge charts for the four Atlantic Coast hurricanes are similar to those for Carol, Edna, and Hazel described in the paper. One exception is that curves of the observed tide have been included on the Hurricane Barbara 1953 chart for the Chesapeake Bay Stations.

For the Gulf of Mexico hurricanes, 24-hour synoptic surface charts are included to show the weather patterns associated with the storm surges.

On the two charts for east coast extratropical storms the central isobar is indicated along with the storm center, and a frontal orientation has been added in some cases.

For the extratropical storms in the Gulf of Mexico 12 or 24-hour synoptic charts are also included. The dashed lines through the storm surge curves indicate the times of frontal passage.

On all of the Gulf of Mexico storm surge charts, the stations east of Pensacola are plotted in 75th Meridian time, whereas Pensacola and stations to the west are plotted in 90th Meridian time.

In order to facilitate matching tide records to geographical locations, tide records for Atlantic Coast stations and the locations of the stations have been identified by capital letters (except in fig. 9); those on the Gulf Coast by lower case letters.

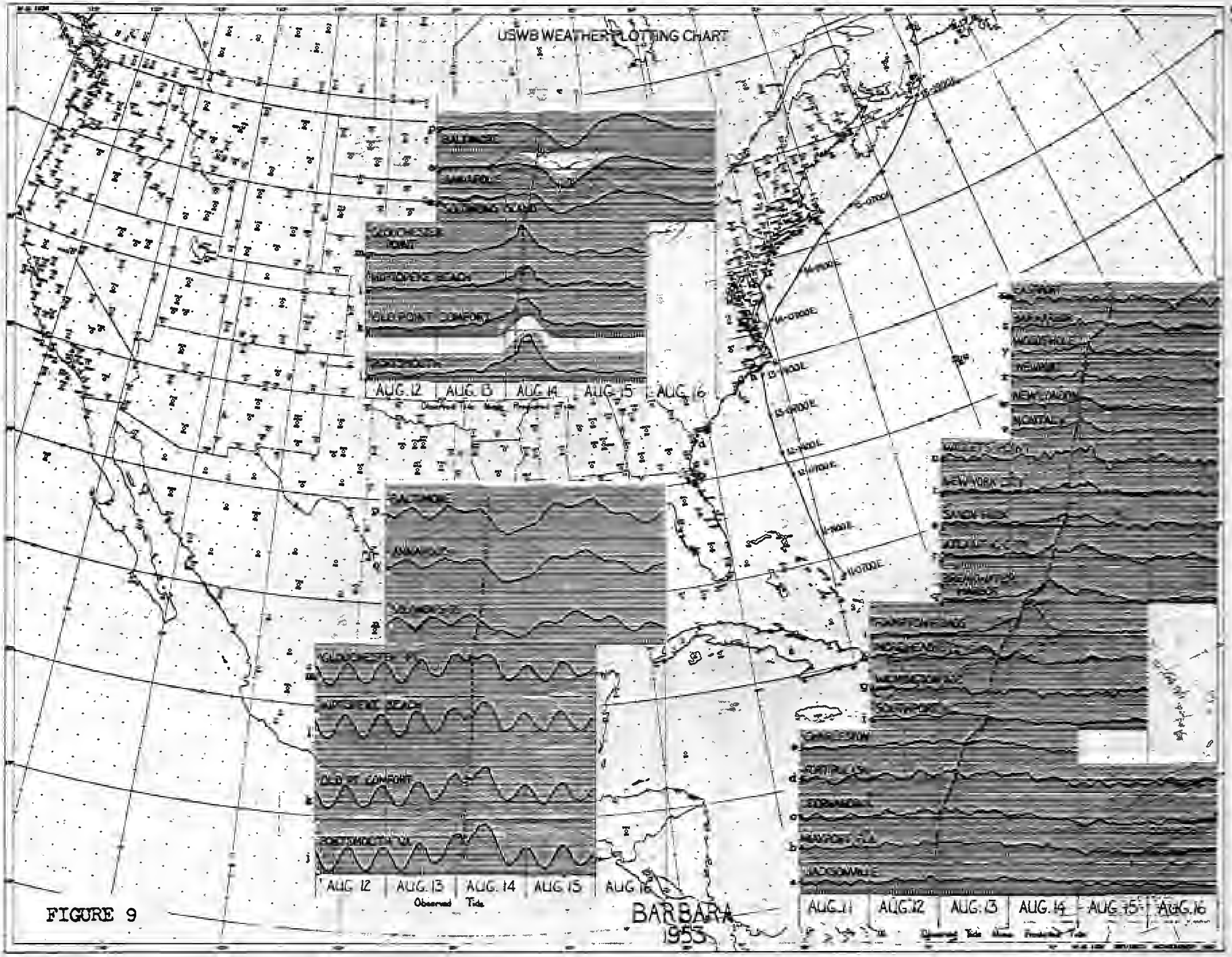

USWB WEATHER PLOTTING CHART
BALTIMORE
ANNAPOLIS
SOLOMONS ISLAND
GLOUCESTER POINT
KIPTOPEKE BEACH
OLD POINT COMFORT
PORTSMOUTH
AUG. 12
AUG. 13
AUG. 14
AUG. 15
AUG. 16
Observed Tide Minus Predicted Tide
BALTIMORE
ANNAPOLIS
SOLOMONS IS.
GLOUCESTER PT.
KIPTOPEKE BEACH
OLD PT. COMFORT
PORTSMOUTH VA.
AUG. 12
AUG. 13
AUG. 14
AUG. 15
AUG. 16
Observed Tide
EASTPORT
WOODS HOLE
NEWPORT
NEW LONDON
MONTAUK
WILLETS POINT
NEW YORK
SANDY HOOK
ATLANTIC CITY
BREAKWATER HARBOR
HAMPTON ROADS
MOREHEAD
WILMINGTON N.C.
SOUTHPORT
CHARLESTON
FORT PULASKI
FERNANDINA
MAYPORT FLA.
JACKSONVILLE
AUG. 11
AUG. 12
AUG. 13
AUG. 14
AUG. 15
AUG. 16
Observed Tide Minus Predicted Tide
BARBARA
1953

FIGURE 9

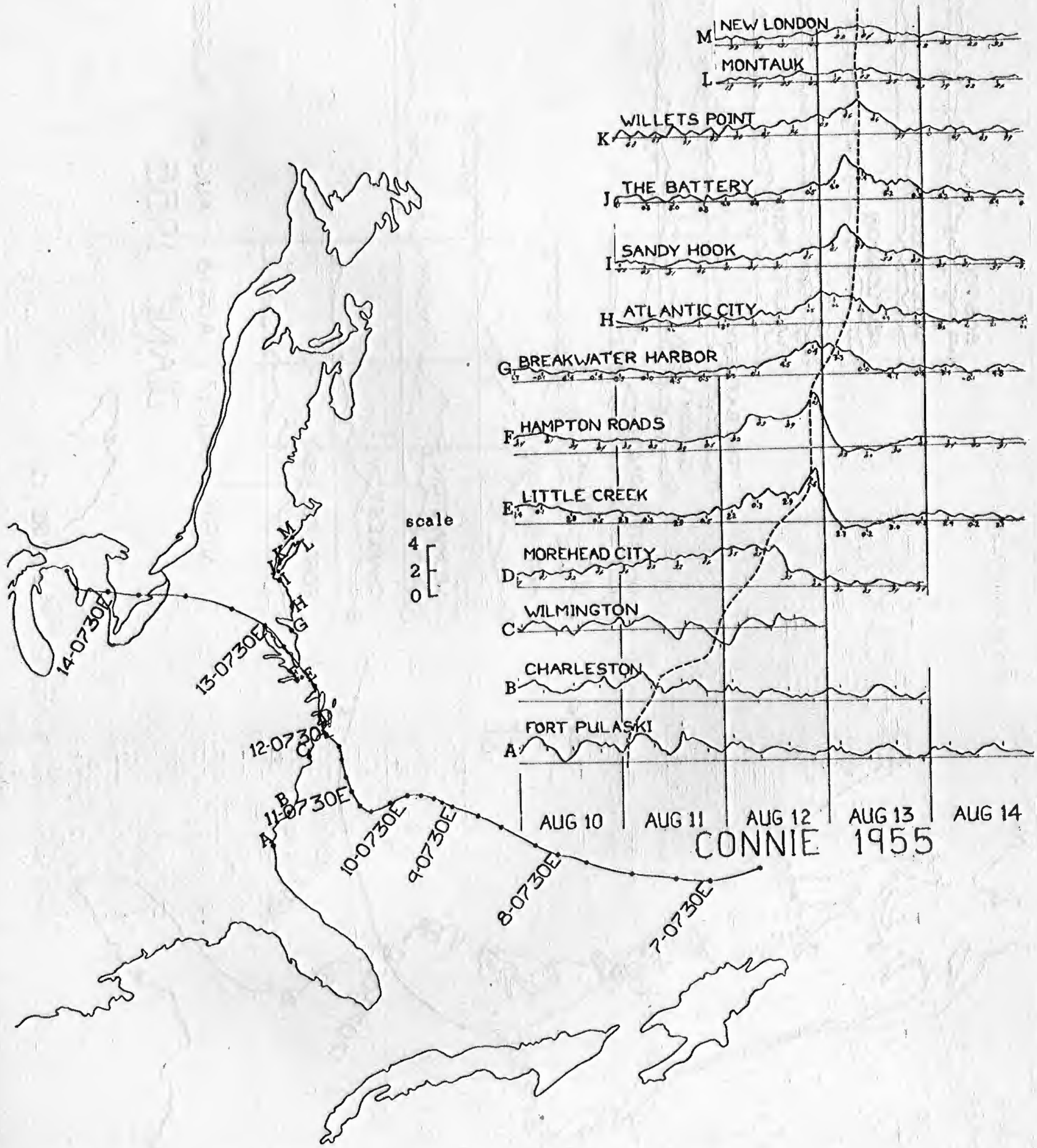
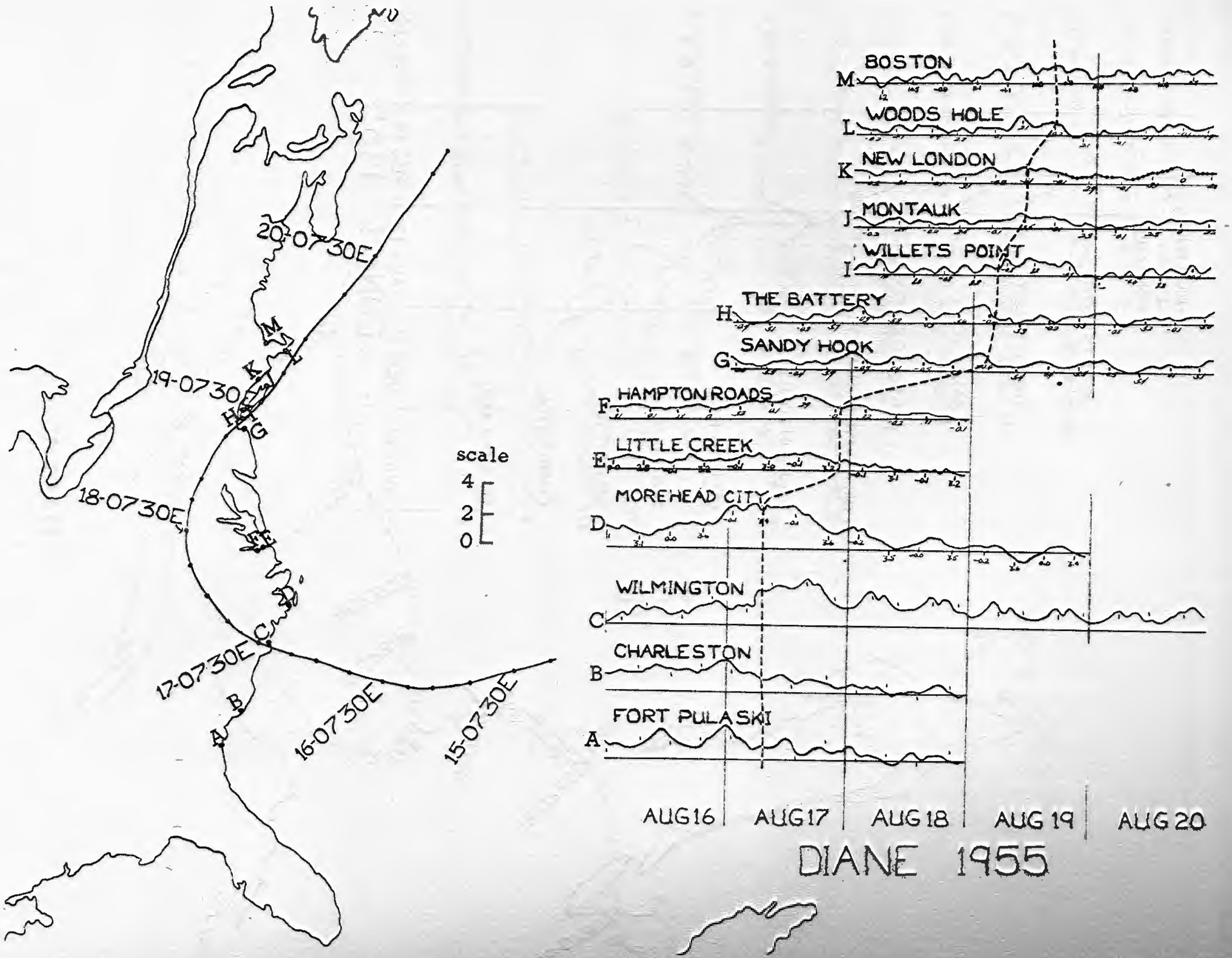

