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Characteristics of the Hurricane Storm Surge

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Characteristics of the Hurricane Storm Surge

D. LEE HARRIS
U.S. Weather Bureau

WASHINGTON, D.C.
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CHARACTERISTICS OF THE HURRICANE STORM SURGE

D. LEE HARRIS

U.S. Weather Bureau, Washington, D.C.

Part One

General Discussion

1. INTRODUCTION

Abnormally high water levels along the coasts have long been associated with the passage of hurricanes and other severe storms. Below normal water levels associated with the passage of storms have also been reported on numerous occasions. Accurate and detailed observations of the abnormal water levels during hurricanes are difficult to acquire and few systematic collections of such data are available.

Because of this lack of basic data, theoretical research has been largely restricted to calculations based on unverified postulates concerning the phenomena involved and on attempts to evaluate them by the available empirical data. Although studies of this kind have led to a better understanding of the phenomena, they have not led to the development of any outstandingly successful prediction systems.

An effort has been made by the Storm Surge Research Project associated with the National Hurricane Research Project to collect all of the available quantitative data for storm surges produced by tropical cyclones and hurricanes of the last half a century in the United States in order to provide the basic data necessary for an identification of the phenomena responsible for the changes in water level associated with hurricanes in coastal regions. These data have been useful in improving the hurricane warning system and are being used as a guide for our theoretical research.

The amount of data available from various hurricanes varies greatly and almost all of it is subject to numerous uncertainties in interpretation. Although these uncertainties require careful examination in any quantitative study of the phenomenon, most of them can be disregarded in a discussion of the principal characteristics of coastal floods. Familiarity with the characteristics of coastal floods caused by hurricanes will provide perspective for evaluating the importance of the aforementioned uncertainties as they are discussed. Therefore, this report will begin with a discussion of the principal characteristics of the coastal flooding produced by hurricanes and of the physical processes which are believed to account for the observations. This will be followed by a discussion of the assembled data, the methods used in processing the data, and the resulting uncertainties in the final figures. The assembled data from a number of the best documented hurricane storm surge cases will be presented in Part Two of the report.

Previous collections of hurricane storm high water data in the United States have been published by Okey [75], Cline, [5, 6], Harris [41] and Redfield and Miller [83]. Significant contributions to the subject have been given in unpublished reports by the various Atlantic and Gulf Coast Districts and Division Offices of the U.S. Army Corps of Engineers, and by Hubert and Clark [48]. Data for Charleston, S.C. have been published by Zetler [116]. Data for Chesapeake Bay and Delaware River have been published by Bretschneider [1, 2], and for Chesapeake Bay by Pore [79]. None of the data presented by Okey or Cline is repeated here. Some of the original data used by later writers have been reviewed and are included. A few discrepancies between these data and those previously published resulted from the corrections determined after first publication of the data, or from differences in the interpretation of the data.

2. LOCAL VARIABILITY OF THE HIGH WATER LINE

Many phenomena contribute to the rise and fall of the water surface at a beach. These vary in scale from the familiar surface waves with periods in the order of a few seconds and in horizontal dimensions from a hundred to a thousand feet, up to secular trends in sea level which may involve half of the Atlantic Ocean. This report is concerned primarily with those storm-produced changes in water level that are larger in horizontal dimensions and longer in period than the clearly distinguishable surface waves. The surface waves and the larger-scale phenomena are discussed only to the extent required for an understanding of the storm-induced changes in water level. The term "water level" is used to indicate the mean elevation of the water surface when averaged over the shortest period of time sufficient to eliminate the clearly discernible surface waves. Generally this means about a 1-minute period.

The difficulty in eliminating the short-period waves from the water level observations greatly limits the number of such observations obtained for hurricane conditions. The direct effects of the short-period surface waves are greatly reduced by the stilling well used with most recording tide gages. Occasionally closed buildings serve as stilling wells and a debris line left on the walls of such a building may give a good indication of the maximum water level in the vicinity. Occasionally an eye witness reports the variation of the water level in sufficient detail to fix the maximum level to the nearest inch or two. In some areas of the country maximum stage water level gages (Saville [90]), which dampen the waves' amplitude by an order of magnitude or more and record only the highest water level since the last setting of the gage have been widely installed. Data obtained by a combination of these means serve to show the local variability of the maximum water level due to a storm. Supplementary high water mark charts are included for storms for which relatively dense observations of this kind have been obtained. These are indicated in the list of figures.

The variability of the high water elevations within small geographic regions shown by these charts suggests that little is to be gained from showing similiar charts where the average spacing between data points is 10 miles or more. In several cases, pairs of observations which appear to show too great a variation for the short distance which separates them have been verified by independent surveys made only a few days after the initial survey. There is no longer any doubt about the reality of these local variations. They must be recognized and explained satisfactorily by any theory of the effects of storms on sea level.

3. TIME VARIABILITY OF THE WATER LEVEL

The original water level records as well as the tabulated hourly values were examined for most of the data presented in this report. The hourly values were found to be sufficient for a study of the significant storm effects in almost all cases but a few notable exceptions were found. In general, these appear to be more pronounced in the records of the gages exposed in the open ocean or the Gulf of Mexico than in the records obtained from estuaries. An outstanding example of short-period oscillations not adequately represented by hourly values is shown in figure 10.3 with the discussion of the hurricane of September 21, 1944, at Atlantic City, N. J. Other examples are shown in figures 24.6 and 24.7 for hurricane Audrey, June 26–27, 1957.

Although some prominent features of the storm effect on sea level are revealed by the original records, they are usually somewhat obscured by the normal astronomical tide, especially at locations with a large semidiurnal tide range. This obscuration is avoided in most of the records shown in this collection by showing only the storm surge. The storm surge is defined as the difference between the observed water level and that which would have been expected at the same place in the absence of the storm. The method of accomplishing this is discussed in section 8. In a few cases in which the normal tide range at the time of the storm was small relative to the disturbance and the best available approximation to the normal tide was much less than ideal, the original data only are shown.

Continuous water level records from several locations within the same estuary can reveal considerable information about the source of any anomaly. If all records are similar excepting for a phase lag which increases with distance from the coast it is reasonable to assume that the disturbance was generated on the open coast and is being propagated up the estuary as a progressive wave. Occasionally all records are similar but no significant phase lag appears and the disturbance may be interpreted as a standing wave forced by a disturbance generated on the open coast. Most of the storm surge records do have the general appearance of a forced wave. However. there are some notable exceptions.

There are two paths for any tide entering New York City: one from the south through New York Bay and the other from the east through Long Island Sound. The records presented here, especially for the most prominent storms in the area in 1938, 1944, and 1954 show that both paths are traversed by the storm surge. The surge traveling through the Sound may arrive in the western end of the Sound after all other aspects of the the storm have abated; for the travel time through the Sound is much longer than that from the south. In several cases it is possible to identify the impulse arriving at some of the tide recorders by each route. In most cases the surge from the south is the larger of the two but the surge traveling through the Sound was largest in the hurricanes of September 1938, September 1944, and August 30, 1954.

An out-of-phase relationship between the records for Baltimore and Norfolk in several storms, especially those in which the center remained east of Chesapeake Bay (Pore [79]) shows that, for these storms, movement of water already within the Bay is about as important in producing tide anomalies within the Bay as any process going on in the open sea.

The records for the Delaware River during the hurricane of September 1936, suggest a similar process, but the Philadelphia record appears to be complicated by the effects of rainfall runoff. A comparison of the records for High Point, Tex., at the eastern end of Galveston Bay, with those for Galveston and other stations on the western side of the Bay also suggests that the movement of Bay water is prominent in producing the flooding around the shores of the Bay. See the records for the storms of October 2–5, 1949, June 30, 1957, and September 7–12, 1961.

The pattern of high water marks and the subjective reports of the water level changes associated with several other hurricanes suggest that many of the high water levels reported along the shores of bays are due as much to the effects of the wind over the bay as to any development in the open ocean. Sufficient data for a definitive determination of the mechanism involved are available for very few cases.

A comparison of the wind records with the storm surge curves shows that in many cases the surge begins to rise during periods when the local wind is blowing from the land to the sea, and that the water may begin to fall when the wind moves into a quadrant with an onshore component.

The data presented in this report give little support for the concept of a "forerunner" heralding the approach of a hurricane, mentioned by many earlier writers. In a parallel study by this author and his associates and in a published paper by Donn [20] it is shown that northeast winds along the Atlantic Coast of the United States are usually associated with above-normal tide levels. This is true throughout the year regardless of hurricanes. Northeast winds, associated with an anticyclone to the north frequently occur over much of the Atlantic coast for a day or two before the arrival of a hurricane. This local wind field is usually a sufficient cause for any observed abnormal tides more than a few hours before the hurricane circulation itself is felt. Short-period anomalies in the mean sea level, not related to the hurricane, but not fully explained, may account for some of the reported "forerunners." These are discussed in more detail in Section 12.

4. PROCESSES OF STORM SURGE GENERATION

A unified theory of the hydrodynamic processes involved in storm surge generation has been proffered by Fortak [30] but the principal equation, even in tensor notation, fills most of a page. This unified theory gives a great deal of insight into the storm surge generation process but much additional development work will be needed before the results can be used in quantitative calculations. It is believed that a nonmathematical treatment of the subject will be more useful for the purposes of this report. The ideas presented here are consistent with most of the theory known to the author and most of the available data. They provide a more or less rational framework for interpreting the observations. However, no attempt is being made to present a rigorous development, and modifications in the model are to be expected as theoretical studies continue. References to more rigorous discussions of the theory are given whenever this can be conveniently accomplished.

At least five distinct processes, associated with the passage of a storm, which can alter the water level in tide water regions are recognized. These may be identified as:

a. The pressure effect,
b. The direct wind effect,
c. The effect of the earth's rotation,
d. The effect of waves,
e. The rainfall effect.

a. PRESSURE SET-UP

If the pressure change is not too rapid, the water level in the open ocean will rise in regions of low pressure and fall in regions of high pressure so that the total pressure at some plane beneath the water surface remains constant. The theoretical relation is a rise in water level of 1 centimeter for each millibar drop in atmospheric pressure (13 inches of water for each inch of mercury). This equilibrium state can exist only if there is no restriction to the flow of water into the low pressure region. Thus it should be expected to hold only in the open ocean or along the open coast in regions where the water near the coast is not too shallow. In general, it is difficult to separate this effect from that due more directly to the wind, which is also correlated with the pressure, but whenever this has been accomplished for an open coast location the empirical relation has been found to be within 10 percent of the theoretical value (Proudman [81] Chapter III, Schalkwijk [91], Harris [37], Pore [80]). In these cases this is often referred to as the inverted barometer effect. It cannot be realized in a basin whose horizontal dimensions are small compared to the meteorological disturbance being considered.

If the speed of the atmospheric pressure disturbance is small compared to the shallow water wave speed $(gD)^{1/2}$ where g is the acceleration of gravity and D is the total water depth, one can expect a difference in water level between any two points within the basin which is proportional to the difference in atmospheric pressure. If the pressure disturbance is moving at a speed comparable to the shallow water wave speed, the water level disturbance may be greatly amplified by resonance (Proudman [81], Chapter XIII, Harris [36]).

Although an equilibrium with the reduced atmospheric pressure in a hurricane cannot be realized within a bay, the rise in water level due to this effect at the mouth of an estuary will be propagated into the estuary in much the same manner as the astronomical tide. Thus the correlation between the sea level in an estuary and atmospheric pressure over the estuary may be quite high.

b. DIRECT WIND EFFECT

Theoretical studies of the wind effect over the open ocean in deep water, based on the assumption that the turbulent viscosity is independent of the depth and that the internal friction is proportional to the speed, show that the wind should generate a surface current whose direction is approximately 45° to the right of the wind in the Northern Hemisphere, but that the current should veer to the right with depth at a rate which would give a total transport from bottom to top that is approximately 90° to the right of the wind in the Northern Hemisphere. This is the well-known formulation of the *Ekman Spiral*, first published by Ekman [27] in 1905. The same theory indicates that in shallow water, the currents at all levels should be more nearly parallel to the wind direction, excepting near the coasts where the water is constrained to flow approximately parallel to the depth contours. The depth at which the behavior of the water changes from deep to shallow depends on several poorly determined factors. It is generally about 300 feet at the latitudes considered, but often differs from this by a factor of two and occasionally by a factor of three. Observations show that the surface currents are generally directed to the right of the surface winds but not so far as indicated by the theory. The observed changes with depth are also frequently found to be less than indicated by the classical theory. Ekman has extended the theory to other laws for internal friction in the ocean. A summary of these results is given by Defant [13].

Observations of the turbulent viscosity show that this generally varies with the depth. Under high wind conditions, the turbulence decreases with depth, for the large value near the surface is due to wave action. A simple examination of the classical theory shows that in this case the change of direction with depth will not be so great as with the classical theory. Quantitative results are difficult to derive, especially since the proper form of the function which gives the turbulent viscosity as a function of depth is unknown (Defant [13], Chapter XIII, Shulman and Bryson [95]).

The tendency for water levels to drop at the upwind shore of a lake and to increase at the downwind shore is well known, and is usually referred to as "wind set-up". This effect is inversely proportional to the depth and is greatest when the wind blows along the axis of the lake. This effect is also present on the open coast and in estuaries. The effect of the wind over a bay is almost independent of that over the open ocean. However, the wind set-up on the open coast will penetrate into a bay in a manner similar to the astronomical tide. Thus, from a practical point of view the wind set-up within a bay is in addition to that on the open coast, excepting that, as this effect is inversely proportional to the total depth, the existence of deeper water within the estuary, as a result of the set-up on the open coast, will decrease the set-up generated within the bay slightly from that which would have been developed at normal depths. Other modifying effects of bays are discussed in Section 5.

One can resolve any wind into two components, one normal to the coast and the other parallel. The component normal to the coast, called the onshore component in the following discussion, produces a direct wind set-up, just as in a lake or bay. It is positive and tends to increase the sea level if the wind is blowing toward the coast.

The wind effect is nearly proportional to the wind stress (Harris [37]). The wind stress is a poorly determined function of wind velocity. The best developed theory for the wind stress over water implies that the stress should be proportional to the square of the wind speed and that the coefficient of proportionality should depend on, among other factors, the thermodynamic stability of the air and the roughness of the underlying surface. Over water, the roughness of the surface is itself a function of the wind speed and some modification of the quadratic stress law as used over a rigid surface is needed. Neumann [71, 72] has proposed a three-halves power law. A few writers have reported empirical evidence favoring some other power. Classical theory has assumed a linear law whenever this greatly facilitated the mathematical treatment, and a quadratic law otherwise. In general, empirical data tend to support the assumption of a linear, quadratic, or any compromise of the two used in the analysis. Pore [80], Harris and Angelo [43], report on several sets of data which were analyzed once with a linear law, and again independently with a quadratic law. The two laws fit the data about equally well, and in each case further statistical analysis of the processed data tends to support the particular assumption used in its analysis as being about the best possible. Sutton ([104] and [105], Chapter 3) has discussed several difficulties in the derivation of the quadratic law but has offered no better replacement. Stewart [98] and other writers have presented data and hypotheses which suggest that the basic assumption of a power law may be in error and have pointed the way for an improved understanding of the problem. At the present time the quadratic law appears to be the most acceptable of several unsatisfactory choices for a simple functional relation between wind velocity and wind stress. All we can say for certain is that if other conditions are unchanged the stress between wind and water increases with the wind speed.

c. EFFECT OF THE EARTH'S ROTATION

The rotation of the earth produces an acceleration to the right in any current in the Northern Hemisphere. If motion in this direction is impeded as by a coast line, the acceleration must be balanced by an increase in water level to the right (Sverdrup, Johnson, and Fleming, [106], Chapter XIII). The component of the wind parallel to the coast, called the alongshore component in the following, will generate a current in the same direction if flow is unimpeded in this direction. Because of the earth's rotation, this leads to an increase in sea level at the coast. This effect is positive if the coast is to the right of the current, negative if the converse is true. This process has been discussed at length by Freeman, Baer, and Jung [32].

d. EFFECT OF WAVES

The wind generates waves which generally move in more or less the same direction as the wind. Although these surface waves are responsible for very little water transport in open water, they may be responsible for significant transport near the shore. When waves are breaking on a line more or less parallel to the beach they carry considerable water shoreward. As they break, the water particles moving toward the shore have considerable momentum and may run up a sloping beach to an elevation above the mean water line which may exceed twice the wave height before breaking (Granthem [34]). If the beach berm is narrow, water may spill over the berm, and if the flow of water from the landward side of the beach is impeded, ponding will occur and the mean water level in the pond, when averaged over a period of several minutes or longer, may be several feet higher than the mean water level on the seaward side of the beach. The wave run-up and wave overtopping processes are illustrated in figure 0.1.

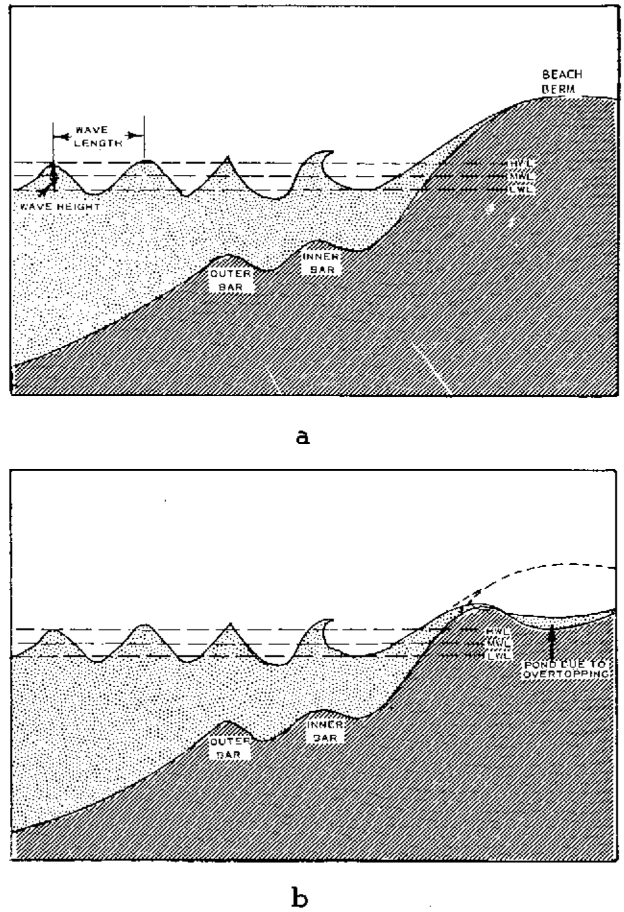

FIGURE 0.1.—Schematic diagram illustrating (a) the effect of wave run-up on a beach and (b) wave overtopping and ponding. The dashed line in (b) shows the profile appearing in (a).

The overtopping process was a significant factor in the damage produced in the Netherlands flood of February 1, 1953 (Wemelsfelder [114]). It has been discussed in considerable detail by Saville [89], Sibul [96], Sibul and Tickner [97], and many others. The amount of overtopping has been found to be a function of the wave steepness, slope of the beach, and the existing wind directions, as well as the wave height and period. The wave steepness is the wave height divided by the wave length, when both wave height and wave length are measured in deep water. For waves of a given height the overtopping appears to be greater for longer waves. Other conditions remaining the same, the overtopping is at a maximum for a slope of approximately 1/2 and is slightly greater when strong winds blow toward the beach. It achieves a peak value when the waves break at the berm of the beach or at the crest of any reef, bar, or sea-wall.

If waves break far enough from the shore, the energy of the breaking wave is dissipated as turbulence and very little run-up occurs. However, in this case the water carried shoreward by the breaking waves cannot flow back to the open sea as rapidly and effortlessly as it was brought shoreward. This leads to the establishment of a gradient in water level between the beach and the open sea. This phenomenon, called "wave set-up," is a piling up of the water near the shore under the direct influence of the waves, as distinct from the wind set-up which is the piling up of water under the direct influence of the wind. Model studies of wave set-up have been published by Fairchild [28] and Saville [88]. Theoretical studies have been carried out by Dorrestein [21], Fortak [30, 31] and by Longuet-Higgins and Stewart [55]. Longuet-Higgins and Stewart [54] have applied their theory to the laboratory data of Saville. All of these studies call for a depression of the mean sea surface in the region where the wave amplitude is greatest and an increase in the mean water level shoreward of this zone. The wave amplitude is greatest in the breaker zone. It appears that the wave set-up is proportional to the difference between the mean water depth in the breaker zone and the mean water depth at the point of observation. The wave set-up is an increasing monotonic function of wave period and the height measured before breaking.

Thus the maximum value of the wave set-up occurs at the beach line where the mean water depth is zero. The amount of set-up due to this cause also depends on the orientation of the wave crests to the beach and any irregularities in the shore line which may impede the flow of the gravity current generated by the wave set-up. The maximum wave set-up is to be expected when the waves break along a line parallel to the beach. The theoretical studies have not yet been carried far enough to permit an evaluation of the importance of this process in nature. The laboratory studies indicate that breaking waves may easily account for as much as 3 feet of the total storm surge on a beach. Under very favorable conditions the wave set-up may amount to as much as 6 feet.

This process can be expected to have its peak effect on open coasts in regions where the depth increases rapidly with distance from the shore, so that the large waves can approach very near to the shore before breaking. It is unlikely to be very important in estuaries where only short-period waves can develop fully. The operation of this process outside a harbor entrance can, however, increase the mean water level within the harbor. McNown [5] reported a laboratory investigation which indicates that the water level within a harbor can be increased by the presence of waves at the harbor entrance even though the waves do not break. Harris [42] reports field data which appear to support this hypothesis.

The peak water elevation observed on a beach should generally be higher than that reported at a nearby tide gage because most of the tide gages are located in water deep enough to give useful data at the lowest stages of the tide and therefore they do not receive as great an increment from the wave-breaking process as does the nearby beach. The variability in the peak water elevations reported from the shores of an estuary should be less than for those reported from the open coast because the peak wave heights in the estuary are generally less than those on the open coast.

Waves breaking at an oblique angle to the coast generate less set-up than those breaking parallel to the coast. These waves generate a narrow current, parallel to the shore, which moves in the general direction of the waves (Shepard [94]). This current is too narrow to permit much pile-up of water because of the earth's rotation, but if the current is forced to change its direction abruptly, due to the curvature of the coastline, an increase in water level on the side of the current opposite the center of curvature of the streamlines, due to the centrifugal force of the moving water, is to be expected. This wave-generated current is a significant factor in the beach erosion produced by the hurricane surge (Hall [35]).

e. RAINFALL EFFECT

Hurricanes may dump as much as 12 inches of rainfall in 24 hours over large areas and even more over areas of a few square miles. The fluvial flood resulting from this rainfall can increase the water level near the head of many tidal estuaries. The existence of above normal water levels at the mouth of the estuary may eliminate or reverse the normal gradient in river level so that the rainwater accumulates in the river bed to a much greater depth than would be the case with normal tides at the coast. In some bayous and swamps, even though very near the sea, the drainage is so poor that several days may be required to carry away the excessive rain produced by a hurricane.

5. MODIFICATIONS OF THE SURGE

The first three of the processes listed in section 4 are believed to represent medium-scale phenomena with horizontal scales measured in tens of miles and time scales measured in hours to one or two days. A disturbance of this scale, formed on the open coast or at sea, will be propagated into any estuary or other indentation of the coastline in much the same manner as the astronomical tide. Several factors act to change the disturbance within the estuary. In the usual case, the estuary is more shallow than the continental shelf outside the bay. Since the speed of such a distance is approximately proportional to the square root of the total depth, the speed of the disturbance up a river is generally slower than its speed as it enters the river. This leads initially to a convergence of water near the mouth of the estuary and an increase in the surge heights. The crest of the disturbance having a greater depth than the preceding trough, will move more rapidly and the interval between the beginning of the water level disturbance and its peak value is generally less as it goes farther inland. Two factors may disturb this general law. If the shores of the bay are very flat so that the total flooded area is much greater at the crest than at the beginning of the disturbance, the average total depth may actually be less at the crest so that its speed is decreased relative to that of the beginning of the disturbance. Friction at the bottom and sides of the estuary, especially when areas covered with vegetation have been flooded, may decrease the speed and change the phase of the disturbance as it moves inland.

The height of the surge entering from the sea is decreased if the estuary widens out inland from the mouth. In general, the height will increase if the shores of the estuary converge toward its head. However, it should be remembered that the shores which converge for normal tide heights may actually diverge if extensive flooding occurs or vice versa. In a few situations friction overcomes the effects of convergences so that the heights fails to increase in a converging portion of a shallow estuary.

Narragansett Bay, Rhode Island, furnishes a good example of a convergent bay. The ratio of the surge amplitude inside the Bay to that at the entrance is in good agreement with the ratio of the astronomical tides at the same locations. This is well illustrated by the storms of 1938, 1944, and 1954. The Chesapeake Bay may by taken as an example of a divergent bay in which tides and surges decrease in amplitude from the entrance to the head of the Bay, but the example here is not so clear, as the winds over the Bay greatly modify the disturbance which enters at Hampton Roads. The records for the 1938, 1944, 1954, and 1960 hurricanes over Long Island Sound give the clearest example of a propagating surge with the amplitude decreasing over the wider portion of the Sound and increasing again over the narrow western end. The peak surge at Willets Point at the western end of the Sound generally occurs several hours after the passage of the hurricane. The peak at the Battery, only a few miles away but with a much shorter hydraulic path to the sea, coincides approximately with the passage of the storm.

The surge propagates into estuaries as a gravity wave whose speed of propagation increases with the depth. Thus, it moves faster on a high tide than on a low tide. It will be recalled that the direct wind effect is inversely proportional to the total depth. Thus, a given wind will generate a larger disturbance at low than at high tide. Doodson [17,18], and Rossiter [87] have shown that these two effects combine in such a way that the resulting surge in an estuary tends to be greater on the rising stage of the tide. Rossiter also presents empirical data to show that this theoretical result is realized in nature.

The wind field over a bay will control the development of set-up and waves within the bay. Winds blowing toward the sea may greatly reduce the effects of the propagating surge. Winds blowing inland from the entrance will enhance the set-up at the head of an estuary. Since the total depth of a bay is greater when a surge is being propagated inward from the open coast, the direct set-up will be slightly less in this situation, but the height of the waves generated within the bay and of the waves propagated into the bay will be greater when the mean depth is greater.

In considering the modification of a surge by the topography and shape of an estuary it is necessary to bear in mind that these may be greatly changed by the surge itself. In many areas, the land elevations near the coast are only a little above the normal high water line at the beach and even lower for a considerable distance inland. In such regions the inlets, apart from dredged channels, are usually shallow, so that a rise in water level of only a few feet at the beach will greatly change the cross section of the channel through which the surge flows inland. If a series of ridges with heights increasing with distance from the open sea run parallel to the coast, little flooding is to be expected inland from any ridge until it is topped by the surge. The valley between ridges may fill up rapidly once this occurs. This appears to be the cause of some of the reports of tidal waves accompanying hurricanes (See the description of hurricane Audrey, 1957).

6. A SIMPLE PREDICTION MODEL

In the first approximation, the effects of the earth's rotation, waves, and wind set-up on sea level at the beach are all approximately proportional to the wind stress. The wind stress is approximately proportional to the wind speed, or the wind speed squared, or to some intermediate power of the wind speed. The wind speed itself is a function of the pressure gradient. In general, the wind speed is assumed to be proportional to the pressure gradient (geostrophic wind), but in the wind speed zone of a hurricane it is more nearly proportional to the square root of the pressure gradient. In fact, the maximum wind speed in a hurricane is usually estimated from the observed pressure gradient. (Myers [67], Fletcher [29], Myers [68]). Rainfall is likewise correlated with below normal pressures. Thus all of the factors which tend to produce storm surges are correlated with pressure gradients or low pressures and one might expect the peak water levels associated with a hurricane to show a similar correlation. This is found to be the case (Connor, Kraft, and Harris [7], Hoover [47] and Harris [40]). The latter study shows that the size of the storm has little demonstrated effect on the peak water level and that the slope of the continental shelf has only a minor effect. The prediction nomogram derived in this latter study is presented in figure 0.2. The numbers near 1.00 shown along the coast line give the factor by which the average value of the peak storm surge, expressed as a function of central pressure only, should be multiplied to account for the variation in offshore depth. The graph in the upper left has this factor, Θ, as the abscissa and the central pressure, p_0, as the ordinate. The sloping lines across the graph give the expected peak storm surge. The standard error of the estimate obtained from this graph is less than 1.5 feet; that is to say, that there is a probability of one-half that the difference between the peak surge observed on the open coast and the value obtained from this graph will be no more than 1.5 feet. The peak surge in bays may be much higher than the peak surge on the coast.

This graph is entirely empirical and the data on which it is based leave much to be desired. It has no validity for storm surges caused by extratropical storms, or for other regions of the world. It has proved surprisingly useful in the evaluation of surges produced in the United States by hurricanes. Since the technique is entirely empirical, it is possible to derive many similar schemes which are not much better or much worse.

Although the peak surge is not much affected by the size of the storm, the extent of the coast line which experiences the surge is very much affected by the size of the storm and by its path as can be seen by the data contained in this report.

7. PRESENTATION OF DATA

The primary purpose of this report is a presentation of the data on which the discussion of the hurricane storm surge characteristics and the mechanism of storm surge generation is based. It is to be expected that further theoretical and empirical studies will lead to changes in the model but that extensive improvements to this collection of past data are unlikely.

The goal, in this report, is to show as nearly as possible the effects of the storm on the height of the sea surface, as averaged over a period of several minutes.

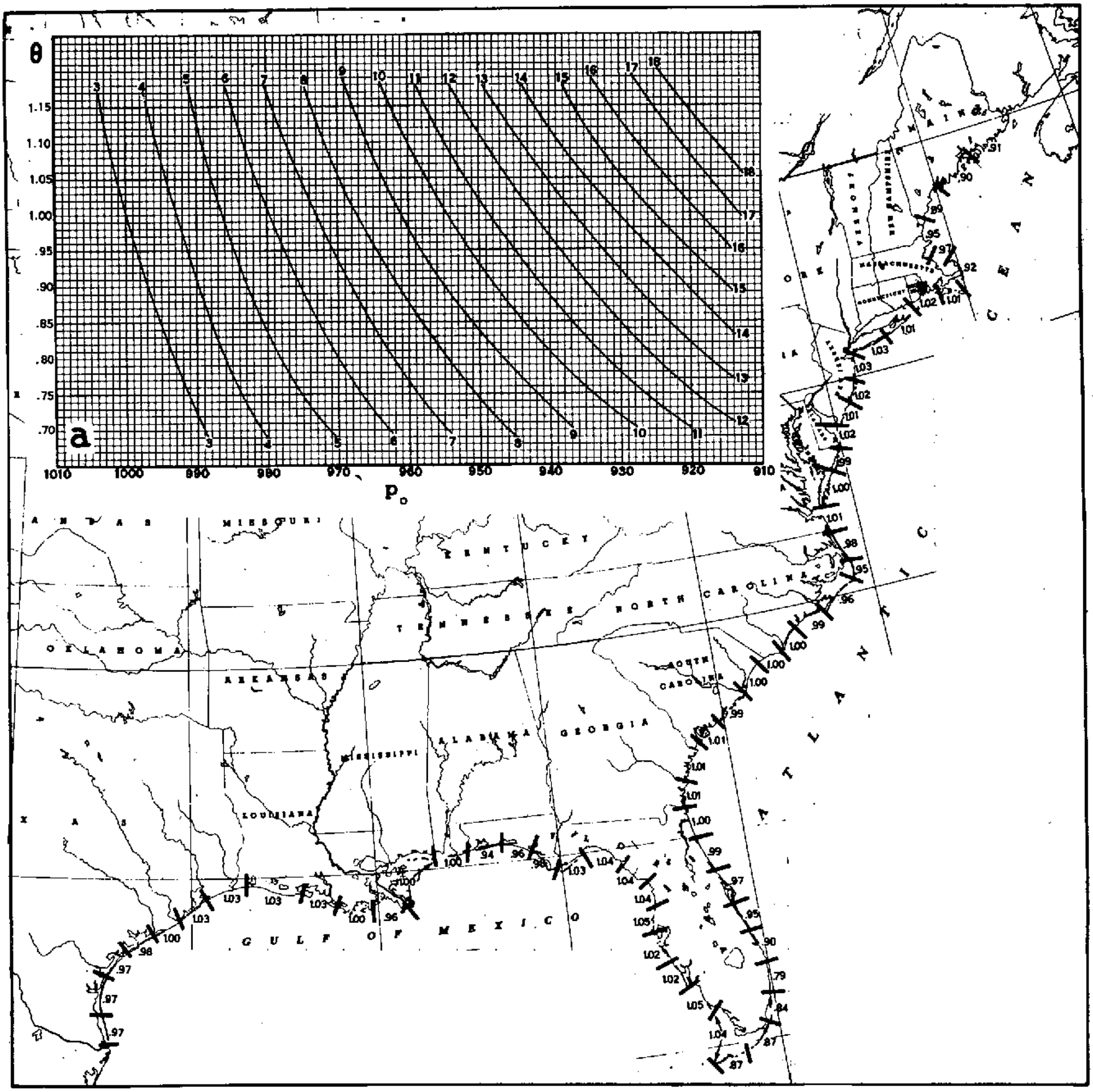

FIGURE 0.2.—A simple hurricane surge prediction model. The slope factor near 1.00, representing the effects of the off-shore depths, is obtained from the map. The expected storm surge is given by the curved lines at the intersection of the slope factor and the central pressure. There is a ⅔ probability that the actual peak surge will not differ from the expected value by more than 2.1 ft.

Variations in water level with periods of less than 1 minute are excluded from consideration. This is necessarily a derived quantity as the observed elevation of the sea results from the combination of many factors in addition to the storm. Most of the primary data are presented in the form of storm surge graphs. Since the storm surge is defined as the difference between the observed sea elevation and the "normal" tide elevation for the same time and place, any interaction between the effects of the normal tide and the storm are, of necessity, included in the storm surge.

The "normal" tide is necessarily the author's estimation of the tide which would have occurred in the absence of the storm being considered. Basically, this is the predicted astronomical tide as given in the *Tide Tables*, published annually by the U.S. Coast and Geodetic Survey, corrected for seasonal anomalies and the rising trend in sea level. Primary tide predictions have been made for many stations not included in the *Tide Tables*. A more detailed description of the procedure used in estimating the normal tide and the motivation for this procedure is given below.

The surge graphs presented in part two were plotted from tabulations of the hourly differences between the observed and predicted tides, with a few additional points entered to show the peak surge when it was clearly evident that this occurred between hourly observations. Approximate data are indicated by a large dot for each interpolated observation. Observed data, plotted from hourly observations, are included in many cases in which efforts to remove the effects of the normal tide were unsatisfactory. Copies of the original tide gage records are included for a few cases in which oscillations, not apparent in the hourly records, appear to be significant features of the original data. A dashed line running across the graph intercepts the surge curve at the approximate time of the nearest approach of the storm center. The date is entered at noon each day. A chart showing the best estimate of the hurricane track as given by Cry, Haggard, and White [11] and the location of the gages from which data are available is supplied for each storm. The track charts for storms which occurred after the publication of the above report are taken from the hurricane article contained in the annual issue of *Climatological Data, National Summary* [108] for each year. Most of the storm surge data are included on these charts.

Selected synoptic charts are also shown for each storm to present a better picture of the wind and pressure fields than could be estimated from the hurricane track alone. For the period 1919–1939 these charts were taken from the Historical Map Series [110]. For the later years they were taken from the manuscript maps of the National Weather Analysis Center or the Hurricane Forecast Center at Washington National Airport. The overwater portion of the hurricane tracks as determined from the synoptic charts sometimes differs by as much as a hundred miles or more from that given by Cry et al. [11], especially for the earlier years. This difference results from the inability of meteorologists to locate the storm center precisely from the limited data available for these storms.

8. ESTIMATES OF THE NORMAL TIDE

The principal component of the normal tide is the rise and fall of the sea surface twice each lunar day (at most stations). Secondary components arise from seasonal variations in sea level and a trend toward rising sea levels or sinking coastal lands in many areas.

Basic tide predictions for the United States are based on the harmonic method of tide prediction described by Schureman [92], Doodson and Warburg [19], Pillsbury [77], and many others. The Coast and Geodetic Survey has derived the harmonic constants for most of their stations and for a few of those operated by other agencies. If constants for the location of any tide gage were available, they were used to compute hourly values of the predicted tide for use in determining the storm surge. If constants were not available for any station, computations were made for two or more nearby stations, or stations believed to have similar tide characteristics. These computations were compared with the observed tides during periods of fair weather to determine which best represented the observed tide. Changes in amplitude and phase of the tide between the two stations were permitted in this comparison and the subsequent predictions for storm periods. If any of the predictions were satisfactory, those which gave the best agreement with observations during fair weather were used. If none was satisfactory, only the observed tide curve is shown. Most of

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the predictions used for the years 1950, 1953, and 1954 were made by the Coast and Geodetic Survey, using the tide prediction machine described by Schureman. Most of the remaining predictions were made on an electronic computer using constants furnished by the Coast and Geodetic Survey.