M NEW LONDON
L MONTAUK
K WILLETS POINT
J THE BATTERY
I SANDY HOOK
H ATLANTIC CITY
G BREAKWATER HARBOR
F HAMPTON ROADS
E LITTLE CREEK
D MOREHEAD CITY
C WILMINGTON
B CHARLESTON
A FORT PULASKI
AUG 10
AUG 11
AUG 12
AUG 13
AUG 14
scale
4
2
0
CONNIE 1955
14-0730E
13-0730E
12-0730E
11-0730E
10-0730E
9-0730E
8-0730E
7-0730E
A
B
C
D
E
G
H
I
J
K
L
M

FIGURE 10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19-0730E
18-0730E
17-0730E
16-0730E
15-0730E
A
B
C
D
E
F
G
H
K
L
M
scale
4
2
0
M BOSTON
L WOODS HOLE
K NEW LONDON
J MONTAUK
I WILLETS POINT
H THE BATTERY
G SANDY HOOK
F HAMPTON ROADS
E LITTLE CREEK
D MOREHEAD CITY
C WILMINGTON
B CHARLESTON
A FORT PULASKI
AUG16
AUG17
AUG18
AUG 19
AUG 20
DIANE 1955

FIGURE 11

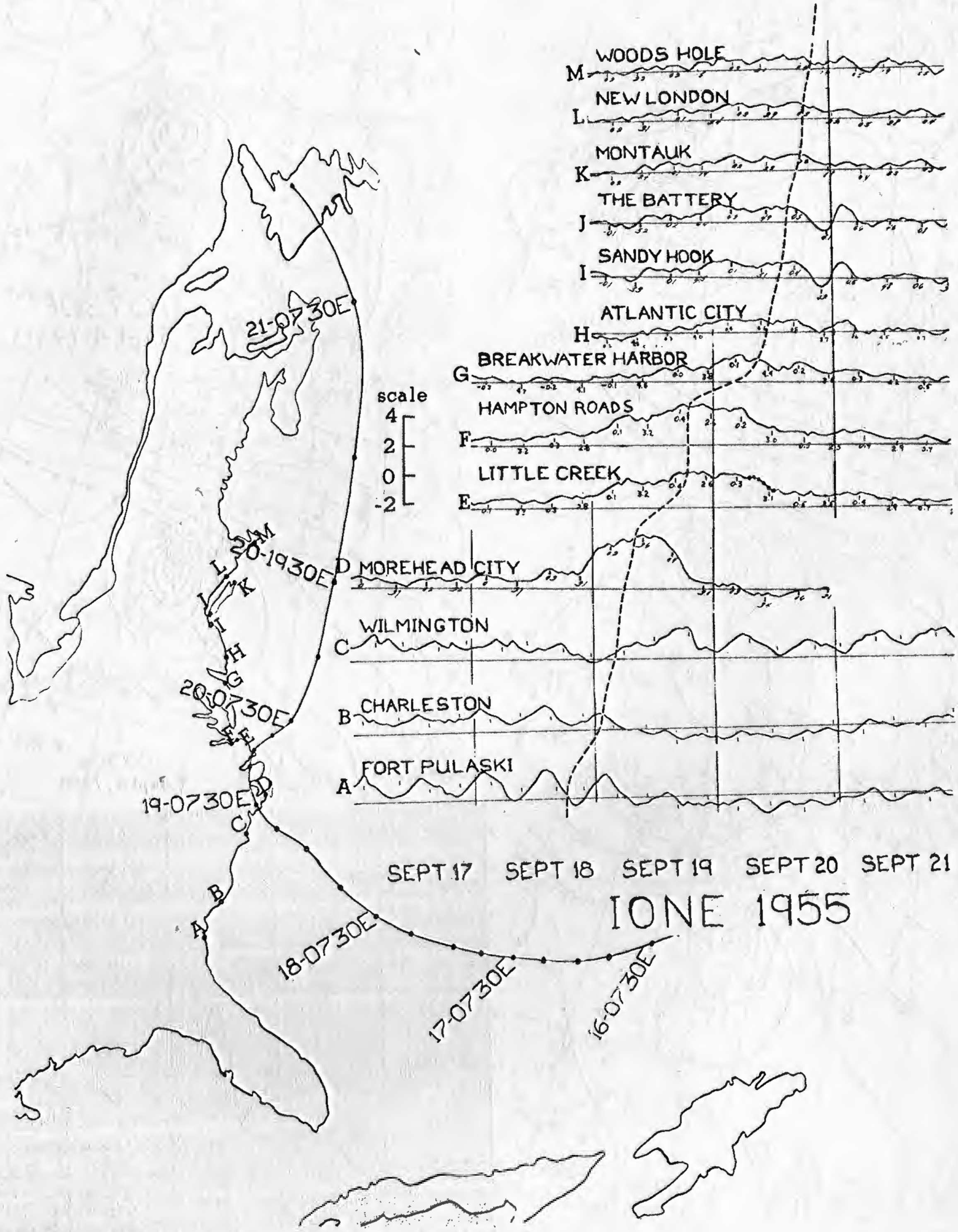
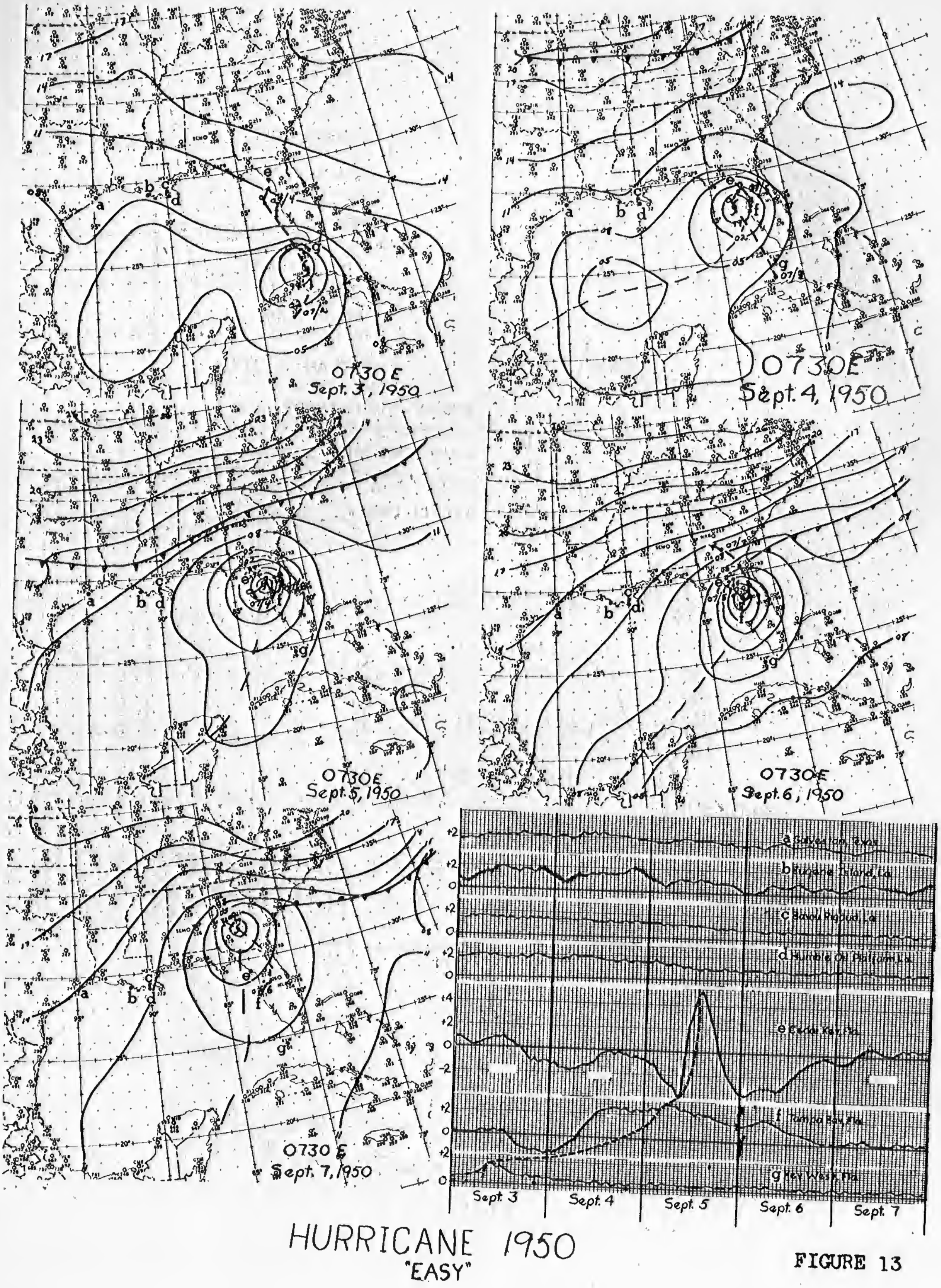
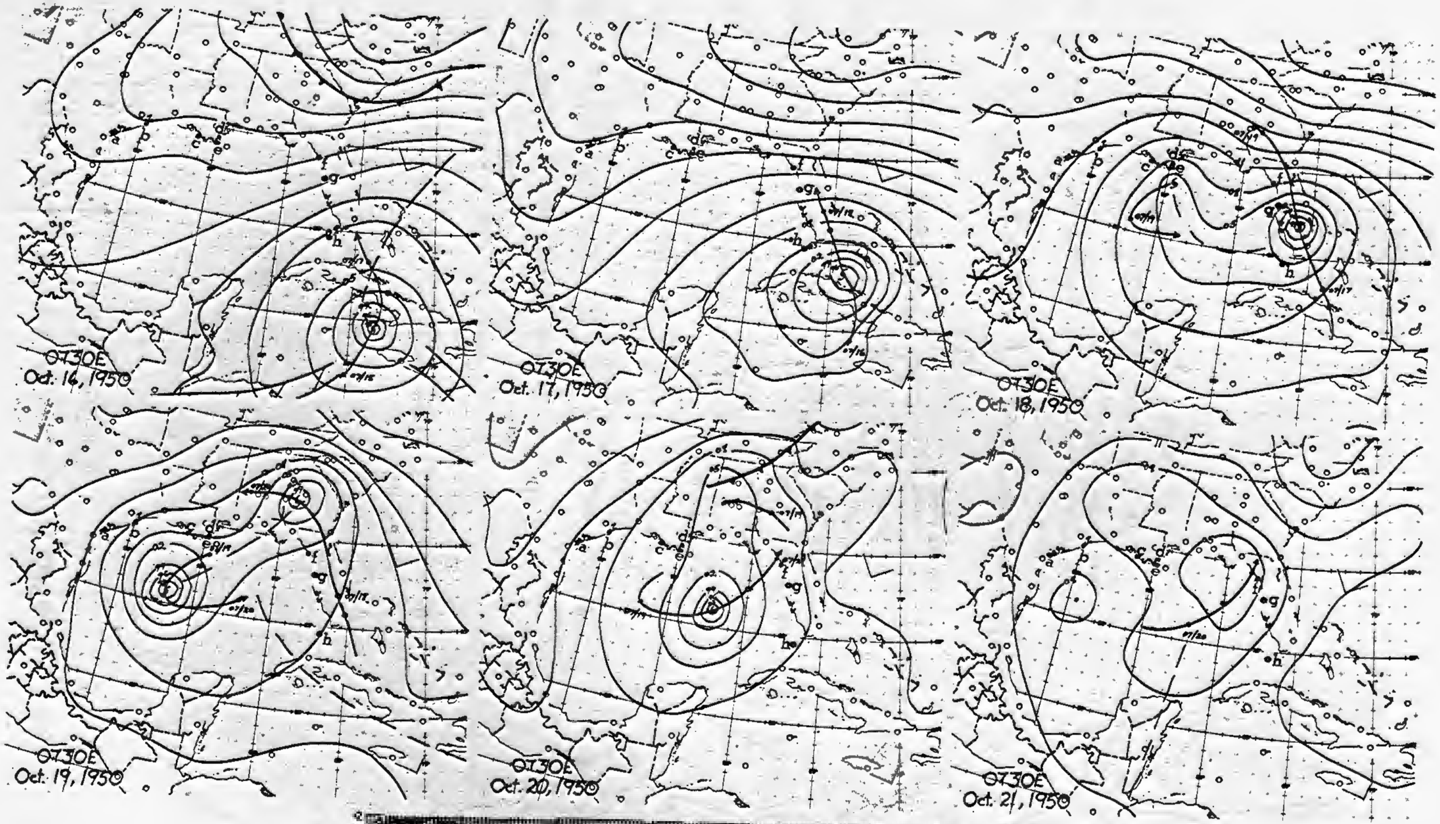

WOODS HOLE
M
NEW LONDON
L
MONTAUK
K
THE BATTERY
J
SANDY HOOK
I
ATLANTIC CITY
H
BREAKWATER HARBOR
G
HAMPTON ROADS
F
LITTLE CREEK
E
MOREHEAD CITY
D
WILMINGTON
C
CHARLESTON
B
FORT PULASKI
A
scale
4
2
0
-2
SEPT 17
SEPT 18
SEPT 19
SEPT 20
SEPT 21
IONE 1955
21-0730E
20-1930E
20-0730E
19-0730E
18-0730E
17-0730E
16-0730E

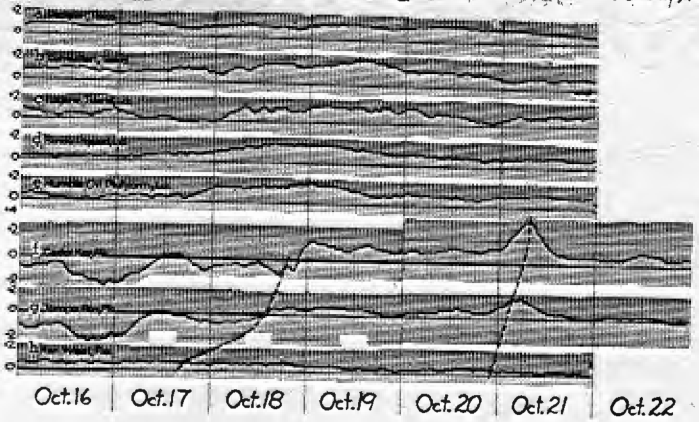
FIGURE 12



HURRICANE 1950
"EASY"