These calculations were modified from the standard Coast and Geodetic Survey predictions by subsitituting the observed sea level for the month of the storm in preference to the computed mean as determined from the use of long period terms Sa and Ssa, of the usual tide prediction equation. The mean of two consecutive months was used if the storm occurred within the first or last five days of any month. The reasons for this modification are discussed more fully below.

The absence of any pronounced oscillation of tidal periodicity in most of the resulting storm surge curves is evidence of the general validity of this procedure. The residual oscillation of tidal period in the storm surge curve may indicate interaction between storm effects and the normal tide, some deficiency in the tide observations or the tide prediction scheme, or possibly some other factor.

In a few cases, notably Willets Point, N.Y. and Philadelphia, Pa., the harmonic constants developed for the most effective prediction of the high and low waters do not describe the water level between high and low waters in a manner which is entirely adequate for the determination of the storm surge. At some tide stations, the tide predictions which generally give smooth storm surge curves sometimes appear to lose calibration for several days and then recover their normal accuracy. The resulting storm surge curves show oscillations approximately of tidal period with a range as great as 2 feet in regions where the normal tide range is only about 5 feet. This phenomenon appears in the records from several stations for a few days preceding several of the hurricanes whose records are included in this report. If only these data were examined, one might be led to believe that this oscillation is a precursor of the storm. However, a more extensive investigation of the records shows that this phenomenon may occur at Charleston, S.C., and presumably at other stations, in periods of excellent weather as well as in stormy periods. Prelinary efforts to relate this phenomenon to lunar cycles were unsuccessful. In a few cases the undesirable tidal periods in the residuals could be removed by a slight shift in phase between the observed and predicted tides, suggesting that the error resulted from a small clock error in recording the original tide observations. This could be the result of an error in the clock or watch used by the tide observer in making time checks on the tide records. However, this technique does not always lead to an improvement in the appearance of the storm surge curve, and it appears that at least some of the residual tidal periodicity has a more fundamental physical cause. This technique for removing the tidal periodicity has not been used for any of the data in this report if standard observations and prediction constants were both available.

9. SOURCES OF DATA

The principal source of recorded data for this study has been the tide records of the Coast and Geodetic Survey. The harmonic constants necessary for primary tide predictions are available for most of these stations. The time scale, generally about 1 inch to the hour, is sufficiently open to permit the timing of most events to the nearest 5 minutes and data for the entire coastline are available in one general format. All of the Coast and Geodetic Survey tide records for tropical storm periods during the years 1919–1959 were examined if it appeared likely that the records for any station would show a tide anomaly of 2 feet or more associated with a tropical storm.

Harris and Lindsay [44] list many additional gages operated by the U.S. Army Corps of Engineers, U.S. Geological Survey, and a few other organizations which may, on occasion, be expected to show storm surge effects during hurricanes. Copies of many of these records were obtained and used in this study if the data already available indicated a reasonable probability that tide anomalies in excess of 2 feet were to be expected at the gage site.

The emphasis in this study is placed on tide anomalies along the open coast, and it is believed that practically all of the available data since 1940 and most of the earlier data which would contribute to such study have been examined. Many records for rivers and open bays have been included, but inasmuch as these data are rather local in their applicability, no attempt has been made to include all data of this type.

A great deal of potentially useful data for this study has been lost until recently, because most of the gage installations were planned to give something near the maximum resolution over the normal tide range and did not have the extra capacity to record the hurricane tide. In many cases also, the gage suffered damage during the storm so that the record of the storm and sometimes the gage itself was lost. Thus the amount of data actually available is much less than indicated by the information given by Harris and Lindsay [44]. These supplementary gages are indicated by asterisks in the following charts.

A malfunctioning gage does not necessarily mean that all data from the gage are lost. For example, the Coast and Geodetic Survey gages are equipped with two clocks. The timing of the record can be resolved at least to the nearest hour if either of these clocks stops for a period of a day or less and the other continues to operate. If the gage continues to operate properly but goes off scale due to a high tide, the height of the tide can be determined at least to the nearest foot and often more accurately. Occasionally, the paper may tear, but a valid record can be obtained from marks on the drum for a period of several hours. When the gage fails entirely, it may be possible to recover the peak tide from a debris line inside the gage house or at some nearby establisment. Supplementary data are sometimes available from other nearby gages or from visual records made during the storms. Useful approximations to the true record can be made in all of these cases. Approximate data of this type have been treated as observed data in all of the following charts and the source of the approximate data is stated in the text if it is known. However, approximate data have been indicated on the charts by plotting the data as a large dot.

10. HIGH WATER MARKS

The principal sources for high water mark data are the reports of the U.S. Army Corps of Engineers referred to above; most of these have not been previously published. Some additional data were obtained from the Coast and Geodetic Survey, earlier Weather Bureau reports, local governmental units, and elsewhere. As far as possible all water levels have been referred to the Coast and Geodetic Survey's Sea Level Datum of 1929 as this is the datum used in the construction of the topographic charts published by the Geological Survey and appears to be the most suitable datum for the expression of land elevations. High water charts are shown only when quantitative data of known validity are available.

11. THE MEANING OF REPORTED TIDE HEIGHTS

There is a great deal of confusion concerning the meaning of most of the early reports and some of the more recent reports of tide heights during storms. Many writers have quoted figures with no reference to the zero of the scale used in determining the figure, and often with no knowledge of this zero. Some of the often quoted values refer to height above a gage zero, which itself may be several feet below the normal sea level for the gage site. Some values of heights above mean low water or "normal" tide have been given with no hint of the meaning assigned to these terms. Later writers sometimes try to improve incomplete tide quotations by supplying identification of the data which they believe the original writer intended but without going back to the original source of the data. This has led to a great deal of confusion concerning the actual past events, and most of the discrepancies between this publication and earlier publication of similar data result from an attempt to go back to the original source whenever possible to determine the meaning of the original data and to make the reports more explicit. The following brief discussion of datum planes and sea level variations is presented with the hope of bringing some order out of this chaos.

Marmer [59] gives an extensive discussion of the problems involved in the determination of mean sea level and the other tidal datum planes. He defines the daily sea level as the average of the instantaneous elevation of the sea surface at the beginning of each of the 24 hours of the day. The monthly sea level is similarly defined as the average of the daily sea level values for each day of the month. The yearly sea level is defined as the average of the 12 monthly sea level values for the year. A primary definition of *mean sea level* is then obtained as the average of the yearly sea level values for a 19-year period. The practical importance of the 19-year period in the determination of mean sea level is not clearly established, but it is generally agreed that this is something near the optimum length of record for a stable determination of the long-time mean. The 19-year period is essential in the determination of *mean low water* and the other commonly used tidal datum planes. A secondary determination of mean sea level may be obtained from a much shorter period of record by comparing the observed sea level at a secondary station with that observed at the primary station during their common period of operation. In actual practice this common period of data may vary from a few days of record at some relatively obscure locations to several years at major ports.

Marmer defines *mean low water* at any place as the average height of the low waters at that place over a period of 19 years, and *mean high water* as the average height of the high water over the same period. The mean-tide level is defined as the plane which lies half-way between mean high water and mean low water. It is approximately equal to *mean sea level* but is rarely identical. Nevertheless, the two terms are often used interchangeably. This may frequently lead to discrepancies of 0.2 of a foot or so in the heights assigned to a particular point. The mean low water and mean high water planes depend on both the half-tide level or mean sea level and the mean range of tide. But the range of tide varies from place to place (sometimes by several feet within a few miles), and from day to day, month to month, and year to year. This variation in range with time is cyclic and has a period of approximately 19 years. This is the origin of the 19-year period necessary in the determination of mean low water and mean high water. Primary determinations of the high and low water datum planes are based on 19 years of observations. Secondary determinations are obtained from shorter periods of record by comparisons between nearby stations and theoretically determined corrections for the epoch of the observations.

Since the range of tide may vary by several feet within short distances, elevations of flood water referred to mean low water are always ambiguous unless the site at which the mean low water was determined is specified. Such a reference is not often given with the published figures.

One other widely used datum must be defined. This is referred to by the Coast and Geodetic Survey as "The Sea Level Datum of 1929" and by the U.S. Geological Survey as "Mean Sea Level." It is the datum reference used on the quadrangle charts and for the most widely distributed set of bench marks in the country. The datum of 1929 was developed by holding the zero of the sea level datum equal to the value then in use for mean sea level at 21 tide stations in the United States, and 5 in Canada, and connecting these by precise leveling. This permits a systematic means of estimating the mean sea level at locations where no observations are available, as well as the determination of the difference in elevation of any two points in the country (Rappleye [82], Harris and Lindsay [44]).

Not only are there several conventions for reporting absolute height of the tide, but the average height of the tide for a month or a year varies almost continuously. The rising trend in sea level along the Atlantic Coast of the United States is well established (Marmer [59], and Disney [16]), and the actual value of the sea level now or during the month or year of any hurricane may be different from either the mean sea level or the datum of 1929. A study of the data shows that the datum of 1929 is the most conservative of the various datum planes that could be used, and that the yearly observed sea level or the officially accepted local sea level rarely differ from this by more than 0.4 ft. Therefore, the datum of 1929 has been used as the reference datum for all absolute elevations given in this publication, if this datum is known. Any exceptions to this rule as applied to Coast and Geodetic Survey data are clearly identified. It is not always possible to do this for data from other sources, for in general the records do not show which of the possible sea level datum planes was used. This uncertainty, although finite, is small when compared with the local variability in peak water level as discussed in Section 2.

12. VARIATIONS IN MEAN SEA LEVEL

Figure 0.3 shows the variation in monthly mean sea level at seventeen Coast and Geodetic Survey tide stations for the period 1919–1959. A very casual inspection of this figure will show that at any station the annual cycle may differ very much from one year to another, but that major disturbances in the annual cycle are similar at a large number of stations at any one time. For example, the peak in November 1944 followed by a drop to a lower value in December 1944, so apparent in the record for Eastport, can be easily followed southward to Key West and is not difficult to identify in the Gulf of Mexico records. The peak in the record for Port Isabel in October 1958 can be identified as far north as Boston. The large spatial continuity of these anomalies and the fact that they appear to have durations of several months suggest that they cannot be due to hurricanes or other isolated storms. In order to investigate this point further, the time of occurrence of each hurricane which produced a tide anomaly of as much as 2 feet at any hourly observation has been indicated above the record for each tide station significantly affected by the storm. No systematic relationship between the occurrence of tropical storms and the trend in mean sea level is apparent. The annual cycle assumed in standard tide predictions is shown by a dashed line superimposed on the record for 1919.

A closer inspection of the record will show a slight trend toward rising sea levels throughout the period of record. However, this rate of rise appears to have decreased since the mid-forties, and at several stations there is a hint of a downward trend in the record for the past few years. However, the variability from year to year is too great to justify any extrapolation of the trends indicated in this way without an adequate physical explanation of their cause. For the present purpose, however, it is sufficient to note the variability in annual and monthly mean sea levels and to observe that small-scale storms such as tropical cyclones cannot be an important contributing cause.

The variations in the annual cycle are believed to be predominantly meteorological in origin (Hela [46], Lisitzin and Pattullo, [53]) and hence are no more predictable than the weather from year to year. The trend may also depend in part on climatic factors, but other geophysical factors are also involved (Hela [46], Dietrich [14] and Dietrich and Kalle [15] Chapter 9, 343–4). No physical prediction scheme of demonstrated reliability has been established for predicting either the secular trend or the year-to-year variations in the annual cycle. Hence, it is not practicable to include these effects in the tide tables which must be published a year or more in advance. However, it is practicable to take these phenomena into account when evaluating the influence of a particular storm on the tide record. If current tide readings are available to the forecaster, as they are now, it is possible to take these phenomena into account in issuing warnings for a storm expected within the next few days.

Whenever possible, the variations in the seasonal cycle and the secular trend in sea level have been taken into account in this study in estimating the tide which would have occurred in the absence of a particular storm. This was done by replacing the monthly mean sea level as computed in the published tide prediction by the actual monthly mean sea level for the period of the storm.

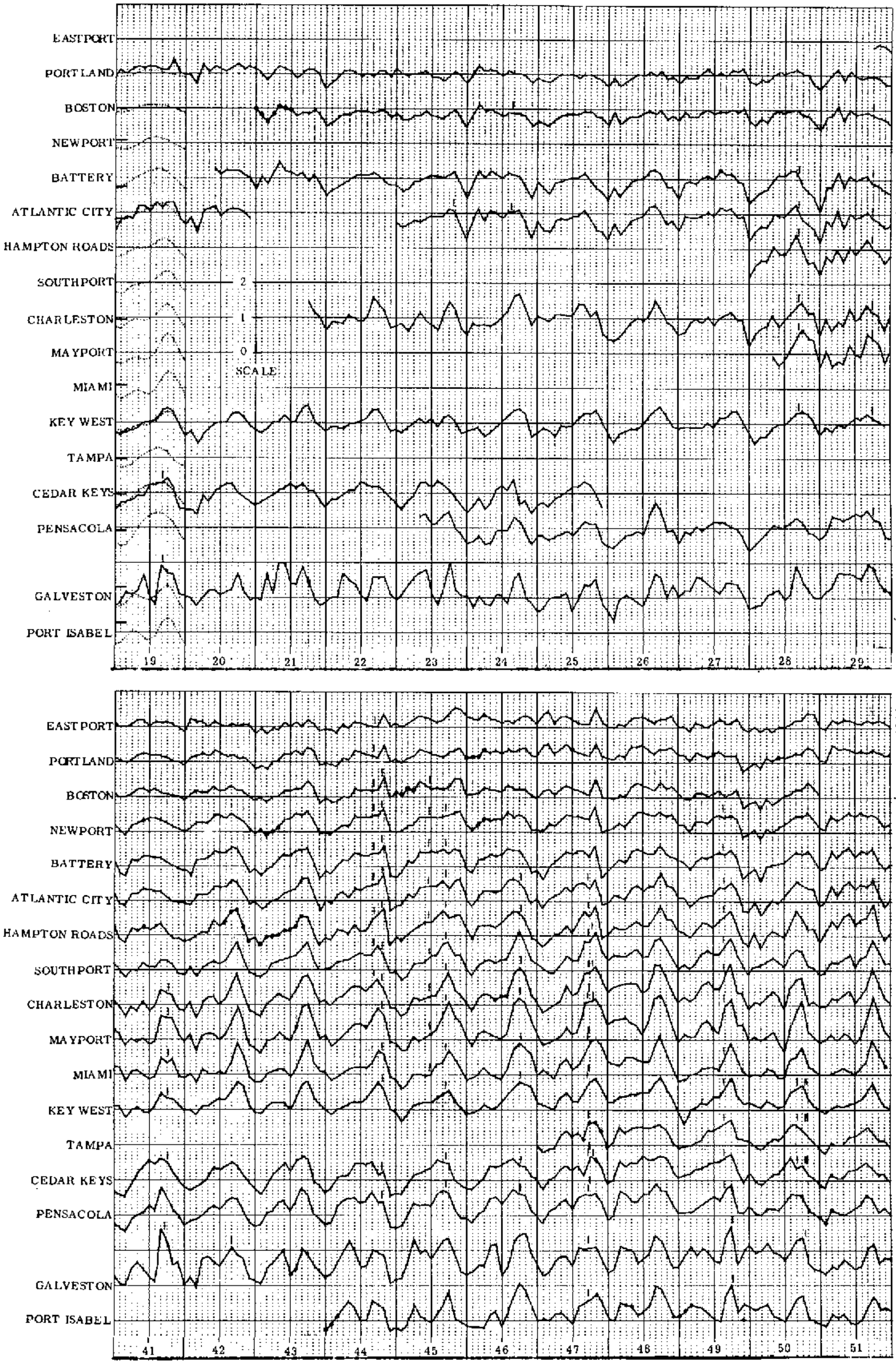
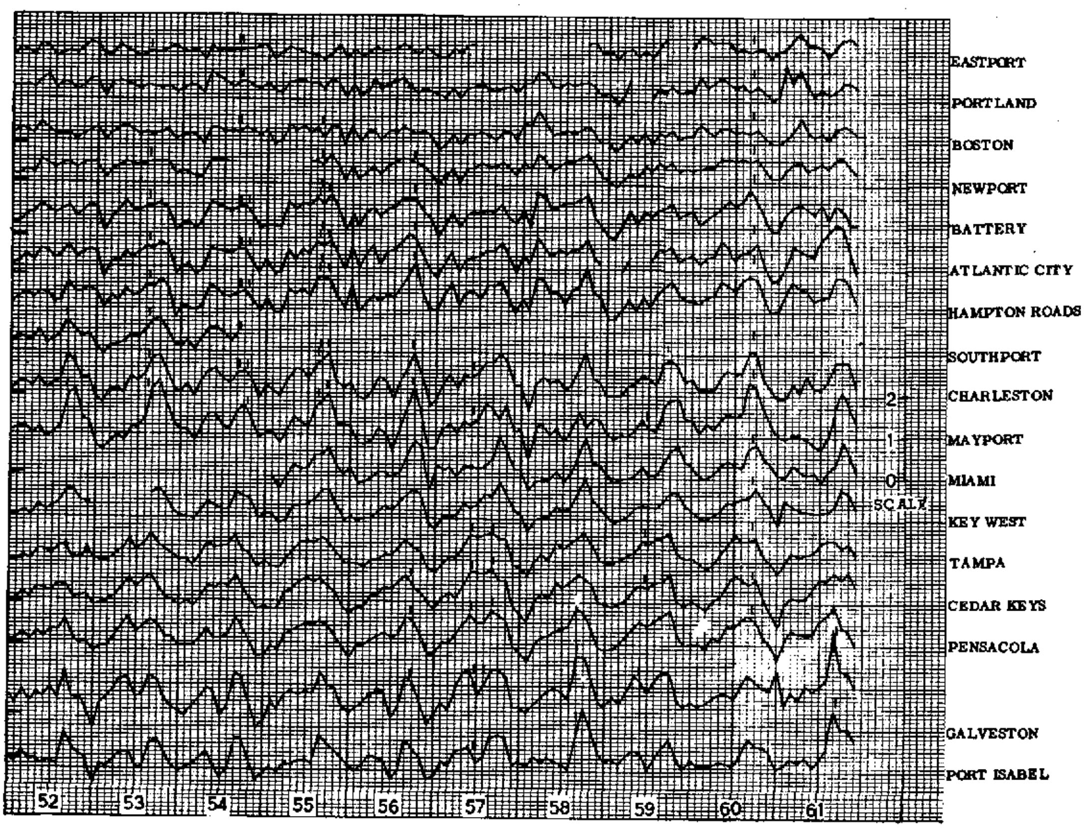


FIGURE 0.3.—Monthly mean sea level at selected Coast and Geodetic Survey tide stations, 1919–1961. The normal monthly means included in the official tide predictions are shown as dashed lines along with the observed values



for 1919. The year number is plotted on June. Marks indicate time of occurrence of a hurricane which produced a tide anomaly at that station of as much as 2 ft. at any hourly observation.

13. SUMMARY AND FUTURE OUTLOOK

It has been shown that many different dynamic processes combine to produce the hurricane storm surge. As a consequence, the elevation of the high water line, at least along the open coast, may vary by several feet within a distance of a mile or less. Nevertheless, there is a great deal of regularity in the data, suggesting the existence of some large-scale organization, or some small-scale organization which is repeated more or less systematically over large regions. Several definite patterns have been found which repeat whenever storm conditions are locally similar. Further study of the data presented in this report will undoubtedly reveal many patterns not specifically mentioned. Empirical predictions of the peak surge on the open coast for the past three years, based on data of this type, have been about as accurate as the data themselves appear to justify.

The differential equations governing most of the processes other than wave set-up are believed to be well established. However, the complexity of the boundary conditions prevents the analytic solution of these equations for any but the simplest cases. It should be possible to remove this limitation by the use of high speed computers and considerable progress has been made in solving slightly simpler storm surge problems by computer techniques (Welander [113], Platzman [78], Harris [37]), and many others.

Because of the lack of information about the structure of the hurricane wind field while the storm is still at sea and the uncertainty of the laws relating the wind field to the stress field mentioned in Section 4, it is unlikely that the results of the first computer solutions can be interpreted directly in terms of inundation depths. Rather, it is to be expected that the computer studies will provide information about the relative importance of fetch length, duration of the wind, angle and speed of approach of the storm, and perhaps surge profiles which indicate regions of greater or lesser flooding, before any of these data can be expressed in absolute terms. Data of this kind can be very valuable, however, in a more efficient administration of hurricane protection plans and can aid in solving the problems of determining the economics of engineering protective works, planning for evacuation during a storm, or determining zoning regulations to control the use of land which is subject to extensive flooding.

It is believed that the essential features of the hurricane storm surge are well established by the data contained in this report. However, much additional field data will have to be collected and analyzed and many additional theoretical studies will have to be completed before any great quantitative improvement in operational predictions can be expected.

Part Two

Records of Individual Storms

Considerable effort has been spent to insure the accuracy of the storm surge curves and the high water marks quoted in the following reports of individual storms. However, the major purpose of this collection is to show the types of phenomena that do occur, and to illustrate the time rate change in water level under the influence of severe storms and the variability of the effects over small horizontal distances. These can be well illustrated without regard to the absolute values of the elevations. In many cases, especially for the earlier storms, it would be impossible to obtain an absolute accuracy to a tenth of a foot, and in many cases when this might have been possible, the value of the slight improvement in the record did not appear to justify the work involved. Few, if any, errors greater than 0.5 ft. should occur in any of the data. The maps and charts are numbered in a decimal system in which the whole number is the serial number assigned to the storm in this publication with the decimal assigned serially to each chart in the series for any storm. The presentation of the data is described in Section 7. The date on the surge graphs is shown at noon for each day. High water mark data are referred to mean sea level except where otherwise noted.

STORM NO. 1.—HURRICANE 1926, SEPTEMBER 17–21

This storm appears to have been the most severe of record in the Miami area, and is one of the first for which extensive high water mark data are available. A consolidated summary of the high water data is given in figure 1.3. Most of these data are taken from C. L. Mitchell [63] but a few are added from the other figures prepared for this report. Figure 1.4 presents a dense collection of high water marks in the Miami area. These data were obtained by the city engineers of Miami and Miami Beach, and are referred to the Harbor Division datum in use in Miami in 1926, which is 0.49 ft. below the Mean Sea Level datum of 1929. The profile of the land surface and the high water marks as determined by the city engineer of Miami Beach are shown for four traverses of the island in figure 1.5. The locations of these profiles are indicated by the heavy lines labeled A, B, C, and D in figure 1.4. It should be observed that in general both the land surface and the high water lines slope downward from the ocean to the bay side of the island.

Five separate cuts 60 to 80 feet in width were eroded across the northern part of Miami Beach by this storm. The bottom of each cut was approximately at the normal high water level. The explanation of the formation of these cuts as given by the district engineer in a memorandum dated October 1, 1926 is rather interesting and is repeated below:

> . . . During the first part of the storm the wind came from the northeast. It eroded the beach in many places as much as 50 to 100 feet, by carrying the sand from the key and depositing it on higher ground. In many places the concrete road is now covered by a layer of sand 3 feet deep. After the center of the storm passed the wind came from the southwest, and at the same time the tide began to fall. This southwest wind piled the water into Biscayne Bay and Indian Creek, and the recession of the tide caused the water to spill over the key in an easterly direction. It was during this stage of the storm that the cuts in question were formed. At the site of these cuts there were a number of vacant lots, with hedge rows on the property lines running in an east and west direction. The hedges, by catching drift,

TABLE 1.1.—*Wind conditions near time of hurricane passage, September 17–21, 1926*

Date	Miami			Key West			Tampa		
	Time (EST)	Direction	Speed (m.p.h.)	Time (EST)	Direction	Speed (m.p.h.)	Time (EST)	Direction	Speed (m.p.h.)
17th	1200	NE	4						
	1300	NE	5						
	1400	NE	11						
	1500	NE	8						
	1600	NE	12						
	1700	NE	16						
	1800	NE	17						
	1900	NE	16						
	2000	NE	18						
	2100	NE	19						
	2200	NE	20						
	2300	NE	24						
18th	0000	NE	27	0000	N	16	0000	NE	10
	0100	NE	30	0100	N	16	0100	NE	12
	0200	NE	31	0200	N	17	0200	NE)	13
	0300	NE	39	0300	N	19	0300	NE	12
	0400	NE	50	0400	NW	27	0400	NE	12
	0500	NE	67	0500	NW	26	0500	NE	11
	0600	NE	69	0600	NW	27	0600	NE	11
	0700	NE	21	0700	NW	34	0700	NE	14
	0800	NE	32	0800	NW	38	0800	NE	18
	0900	NE	52	0900	NW	41	0900	NE	20
	1000	SW	49	1000	NW	44	1000	NE	23
	1100	SW	38	1100	W	47	1100	NE	18
	1200	SW	30	1200	W	46	1200	NE	23
	1300	SW	26	1300	W	44	1300	NE	26
	1400	SW	24	1400	W	46	1400	NE	25
	1500	SW	19	1500	W	42	1500	NE	23
	1600	SW	17	1600	SW	41	1600	NE	29
	1700	SW	16	1700	SW	40	1700	NE	29
	1800	SW	15	1800	SW	37	1800	NE	31
	1900	S	13	1900	SW	33	1900	NE	35
	2000	SW	14	2000	SW	33	2000	NE	34
	2100	SW	11	2100	SW	30	2100	NE	35
	2200	SW	14	2200	SW	30	2200	E	39
	2300	S	10	2300	S	31	2300	E	36
19th	0000	S	13	0000	S	31	0000	E	37
	0100	S	11	0100	S	31	0100	E	40
	0200	S	10	0200	S	36	0200	E	42
	0300	SE	13	0300	S	33	0300	E	41
	0400	S	12	0400	S	35	0400	E	38
	0500	SE	11	0500	S	31	0500	E	36
	0600	S	11	0600	S	30	0600	E	33
	0700	S	9	0700	S	28	0700	SE	32
	0800	SE	9	0800	S	26	0800	SE	32
	0900	SE	9	0900	S	26	0900	SE	28
	1000	SE	8	1000	S	22	1000	SE	26
	1100	SE	8	1100	S	24	1100	SE	24
	1200	SE	8	1200	S	23	1200	SE	22
				1300	S	23	1300	SE	23
				1400	S	24	1400	SE	16
				1500	S	23	1500	SE	16
				1600	S	21	1600	SE	17
				1700	SW	26	1700	SE	19
				1800	SW	23	1800	SE	19
				1900	S	19	1900	SE	13
				2000	SW	17	2000	SE	19
				2100	S	16	2100	SE	20
				2200	S	16	2200	SE	20
				2300	S	12	2300	SE	18
20th				0000	S	12	0000	SE	14

served as training walls to guide the flow of water, and in every case the cuts have been formed between the adjacent rows of shrubbery. The old mangrove roots underneath the fill seem to have acted at mattresses in preventing erosion to dangerous depth. Within the past few days the littoral drift of sand along the beach has built up sand bars at the mouths of the cuts, and it is believed to be only a question of a few weeks before these cuts will be closed completely at the open end . . .

Hourly wind observations at six Weather Bureau offices for the time of this hurricane are given in table 1.1.

TABLE 1.1.—Continued

Date	Pensacola			Mobile			New Orleans		
	Time (EST)	Direction	Speed (m.p.h.)	Time (EST)	Direction	Speed (m.p.h.)	Time (EST)	Direction	Speed (m.p.h.)
19th	1200	NE	31	1200	NE	23	1200	NE	14
	1300	NE	35	1300	NE	24	1300	NE	12
	1400	NE	34	1400	NE	25	1400	NE	15
	1500	NE	37	1500	NE	23	1500	NE	14
	1600	NE	29	1600	NE	25	1600	NE	16
	1700	NE	32	1700	NE	23	1700	NE	14
	1800	NE	34	1800	NE	23	1800	NE	15
	1900	NE	39	1900	N	24	1900	NE	14
	2000	NE	43	2000	N	27	2000	NE	16
	2100	NE	48	2100	NE	29	2100	NE	16
	2200	NE	49	2200	NE	32	2200	NE	15
	2300	NE	50	2300	NE	34	2300	NE	18
20th	0000	NE	52	0000	NE	30	0000	NE	16
	0100	NE	54	0100	NE	33	0100	NE	17
	0200	NE	55	0200	NE	33	0200	NE	16
	0300	NE	53	0300	NE	38	0300	N	13
	0400	NE	61	0400	NE	43	0400	N	13
	0500	NE	62	0500	NE	44	0500	N	14
	0600	NE	60	0600	NE	48	0600	N	16
	0700	NE	71	0700	NE	50	0700	N	16
	0800	NE	76	0800	NE	62	0800	N	17
	0900	E	91	0900	NE	60	0900	N	18
	1000	E	101	1000	N	68	1000	N	18
	1100	E	101	1100	N	76	1100	N	17
	1200	E	106	1200	N	75	1200	N	19
	1300	E	90	1300	NE	77	1300	N	18
	1400	SE	60	1400	N	84	1400	N	21
	1500	SE	74	1500	N	82	1500	N	21
	1600	SE	90	1600	N	78	1600	N	19
	1700	SE	88	1700	N	77	1700	N	20
	1800	SE	93	1800	N	80	1800	N	18
	1900	S	97	1900	N	78	1900	N	16
	2000	S	83	2000	N	74	2000	N	16
	2100	S	85	2100	N	72	2100	NW	18
	2200	S	65	2200	N	71	2200	NW	19
	2300	S	45	2300	N	68	2300	NW	18
21st	0000	S	45	0000	NE	48	0000	NW	18
	0100	S	55	0100	E	62	0100	NW	21
	0200	S	55	0200	E	64	0200	NW	19
	0300	S	55	0300	E	56	0300	NW	19
	0400	S	55	0400	E	54	0400	NW	19
	0500	S	45	0500	E	45	0500	NW	21
	0600	S	45	0600	SE	39	0600	NW	23
	0700	S	40	0700	SE	41	0700	NW	22
	0800	SE	40	0800	SE	48	0800	NW	23
	0900	SE	35	0900	SE	41	0900	NW	23
	1000	SE	35	1000	SE	38	1000	NW	20
	1100	SE	50	1100	SE	39	1100	NW	19
	1200	SE	51	1200	SE	32	1200	NW	19

DISCUSSION OF THE DATA

The amount of data available from this storm and the existing state of the theory are not yet sufficient to permit a unique explanation for the observed events. However, some intelligent speculation is justified, and as this is needed as a guide to more fundamental research, a hypothetical explanation for some of the observations is offered.

Miami-Miami Beach area

This storm passed directly over Miami. For more than a day before the storm, the wind was from the northeast; both onshore and alongshore components of the wind were conducive to an increase in sea level near the shore. The wave crest which would be expected to be nearly normal to the wind offshore would be turned more nearly normal to the shore by refraction near the beach. The direct wind effects might be supposed to have produced a mean water level slightly higher than the 6.4 ft. shown in the channel south of the line marked A–A in figure 1.4. The channel record was obtained at the western end of the channel, and a slight loss in elevation should have resulted from flow through the channel. The elevation in sea level on the open coast would have allowed the waves to approach much closer to the berm of the beach and to be much higher than normal at breaking. Thus the wave set-up and wave run-up processes would have had the opportunity of spilling a large quantity of water over the beach berm. The landward side of the first street was lined with apartment houses which impeded the flow of this water as it ran down the landward slope of the island toward Biscayne Bay. This hypothesis could explain the gradient of high water marks across the island.

The water level along the eastern shores of the bay may have been lower than the high water marks plotted near the western side of Miami Beach. In the meantime, the northeast wind blowing over the shallow bay would have produced a set-up on Biscayne Bay against the shores of Miami. This would explain the higher water levels on the western side of the Bay, and the gradient from north to south in Miami north of Venetian Causeway. This set-up within the Bay would be almost independent of the process acting along the open coast. After the storm passed Miami, the winds shifted abruptly to the southwest and later to the south. In this phase of the storm, the wind would have had a long fetch over the shallow waters of Biscayne Bay south of MacArthur Causeway and could have produced the high waters in Miami south of the causeway. The set-up south of the causeway would be almost independent of that north of the causeway and of that in the open ocean. Unfortunately, the available information about the surge development does not permit a verification of this hypothesis.

Western Coast of Florida

The tide records for Egmont Key and St. Petersburg show a fall in water level until three or four hours after the storm passed nearest these stations. The storm passed south of these stations and so the wind shift was less abrupt than at Miami. The wind shifted slowly from the northeast to east about 5 hours after the nearest approach of the storm and to the southeast almost a day later. It should be noted that waves could not make a prominent contribution to the tide height at these stations until several hours after the storm passed when some swell, formed by the south winds nearer the storm center, may have made an appearance. The onshore component of the wind remained negative throughout the period of interest. The alongshore component of the wind was negative so long as the wind remained in the northeast, but became positive when the wind shifted into the east. The water level began to rise with the shift to east winds. The south winds which should have made their appearance across the storm track at about this time may have contributed to the rise.

Interpretation of the limited data available for Appalachicola is difficult. However, it should be noted that the city is on the north side of a shallow bay having limited connection with the ocean. The mean elevation of the ridge on St. George Island, which forms the barrier between Appalachicola Bay and the Gulf of Mexico, is about 10 ft. mean sea level, so it appears unlikely that this was topped at any time during the storm. Thus it appears likely that the storm surge was due primarily to the wind set-up within the Bay with very little contribution from the effects of the wind over the Gulf.

Before discussing the record for Pensacola it is worthwhile to examine the report from Gulf Beach, on the open coast 20 miles southwest of Pensacola, where Mitchell [63] reports that no high water was experienced. The storm passed almost over the town with wind from the northeast ahead of the storm and west or southwest after the storm. Both before and after the storm, the winds had an overland trajectory so there was little opportunity for large seas to build up. Before the storm, the onshore component of the winds was negative and the alongshore component was positive. After the passage of the storm, the reverse was true. From the report of no unusually high water accompanying the storm, we may suppose that the two components maintained an approximate equilibrium.

Pensacola is located near the center of the west side of a large shallow bay, having only a limited connection with the Gulf. The wind was from the northeast for more than a day before the hurricane, shifting into the east a few hours before the passage of the center, then to southwest and south with the passage of the storm a little to the south of the city. The storm surge record is most easily interpreted if again we assume that we are concerned mainly with the movement of water within the Bay. From a large map of the area we can see that the tide gage, which is near the center of the business district, is only a little south of the center of the northeast-southwest axis of the Bay, so that northeast winds should have little effect on tides recorded at this point. It is more favorably situated to respond to east winds, and most of the increase in water level occurred during a period of east winds. According to this hypothesis, the highest water level in other parts of the Bay should have occurred at different times, according to the prevailing wind direction. Unfortunately, we have no information concerning the time of the peak at other locations. The tide rose above the limit of the recording gage about 7

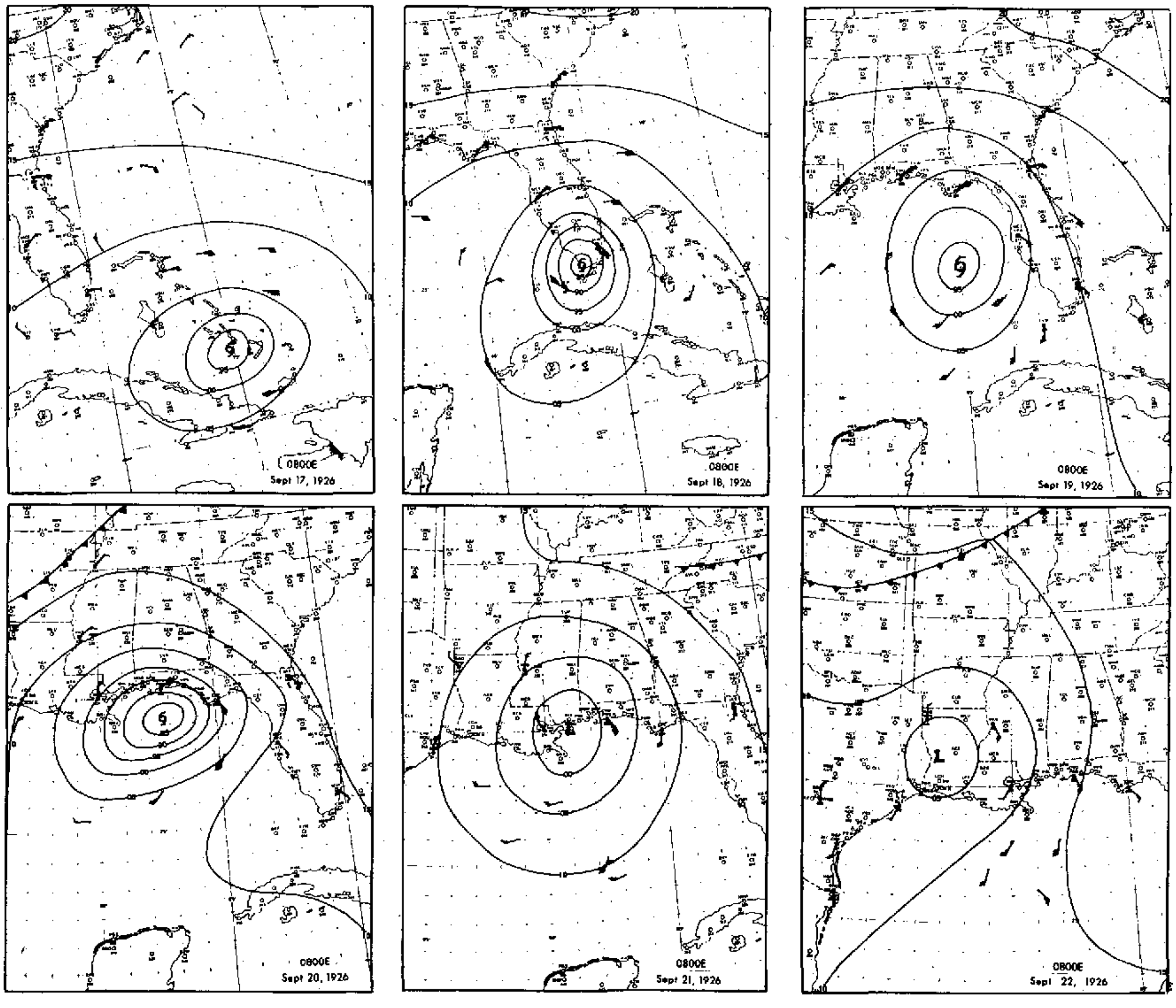


Figure 1.1.—Hurricane 1926, September 17–22. Synoptic charts.

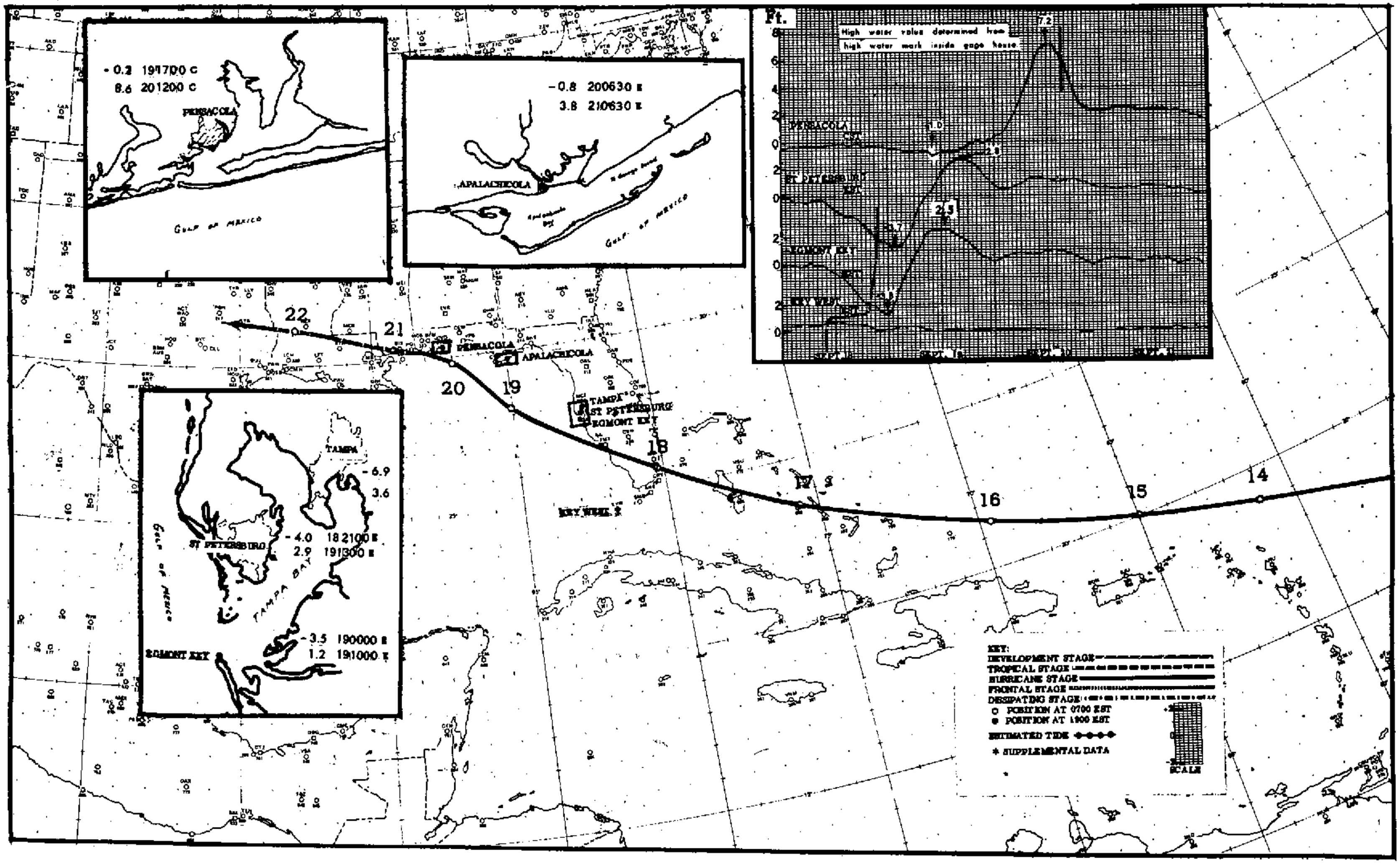


FIGURE 1.2.—Hurricane 1926, September 17–22. Storm surge charts. Insert maps for Tampa Bay, Apalachicola Bay, and Pensacola Bay.

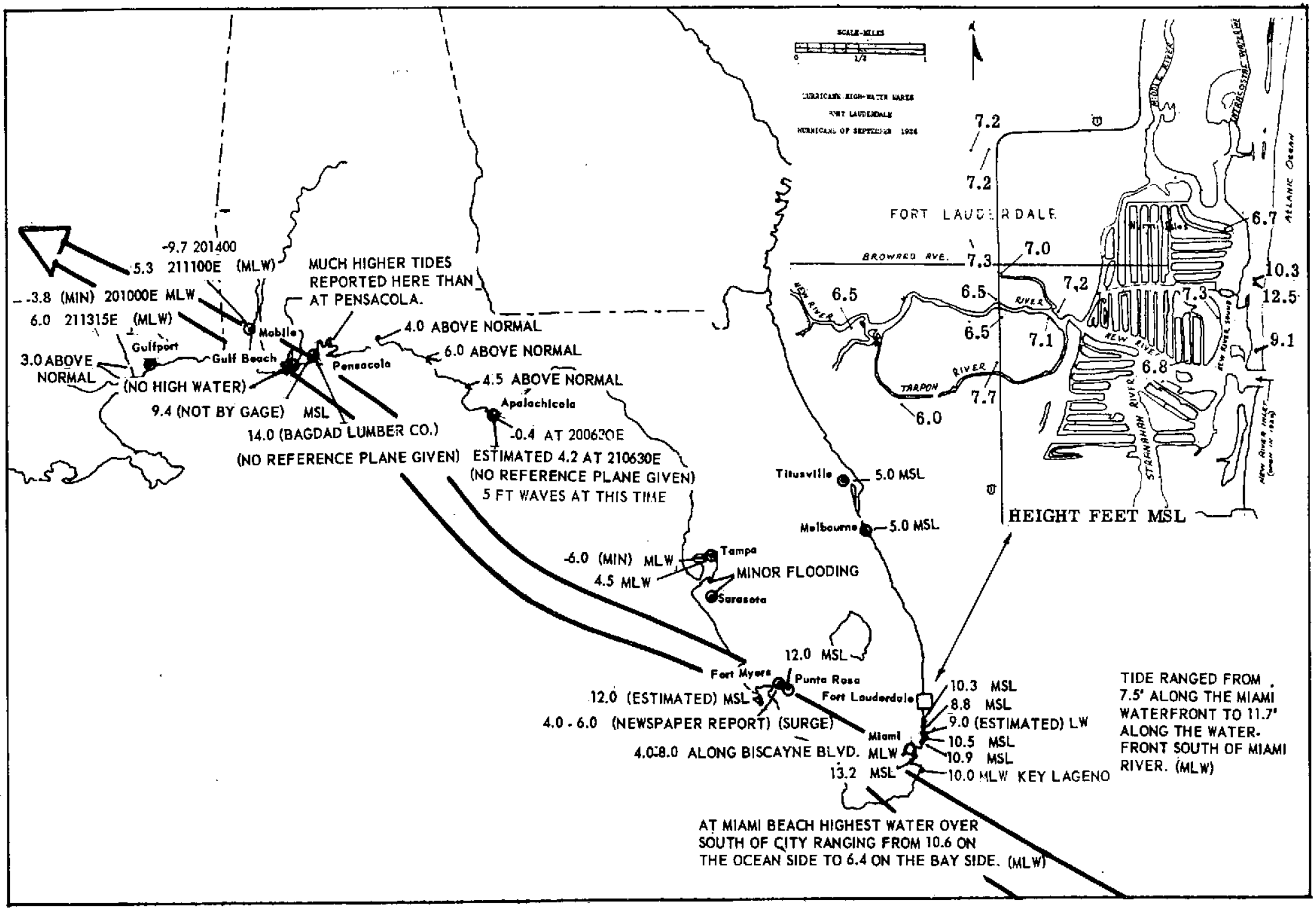


FIGURE 1.3.—Hurricane 1926, September 17–22. Summary of high water marks.

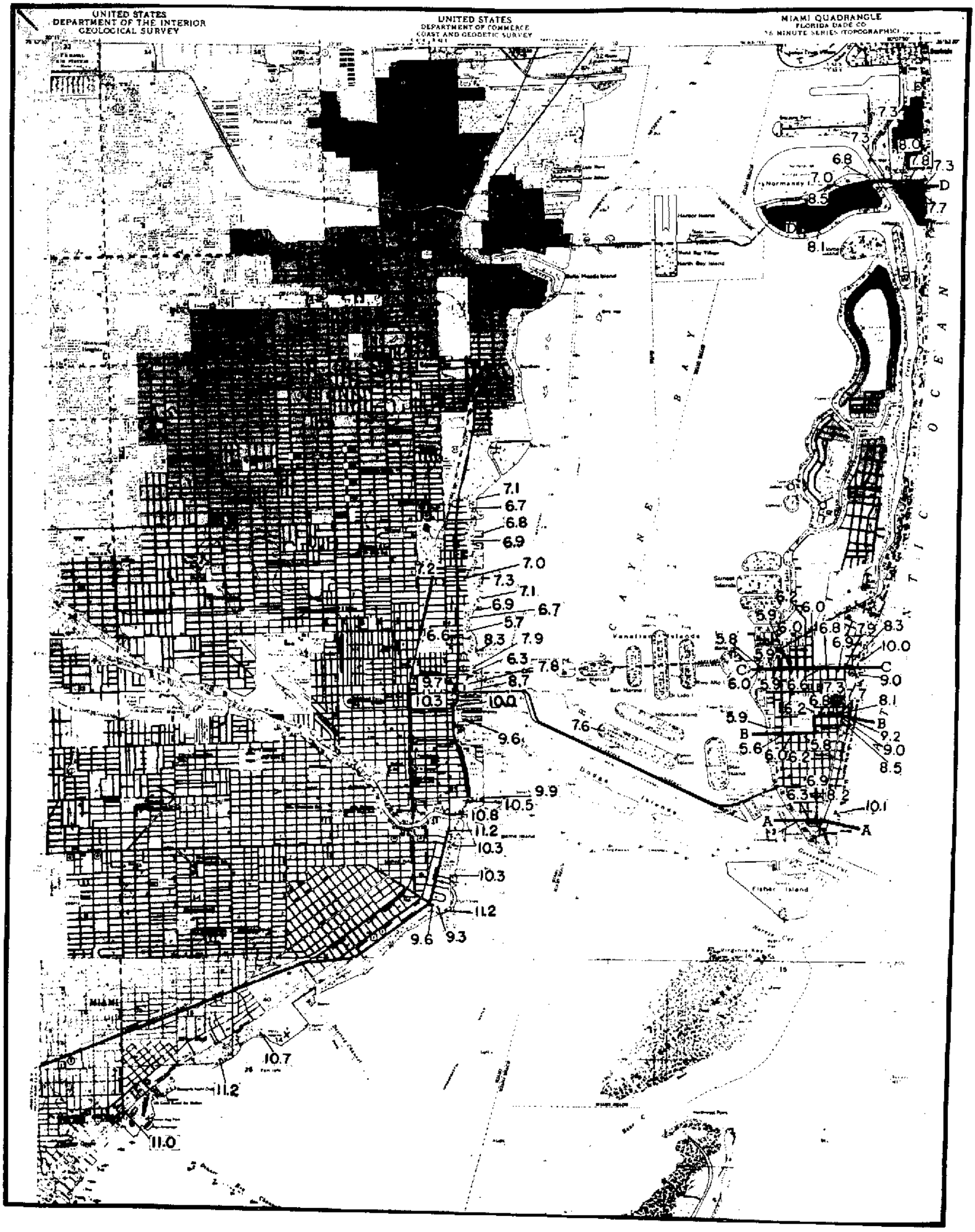


FIGURE 1.4.—Hurricane 1926, September 17–22. High water mark chart for Miami-Miami Beach area.

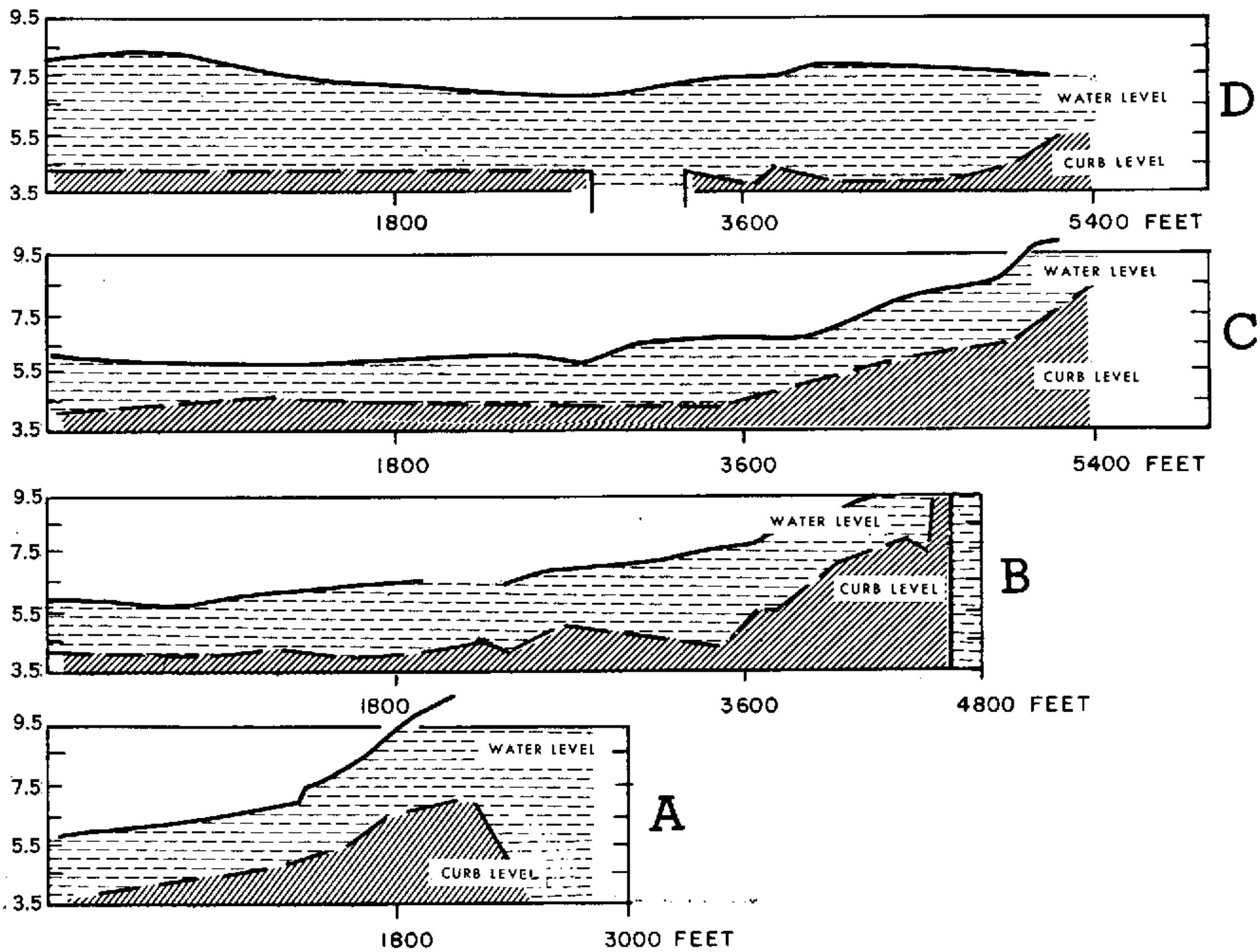


FIGURE 1.5.—Hurricane 1926, September 17–22. High water mark cross sections of Miami Beach at locations A, B, C, D marked on figure 4.

a.m. and at noon. However, as the peak surge occurred near the normal low tide, the peak surge was recorded.

Similar hypotheses could be proposed to explain the other high water marks shown in figure 1.3, but as they would present nothing new to the discussion and the data are too incomplete to permit a verification, these will be left to the reader.

A. J. Mitchell [60] reports that northerly winds over Lake Okeechobee associated with this storm led to a pileup of water to an elevation of approximately 10 ft. above the lake level on the south side of the lake before the storm thus topping the levees in the vicinity of Moore Haven and causing considerable flooding and loss of life south of the lake.

STORM NO. 2.—HURRICANE 1928, SEPTEMBER 16–20

A. J. Mitchell [60] reports that this storm, like the one in 1926, produced floods of approximately 10 ft. above the normal lake level along the south side of Lake Okeechobee. With the reverse in wind direction after the passage of the storm, flooding also occurred on the north side of the lake. The surges on Lake Okeechobee have been studied extensively by the Jackonsville District of the U.S. Army Corps of Engineers. Several of these studies have led to significant contributions to the understanding of storm surge generation on inland lakes and, by extension, to the problem of storm surge generation on the open coast. However, as this publication is concerned mainly with the collection of data on the open coast and in tidal inlets, no effort is being made to provide an exhaustive tabulation of the extensive data collected for Lake Okeechobee.

The surge curves for Charleston and Mayport shown in figure 2.2 show oscillations of approximate tidal periodicity before the storm. This is an example of the apparent loss of calibration between the observed and predicted tides mentioned in section 8 page 12. There appears to be no relation between these oscillations and the storm.

Observe that a slight depression in surge level at Baltimore and Annapolis is associated with the initial rise at the southern part of Chesapeake Bay, and that the surge height is higher at Baltimore than at the open end of the Bay. As pointed out by Pore (79) this is in contrast to the astronomical tide whose amplitude decreases toward the interior of the Bay. This is characteristic of the surges generated by storms which move northward west of the Bay but east of 80° W. longitude. This indicates a gain of energy by the water level disturbance within the Bay and shows the effects of winds over the Bay on the movement of water within the Bay.

A few high water marks, obtained from the Jacksonville District of the Corps of Engineers are shown in figure 2.3 to indicate the magnitude of the surge in the region of landfall. The amount of information available is insufficient for a satisfying discussion of the actual extremes or their causes.

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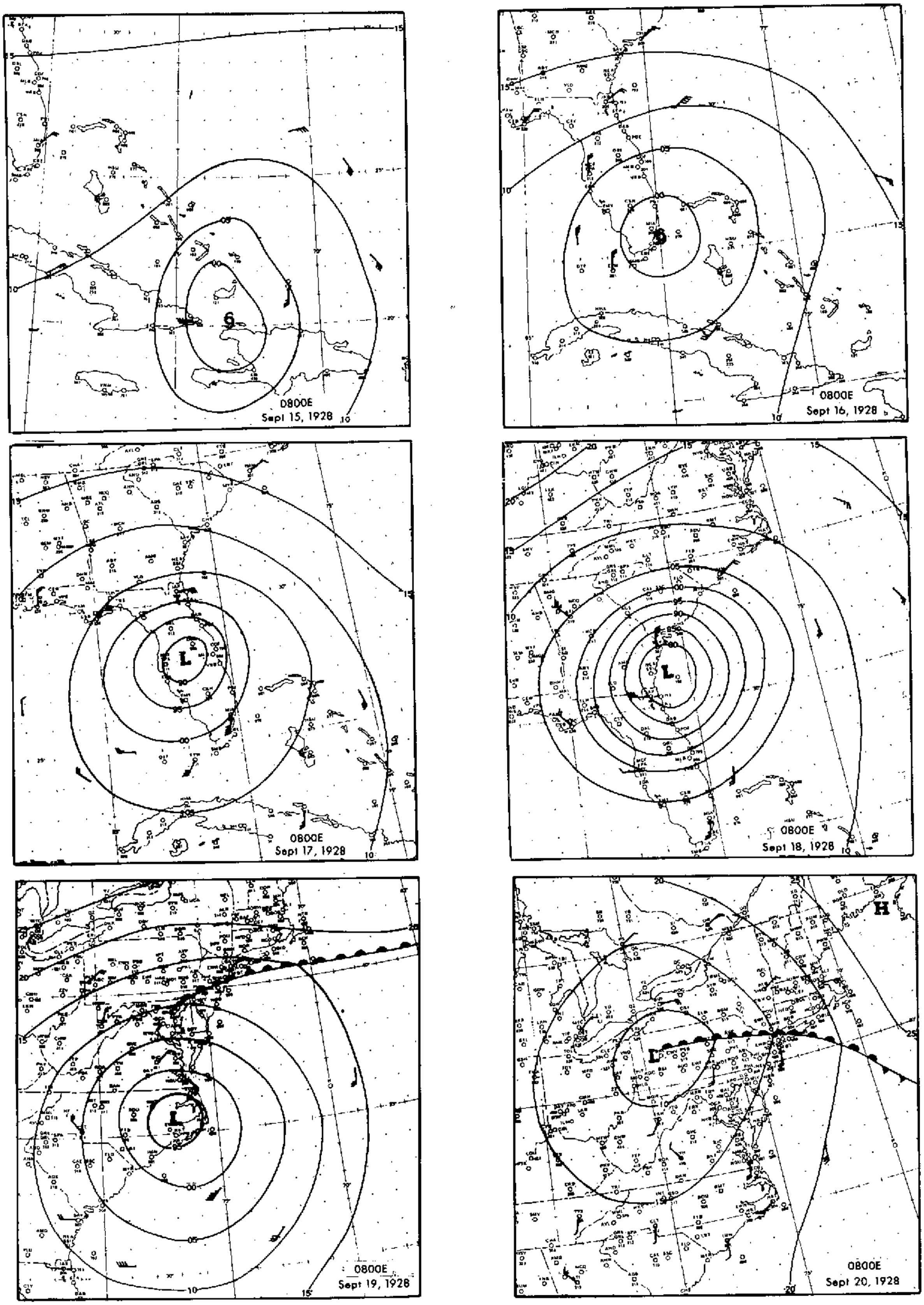

FIGURE 2.1.—Hurricane 1928, September 16–20. Synoptic charts.

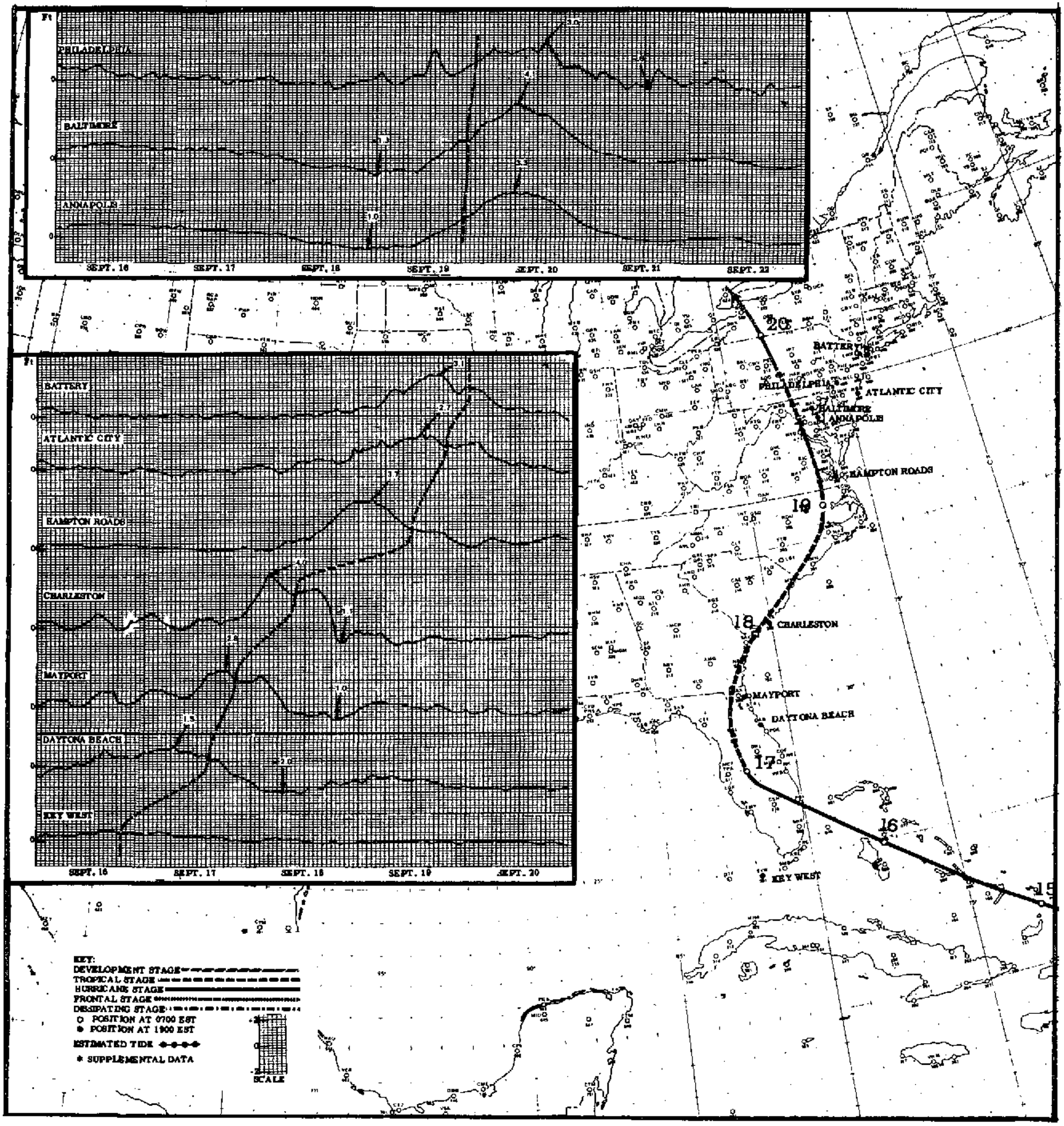

FIGURE 2.2.—Hurricane 1928, September 16–20. Storm surge chart.

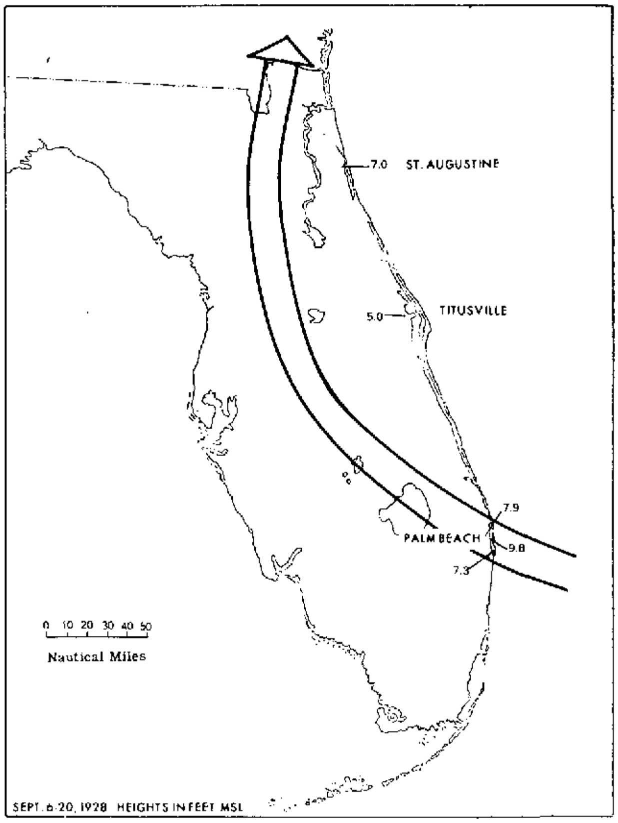

FIGURE 2.3.—Hurricane 1928, September 16–20. High water chart for Florida (based on data obtained from the Jacksonville District of the U.S. Army Corps of Engineers).

No reporting tide gages were operating in the Miami area during this storm, and only a few high water mark elevations were recorded. These are 8.8 ft. m.s.l. on the river near Goulds south of Miami; 8.8 ft. m.s.l. on Key Largo; 6.0 ft. m.s.l. on Long Key: and 6.3 ft. m.s.l. at Everglades. When the great variability in the high water marks experienced in the same areas during Hurricane Donna is considered, it is apparent that few if any deductions can be safely based on such sparse data.

The most interesting feature of the storm tide records is the rapid surge rise at Everglades, shown in figure 3.2. In this instance the paper became damp and was torn by the recorder pencil but the gage continued to record on the metal drum, and although some of the record during the storm is shown as inferred data, it was inferred in a technical sense only, as a valid record was obtained from the drum. Observe the similarities in the records for Everglades during this storm and for Egmont Key during the 1926 storm. The out-of-phase relation for the northern and southern portions of Chesapeake Bay for storms moving west of the Bay is again noticeable.

The slowly rising sea level at Hampton Roads and northward more than 18 hours ahead of the hurricane appears to be due to northeast winds behind a cold front and not to the hurricane. Northeast winds in this area are almost always associated with above normal sea levels (Donn [20], Pore [80]).

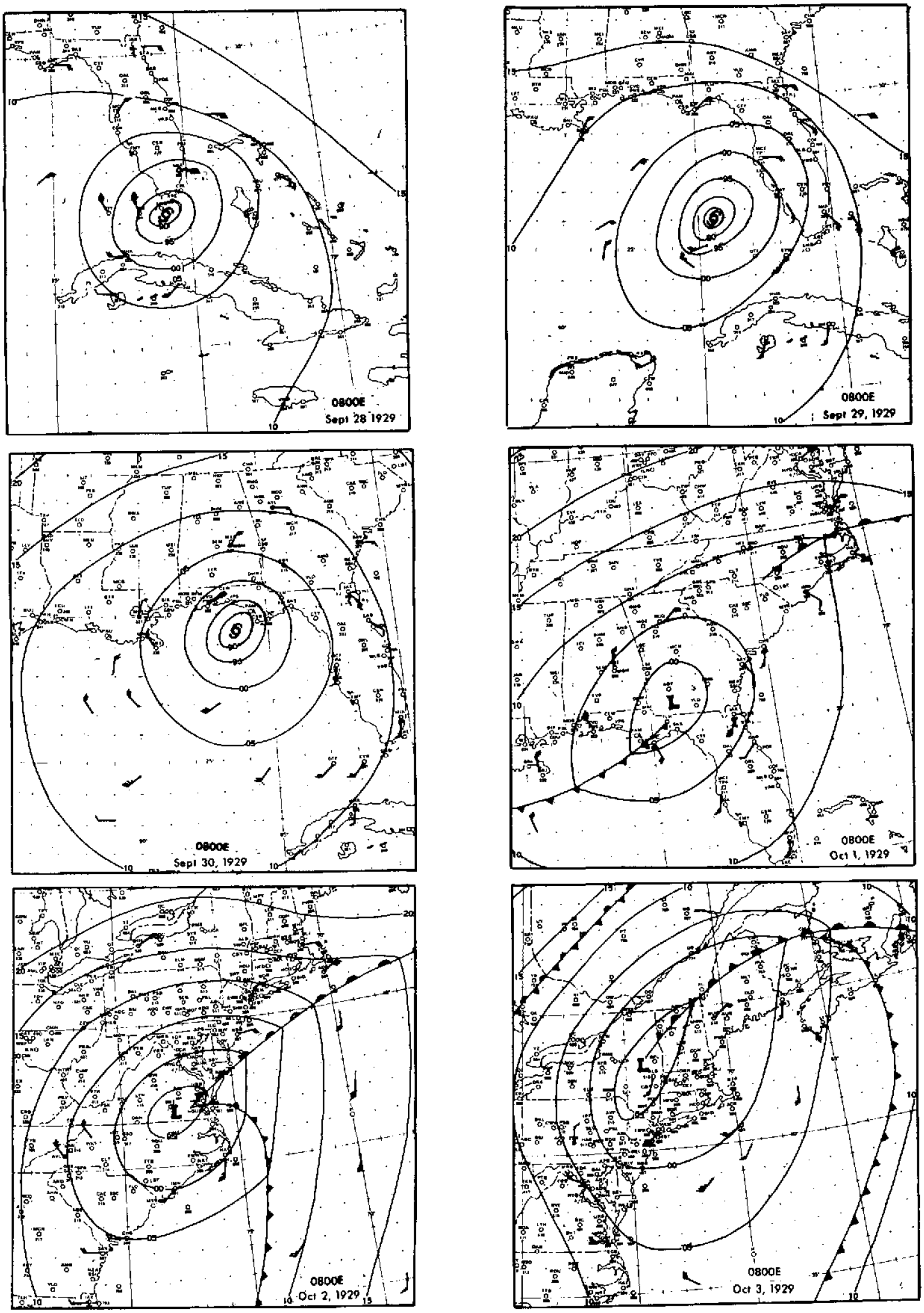

FIGURE 3.1.—Hurricane 1929, September 25–October 3. Synoptic charts.

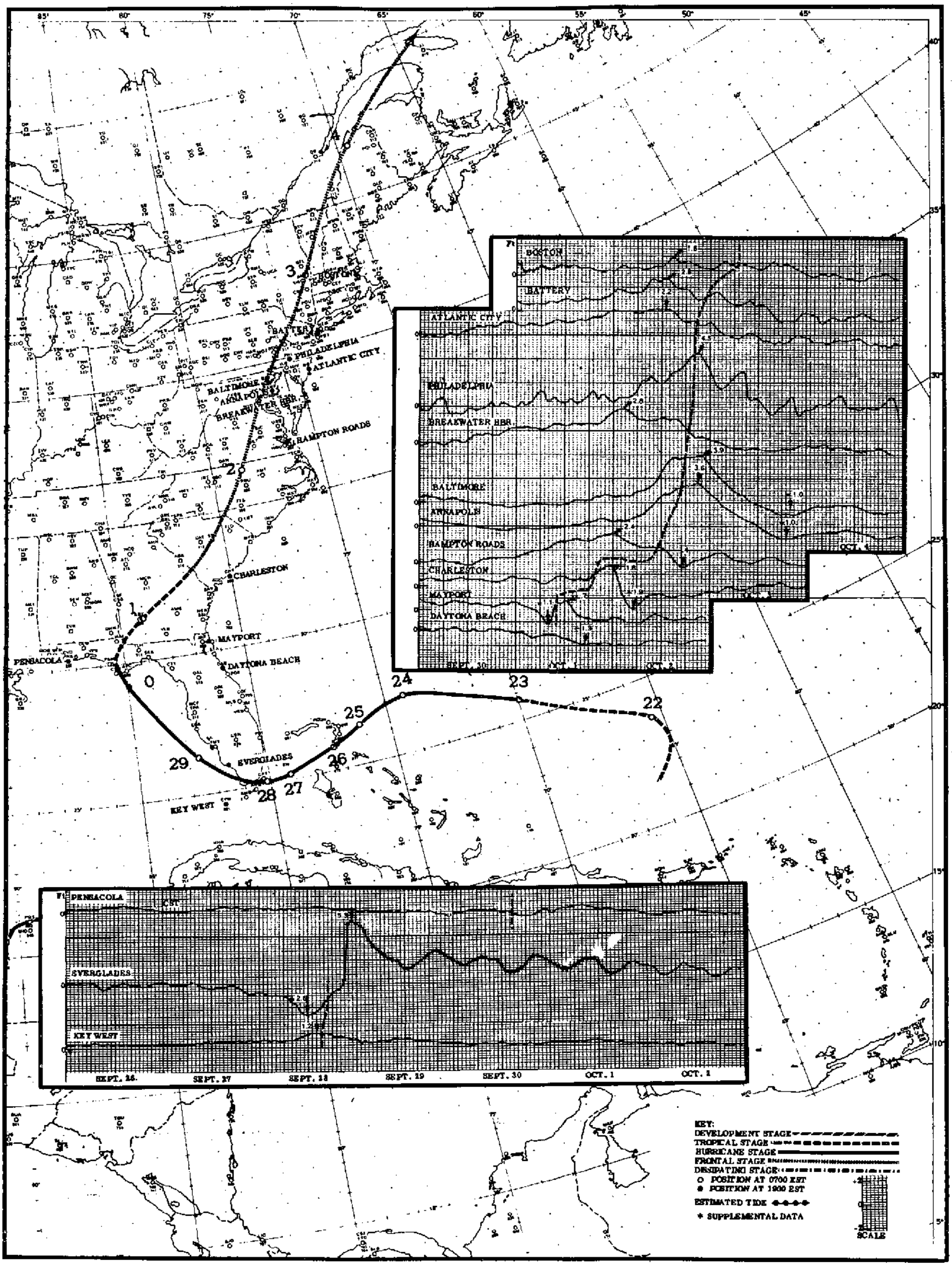

FIGURE 3.2.—Hurricane 1929, September 25–October 3. Storm surge charts.