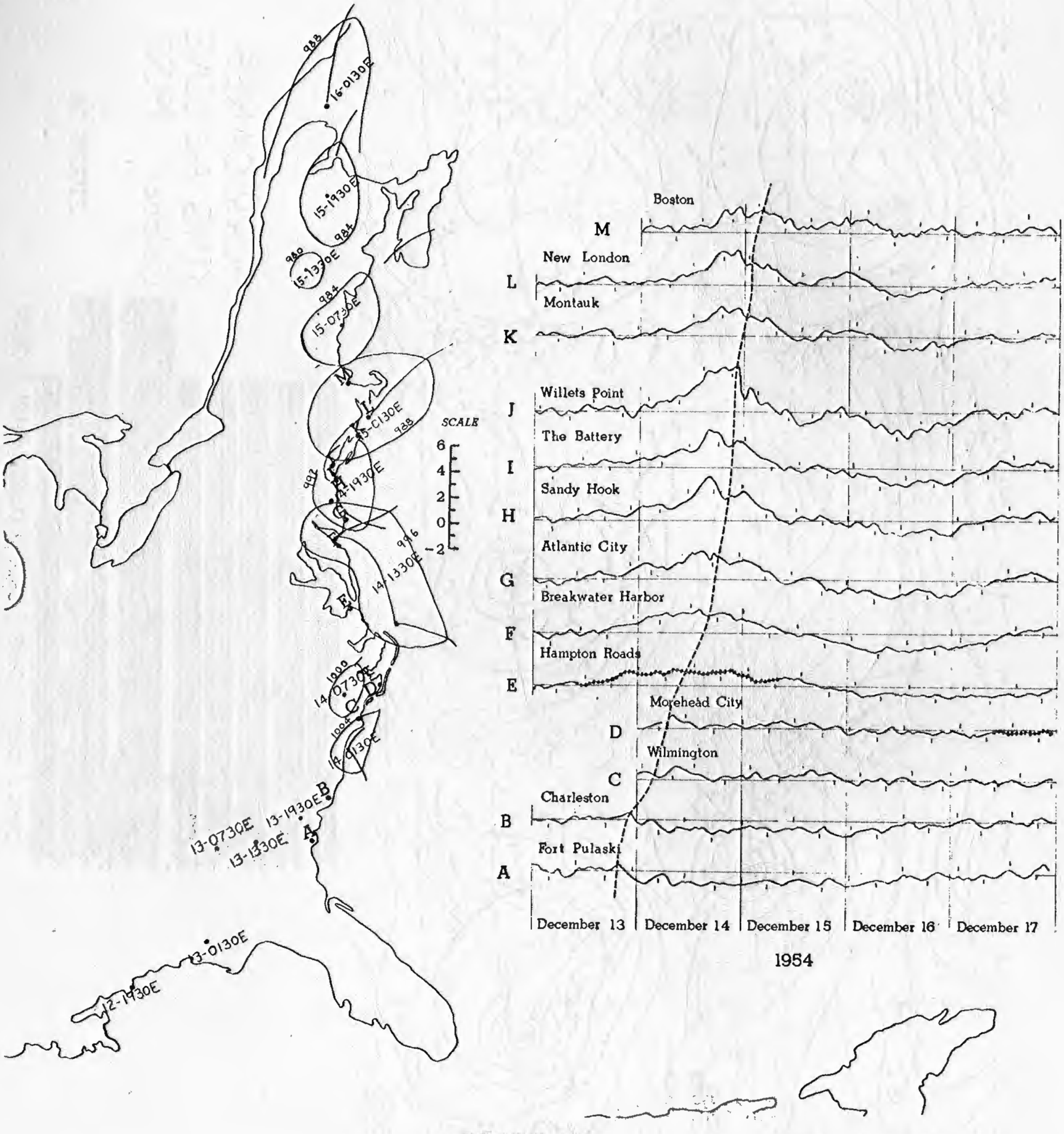
FIGURE 13





HURRICANES
KING And LOVE
October 1950

FIGURE 14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988
15-1930E
984
980
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M
L
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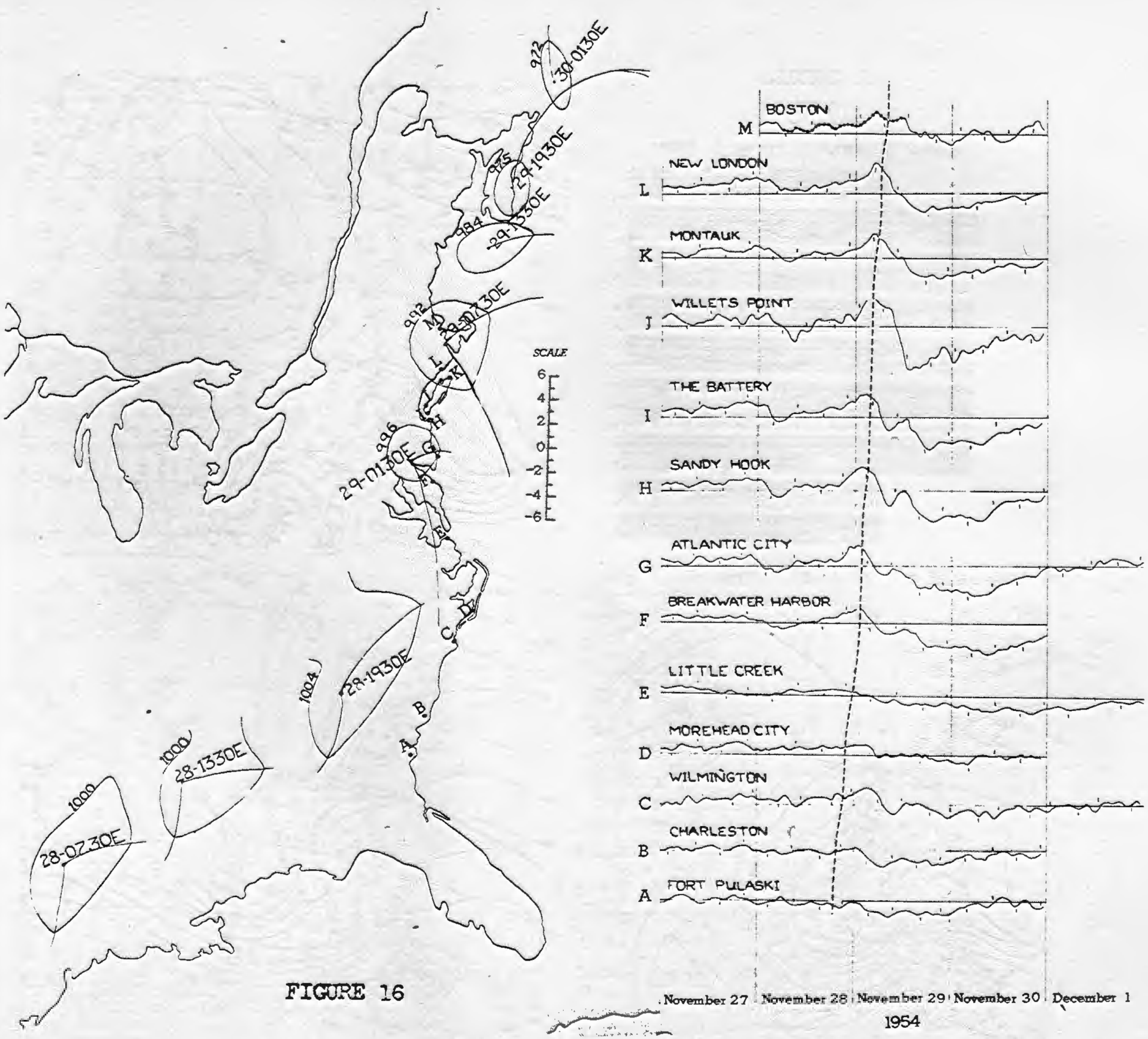
988
K
14-1930E
992
H
G
996
14-1330E
E
1000
14-0730E
C
D
1004
14-0130E
B
13-1930E
A
13-0730E
13-1330E
13-0130E
12-1930E
SCALE
6
4
2
0
−2
Boston
M
New London
L
Montauk
K
Willets Point
J
The Battery
I
Sandy Hook
H
Atlantic City
G
Breakwater Harbor
F
Hampton Roads
E
Morehead City
D
Wilmington
C
Charleston
B
Fort Pulaski
A
December 13
December 14
December 15
December 16
December 17
1954

FIGURE 15


30-0130E
972
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1004
28-1330E
1000
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SCALE
6
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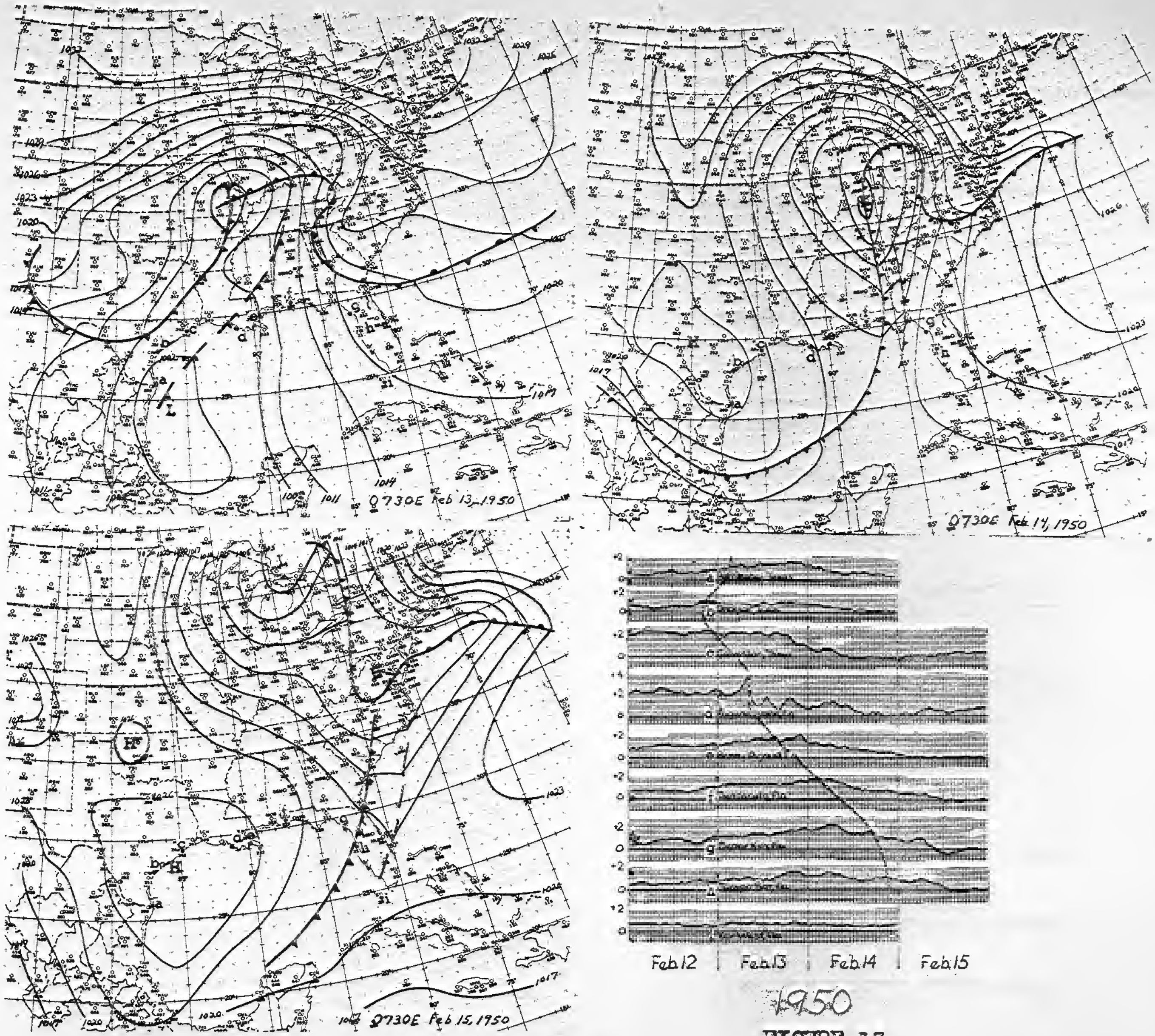
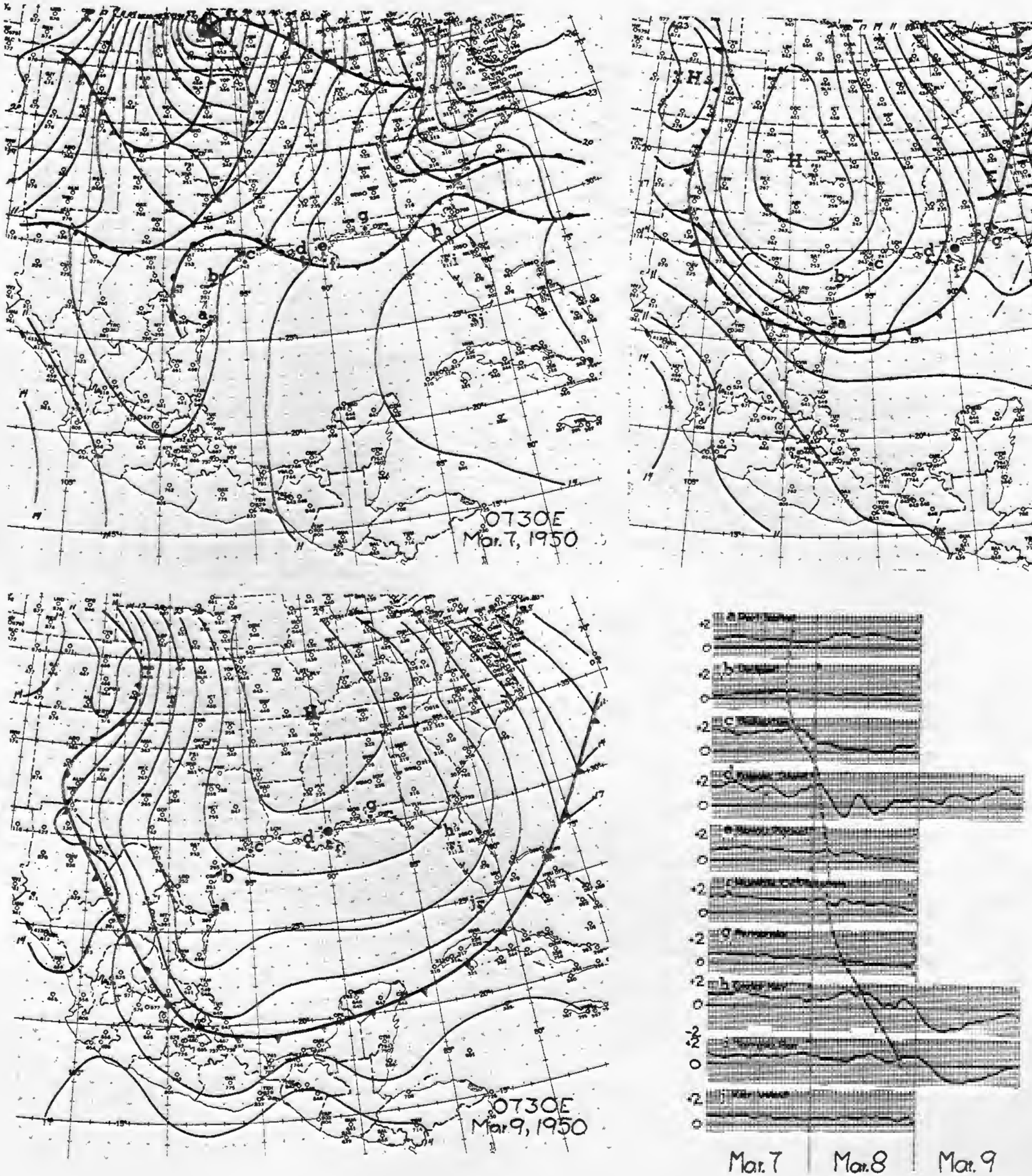
-2
-4
-6
M BOSTON
L NEW LONDON
K MONTAUK
J WILLETS POINT
I THE BATTERY
H SANDY HOOK
G ATLANTIC CITY
F BREAKWATER HARBOR
E LITTLE CREEK
D MOREHEAD CITY
C WILMINGTON
B CHARLESTON
A FORT PULASKI
November 27
November 28
November 29
November 30
December 1
1954