Graham and Hudson [33] have constructed maps of the surface wind fields in the Chesapeake Bay area for this storm, for use in storm surge research. The storm surges experienced in Chesapeake and Delaware Bays have been discussed by Bretschneider [1, 2] and much of the data shown in the supplementary panel (fig. 4.2) for Delaware Bay were obtained from him. No correction for the anomaly in the monthly mean sea level has been applied to these data. The monthly mean sea level at Delaware Breakwater was 0.4 ft. above normal and the monthly mean river level at Philadelphia was 0.7 ft. above normal, during this period. Thus approximately 0.5 ft. should be deducted from the values shown in this panel to put them on the same basis as the data from the Coast and Geodetic Survey tide stations. Prediction constants are not available for all of the stations shown in this supplementary panel and the predictions for these stations were inferred from average corrections between these stations and primary tide stations obtained during periods of comparatively good weather. Model experiments (unpublished) at the Waterways Experiment Station at Vicksburg, Miss., show that the lag of the tide in the Delaware River behind that at Delaware Breakwater is a function of the discharge at the head of the tidewater section of the river. This storm was preceded by heavy rain and the river discharge was somewhat above normal during this period. Thus, one should suspect the lag between primary and secondary tide stations to be different from normal during this storm, and a tidal periodicity in the storm surge curves such as shown clearly by Ship John Light and Miah Maull Light should be expected. Hints of this residual periodicity also appear in the records for some of the other stations.

The same mechanism may explain the residual periodicity in the storm surge curve for Washington, D.C. The author believes this to be true but he does not know of any proof for this opinion. Pore [79] has published the winds at nearby weather stations, as well as the surge values for Hampton Roads, Annapolis, and Baltimore for this storm. The winds over the Bay were from the northeast during the entire period of the buildup at Hampton Roads. During this same period the surge height was decreasing at Baltimore, Annapolis, and Washington. The surge began to fall at the mouth of the Chesapeake, and to rise at the other stations, as soon as the wind shifted to the south in Norfolk. The records seem to imply a convergence of both bay and ocean water in the vicinity of Norfolk during the early phases of the storm, followed by a mound of water of increasing height moving up the Bay after the wind shift. The surge peak propagated up the Bay at very nearly the same speed as does the normal tide. But in contrast to the normal tide the amplitude of the surge increased with distance from the mouth of the Bay. Two causes may be postulated for this behavior. The storm moved up the Bay at a speed only a little greater than the normal speed of propagation of long waves, as determined from tide observations; thus it continued to feed energy into the surge wave as it progressed up the Bay causing a growth in amplitude. The dynamics of this mechanism have been discussed by Proudman ([81] Chapter 13), Harris [36], and Platzman [78]. The copious rains ahead of the storm served to increase the river levels at the location of the tide gages. It is almost certain that the first of these processes was the most important but the contribution from the second may have been significant.

The peak surge produced by this storm coincided approximately with the normal high tide. Extensive flooding resulted and the Norfolk District office of the Corps of Engineers has provided an extensive collection of high water marks near the mouth of the Chesapeake Bay. These data, referred to a mean sea level datum, are presented in figure 4.3. The Washington District Office of the Corps of Engineers has provided numerous high water marks along the Rappahannock and Potomac Rivers. These are referred to the mean low water datum used locally for navigation control at the time and are presented in figure 4.4. In the Washington area

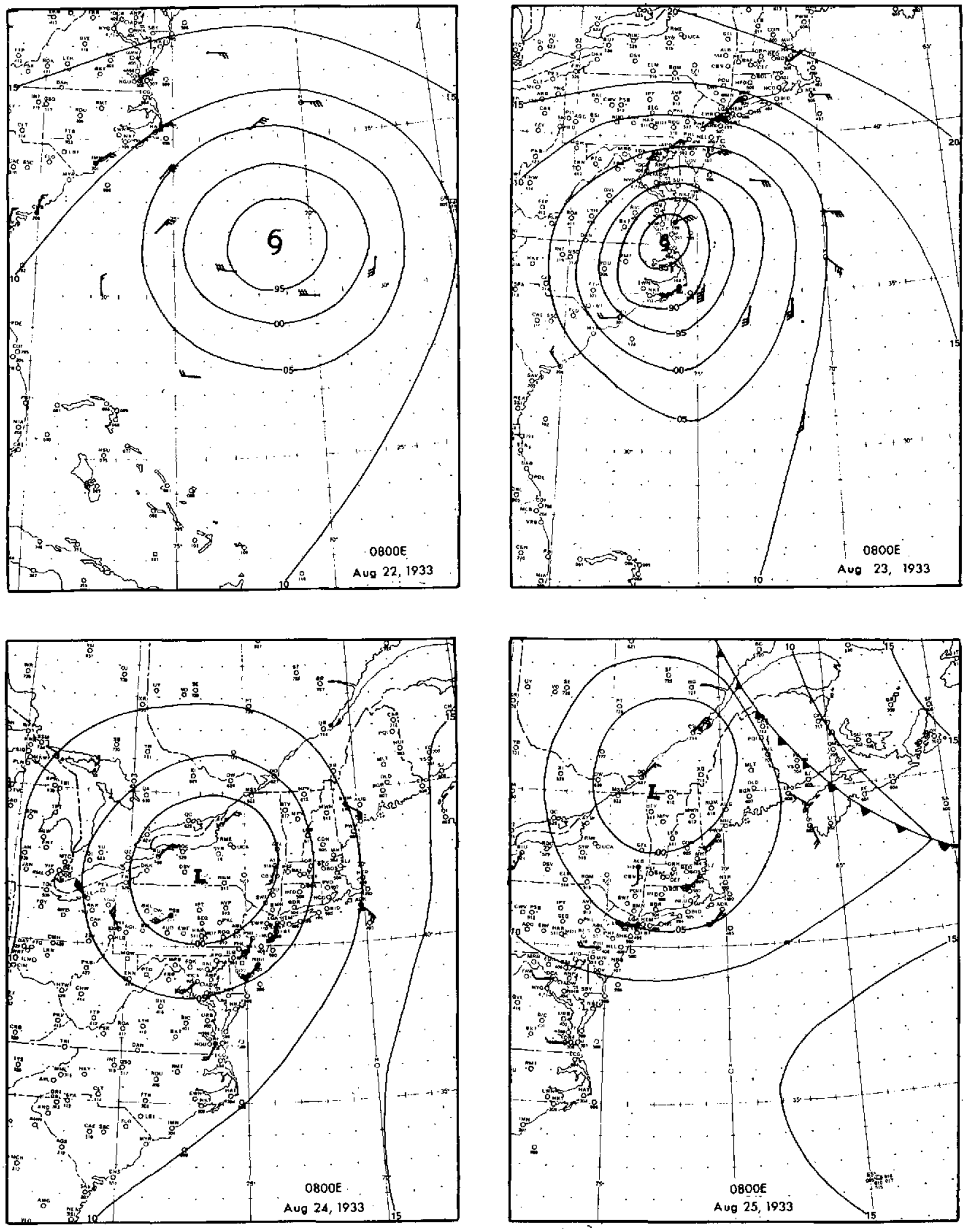

FIGURE 4.1.—Hurricane 1933, August 22–24. Synoptic charts.

mean low water is 1.4 ft. below the sea level datum of 1929. This navigation low water datum has not been tied into the geodetic level network at all locations for which high water marks are shown. South of Dahlgreen the tide range is only about half of that in Washington, and the adjustment needed to correct these values to mean sea level would not differ very much from 0.7 ft. Although the tidal flooding was dominant in all of these values, with the possible exception of the higher value on the Anacostia River, the fluvial flooding is known to have been important and may have made a significant contribution to all of the values near Washington.

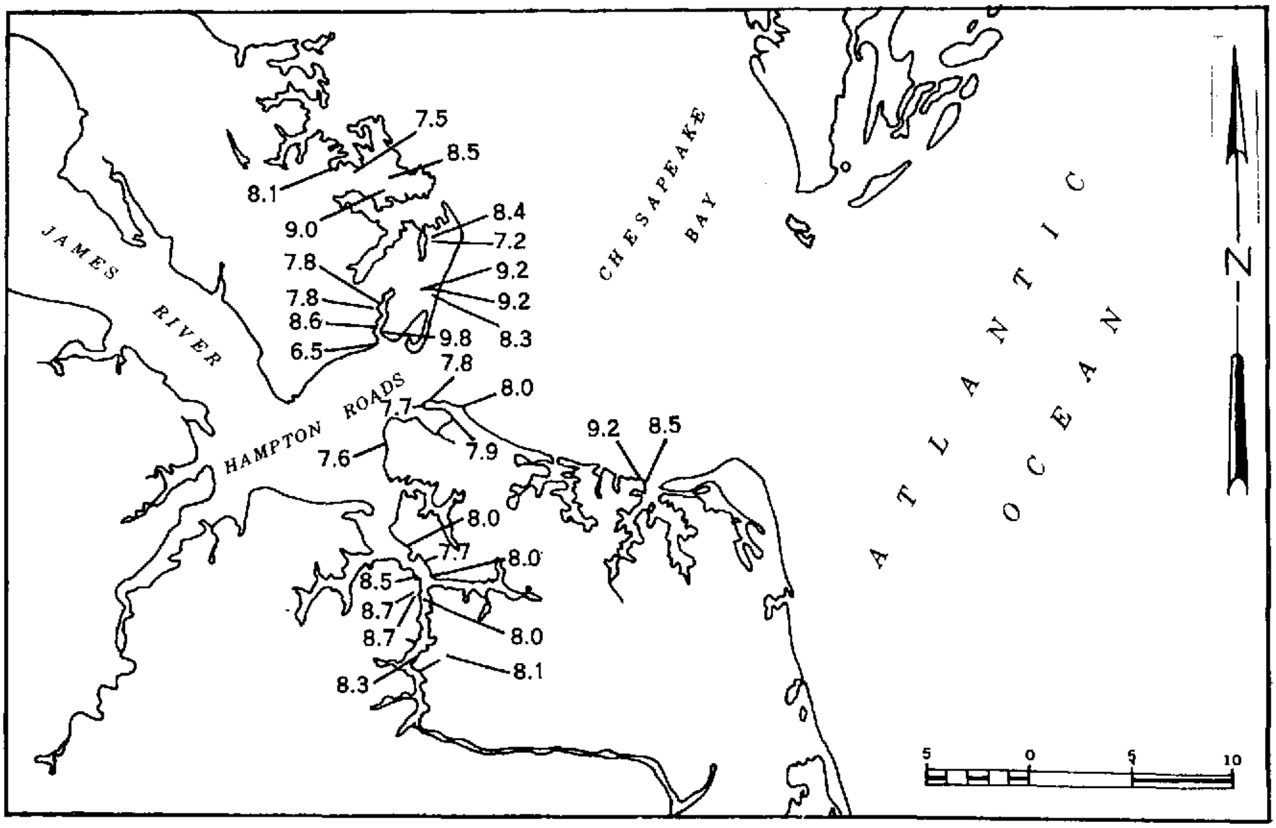

FIGURE 4.3.—Hurricane 1933, August 22–24. High water mark chart, Norfolk, Va. area. Mean sea level datum. (Based on data furnished by the Norfolk District of the U.S. Army Corps of Engineers.)

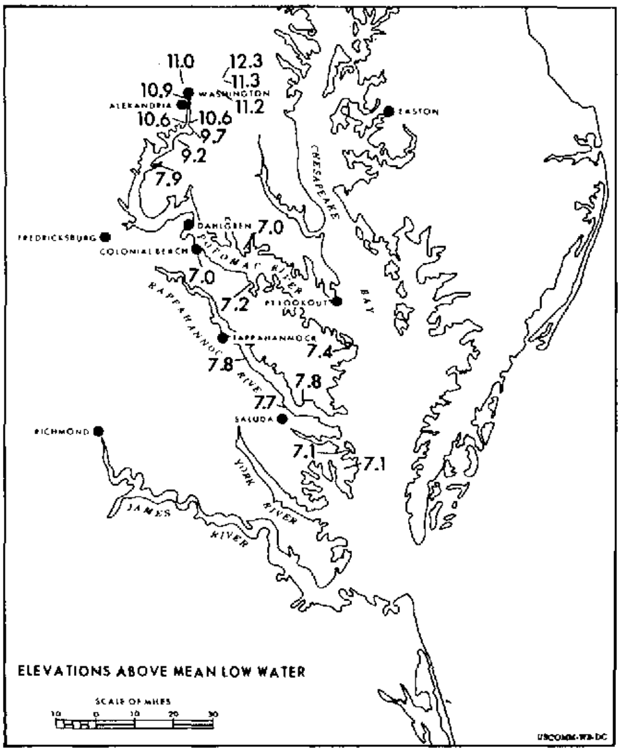

FIGURE 4.4.—Hurricane 1933, August 22–24. High water mark chart, Rappahannock and Potomac River areas. Low water datum (see text). (Based on data furnished by the Washington District of the U.S. Army Corps of Engineers.)

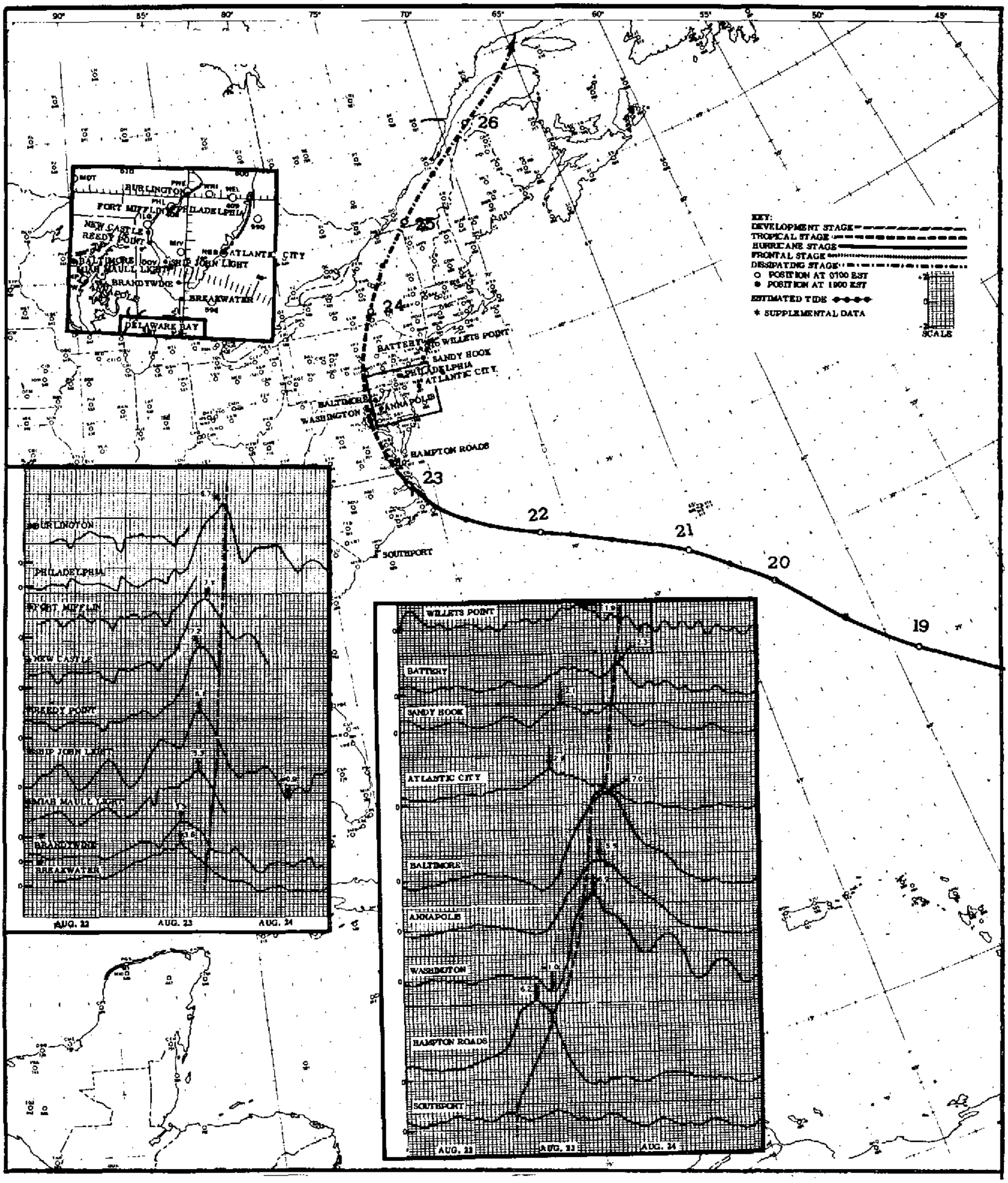

FIGURE 4.2.—Hurricane 1933, August 22–24. Storm surge charts. Insert chart for Delaware Bay.

STORM NO. 5.—HURRICANE 1933, SEPTEMBER 15–18

The surge generated at Hampton Roads by this storm was only a foot lower than that generated by the storm of August 23, about three weeks earlier. However, the peak surge of this storm coincided approximately with the normal low tide and the resultant flooding was much less than that produced by the earlier storm. The storm center remained east of Chesapeake Bay and the wind over the Bay did not become so strong as in the earlier storm and remained in the northerly and westerly quadrants. The resultant surges at Baltimore and Annapolis remained negligible. Here we see an example of a case in which the set-up over the Bay acted in the opposite direction to the disturbance being propagated into the Bay from the ocean.

C. L. Mitchell [62] reports that this storm produced considerable flooding in the North Carolina Sounds. He reports that water reached a height of 2 to 4 ft. in the streets of New Bern, N.C., and that 21 lives were lost, mostly due to high water. His information is not specific enough for direct application to research problems.

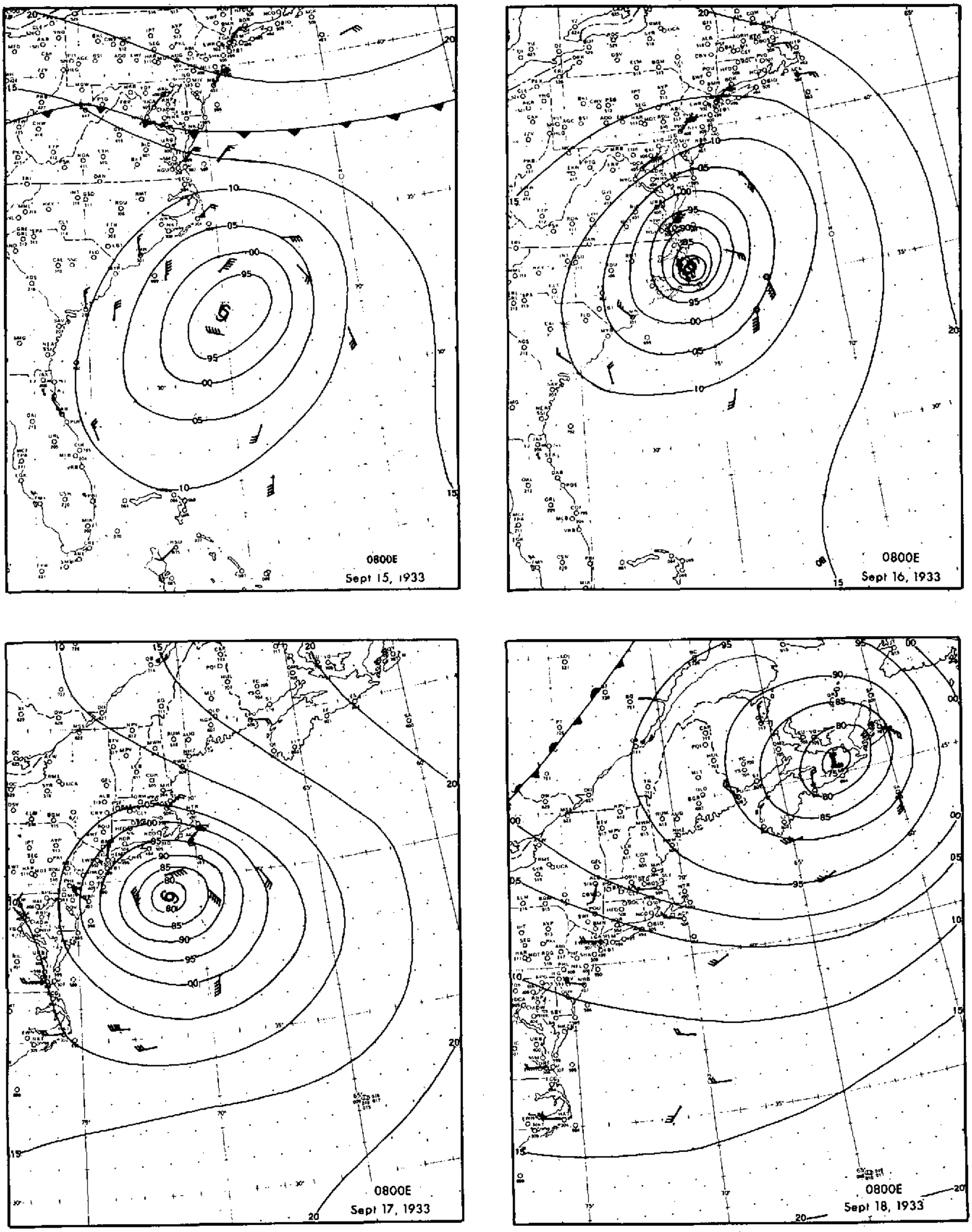

FIGURE 5.1.—Hurricane 1933, September 15–18. Synoptic charts.

STORM NO. 6.—HURRICANE 1934, JULY 25

This is one of the few documented cases of a tropical storm developing from a frontal disturbance of extratropical origin (Mitchell [61]). However, the storm did not develop to hurricane intensity until July 25, and as far as the writer knows, it has not been investigated in any great detail. The Coast and Geodetic Survey gage at Galveston was inoperative during the height of the storm. Data from the Weather Bureau gage were used to complete the record until it too went out about 5 a.m. The source of the interpolated data after that time is unknown. Supplementary reports indicate that the storm tide was slightly higher at Fort Point than at the U.S. Coast and Geodetic Survey gage.

Observe that the surge began in Galveston early in the afternoon of July 24 when the winds within a hundred miles of Galveston were north to northwest, indicating that the rise was due either to the pileup of bay water at the tide gage site near the southern part of Galveston Bay or to the effect of the earth's rotation on a current parallel to the shore in the Gulf. This is characteristic of the hurricane storm surge records at Galveston. Data obtained during hurricane Carla, September 10–12, 1961, strongly support the latter view. The surge decreased when the winds shifted toward the southeast and thus blew directly toward the island.

THE LABOR DAY HURRICANE OF 1935, SEPTEMBER 1–6

This storm was one of the most intense hurricanes ever recorded. The high water levels reported in this storm were higher than those reported for any other storm in the United States prior to hurricane Carla in 1961. It would be desirable to include a discussion of the storm surges produced by this storm in this report. This is not done because very few well-documented quantitative data for the storm surges produced by this storm could be found. Most of the islands in the Florida Keys were connected by a causeway at the time of this storm and the existence of this causeway is believed to have had a significant effect on the generation of the surge. The causeway has since been removed and thus even the same storm would be expected to produce a far different pattern of storm surges if it were to occur in the future.

STORM NO. 7.—HURRICANE 1936, SEPTEMBER 17–19

Pore [79] gives bi-hourly wind velocities at Norfolk and Baltimore in connection with his discussion of this storm. The winds were from the northeast from about 0600 EST September 17 until the peak surge occurred at Hampton Roads. Since northeast winds on the coast generally lead to increasing water levels at coastal tide gages and the surge was negative at the northern part of Chesapeake Bay, we may conclude that the high water recorded in the southern part of the Bay resulted from a convergence of both ocean water and bay water in this region. The period of falling surge level at all stations for several hours after the peak at Hampton Roads suggests that most of the water coming from the ocean returned to the ocean during this period.

The fall in surge level in Washington is also attributed to the northeasterly winds over the Bay and the subsequent peak is believed to be the result of rainfall runoff.

No harmonic prediction constants were available for Leipsic, Del., and the predictions for this station had to be inferred from data derived from other locations and are something less than satisfactory. Nevertheless the near coincidence of the highest peak with the passage of the hurricane

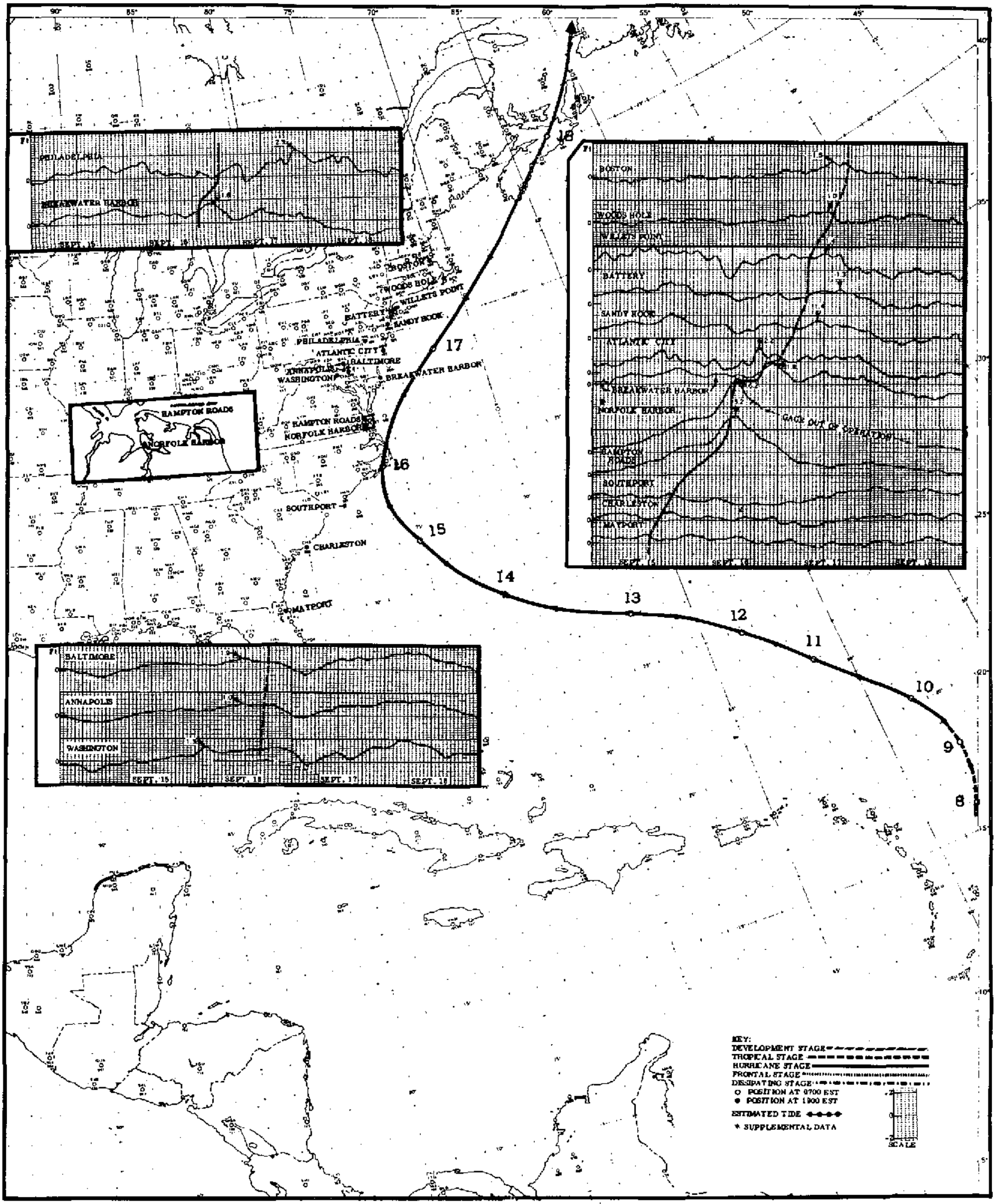

Figure 5.2.—Hurricane 1933, September 15–18. Storm surge chart. Insert chart for Norfolk area.

center to the east suggests that this peak was due, at least in part, to the advection of a surge formed on the open coast through Delaware Bay. The subsequent fall at Philadelphia and Leipsic appears to be due to the northerly winds over the river. The subsequent rise at Philadelphia is attributed to fluvial flooding resulting from the hurricane rainfall.

The two peaks at Willets Point are typical of surge records at this gage, and appear to illustrate the effects of the two paths by which the surge reaches this location No harmonic constants are available for Mill Rock and the predictions inferred from other stations are not altogether satisfactory.

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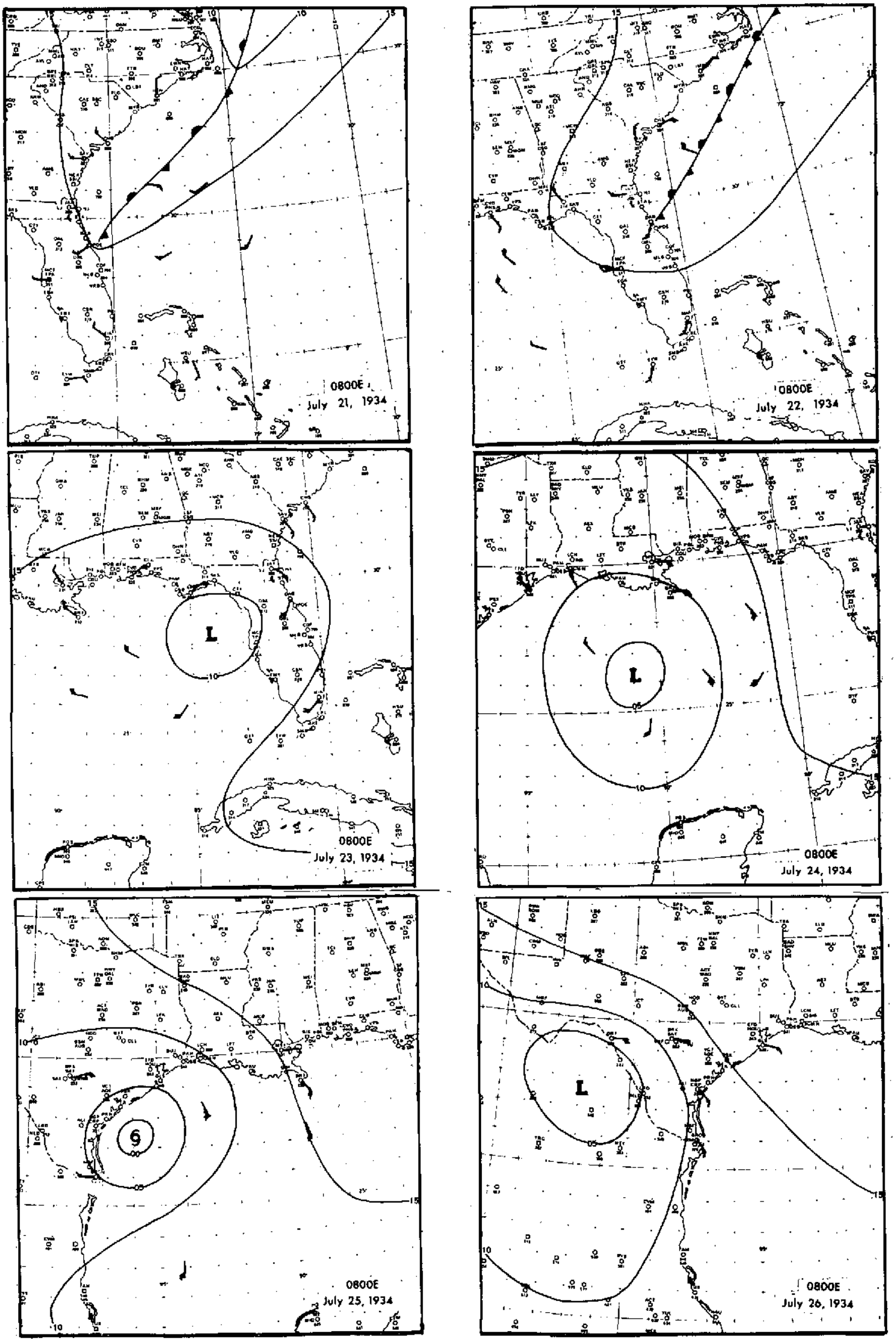


FIGURE 6.1.—Hurricane 1934, July 25. Synoptic charts.

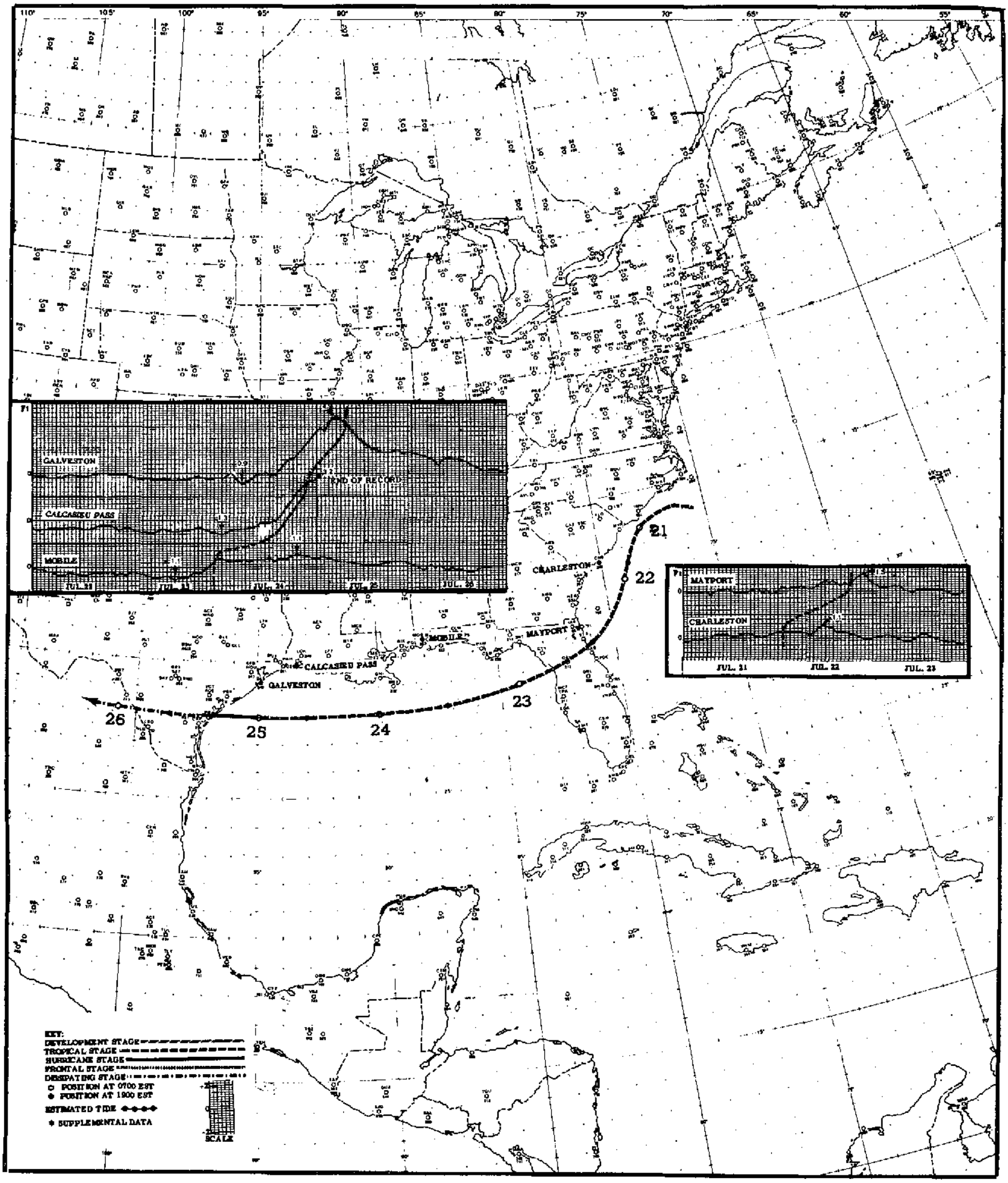


FIGURE 6.2.—Hurricane 1934, July 25. Storm surge chart.