FIGURE 16



1950

FIGURE 17



1950

FIGURE 18

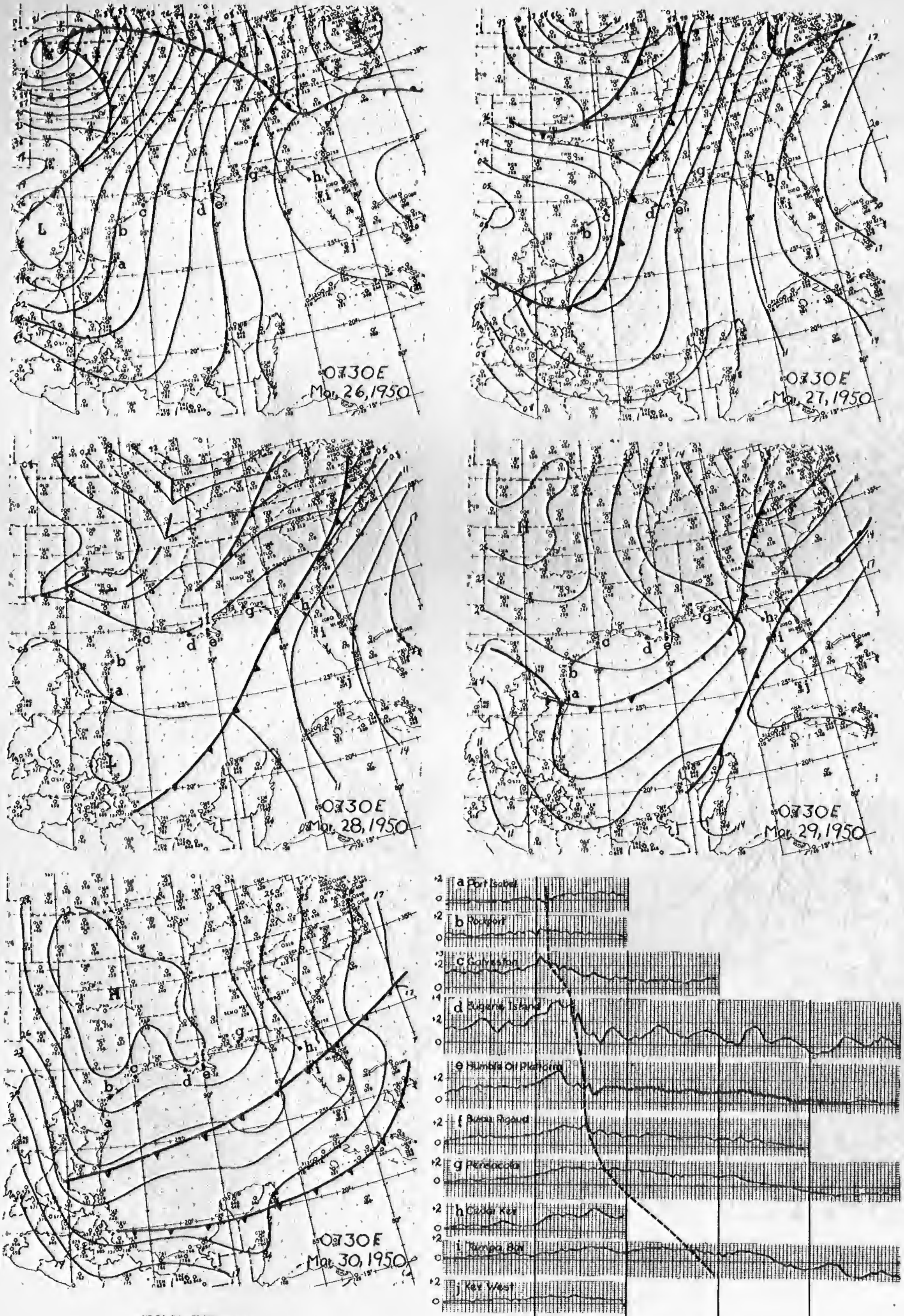
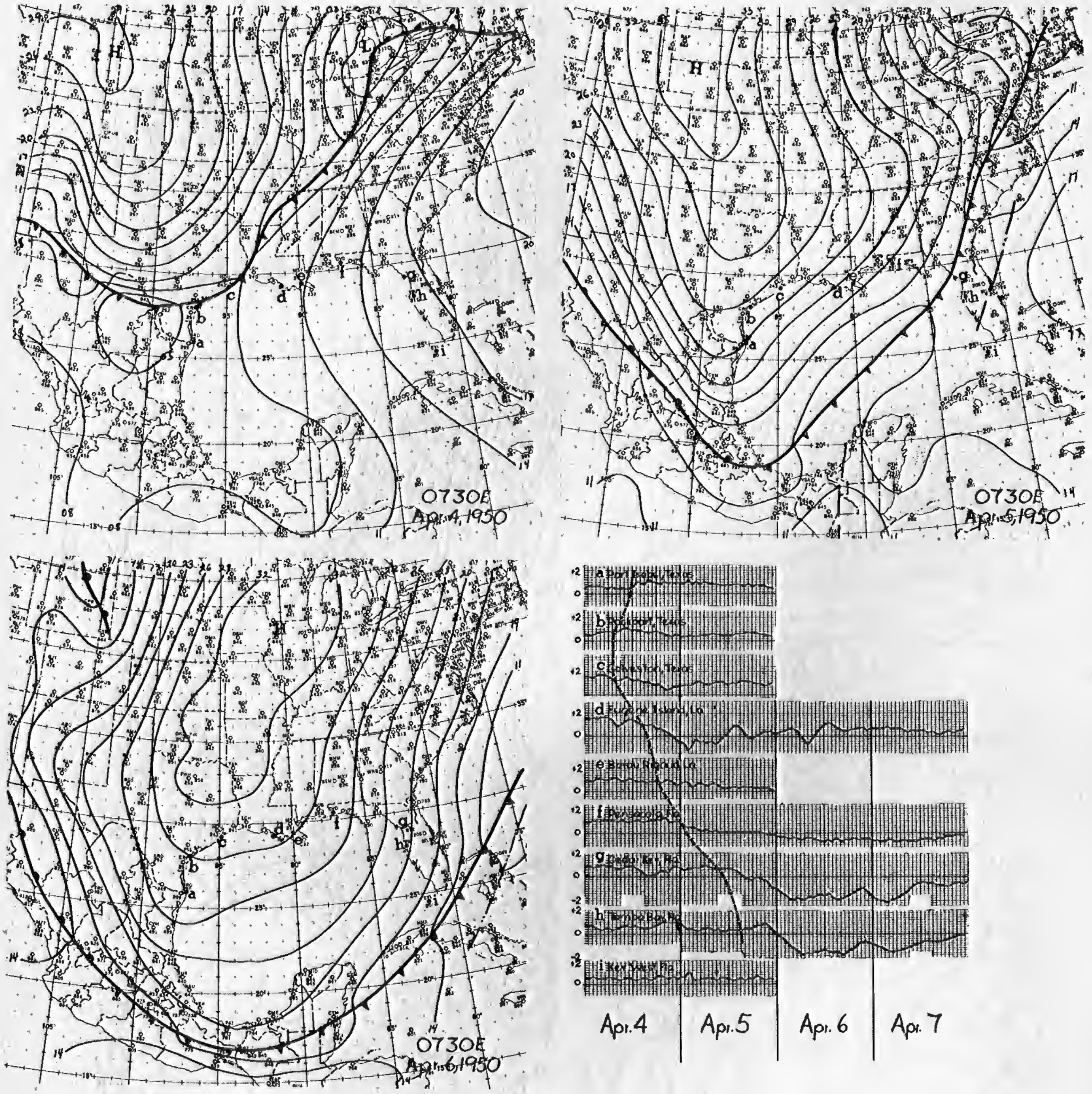
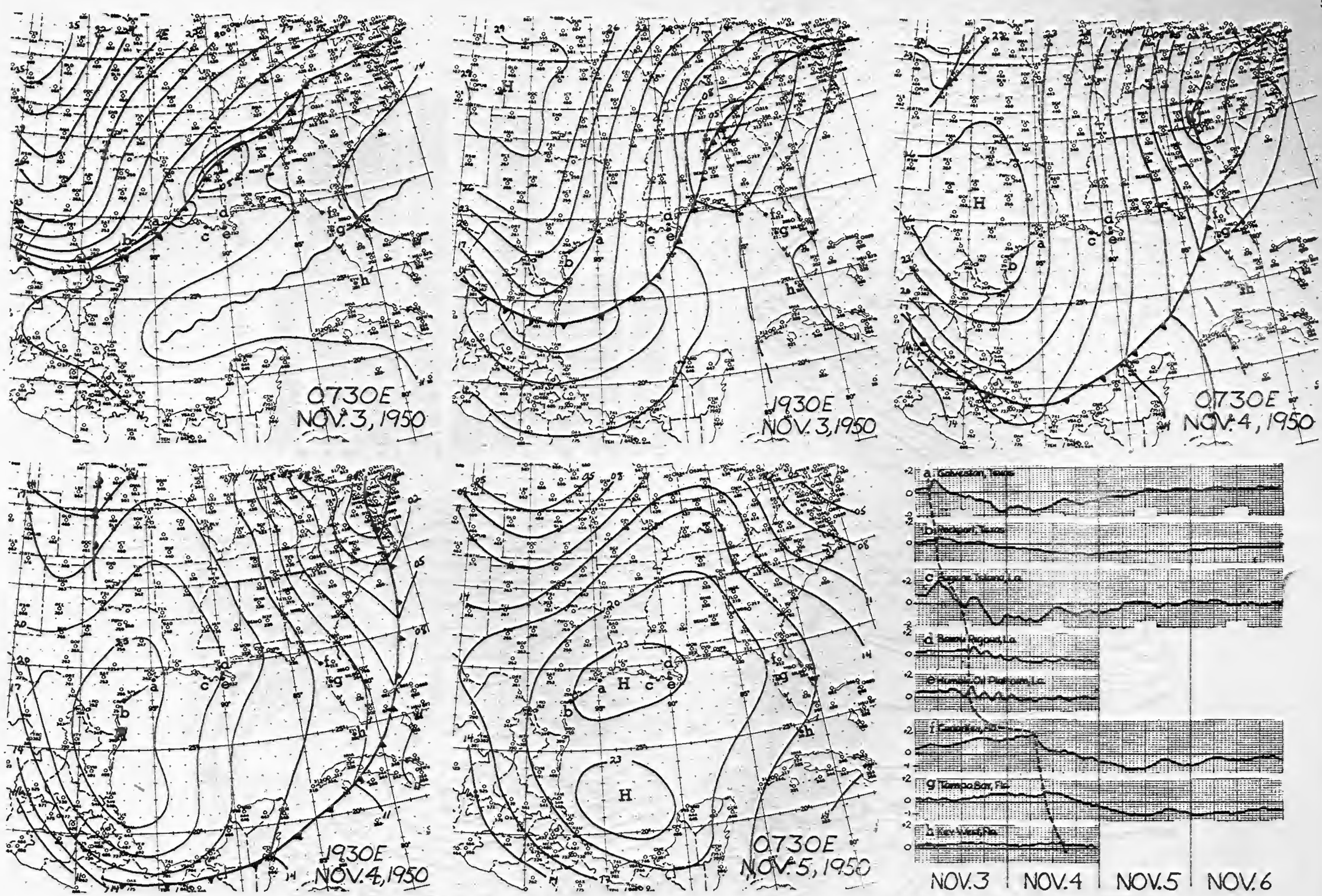

0730E
Mar. 26, 1950
0730E
Mar. 27, 1950
0730E
Mar. 28, 1950
0730E
Mar. 29, 1950
0730E
Mar. 30, 1950
a Port Isabel
b Rockport
c Galveston
d Eugene Island
e Humble Oil Platform
f Bayou Rigaud
g Pensacola
h Cedar Key
i Tampa Bay
j Key West
Mar. 26
Mar. 27
Mar. 28
Mar. 29
Mar. 30

FIGURE 19



1950

FIGURE 20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NOV. 3, 1950
1930E
NOV. 3, 1950
0730E
NOV. 4, 1950
1930E
NOV. 4, 1950
0730E
NOV. 5, 1950
H
a Galveston, Texas
b Rockport, Texas
c Eugene Island, La.
d Bayou Rigaud, La.
e Humble Oil Platform, La.
f Cedar Key, Fla.
g Tampa Bay, Fla.
h Key West, Fla.
+2
0
-2
-1
NOV.3
NOV.4
NOV.5
NOV.6

FIGURE 21

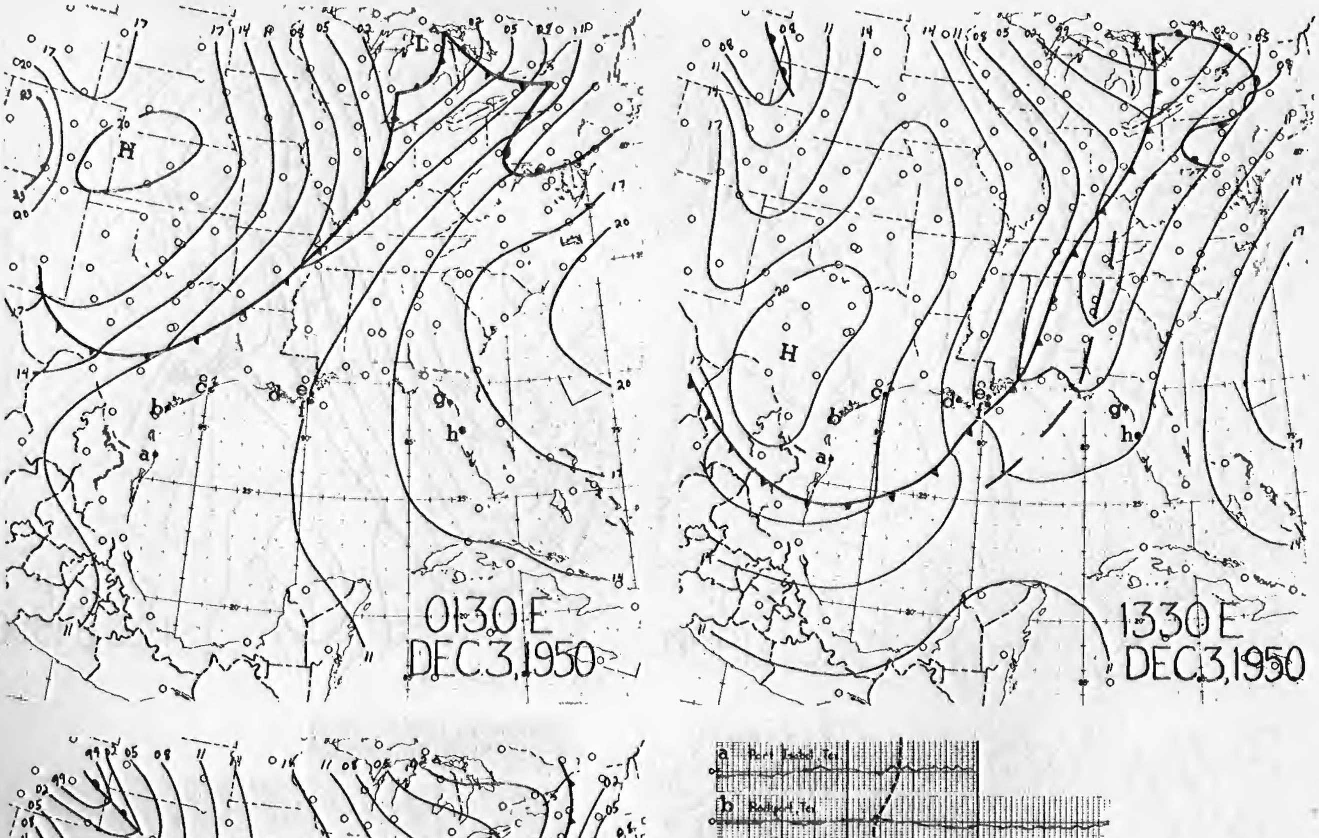
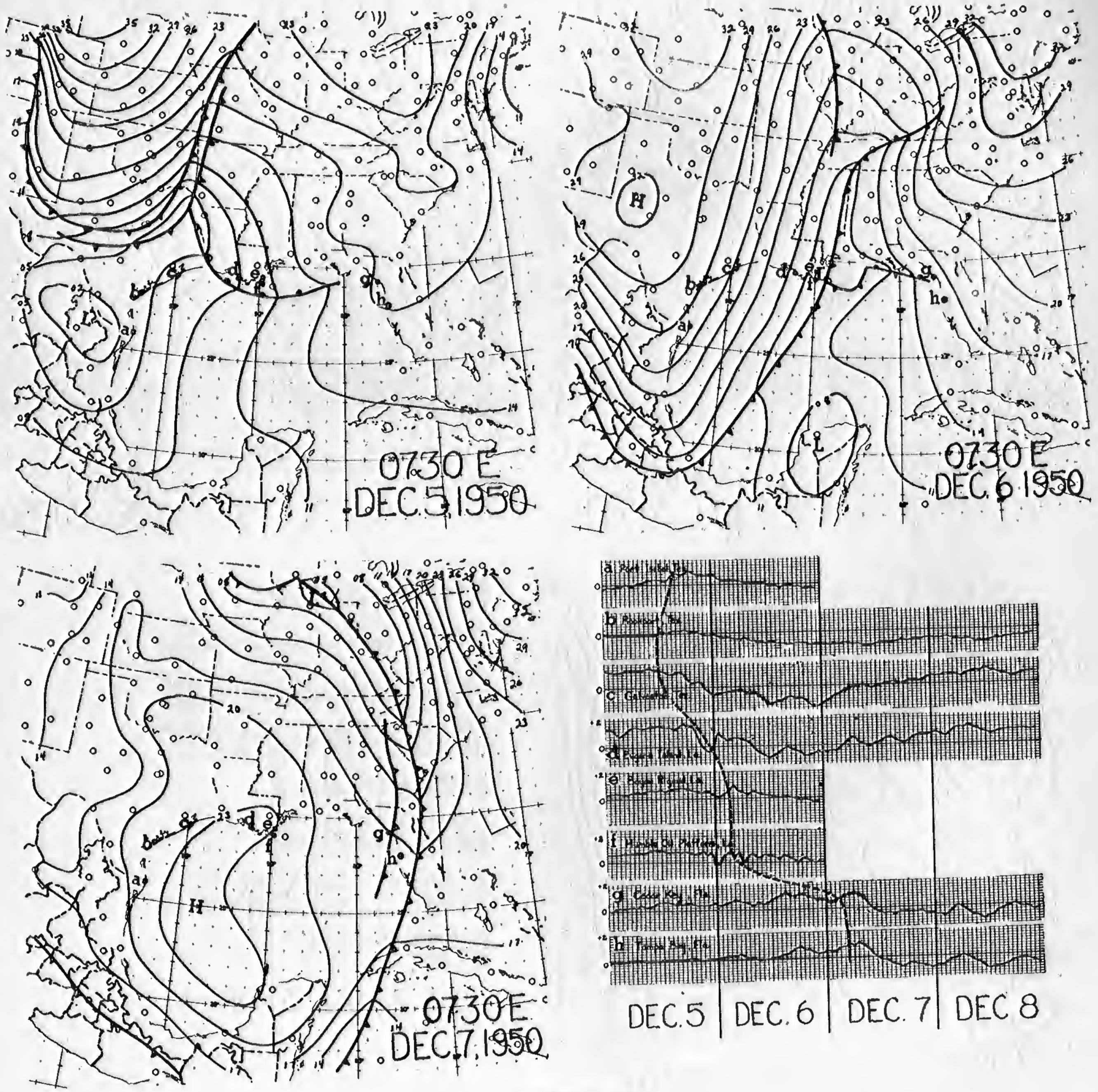

0130 E
DEC.3,1950
1330 E
DEC.3,1950
0130 E
DEC.4,1950
H
L
a
b
c
d
e
f
g
h
a Port Isabel, Tex.
b Rockport, Tex.
c Galveston, Tex.
d Eugene Island, La.
e Bayou Rigaud, La.
f Humble Oil Platform, La.
g Cedar Key, Fla.
h Tampa Bay, Fla.
DEC. 2
DEC. 3
DEC. 4