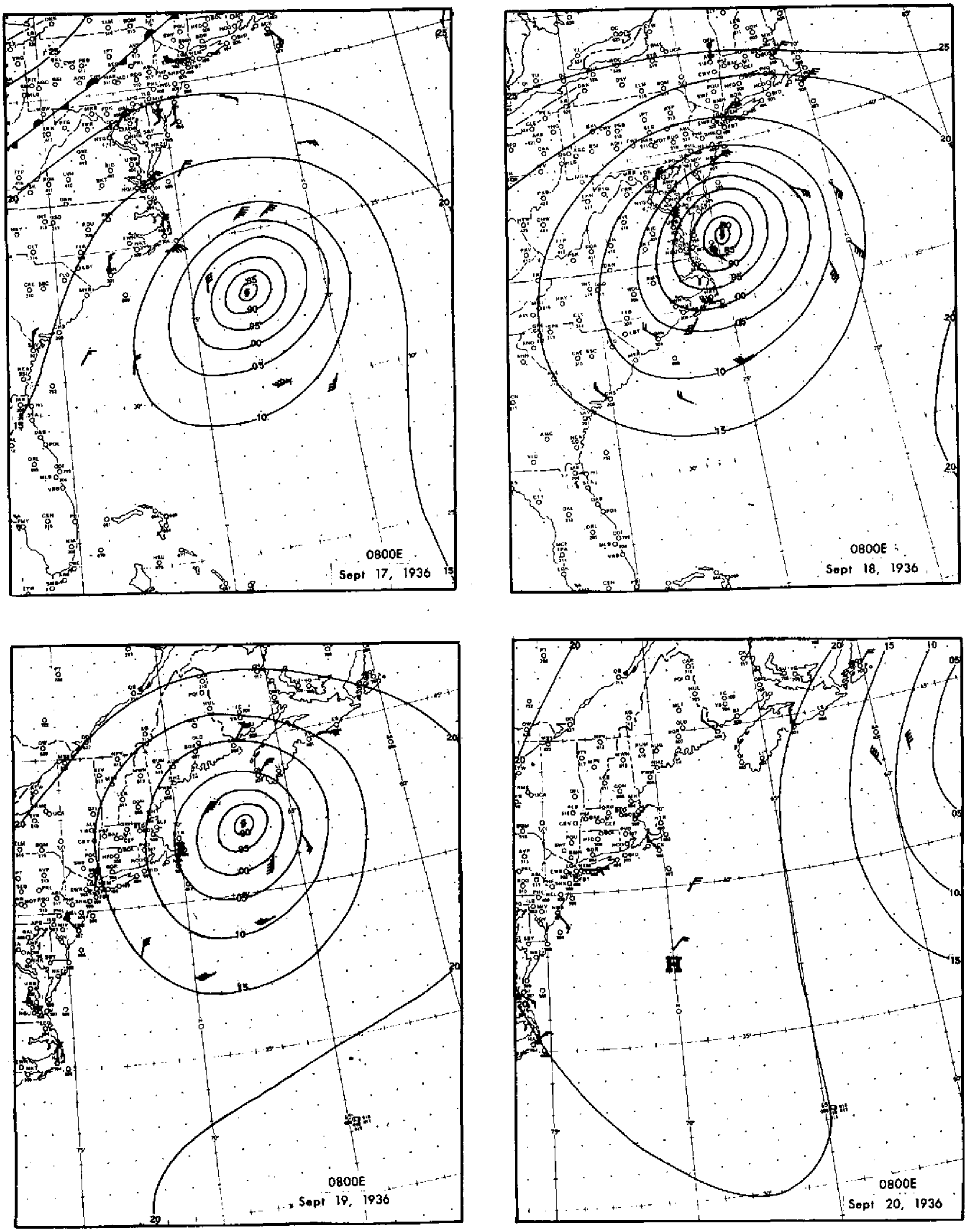


FIGURE 7.1.—Hurricane 1936, September 17–19. Synoptic charts.

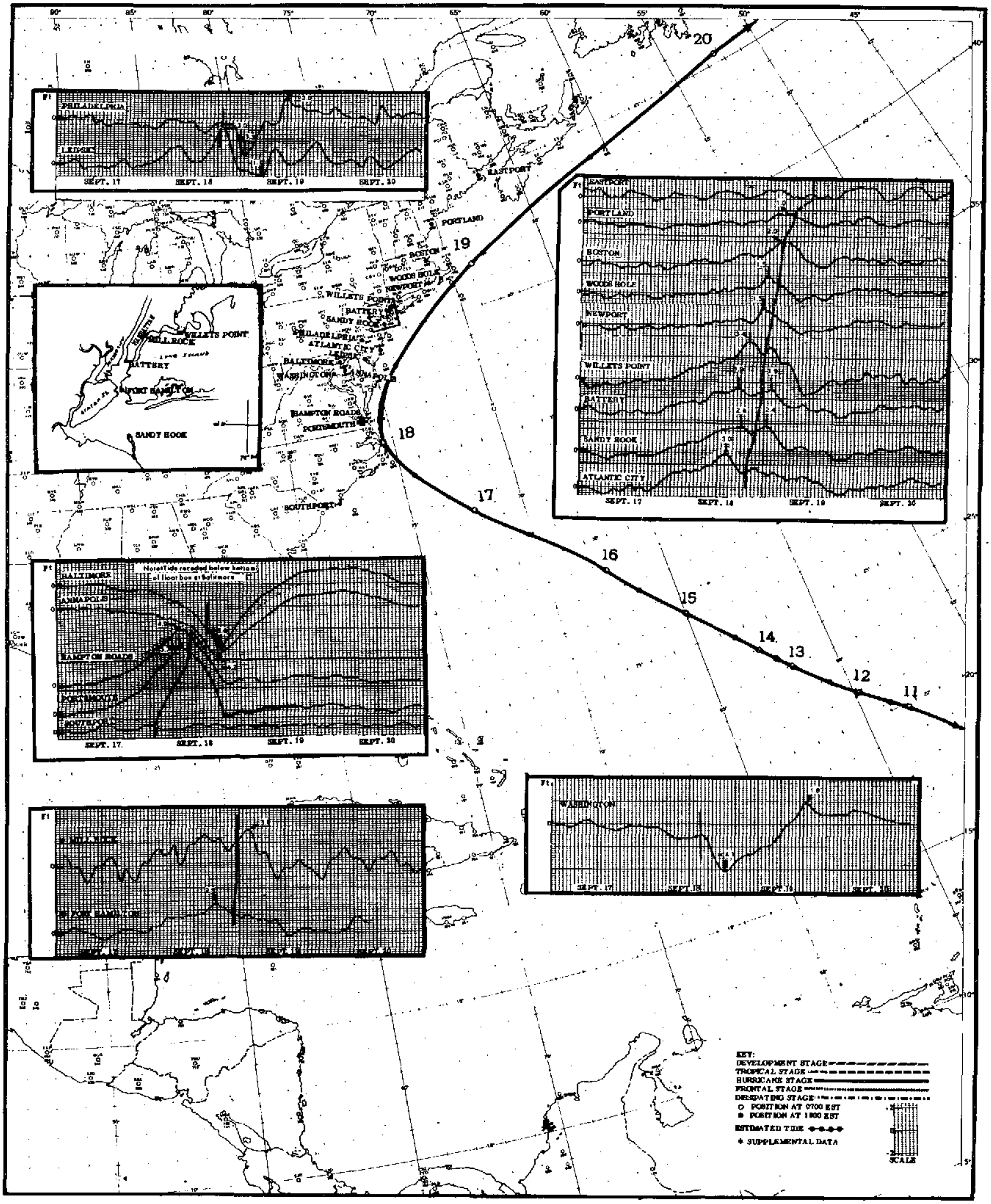


FIGURE 7.2.—Hurricane 1936, September 17–19. Storm surge chart. Insert map for New York Harbor.

The storm surges produced by this storm appear to have led to more study and more reports than those produced by any earlier hurricane. The meteorological history of the storm has been investigated in great detail by Pierce [76]. Myers and Jordan [69] analyzed the pressure and wind fields and constructed isovel charts for the open waters south of Long Island to be used in storm surge computations. Their data have been republished by Graham and Hudson [33].

The U.S. Army Corps of Engineers [107] collected a great many high water marks following this storm. Nichols and Marston [73] have discussed the shoreline changes produced by the storm in Rhode Island. The high water marks and storm surge curves for this storm and other storms which crossed New England have been discussed by Redfield and Miller [83].

The most notable features of the surges produced by this storm are the multiple peaks appearing in all the records for the New York Harbor area. Redfield and Miller have explained the first peak at Willets Point as being due to the advection of the surge in New York Harbor northward through East River, and the second peak as being that which developed east of Long Island and traveled westward through the Sound. There appears to be general agreement on this among all writers who have discussed this point.

The double peak at Willets Point has occurred in other storms, but is not always as clear as in this case. Multiple peaks have also occurred at other stations in the tide records of many hurricanes which have entered southern New England. Redfield and Miller call these multiple peaks resurgences and suggest that they are due to the oscillation of water between the edge of the continental shelf and the shore. Munk, Snodgrass, and Carrier [66] attribute them to edge waves and show their principal characteristics for this storm and several others are compatible with the edge wave theory.

The high water mark data, collected by the Corps of Engineers, Woods Hole Oceanographic Institution, and others, are combined in figure 8.3. The variation in peak water elevations apparent in the charts accompanying the 1926 and 1933 storms is also apparent here. The New England District of the Corps of Engineers has collected so many high water marks that it has been impractical to show them all. Many of the elevations shown result from averaging from two to ten values obtained within a space of one to two miles of coastline. The range of values combined to obtain a single value is frequently greater than 2 ft. The approximate coincidence between the normal high tide and the peak storm surge during this storm led to extensive flooding, and the collection of many high water mark observations.

The data for the supplementary panel for New York Harbor in figure 8.2 were furnished by the New York District of the U.S. Army Corps of Engineers.

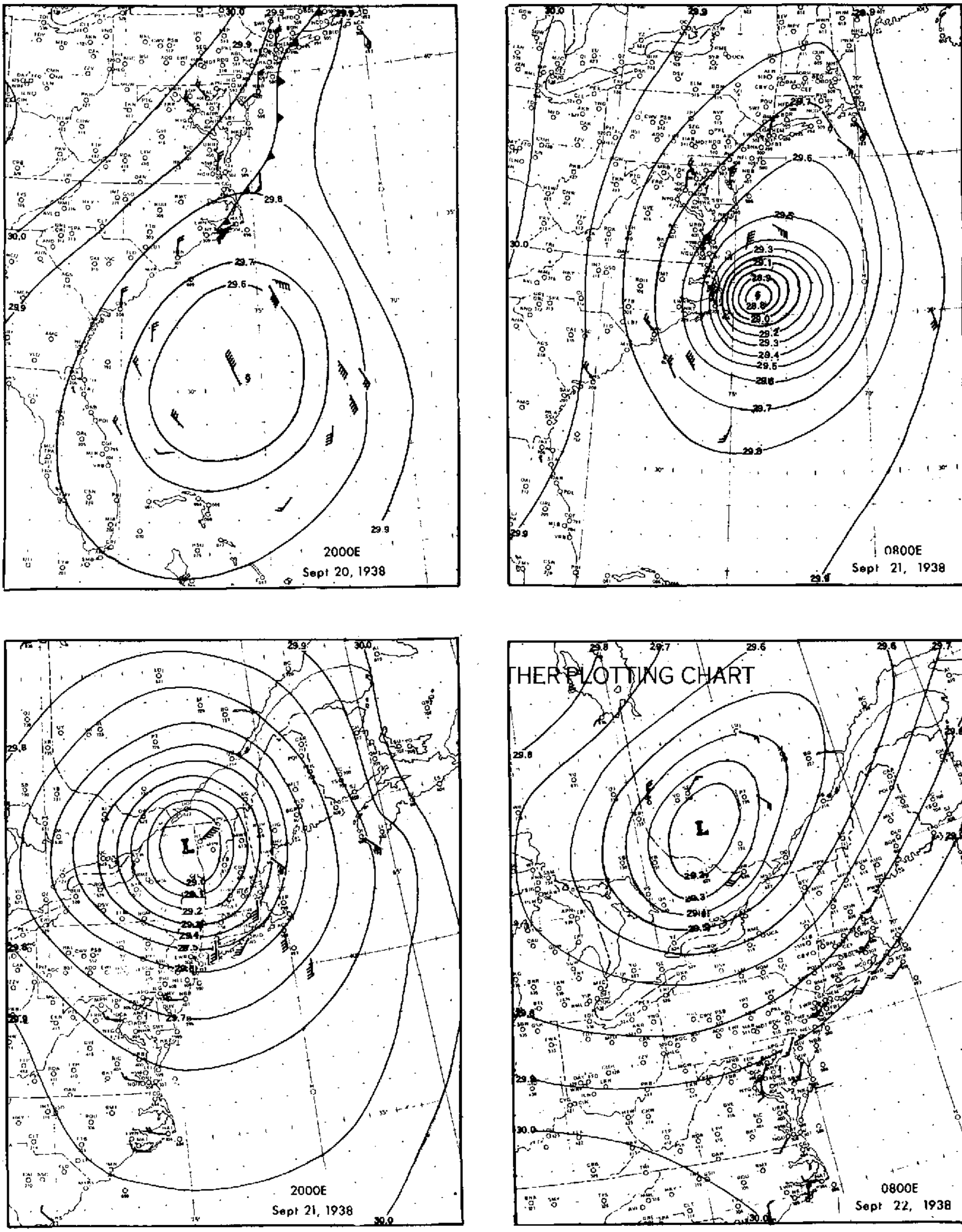


FIGURE 8.1.—Hurricane 1938, September 21–22. Synoptic charts.

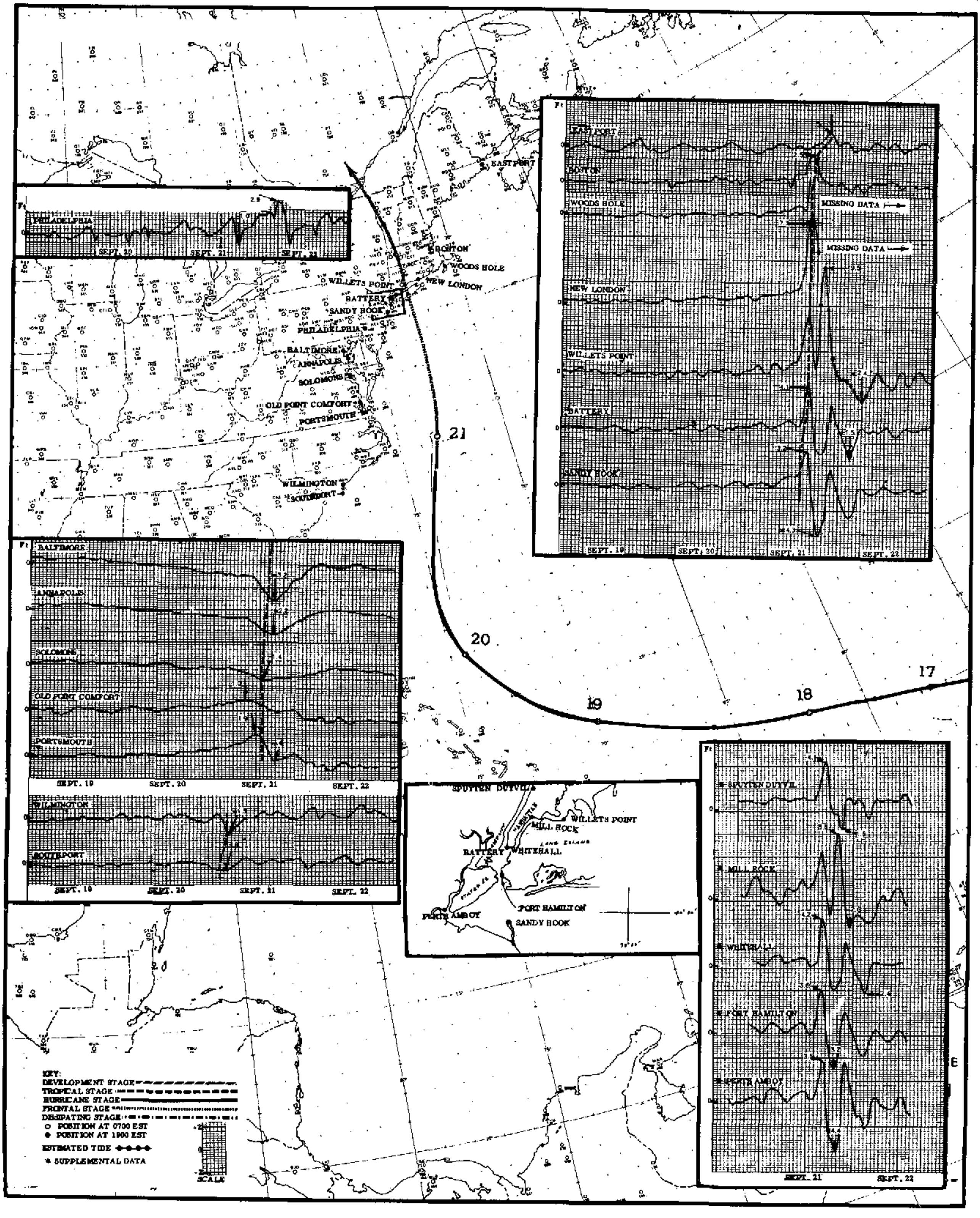


FIGURE 8.2.—Hurricane 1938, September 21–22. Storm surge chart. Insert map for New York Harbor.

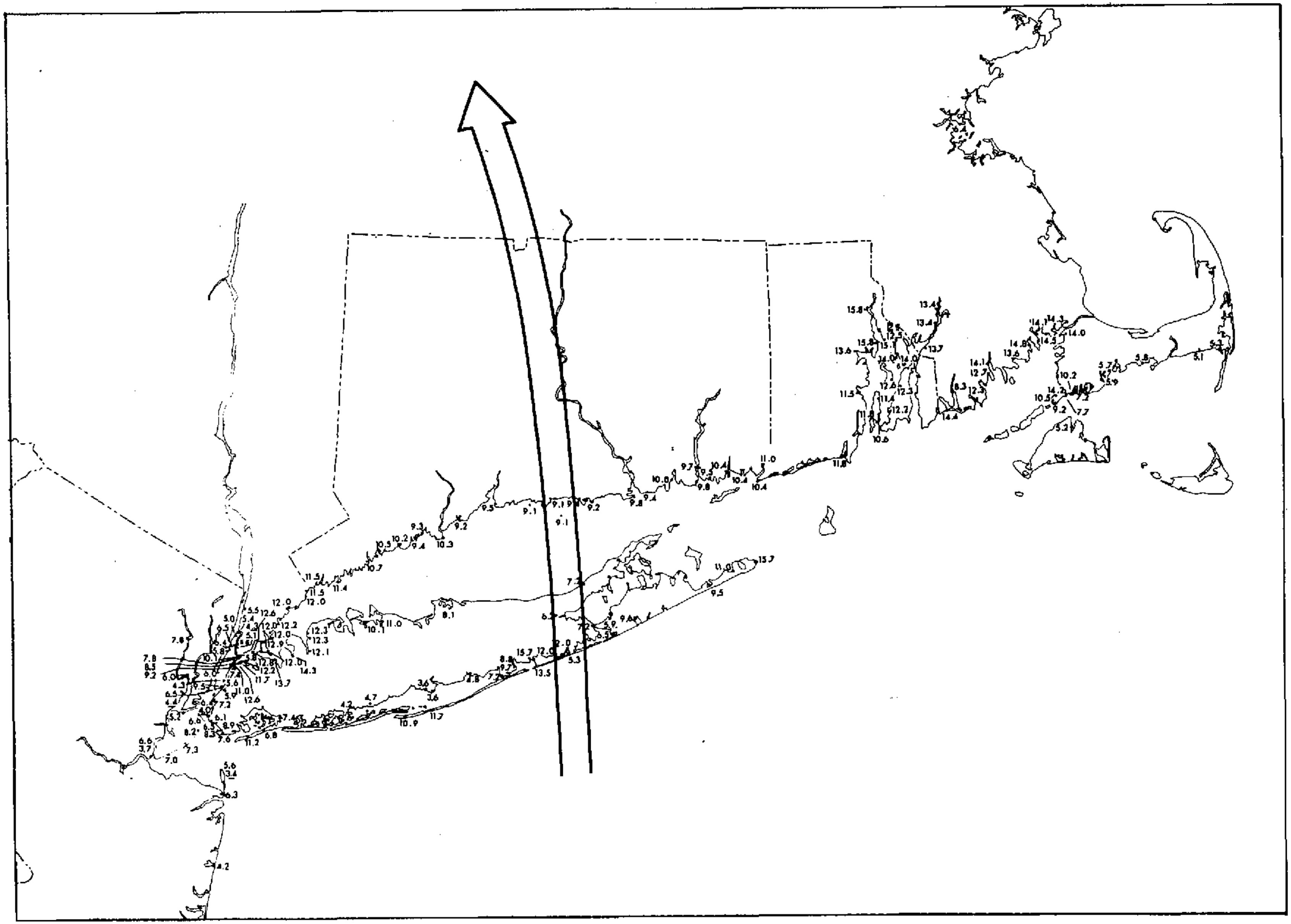


FIGURE 8.3.—Hurricane 1938, September 21–22. High water marks, New York and New England area. (Based on data obtained from New England Division and New York District of the U.S. Army Corps of Engineers and the Woods Hole Oceanographic Institution.)

Several supplementary tide records and high water marks due to this storm were obtained from the Galveston District Office of the U.S. Army Corps of Engineers. It was not possible to obtain a satisfactory removal of the normal tide from all of these records, and therefore, two panels are shown in figure 9.2, one consisting of the surge records for those stations for which this could be obtained with a satisfactory degree of approximation, and one presenting the uncorrected records. Records from some stations were included in both panels to facilitate comparison of the two types of data. Predicted tides, where available, are shown as dashed lines on the observed graph. A slight phase lag between predictions and observations indicates that the prediction constants were not derived for the exact location of the gage for which observations are furnished. Note the out-of-phase relationship between the peak tide at High Island and Fort Point. The High Island gage is located near the head of a long, narrow arm of Galveston Bay (see insert map on fig. 24.3). Note also that the synoptic charts indicate winds parallel to or slightly off-shore during the period in which the surge was increasing at Galveston. This tendency for rising water levels with northerly winds and the phase relationship between the various gages in Galveston Bay in this and other storms suggest that much of the tidal flooding in Galveston Bay region is due to movement of water within the Bay. However, data from other storms, notably Carla (1961) show that the pile-up of water on the Gulf side of the Barrier Islands makes a significant contribution. The same may be true of the other bays in Texas, but the available data are not sufficient to permit a determination.

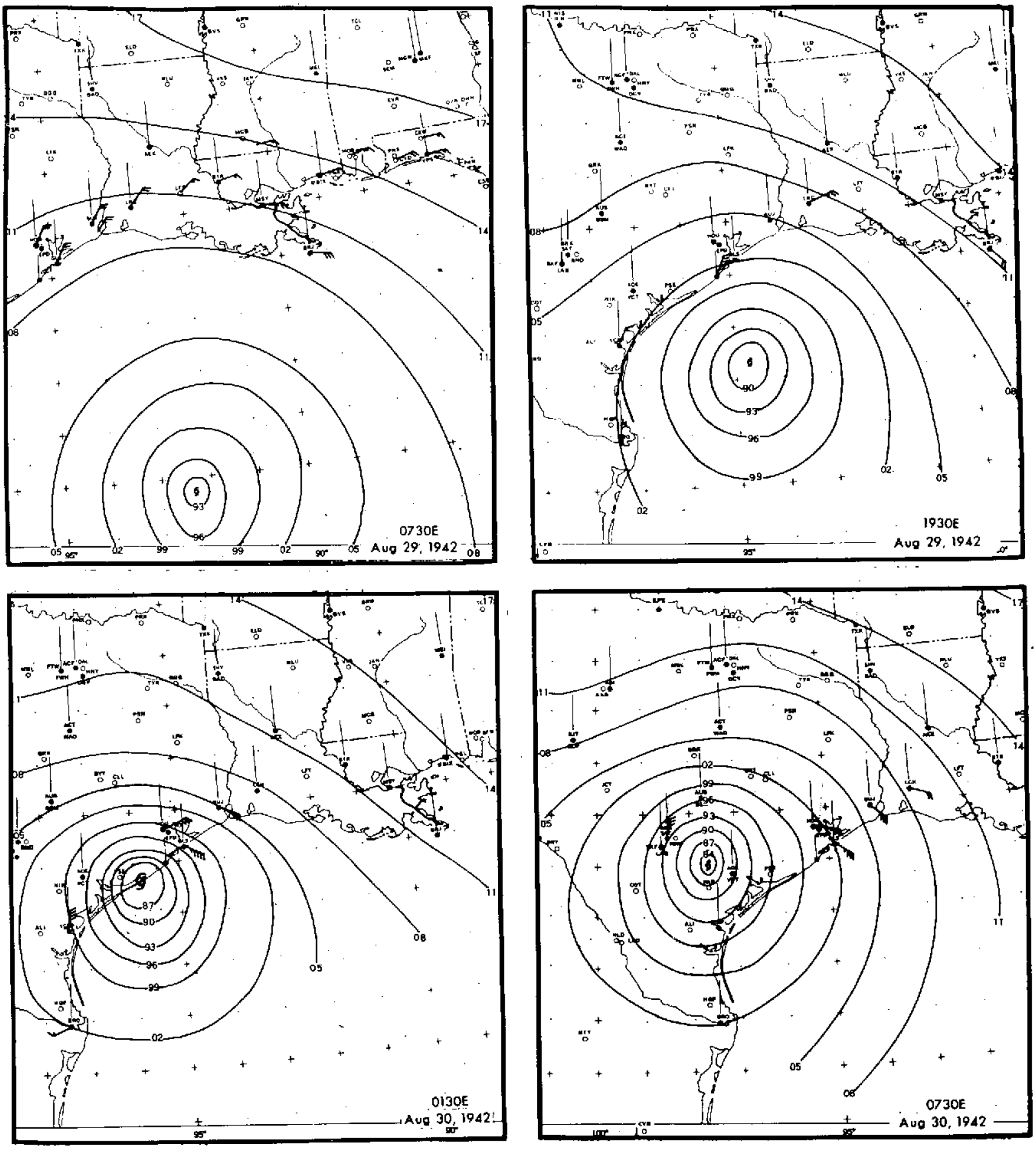


FIGURE 9.1.—Hurricane 1942, August 29–30. Synoptic charts.

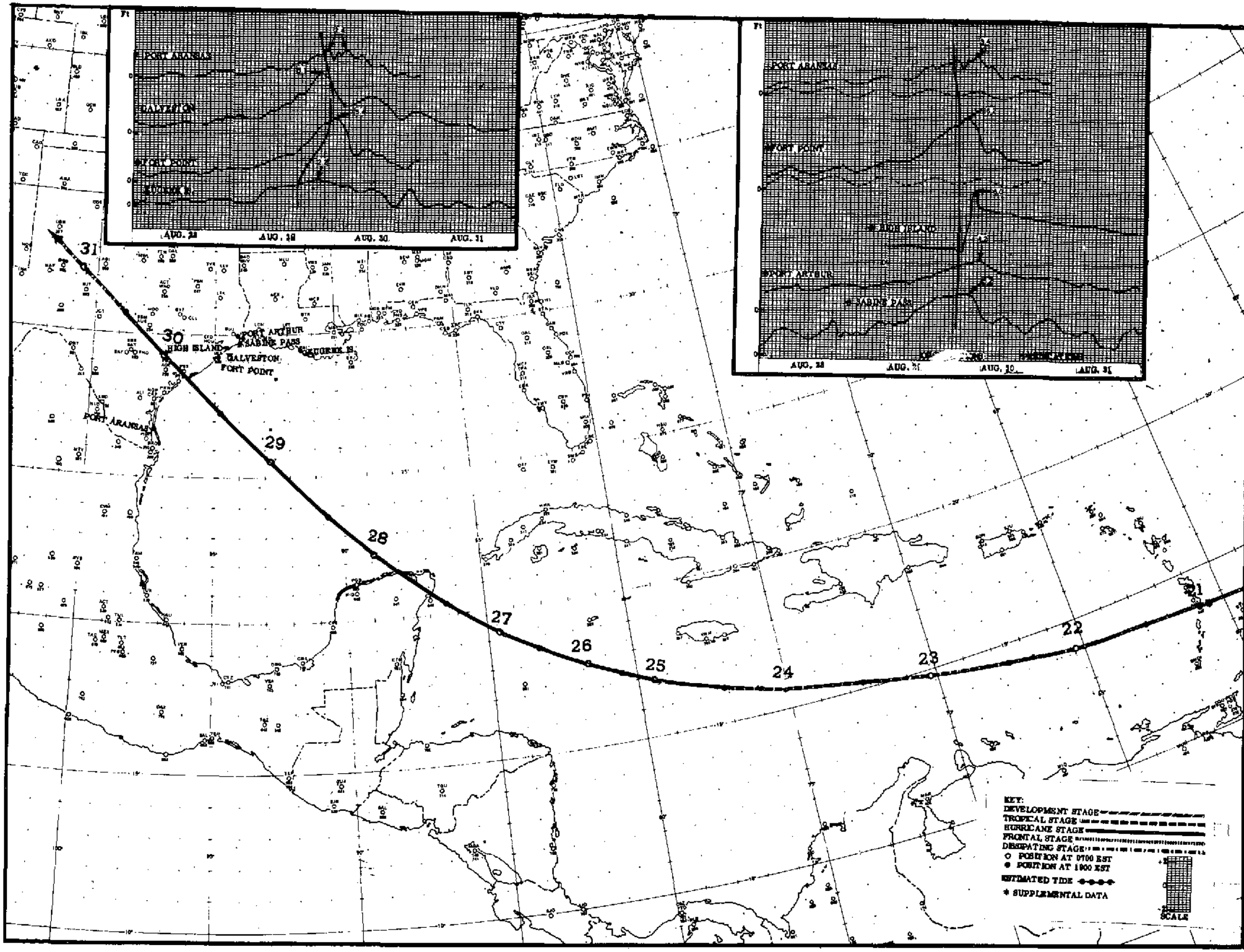


FIGURE 9.2.—Hurricane 1942, August 29–30. Storm surge chart.

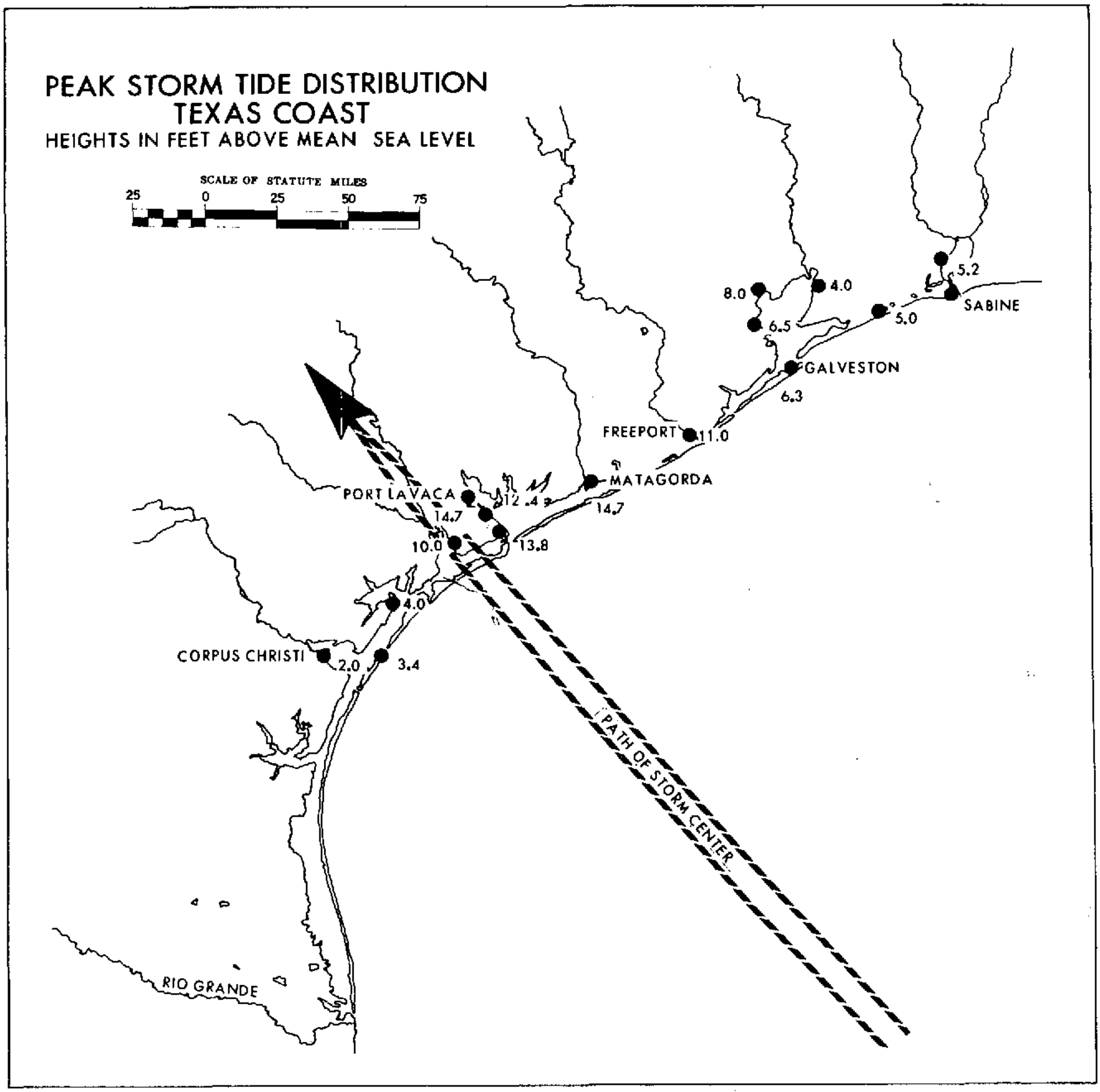


FIGURE 9.3.—Hurricane 1942, August 29–30. High water marks in Texas.

STORM NO. 10.—HURRICANE 1944, SEPTEMBER 13–15

The storm surge associated with this hurricane was similar to that of the September 21–22, 1938 storm. The peak surges associated with this storm (1944) coincided very nearly with the normal low tide, and the peak surges of the 1938 storm coincided very nearly with the normal high tide. Thus the observed tides of this storm were lower and produced less damage. Comparatively few high water marks were recorded. Many of the high water marks that were recorded are plotted in figure 10.3. A copy of the continuous tide record and the predicted tide for Atlantic City during this storm is presented in figure 10.4 to give an example of the type of high frequency oscillations common to the tide records of most well-exposed gages during hurricanes.

This storm and the associated storm tides have been discussed by Sumner [99] and by Brooks and Chapman [3]. The surface wind fields have been analyzed in detail by Graham and Hudson [33]. The three hurricanes September 21–22, 1938, September 13–15, 1944, and September 1954 have been discussed together in many published reports. The references listed under the other two storms should be consulted in connection with any detailed study of this hurricane.

STORM NO. 11.—HURRICANE 1944, OCTOBER 18–20

In general, the storm surges associated with hurricanes and tropical storms rise and fall more rapidly than those associated with extratropical storms. This effect is illustrated by the records of the storm surges produced by this storm, which changed from tropical to extratropical characteristics as it crossed Florida.

The records for the Chesapeake Bay stations show the effects of wind over the Bay and of the surge generated in the ocean. During the early morning of October 20 with the wind from the north to northeast, the water level fell in the northern part of the Bay and rose in the southern section, indicating a convergence of water in that part of the Bay. About 0800 EST the surge level began to increase at all stations, suggesting a net inflow through Hampton Roads. Later, as the wind shifted to a southerly direction, the surge level fell near the mouth of the Bay but continued to rise in the northern sections until about the time of the second wind shift toward more northwesterly winds.

Several high water marks produced by this storm have been collected by the Jacksonville District Office of the U.S. Army Corps of Engineers and are reproduced in figure 11.3. A few additional high water mark data for this storm were collected by Sumner [100]. The density of these high water mark data is much less than that available for the 1926 storm and some later storms in Florida or New England, so it is difficult to determine their meaning in terms of flooding patterns. It is interesting, however, to observe that the peak high water marks, as the storm passed from land to sea near Jacksonville, are of nearly the same magnitude as the peak values near the original landfall of the hurricane.

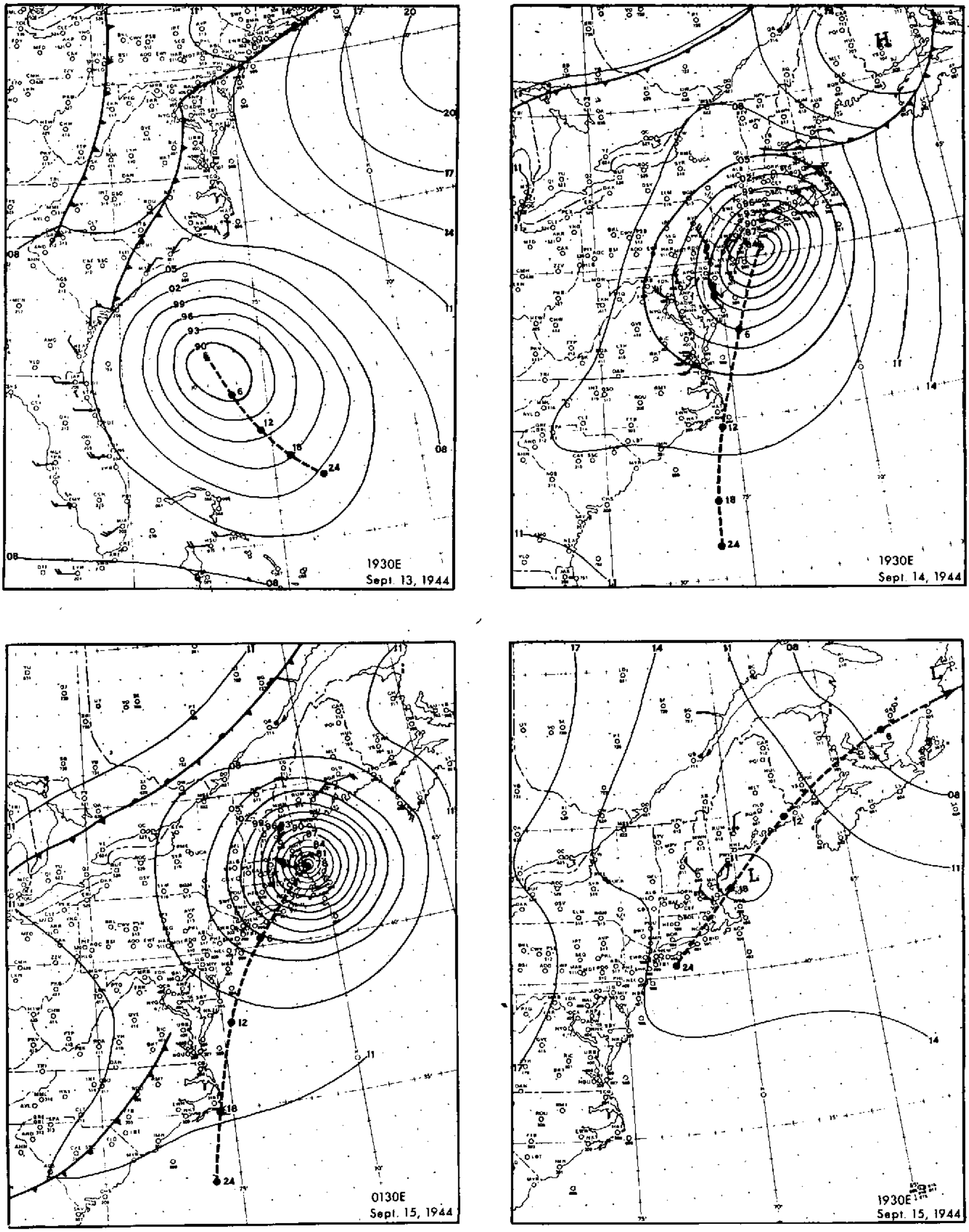


FIGURE 10.1.—Hurricane 1944, September 13–15. Synoptic charts.

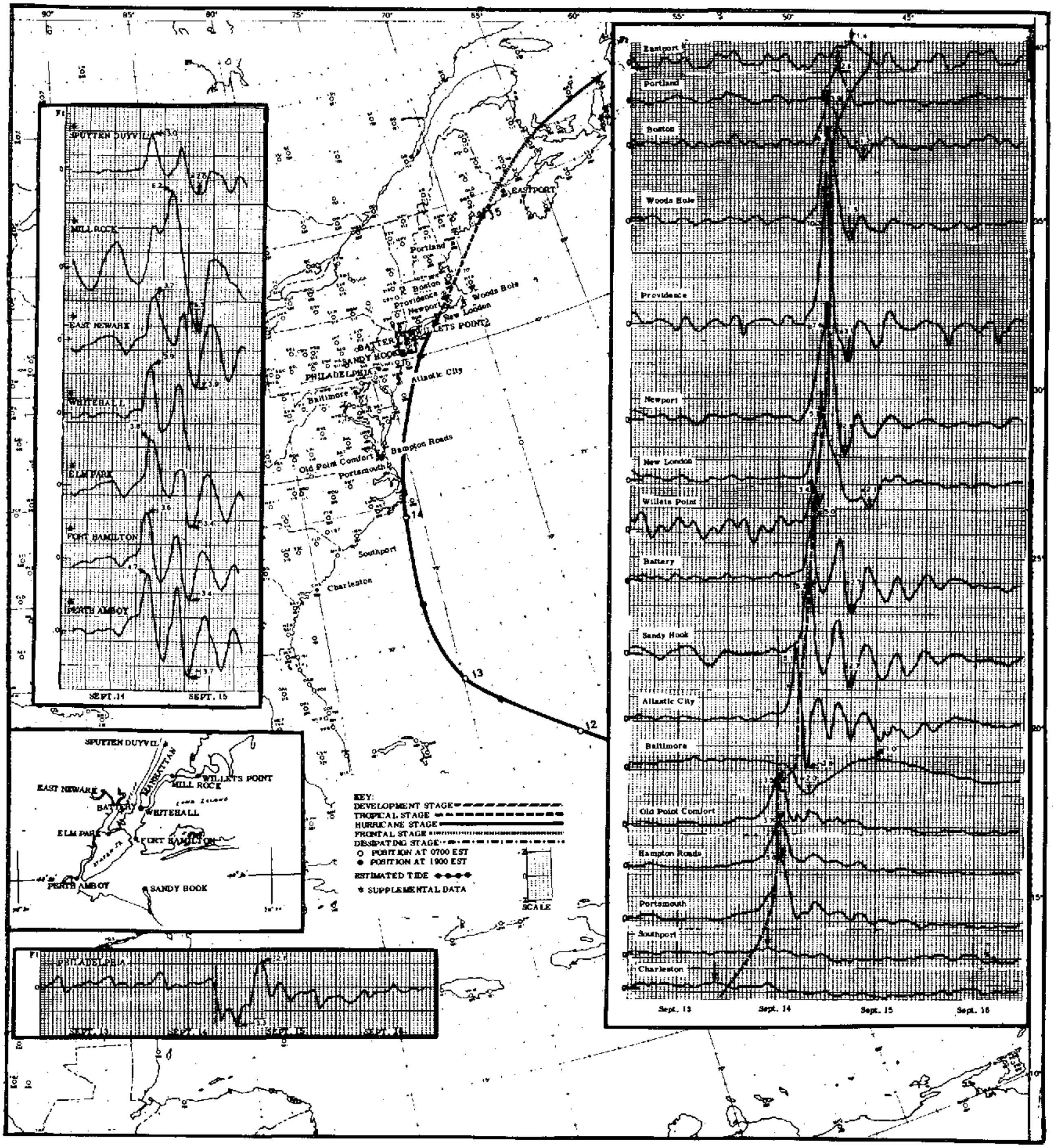


FIGURE 10.2.—Hurricane 1944, September 13–15. Storm surge chart. Insert map for New York Harbor.

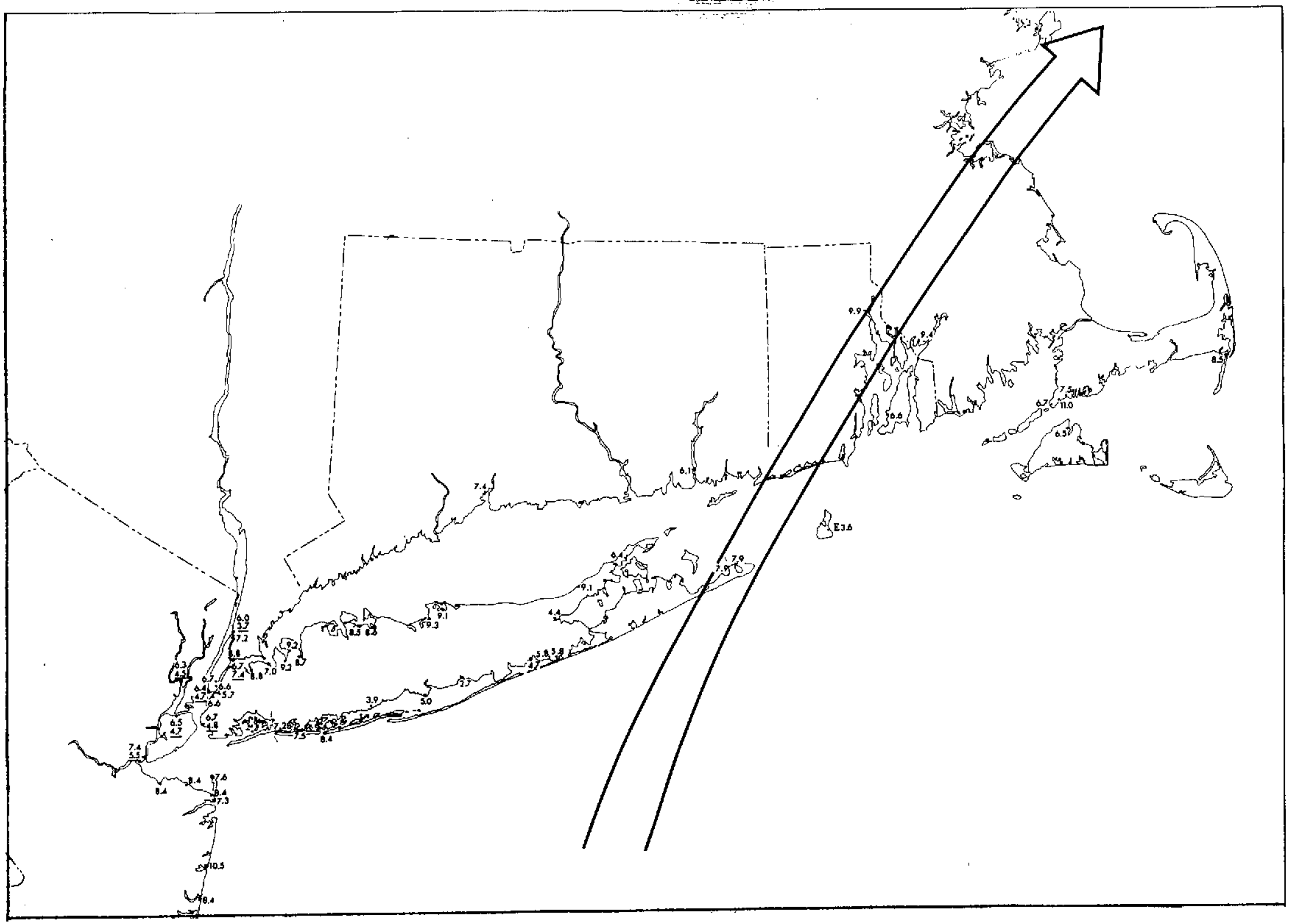


Figure 10.3.—Hurricane 1944, September 13–15. High water marks in New York and New England. Underlined values are peak storm surges. Note that the peak storm surge exceeds the high water mark at some locations.

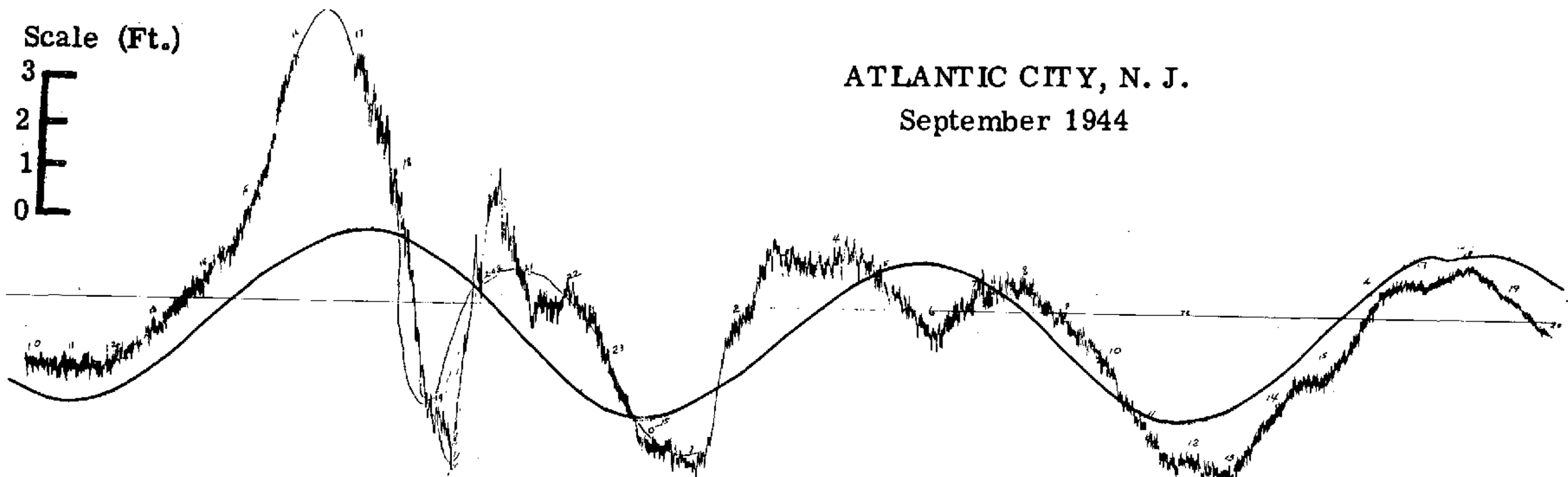


FIGURE 10.4.—Hurricane 1944, September 13–15. Recorded tide traced from original gage record and predicted tide at Coast and Geodetic Survey tide station, Steel Pier, Atlantic City, N.J.

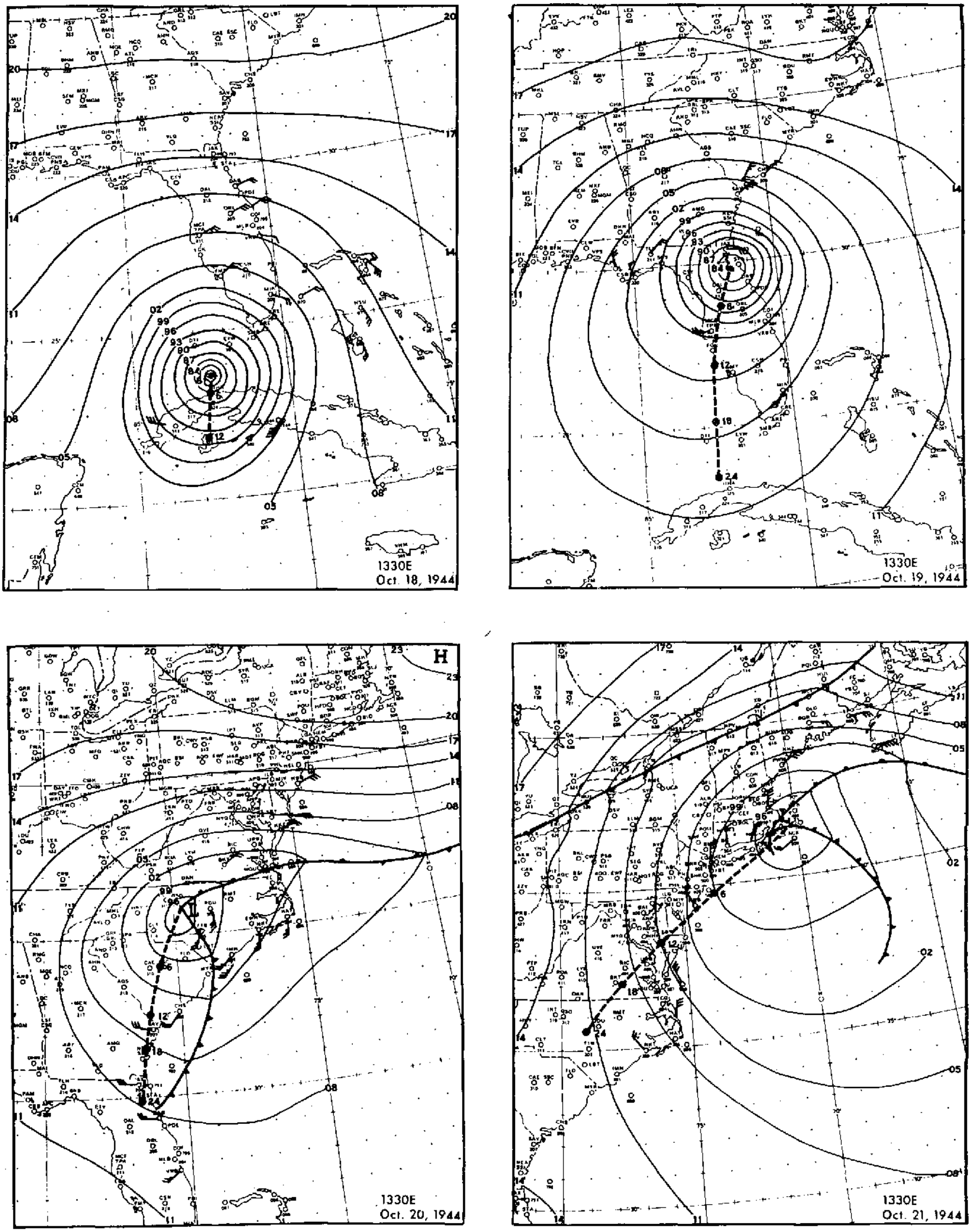


FIGURE 11.1.—Hurricane 1944, October 18–20. Synoptic charts.

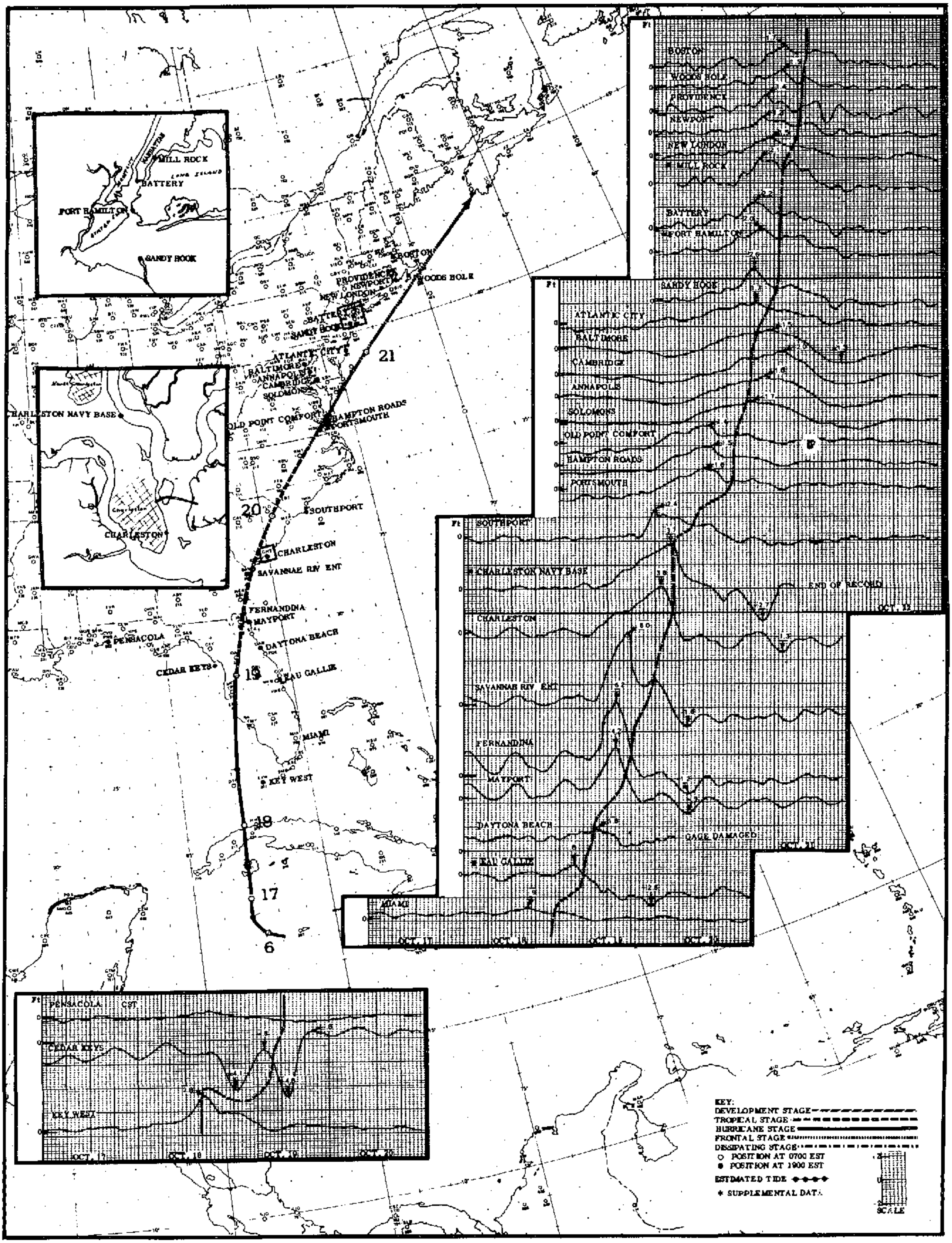


FIGURE 11.2.—Hurricane 1944, October 18–20. Storm surge chart. Insert maps for New York Harbor and Charleston, S.C.

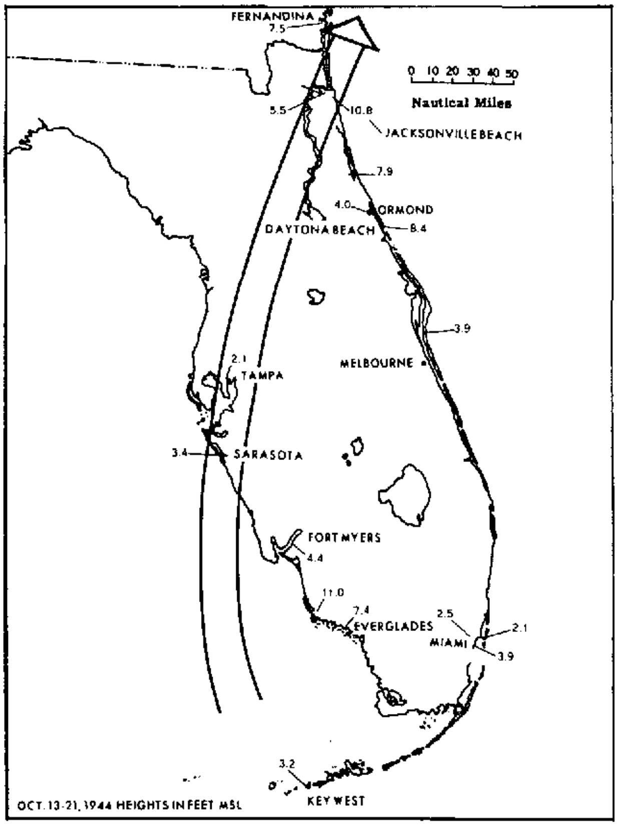


FIGURE 11.3.—Hurricane 1944, October 18–20. High water marks in Florida. (Based on data obtained from the Jacksonville District of the U.S. Army Corps of Engineers.)

The high water mark chart, figure 12.3, and the supplementary tide gage records obtained from the Jacksonville District Office of the U.S. Army Corps of Engineers show clearly the effects of local factors on the generation of extremely high water levels during hurricanes. The tide anomaly at the Coast and Geodetic Survey Tide station near Government Cut on Miami Beach was only 2.0 ft. The three high water marks obtained from the barrier islands are entirely consistent with this surge value. Together they indicate a rather small disturbance in the sea level in the open water just off-shore. The much higher values on the mainland show the effects of additional wind set-up over the shallow waters of Biscayne Bay, wave set-up at the shore in this area, and the effects of convergence in the disturbance moving into the Bay. If one had only the high water marks, he might suspect that these contain a large contribution from wave run-up and are not true high water mark elevations. This possibility cannot be entirely eliminated, but the continuous rise to some level above 8 ft. in the record for the tide gage at Coconut Grove shows that run-up cannot be the primary reason for the increase in reported peak water level within the Bay.

The records for the Chesapeake Bay stations tend to imply that the surge in the northern part of the Bay included contributions both from an inflow of Atlantic water and from wind set-up over the Bay.

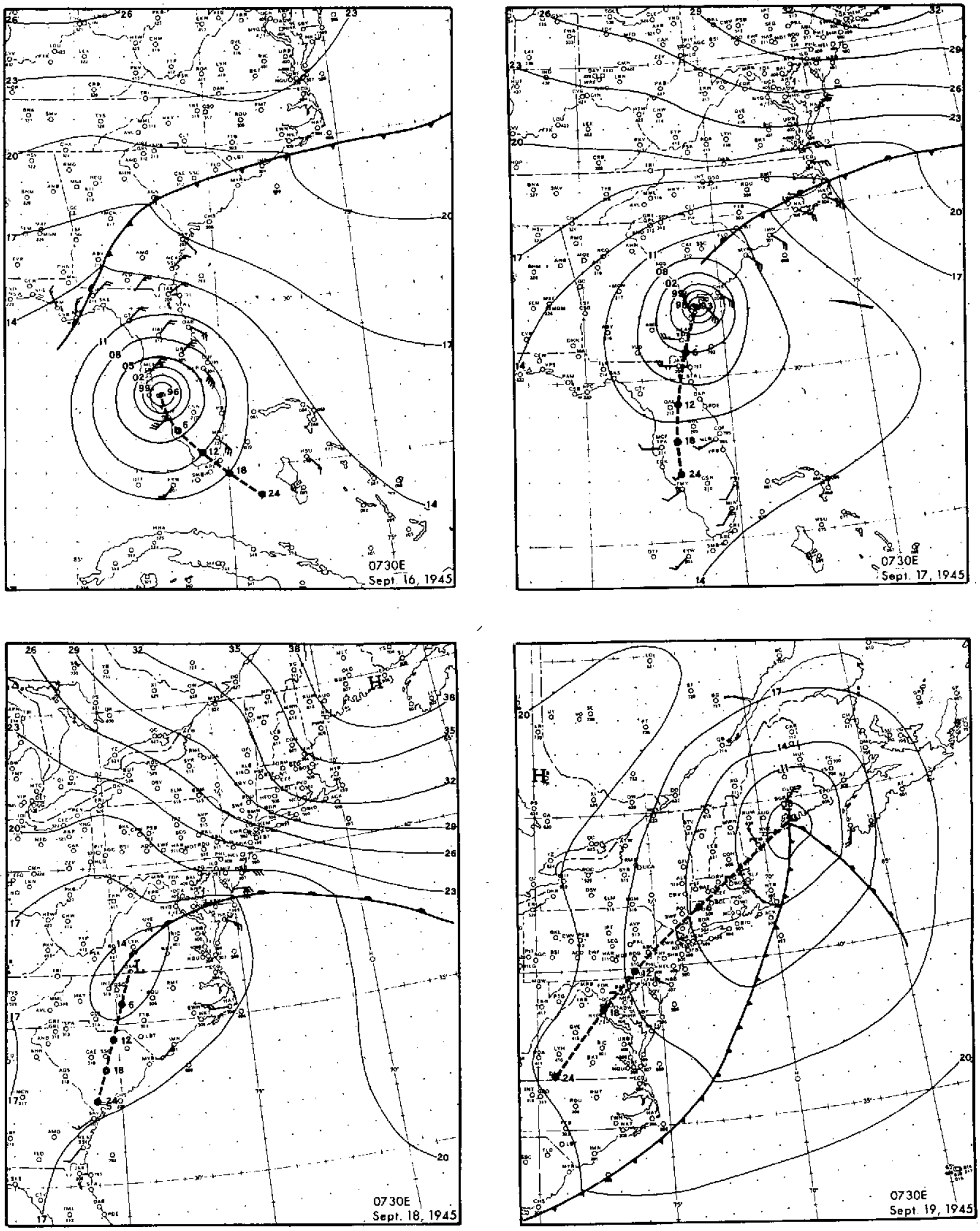


FIGURE 12.1.—Hurricane 1945, September 15–20. Synoptic charts.

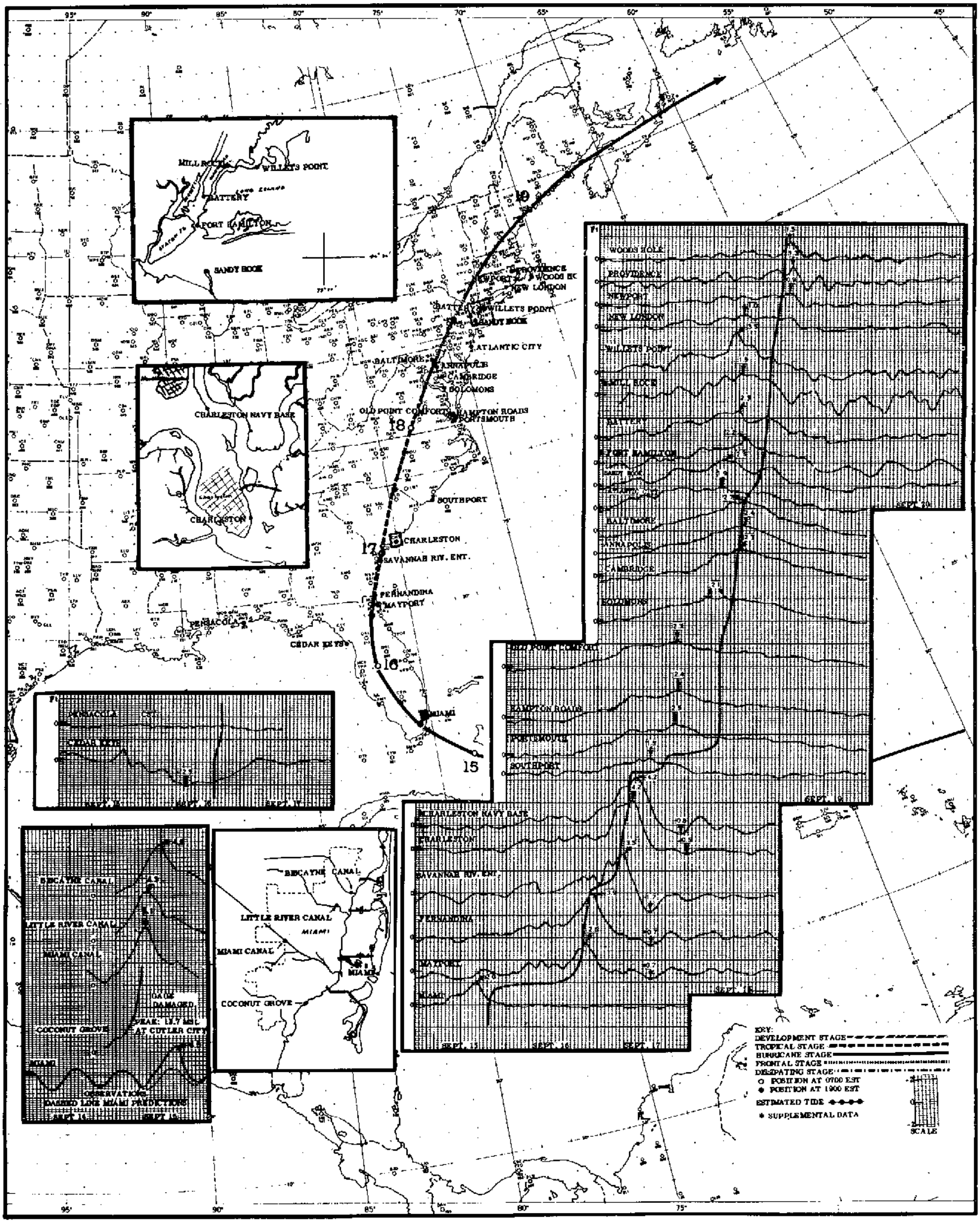


FIGURE 12.2.—Hurricane 1945, September 15–20. Storm surge chart. Insert maps for New York Harbor, Charleston, S.C., and Miami, Fla.

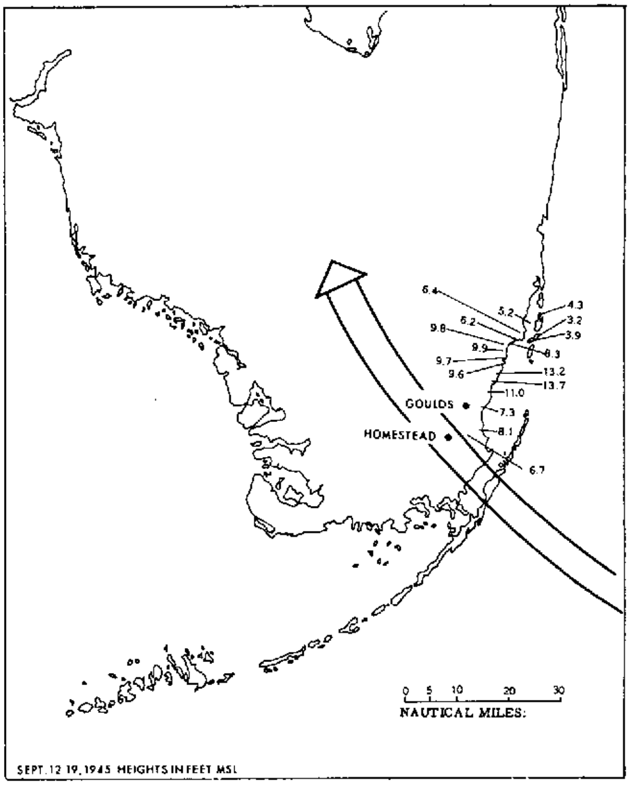


FIGURE 12.3.—Hurricane 1945, September 15–20. High water marks near Miami, Fla. (Based on data obtained from the Jacksonville District of the U.S. Army Corps of Engineers.)

This storm produced extensive tidal flooding in both Florida and Louisiana. An unusually large number of water level records showing the storm effects have been collected and two charts are required to display them all. The four records collected for Miami serve to demonstrate the timing of the surge during this storm and support the physical reasoning offered as speculation in the discussion of the 1926 hurricane. The gage at NW 7th Ave., is influenced mainly by the wind over Biscayne Bay north of MacArthur Causeway. Here the surge is believed to have been generated by the northeasterly winds ahead of the storm. If so, the peak surge should be expected about the time of the wind shift as the storm passed over the Bay. The surge at the Coast and Geodetic Survey gage at the south end of Miami Beach would likewise be generated by the northerly flow more or less parallel to the shore and should reach its peak a little before the storm passed to the north. On the mainland, south of MacArthur Causeway, the surge would be suspected to have resulted from the southwesterly winds over Biscayne Bay after the passage of the storm and therefore the peak surge would have occurred somewhat later than at Miami Beach or the City of Miami north of the Causeway. The water level at Biscayne Bay south of the Causeway is reflected by the gages at 27th and 36th Avenues on the Miami Canal. The time on these gages is consistent with the hypothesis proposed above and in discussion of the 1926 storm.

The wind fields and tide records for the west coast of the Florida Peninsula are similar to those observed during the 1926 hurricane and the same discussion may be expected to apply. Records were obtained from several locations along the west coast of the peninsula for which satisfactory predictions were not available. Therefore the original records for all stations in this area are shown in figure 13.3, while the surge data for those stations whose predictions were usable are given in figure 13.2.

The records obtained for the north shore of the Gulf of Mexico from St. Marks, Fla., to Texas, are likewise very similar to records and descriptions of the tide behavior in this region after the 1926 storm. In this case the records for Gulf Beach and Pensacola are very similar. The records for St. Marks and Carrabelle show secondary oscillations of significant magnitude preceding the storm, and the records of Appalachicola and Panama City hint at these same disturbances. These have not been investigated. The residual oscillations in the records for Eau Gallie and Mayport are believed to result more from inadequate removal of the normal tide than from influences of this storm.

The out-of-phase relationship between the oscillations at Mandeville and New Basin Locks on Lake Pontchartrain suggest that here as well as in many of the other bays discussed, the surge resulted both from the movement of the water in the bay and from a change in the volume of the bay. However, it should be noted here that the mean water level for several days after the storm was about 3 ft. higher than the water level before the storm.

Many high water marks were collected by the New Orleans and Jacksonville Districts of the Corps of Engineers. These are shown in figures 13.4 and 13.5. Sumner [101] reports that Everglades City was inundated to a depth of 2 ft. and that along the Mississippi coast the tides rose to 12 ft. at Biloxi, Bay St. Louis, and Gulfport, and to about 9 ft. at Pascagoula and in the Lake Catherine-Chef Menteur area. He does not specify the datum plane to which these figures refer.