FIGURE 22


0730 E
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0730 E
DEC. 6 1950
0730 E
DEC. 7 1950
H
L
a
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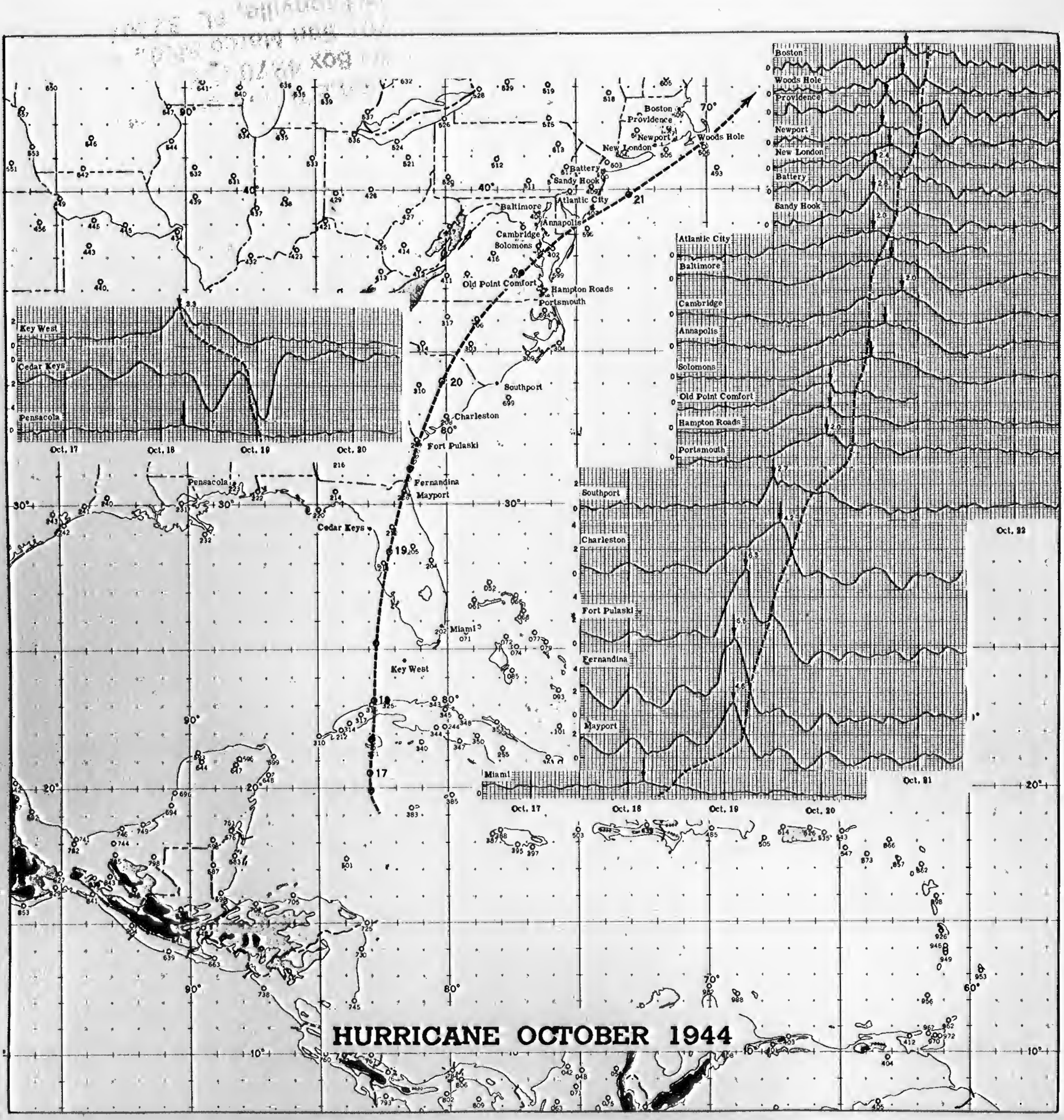
d
e
f
g
h
a Port Isabel, Tex.
b Rockport, Tex.
c Galveston
d Pecan Island, La.
e
f Humble Oil Platform, La.
g Cedar Key, Fla.
h
DEC. 5
DEC. 6
DEC. 7
DEC 8

FIGURE 23

plate 1.



HURRICANE OCTOBER 1944

plate 2.

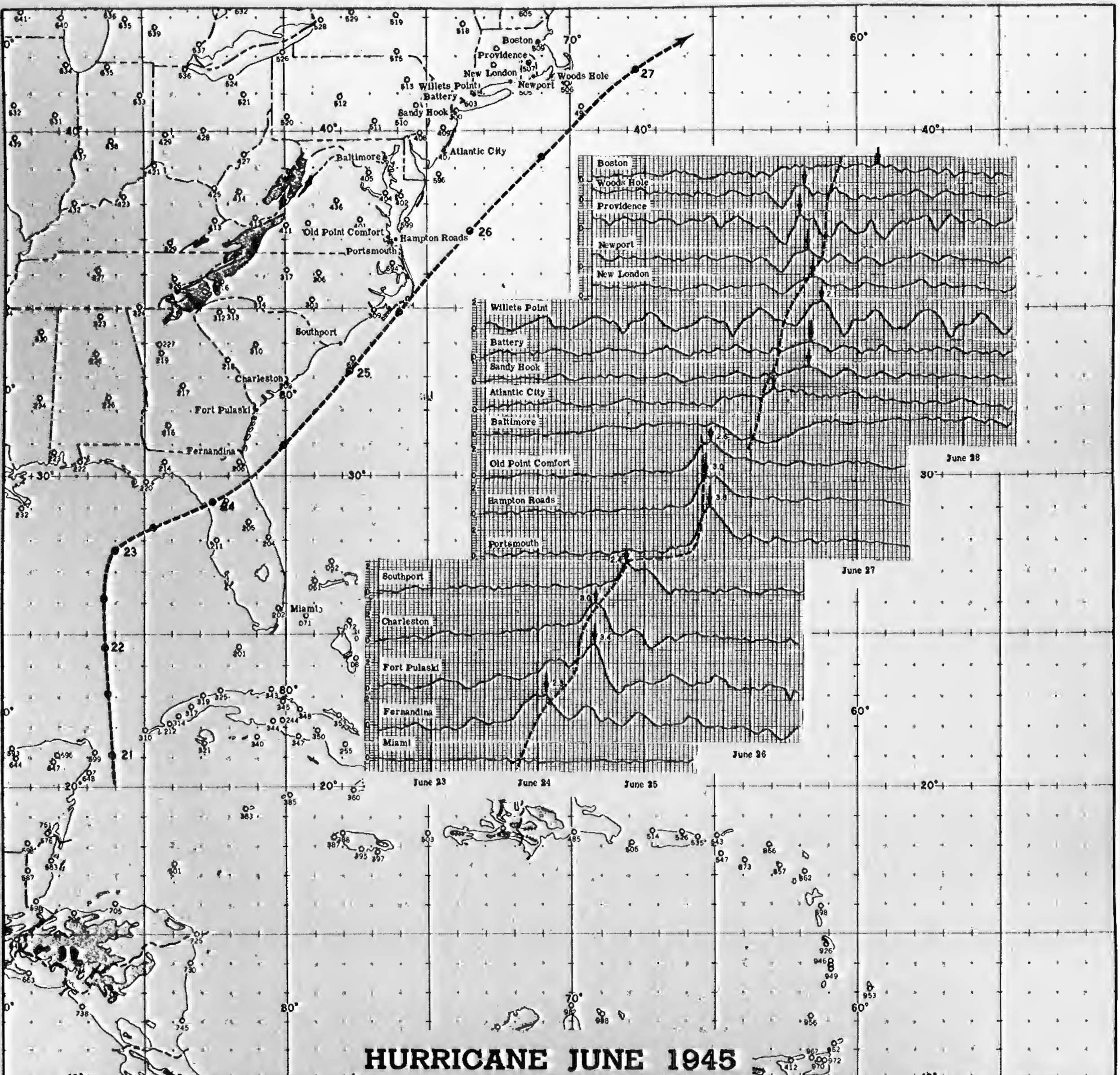
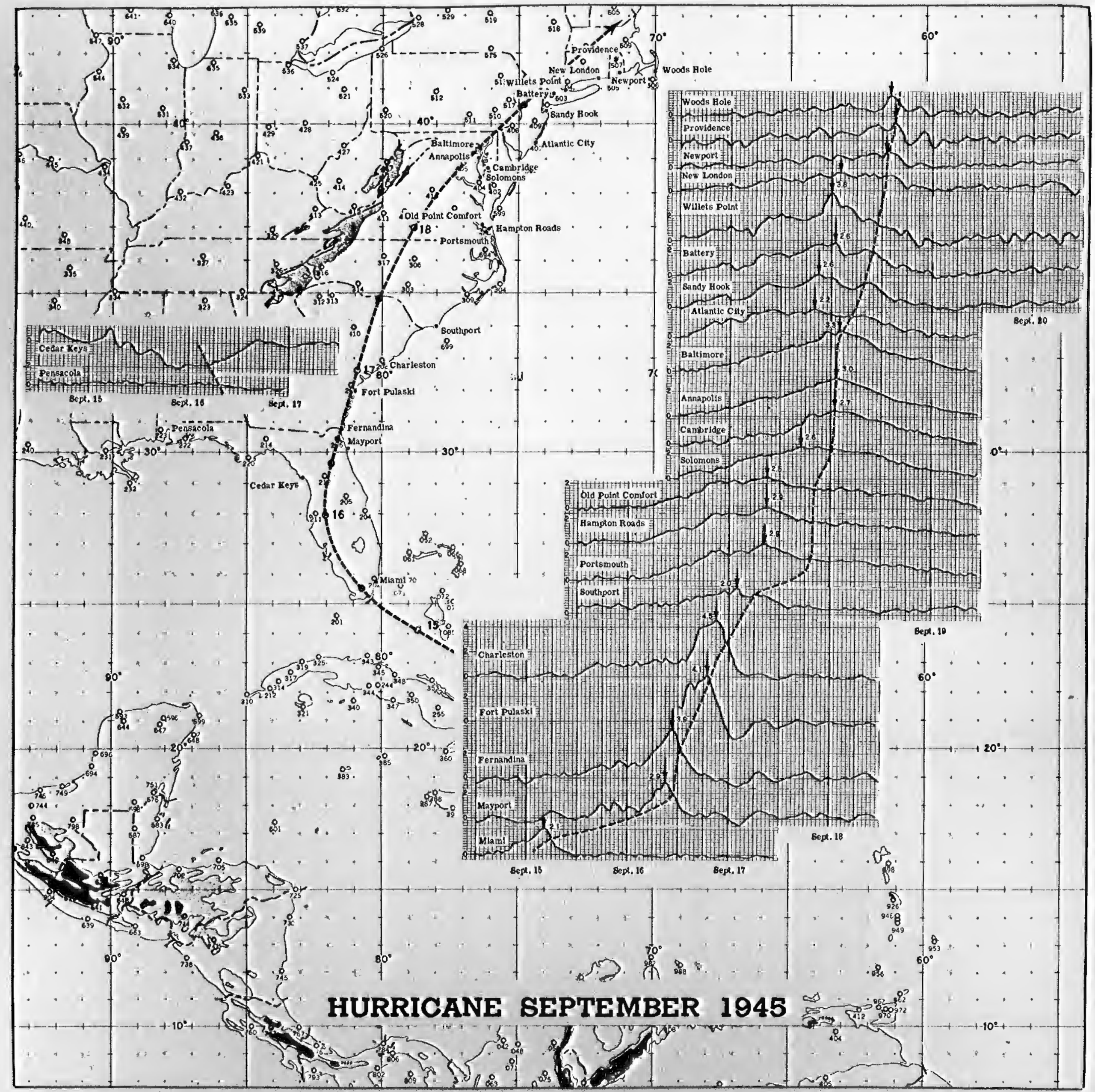
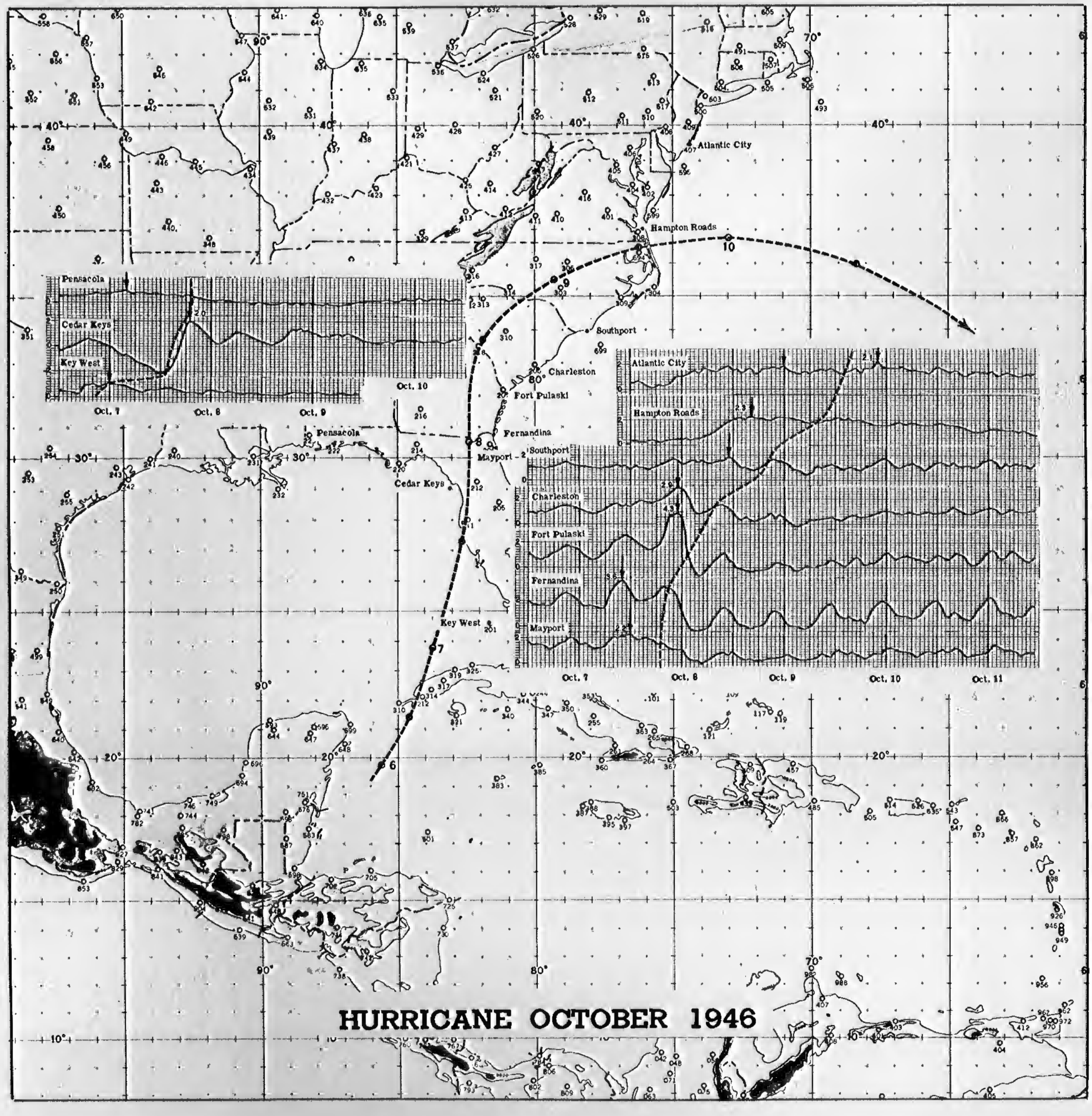

HURRICANE JUNE 1945

plate 3



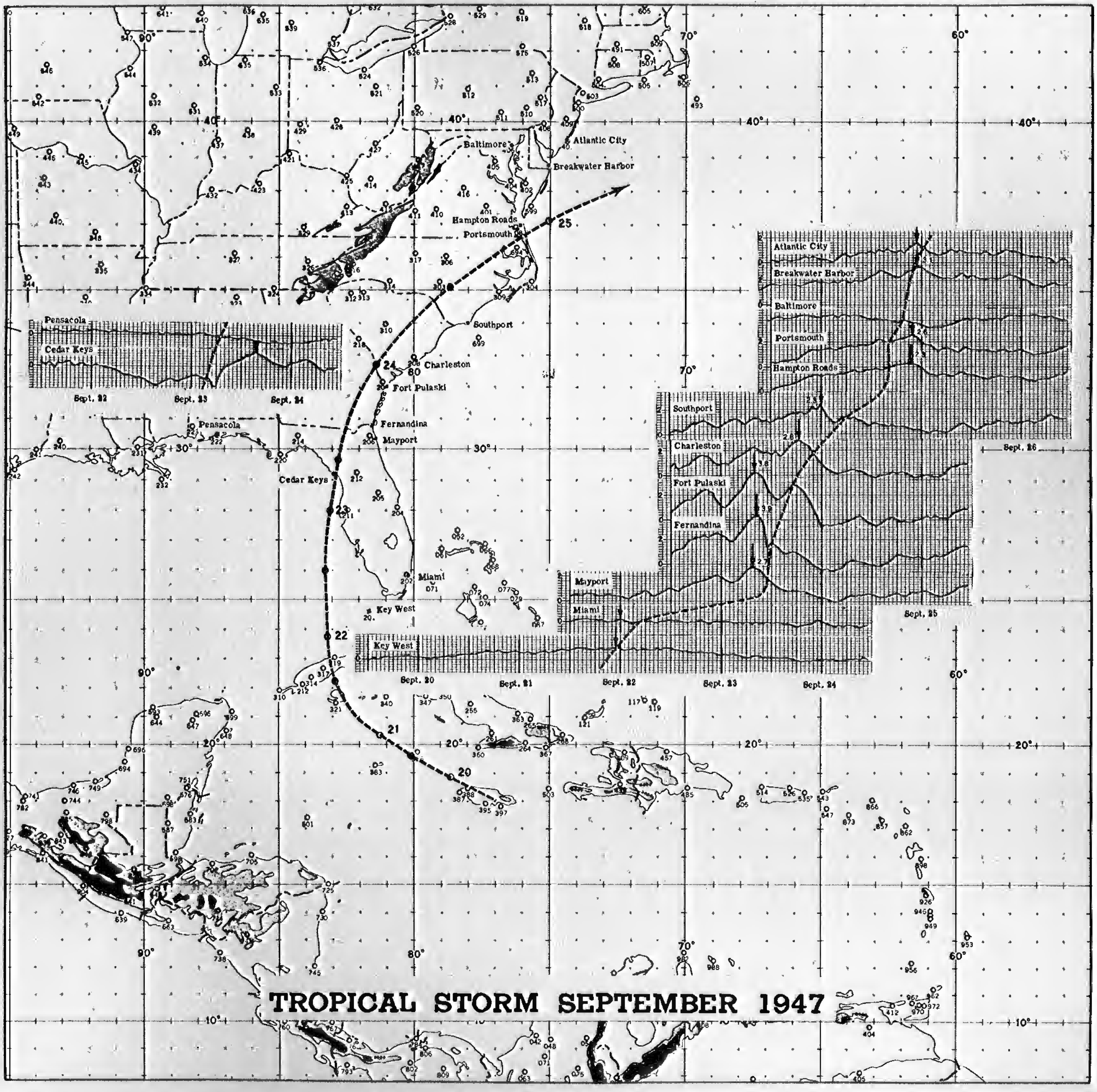
HURRICANE SEPTEMBER 1945

plate 4



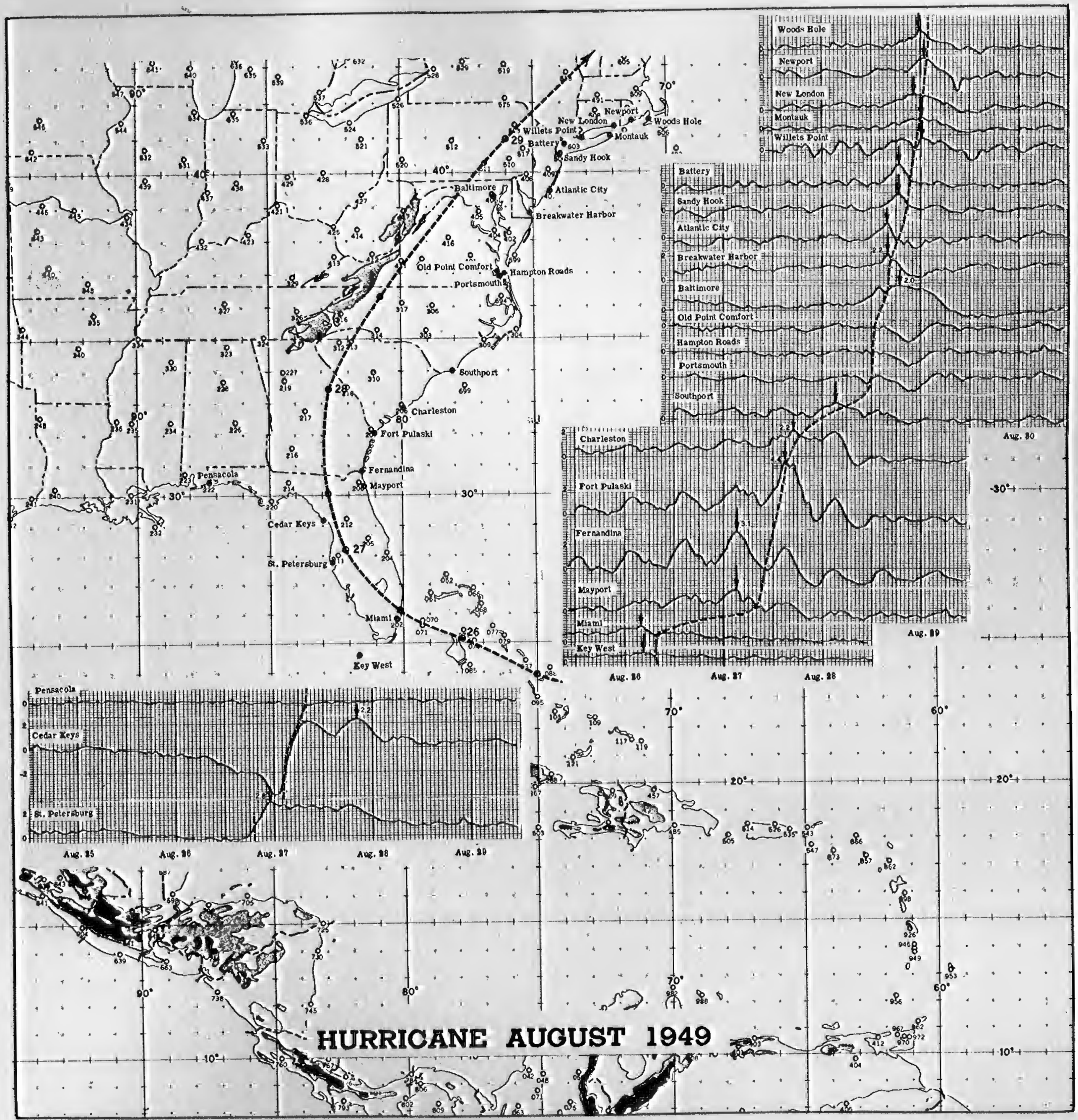
HURRICANE OCTOBER 1946

plate 5.



TROPICAL STORM SEPTEMBER 1947

plate 6.



HURRICANE AUGUST 1949