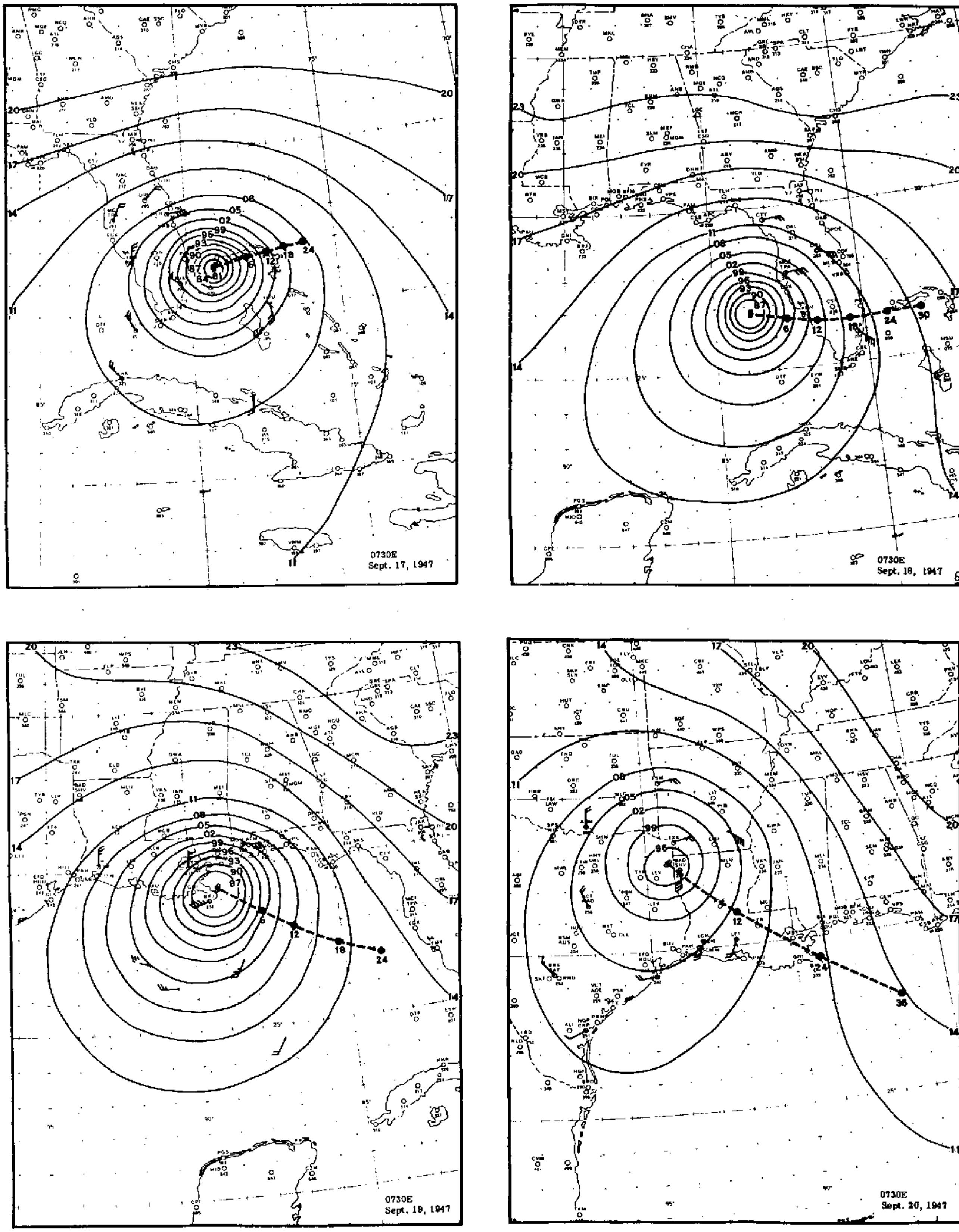


FIGURE 13.1.—Hurricane 1947, September 17–20. Synoptic charts.

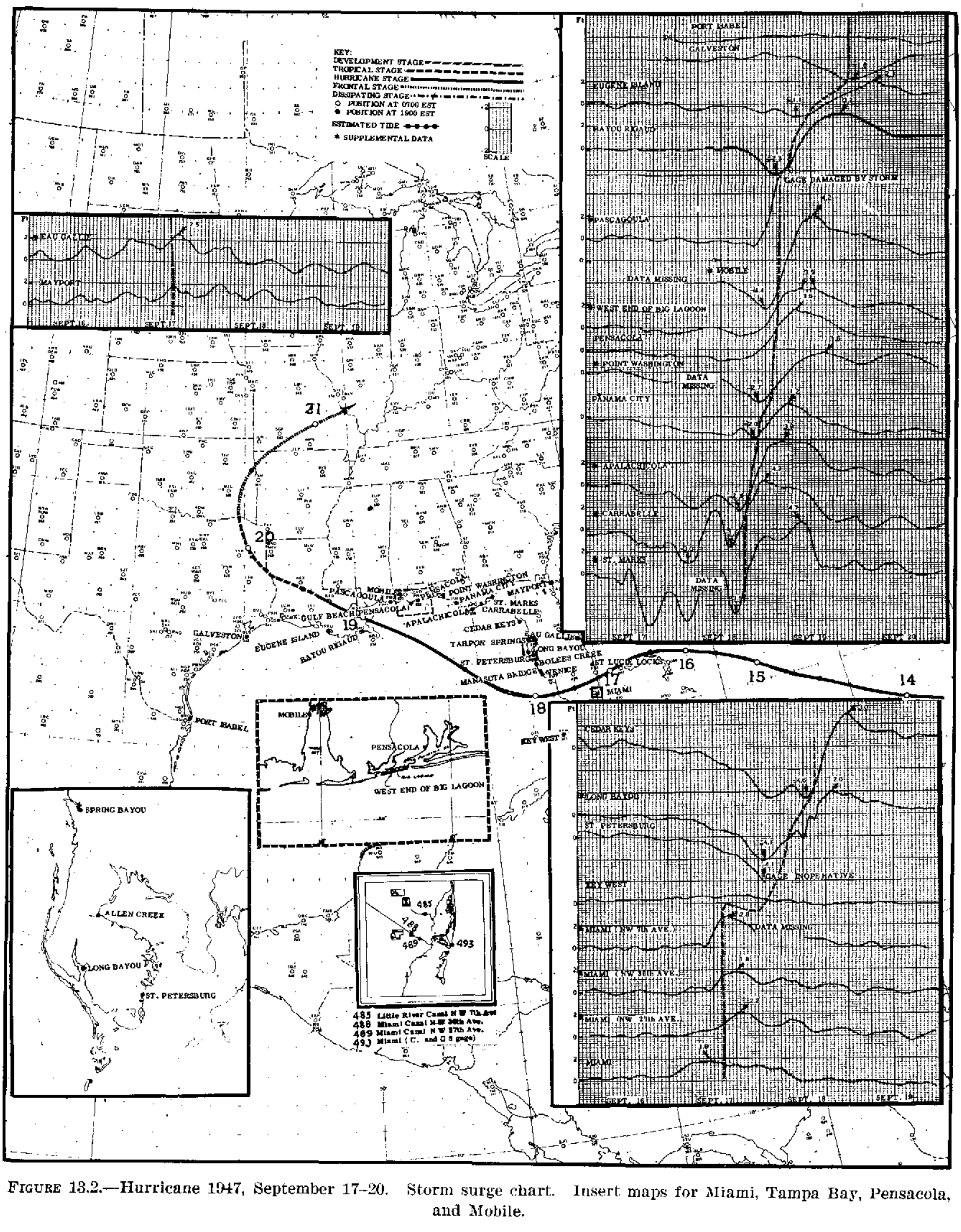


FIGURE 13.2.—Hurricane 1947, September 17–20. Storm surge chart. Insert maps for Miami, Tampa Bay, Pensacola, and Mobile.

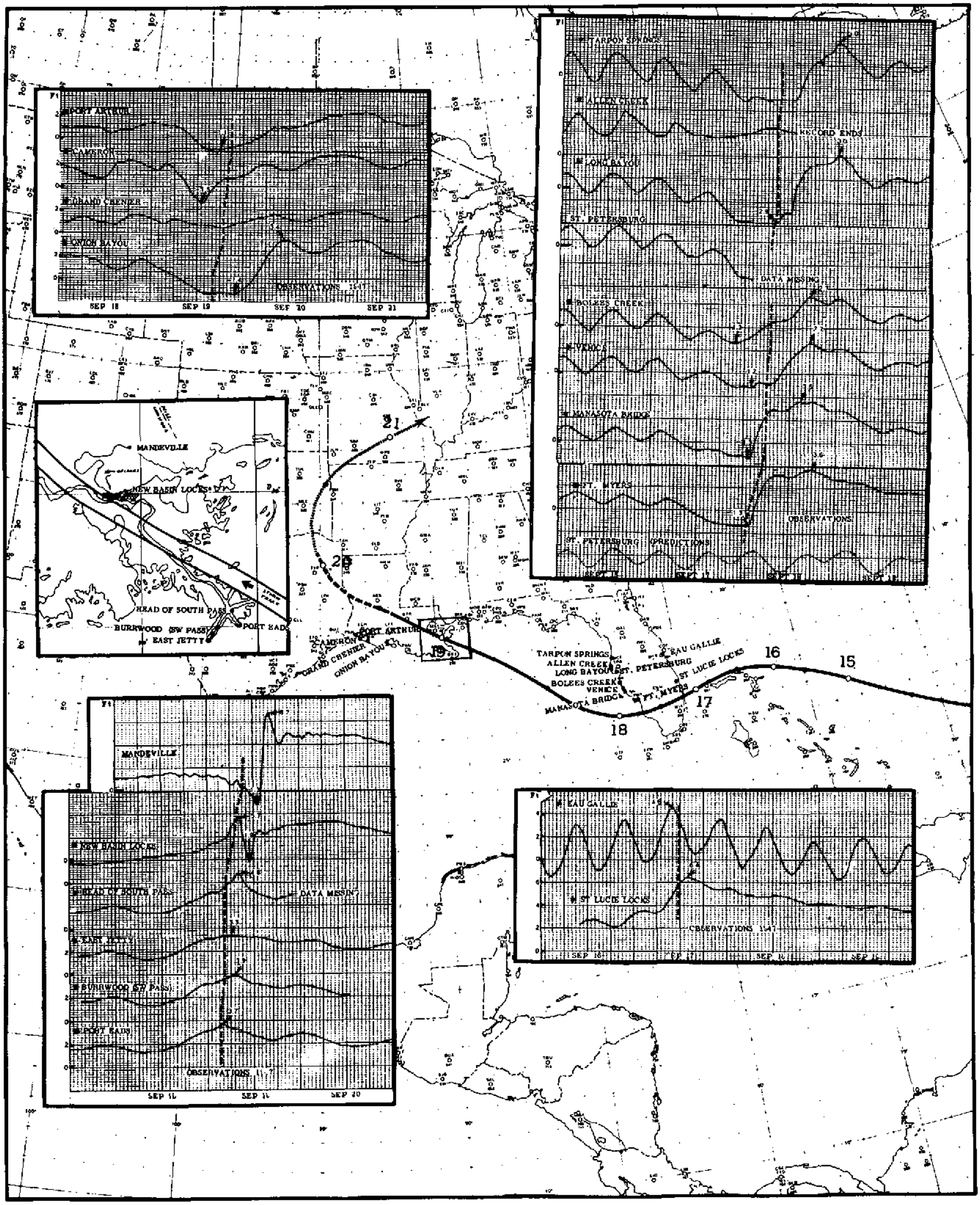


FIGURE 13.3.—Hurricane 1947, September 17–20. Observed tide records, hourly data only.

FIGURE 13.4.—Hurricane 1947, September 17–20. High water marks in Florida. (Based on data obtained from the Jacksonville District of the U.S. Army Corps of Engineers.)

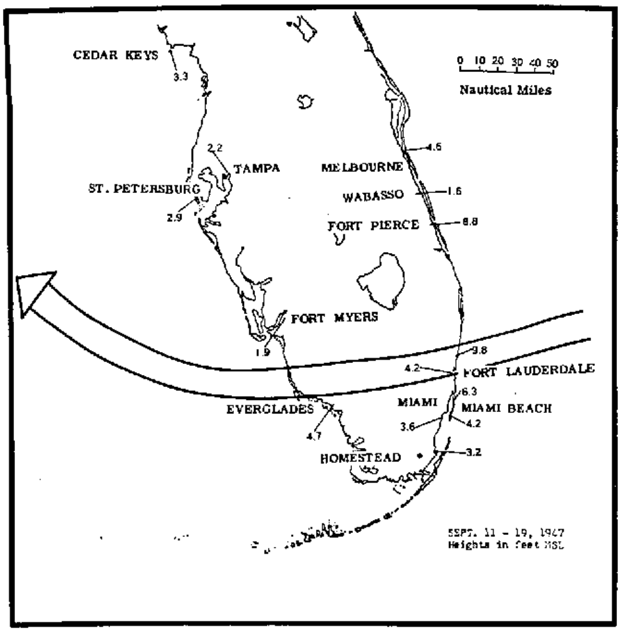
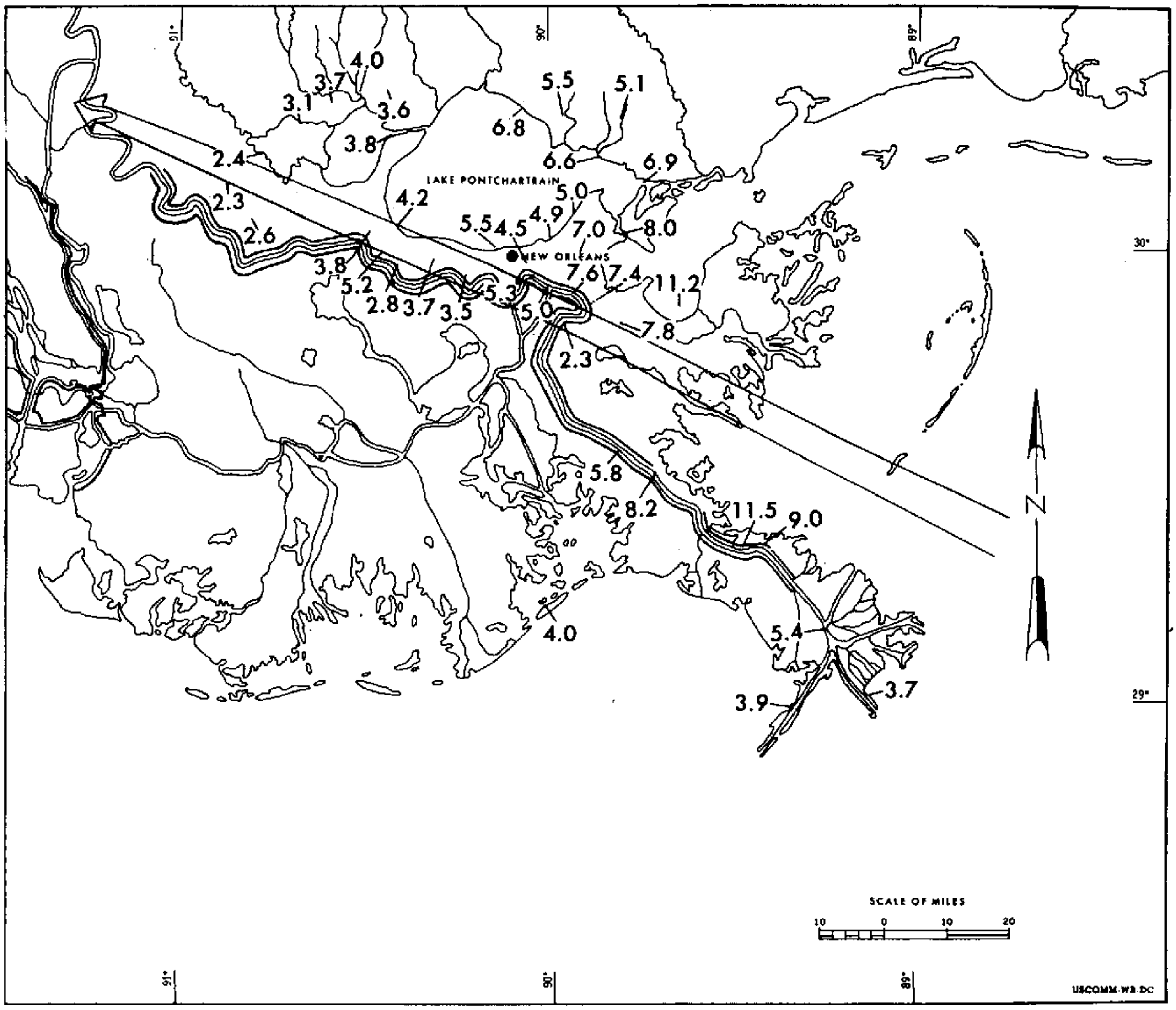


FIGURE 13.5.—Hurricane 1947, September 17–20. High water marks in Louisiana. (Based on data obtained from the New Orleans District of the U.S. Army Corps of Engineers.)



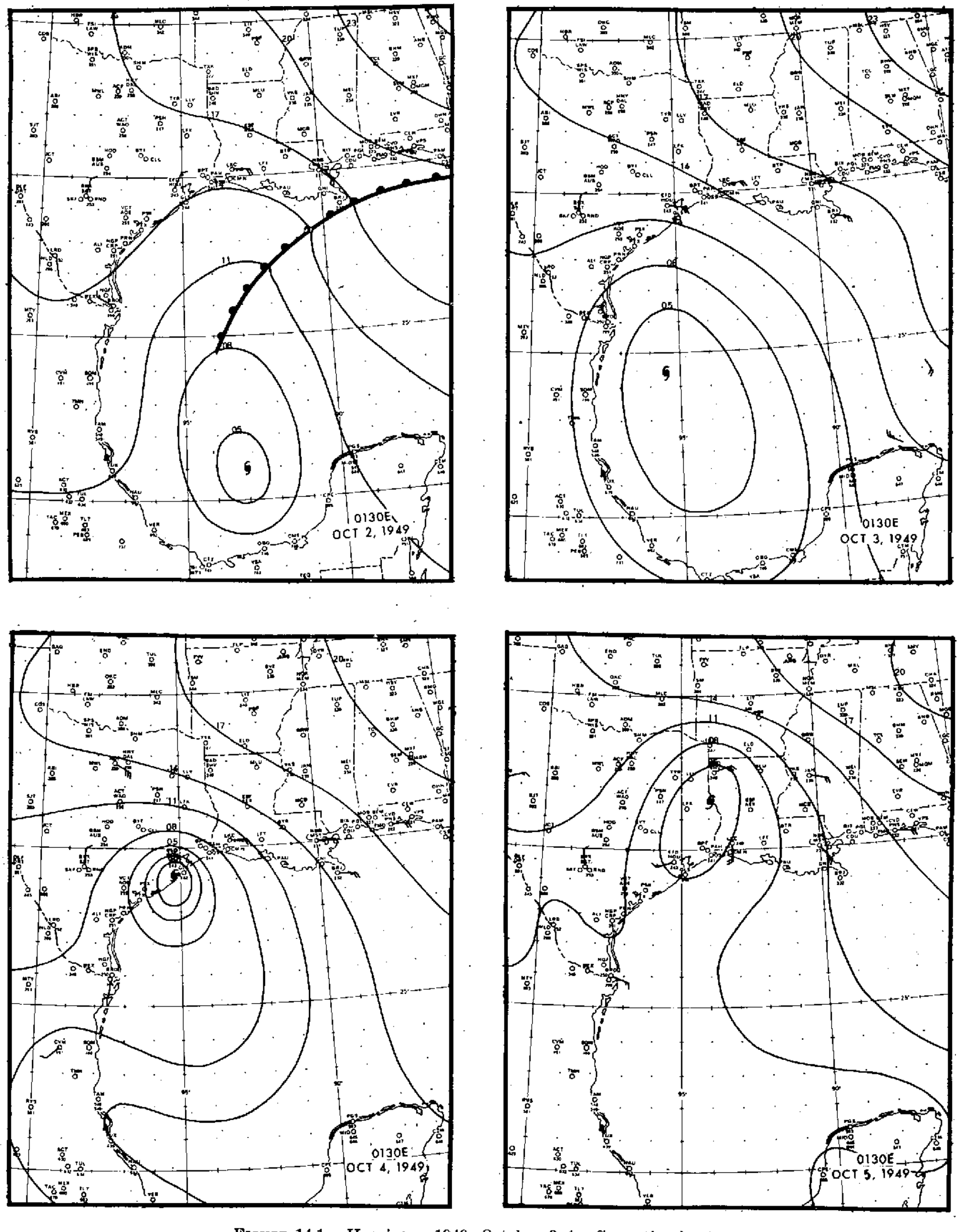


FIGURE 14.1.—Hurricane 1949, October 3–4. Synoptic charts.

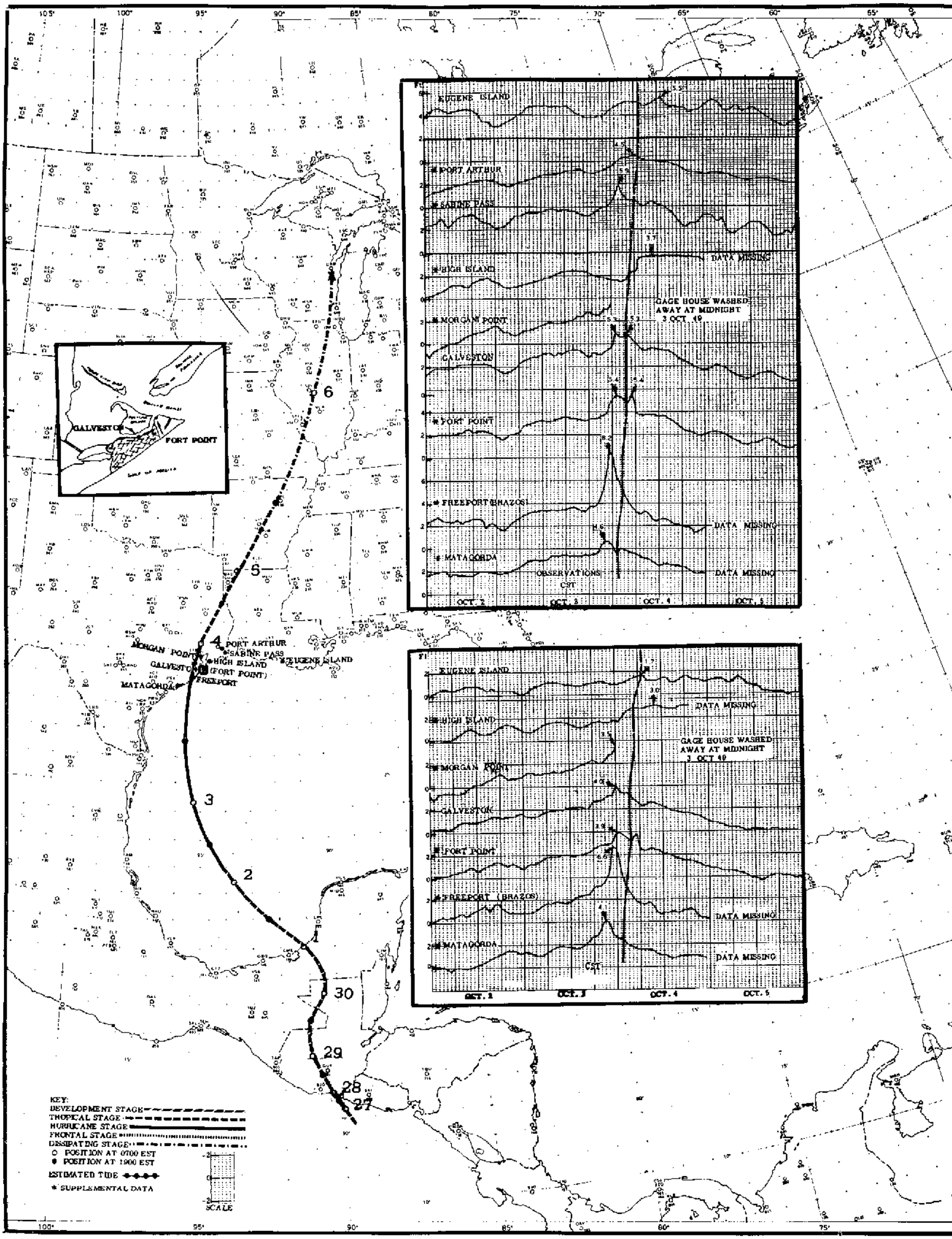


FIGURE 14.2.—Hurricane 1949, October 3–4. Storm surge (upper panel) and tide observations chart (hourly values only). Insert map for Galveston, Tex.

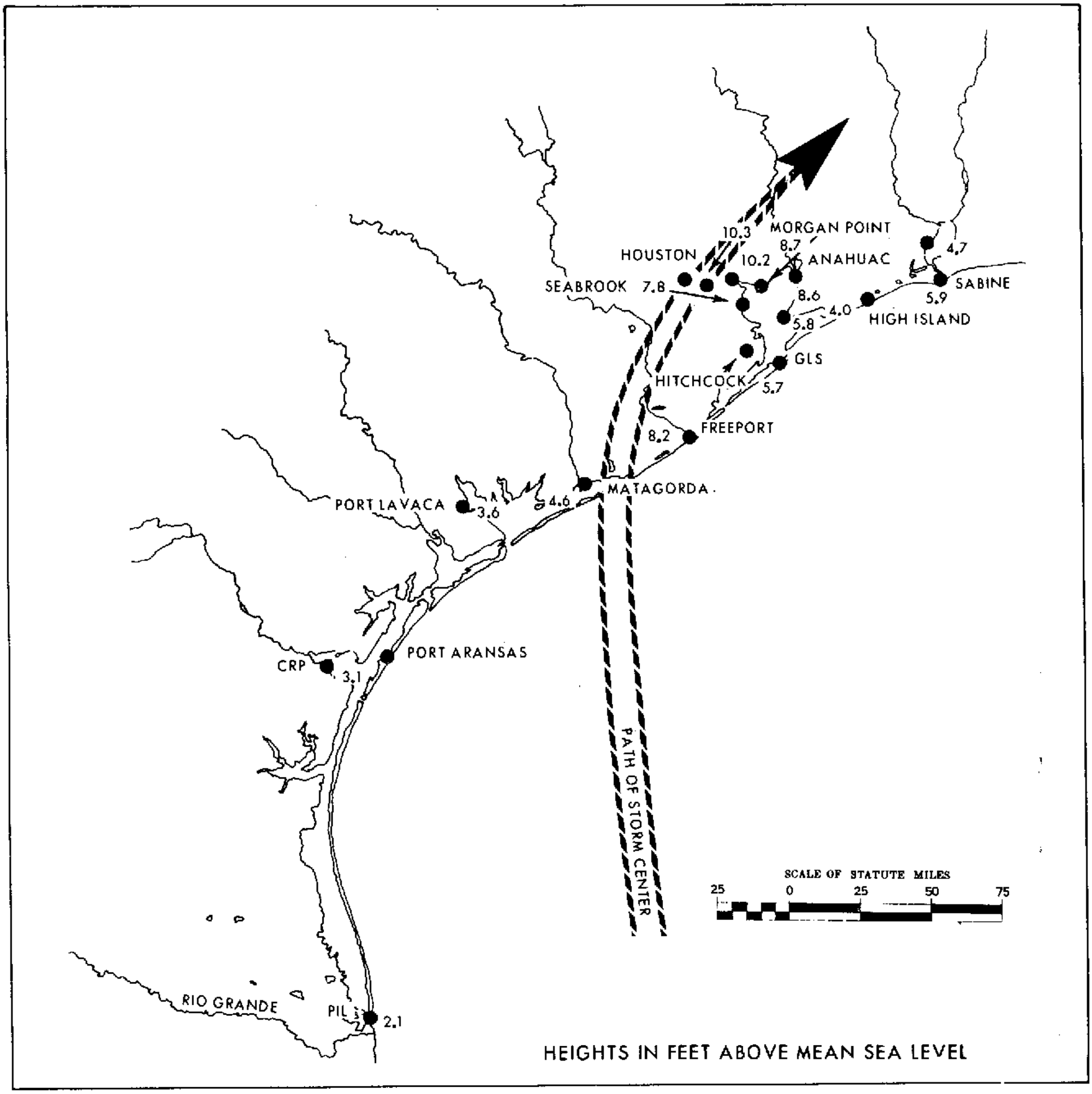


FIGURE 14.3.—Hurricane 1949, October 3–4. High water marks in Texas.

STORM NO. 14.—HURRICANE 1949, OCTOBER 3–4

Zoch [117] quotes high tide values for several locations in Texas. These and others obtained from the Galveston District of the U.S. Army Corps of Engineers and others are collected and presented in figure 14.3. Although the data for this storm indicate no new features not discussed in connection with some of the earlier storms, they are included in the report because they give additional credence to much of the foregoing discussion. Observational data are given in the top panel, storm surge data in the lower panel of figure 14.2.

STORM NO. 15.—HURRICANE 1950, OCTOBER 17–19, 20–21

Norton [74] reports that the first of these storms had an eye diameter of only 5 miles as it crossed the City of Miami. He gives a detailed map of the eye movements across the city. The record from Goulds Canal was obtained a short distance to the left of the storm track. That for 27th Avenue was under the storm track. The other tide records from the Miami area were obtained from locations to the right of the eye trajectory. All of the main land gages show disturbances of short periods compared to that recorded by the gage in the channel south of Miami Beach and labeled "Miami" on this and other storm surge charts in this report. This variation in the appearance of the records for the tide stations in Miami is taken as additional evidence that local influences are extremely significant in the storm surge generation.

STORM NO. 16.—HURRICANE BARBARA 1953, AUGUST 13–15

James and Thomas [49] give an extensive discussion of the meteorological aspects of this storm. The U.S. Weather Bureau, *Climatological Data, National Summary* [109], reports a tide of nearly 6 ft. in New Bern, N.C., and 5.4 ft. in New Holland, N.C. Pore [79] has published the surge data for Chesapeake Bay and included bihourly reports of the surface wind for Baltimore and Norfolk. Again, the data suggest that the wind field over the Bay and over the open ocean made almost independent contributions to the water level disturbance within the Bay.

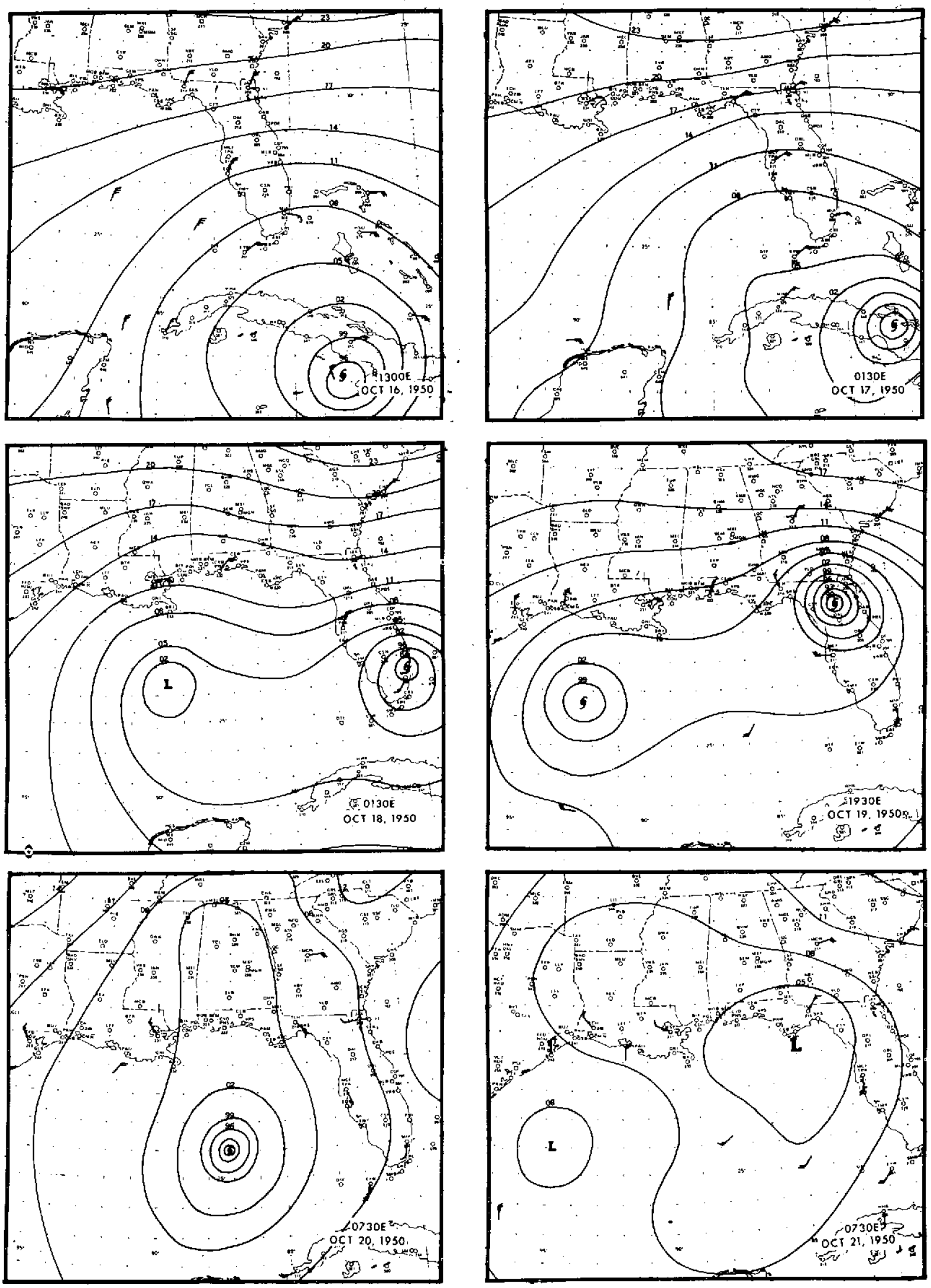


FIGURE 15.1.—Hurricane 1950, October 17–21. Synoptic charts.

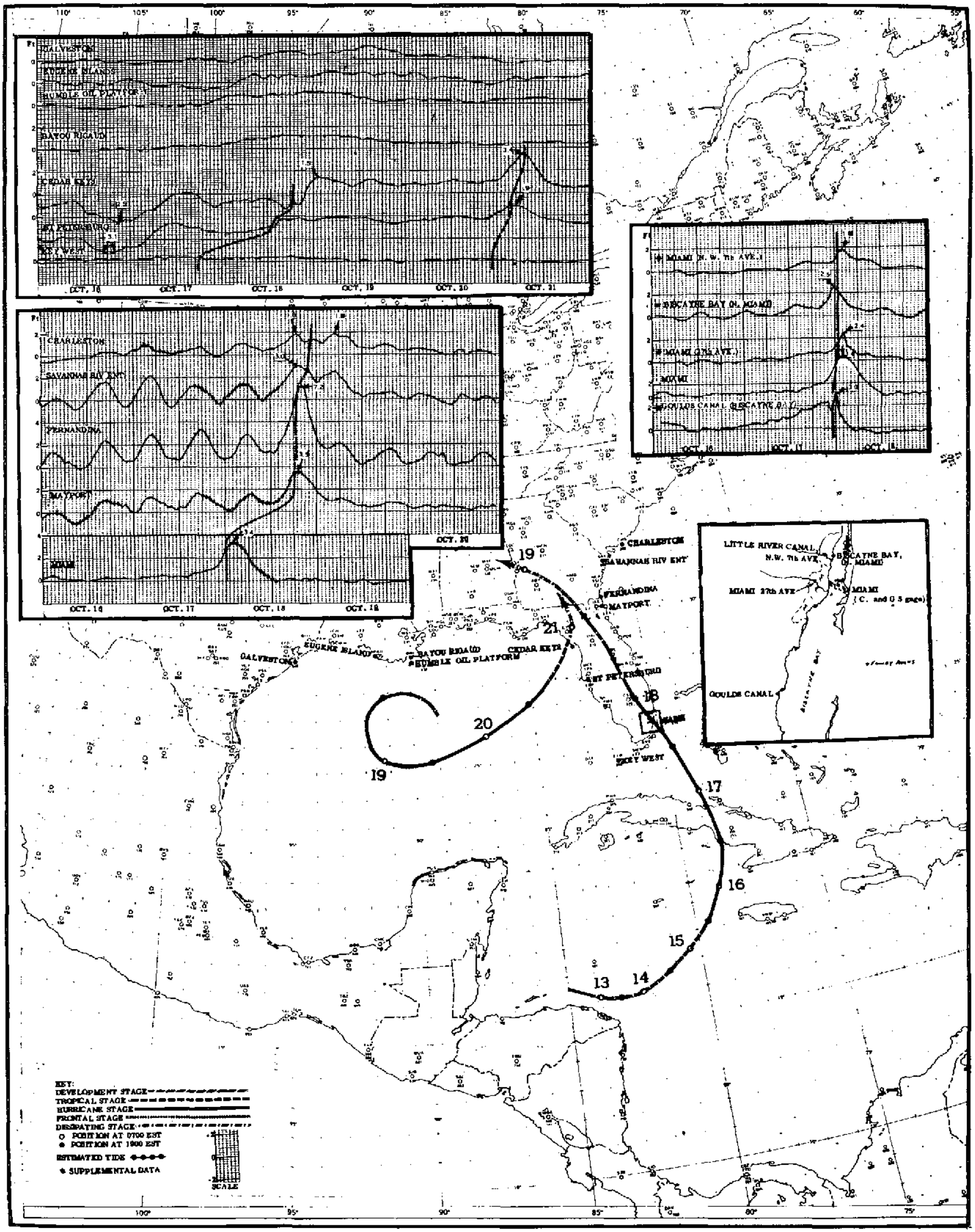


FIGURE 15.2.—Hurricane 1950, October 17–21. Storm surge chart. Insert map for Miami and Biscayne Bay.

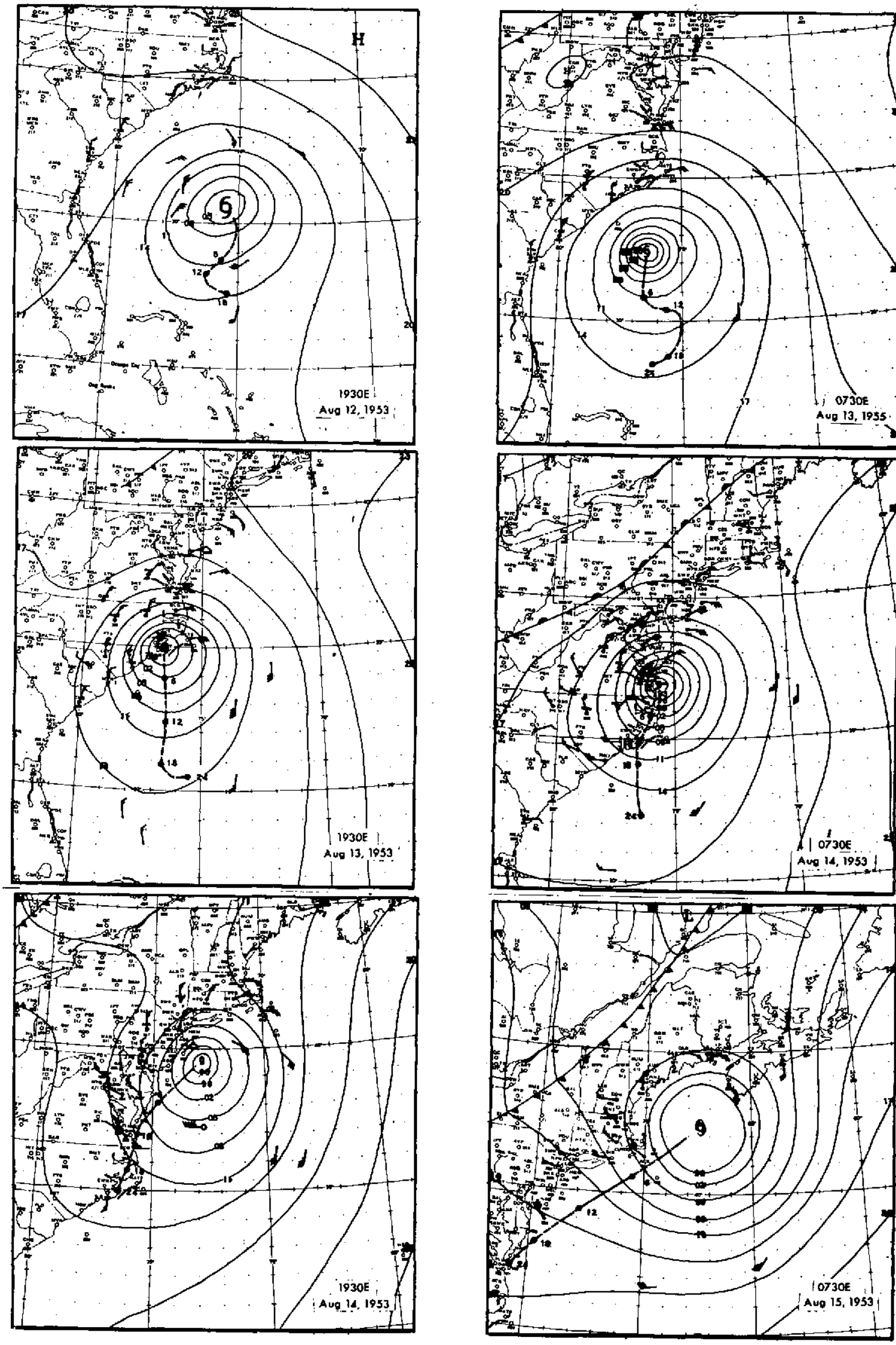


FIGURE 16.1.—Hurricane Barbara 1953, August 13–15. Synoptic charts.

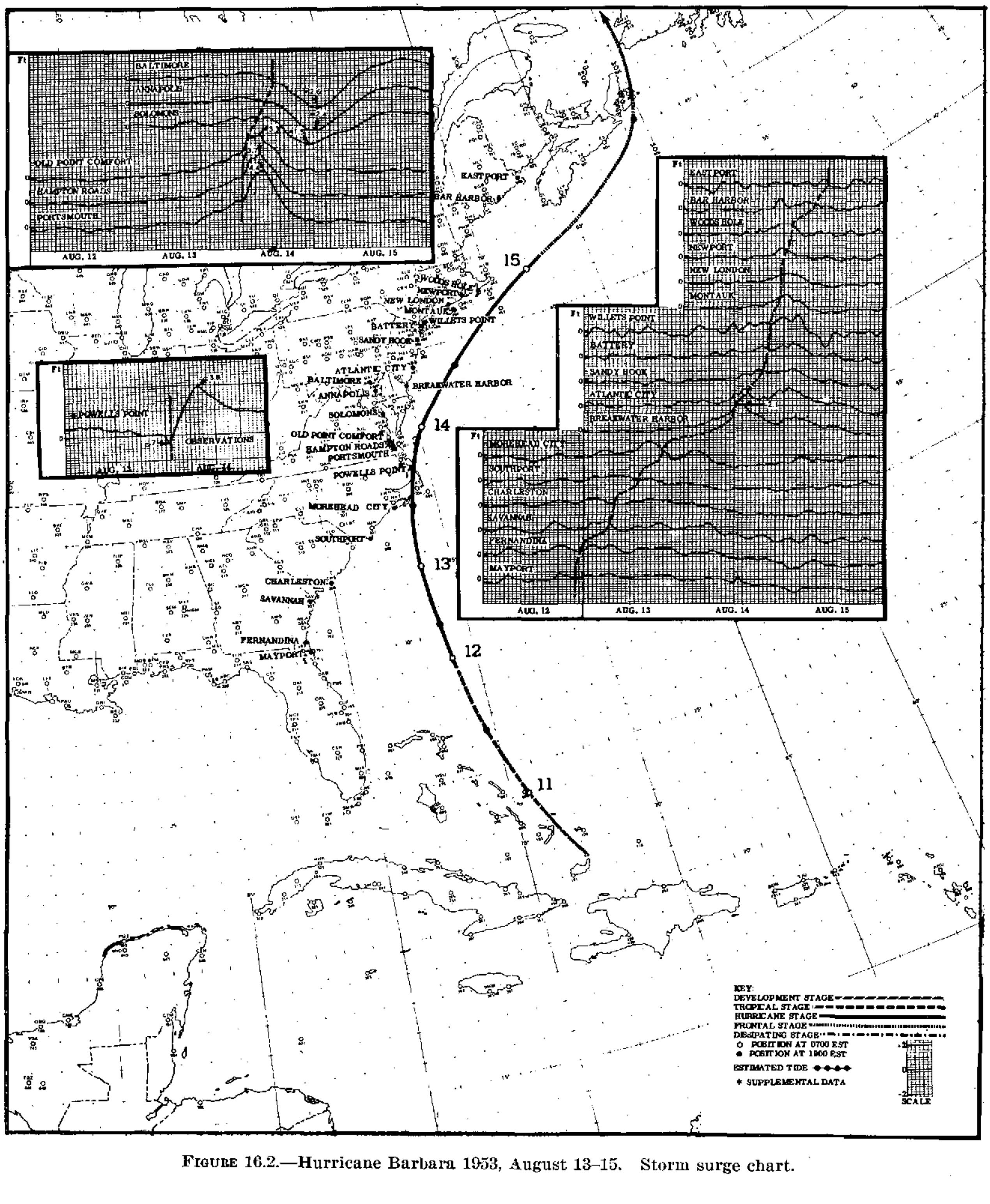


FIGURE 16.2.—Hurricane Barbara 1953, August 13–15. Storm surge chart.

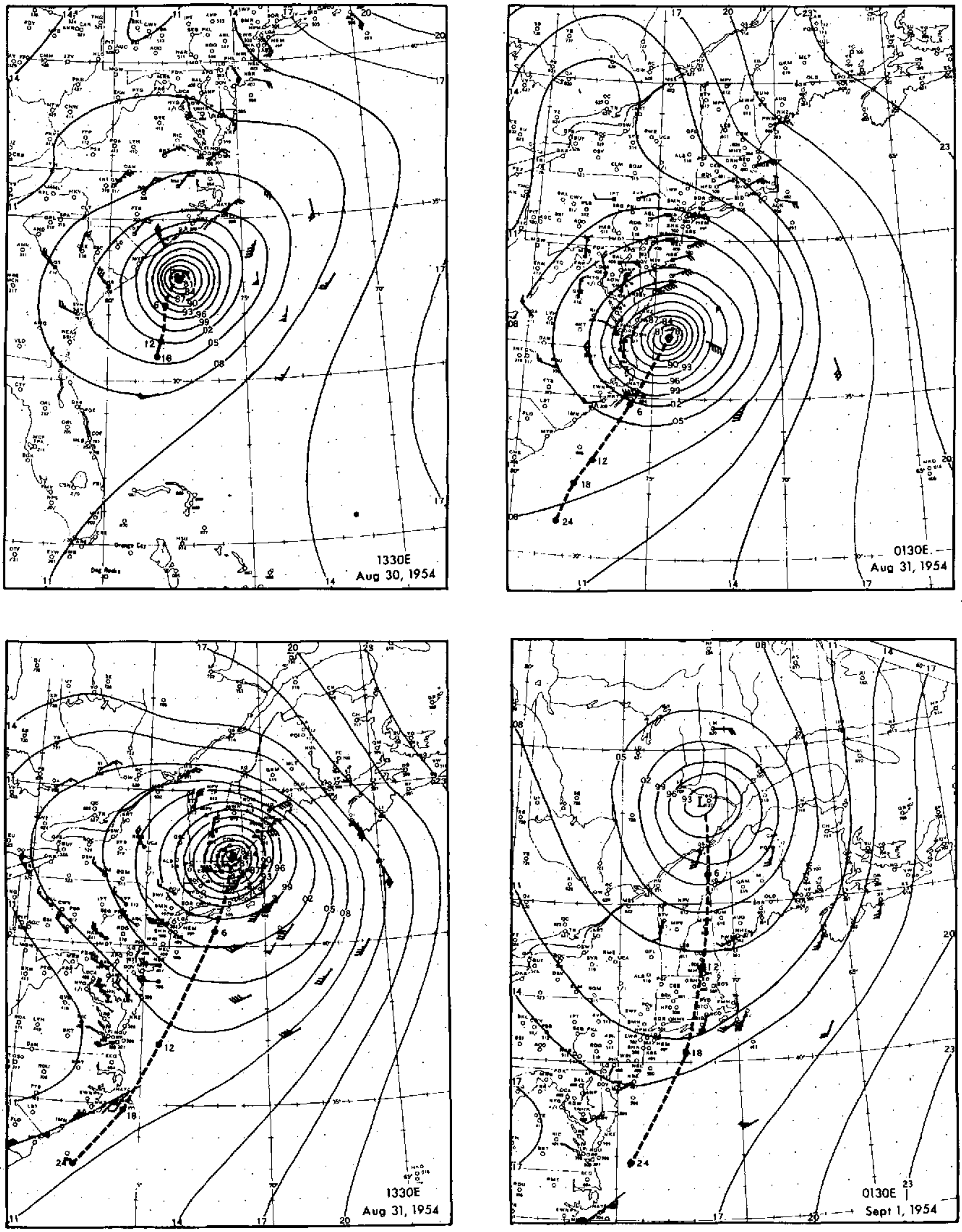


FIGURE 17.1.—Hurricane Carol 1954, August 30–31. Synoptic charts.

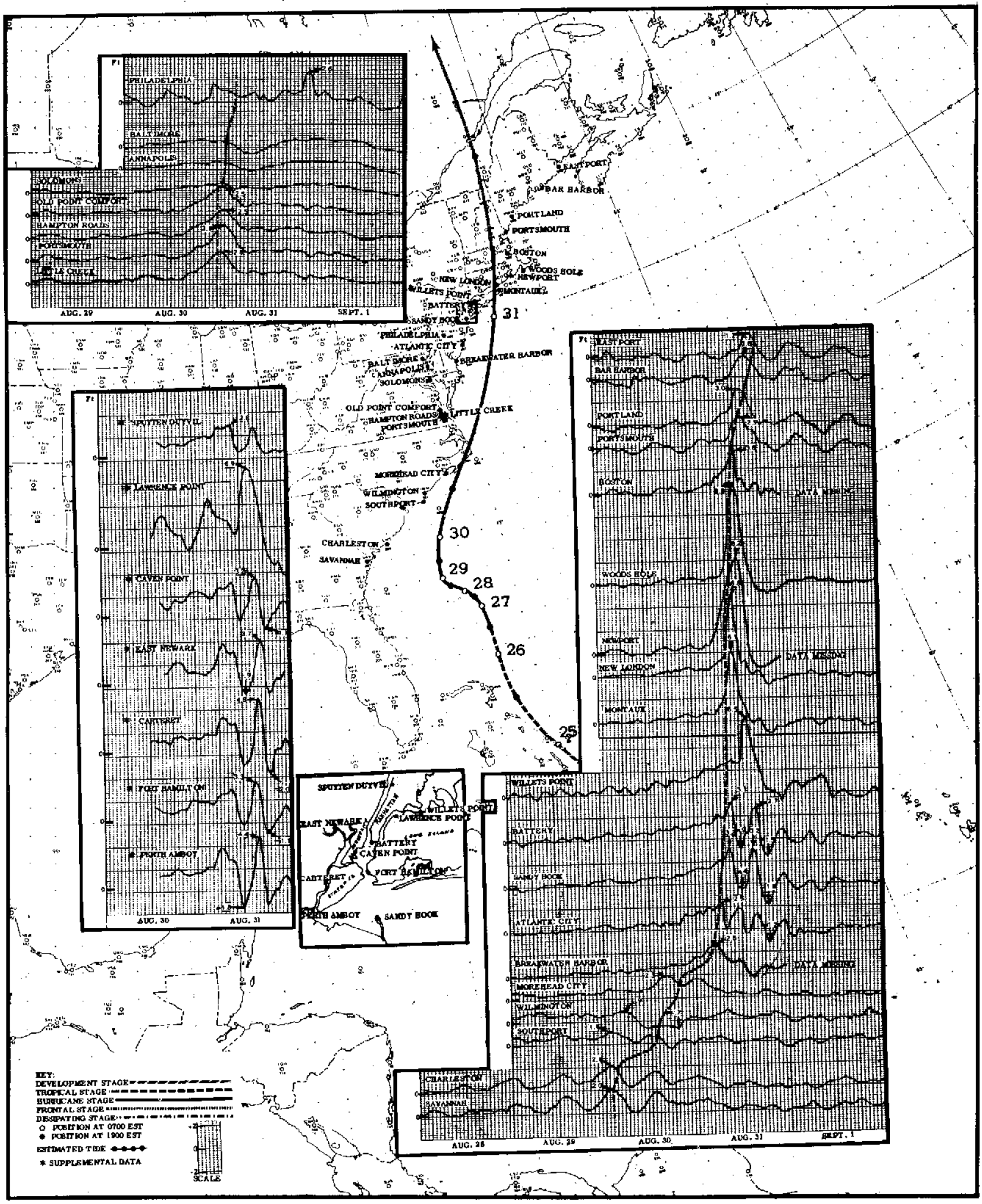


FIGURE 17.2.—Hurricane Carol 1954, August 30–31. Storm surge chart. Insert map for New York Harbor.

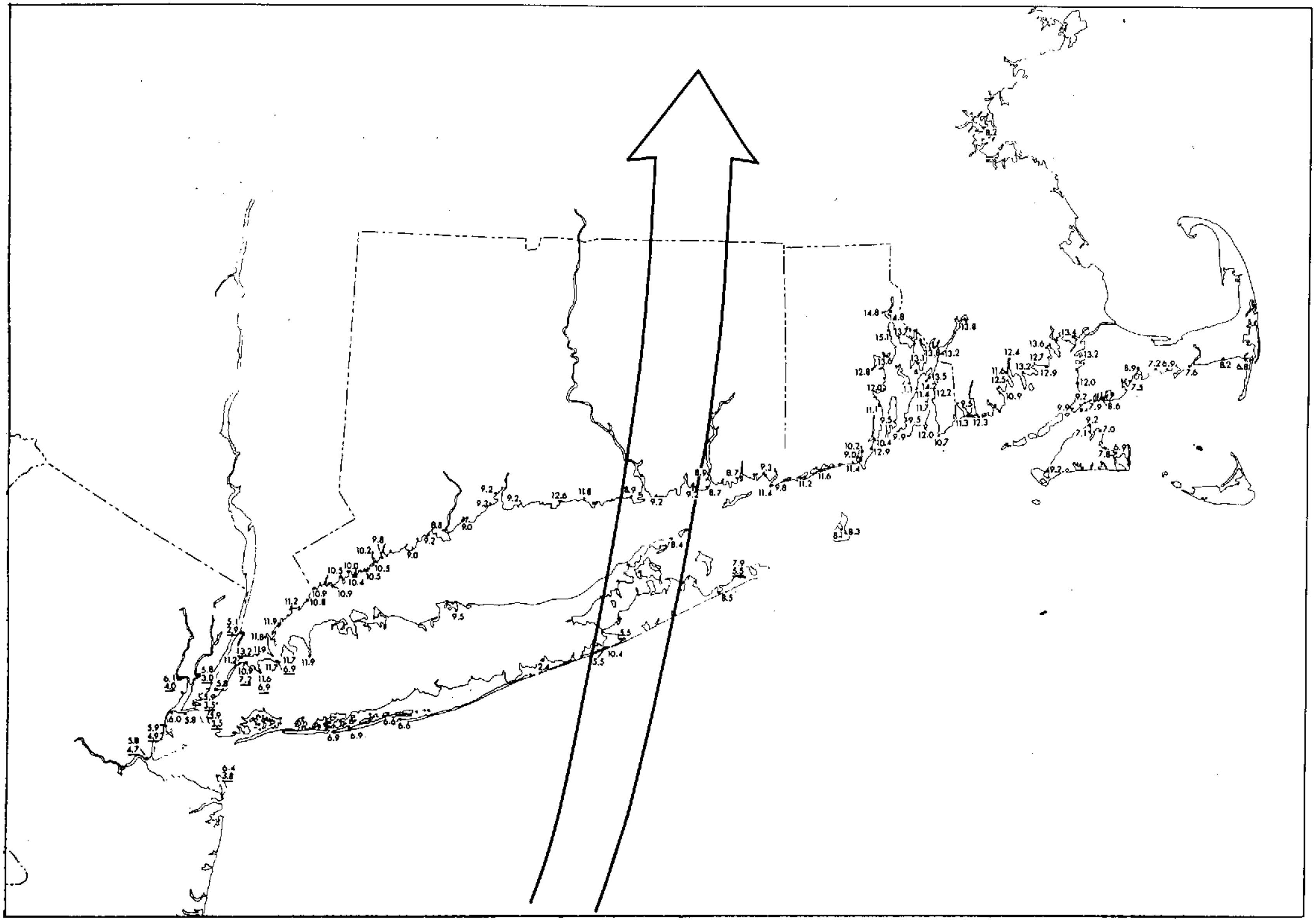


Figure 17.3.—Hurricane Carol 1954, August 30–31. High water marks in New York and New England.

STORM NO. 17.—HURRICANE CAROL 1954, AUGUST 30–31

Historical accounts of this storm have been given by McGuire [56], Rhodes [84], and Davis [12]. The meteorological aspects of the storm as related to the planetary circulation pattern have been discussed by Winston [115]. Redfield and Miller [83] have discussed much of the storm surge data. Extensive high water mark and storm surge data have been collected for this storm by many groups. Selected samples of the data have been widely published. The data included here have been assembled from many sources, particularly from the records of the New York and New England Offices of the U.S. Army Corps of Engineers. However, the presentation is not complete. Several hundred high water mark elevations have been collected for southern New England, and some of the points plotted in figure 17.3 represent the average of five to twenty observations obtained within a mile of the plotted point. The scatter among nearby locations represented by a single value in the plotted data frequently exceeded 2 ft. The scatter in the complete collection of data emphasizes the importance of very local conditions in determining the ultimate high water mark to the nearest foot or two. The homogeneity and reasonably smooth variation in the plotted values for southern New England also show that some large-scale systematic processes were present. It is generally agreed by most writers that the surge in Long Island Sound resulted from the propagation of a gravity wave, formed by the hurricane near the eastern end of the Sound, from east to west through the Sound. This storm, like that of 1938 and unlike that of 1944, came inland near the time of high astronomical tide. Its effects in the New York-New England area were very similar to those of the storms of 1938, 1944, and hurricane Donna of 1960. The accounts of these storms should be reviewed in connection with any study of this storm.

STORM NO. 18.—HURRICANE EDNA 1954, SEPTEMBER 10–12

An historical account of this storm is given by Davis [12], and Rhodes [84]. Malkin and Holzworth [58] give an extensive discussion of the meteorological aspects of the storm. The storm surges have been considered by Redfield and Miller [83]. As this storm did not cross the coastline south of Maine, it did not produce extensive tidal flooding in the United States. Nevertheless, by following so close behind hurricane Carol it aroused considerable interest, and the data are being included in this report because they give additional examples of several of the processes discussed elsewhere in this report.

STORM NO. 19.—HURRICANE HAZEL 1954, OCTOBER 14–15

Historical accounts of this storm have been given by Davis [12] and Seaman [93]. Rhodes [84] gives additional historical data and several high water mark elevations. These and additional high water mark data obtained from the Wilmington, N.C. District Office of the U.S. Army Corps of Engineers are plotted in figure 19.3. Krueger [52] discusses the meteorological aspects of the storm as related to the planetary circulation pattern. Graham and Hudson [33] give reconstructed wind patterns for the surface wind fields over the coastal waters of the Atlantic Ocean and over the Chesapeake Bay area. The associated storm surges have been discussed by Redfield and Miller [83]. Pore [79] gives the bihourly values of the winds as well as the storm surge for the Chesapeake Bay. Bretschneider [1] also discusses the storm effects on water levels in Chesapeake Bay.

A comparison of the surge curves for Philadelphia and the Delaware Breakwater shows the effects of convergence and additional wind set-up within the estuary. The contribution from rainfall runoff may also have been significant in the Philadelphia surge curve.

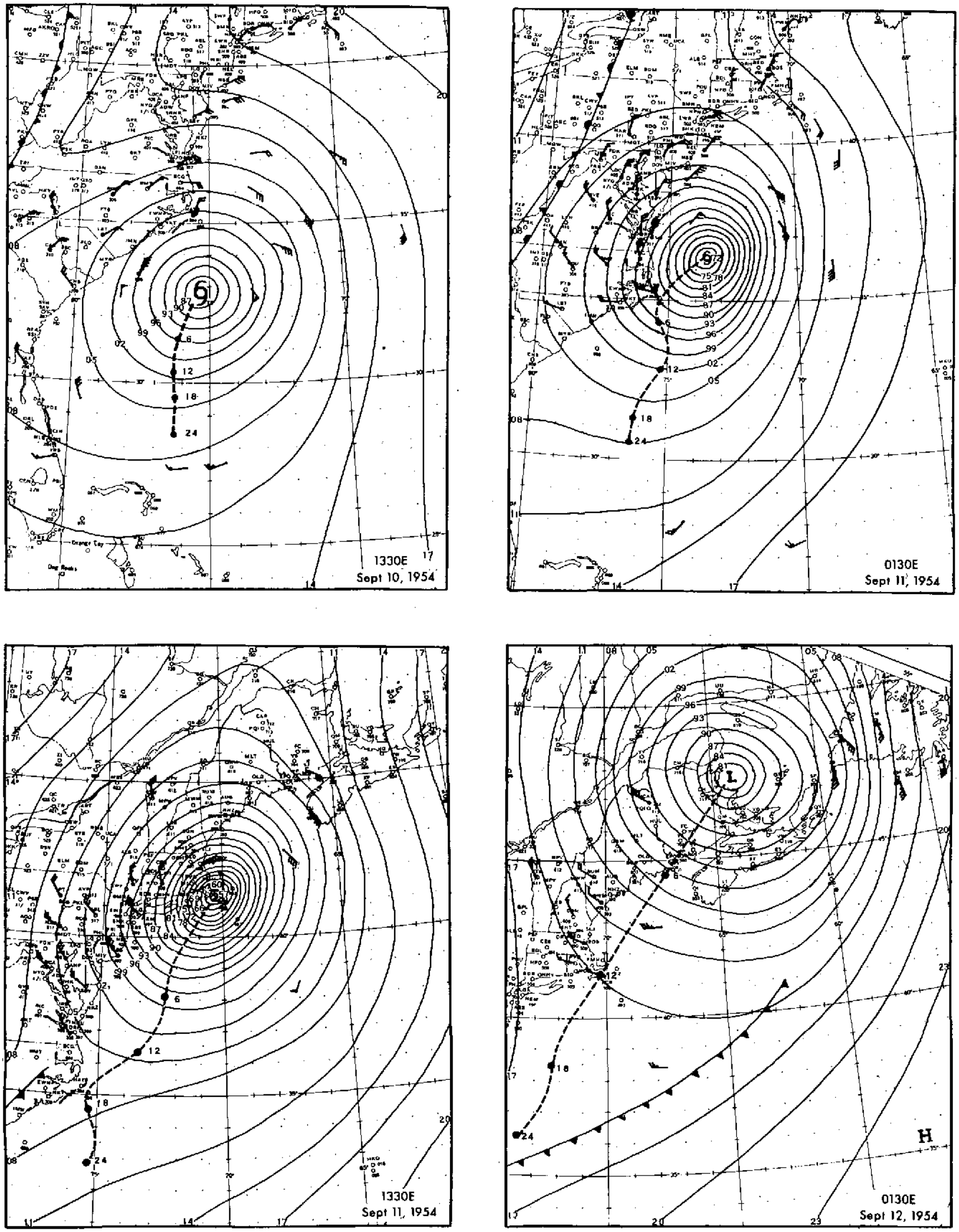


FIGURE 18.1.—Hurricane Edna 1954, September 10–12. Synoptic charts.

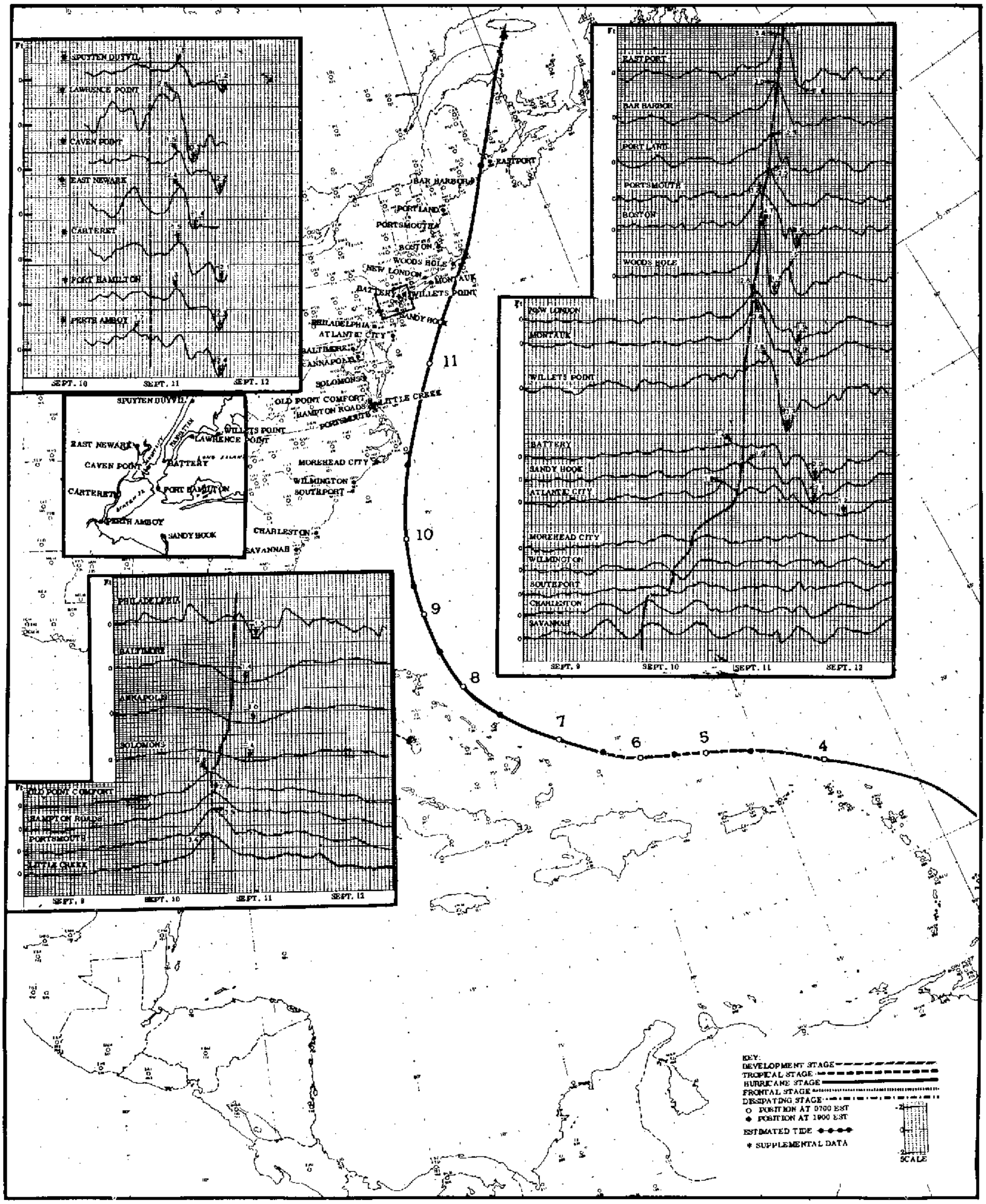


FIGURE 18.2.—Hurricane Edna 1954, September 10–12. Storm surge chart. Insert map for New York Harbor.

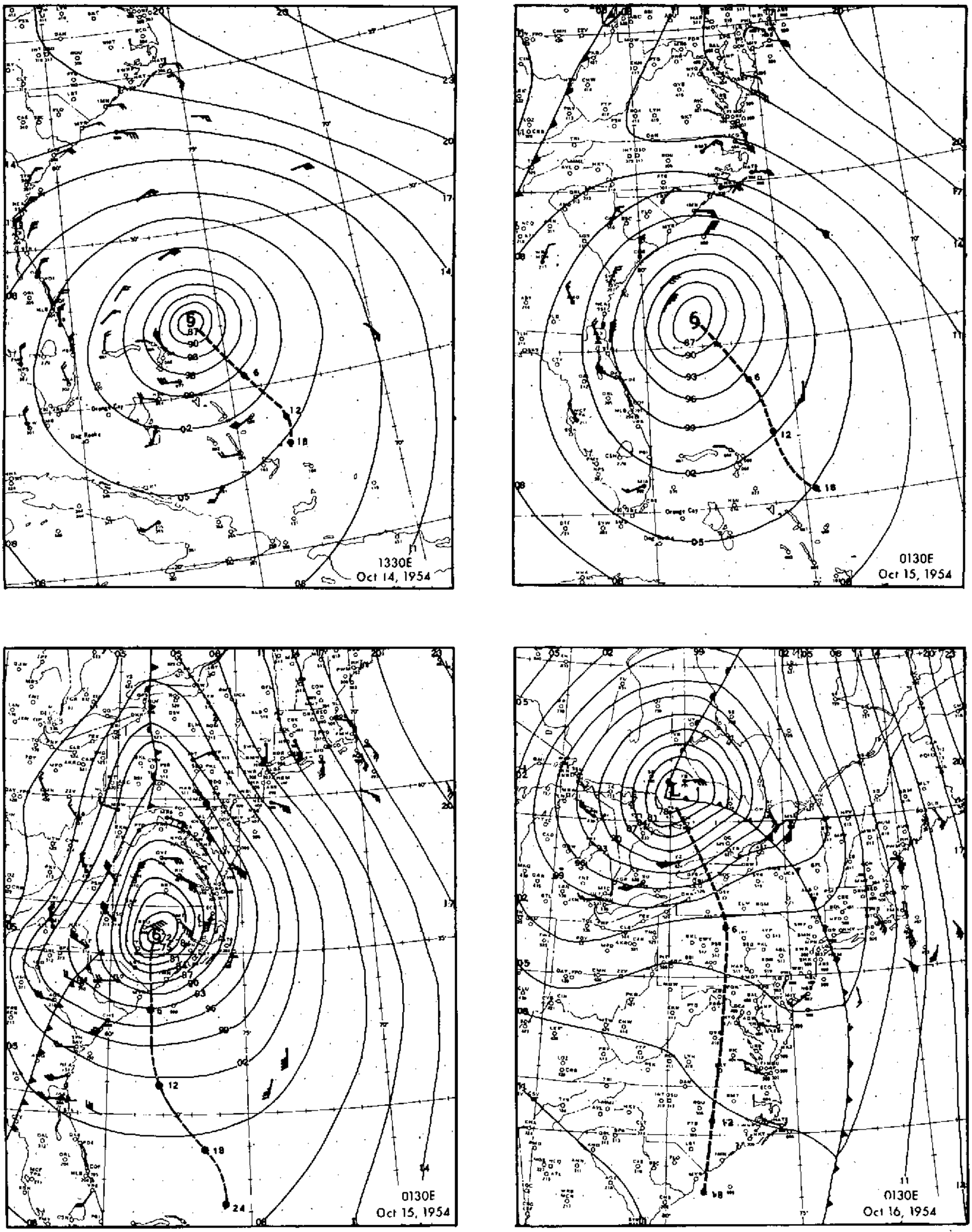


FIGURE 19.1.—Hurricane Hazel 1954, October 14–15. Synoptic charts.

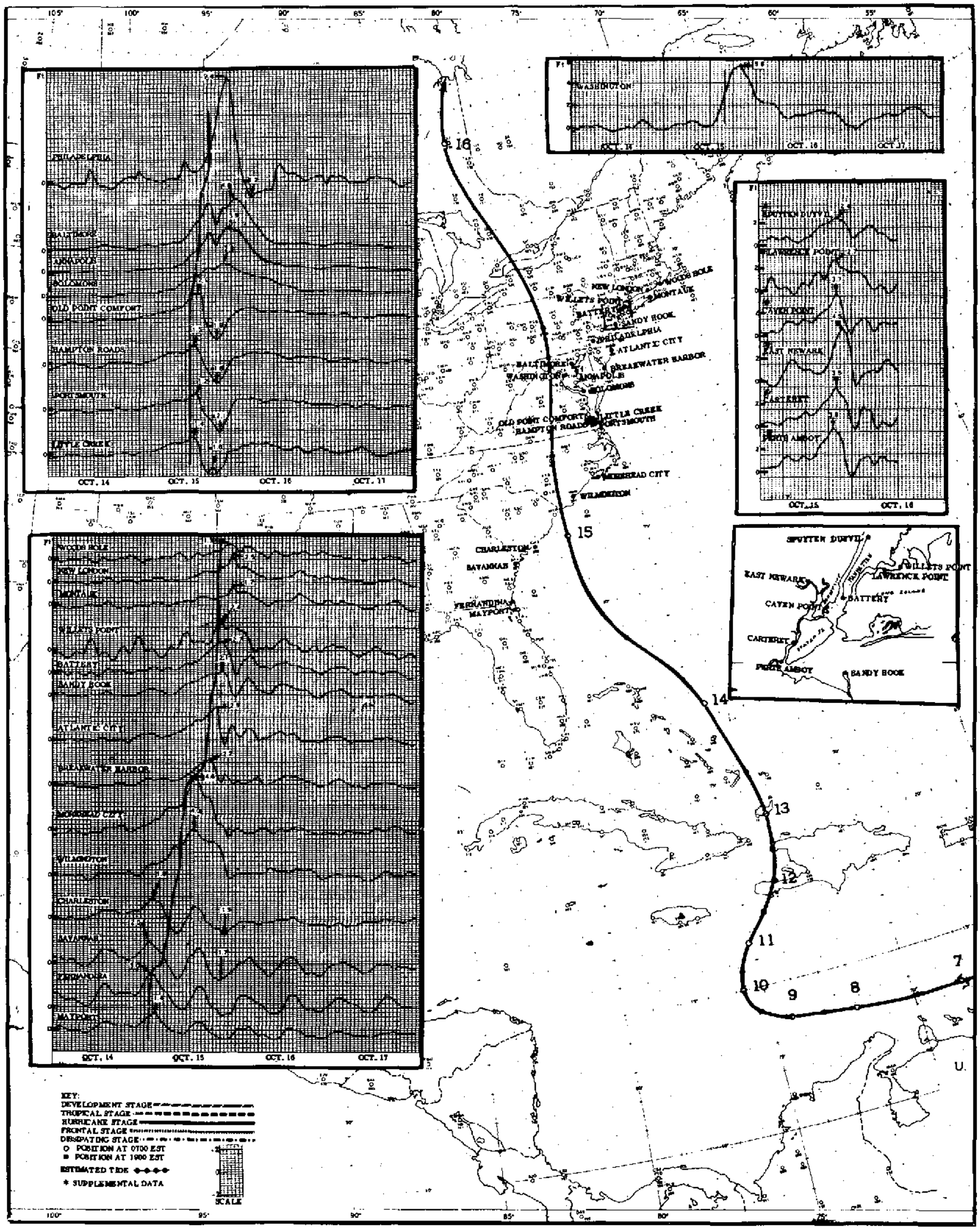


FIGURE 19.2.—Hurricane Hazel 1954, October 14–15. Storm surge chart. Insert map for New York Harbor.

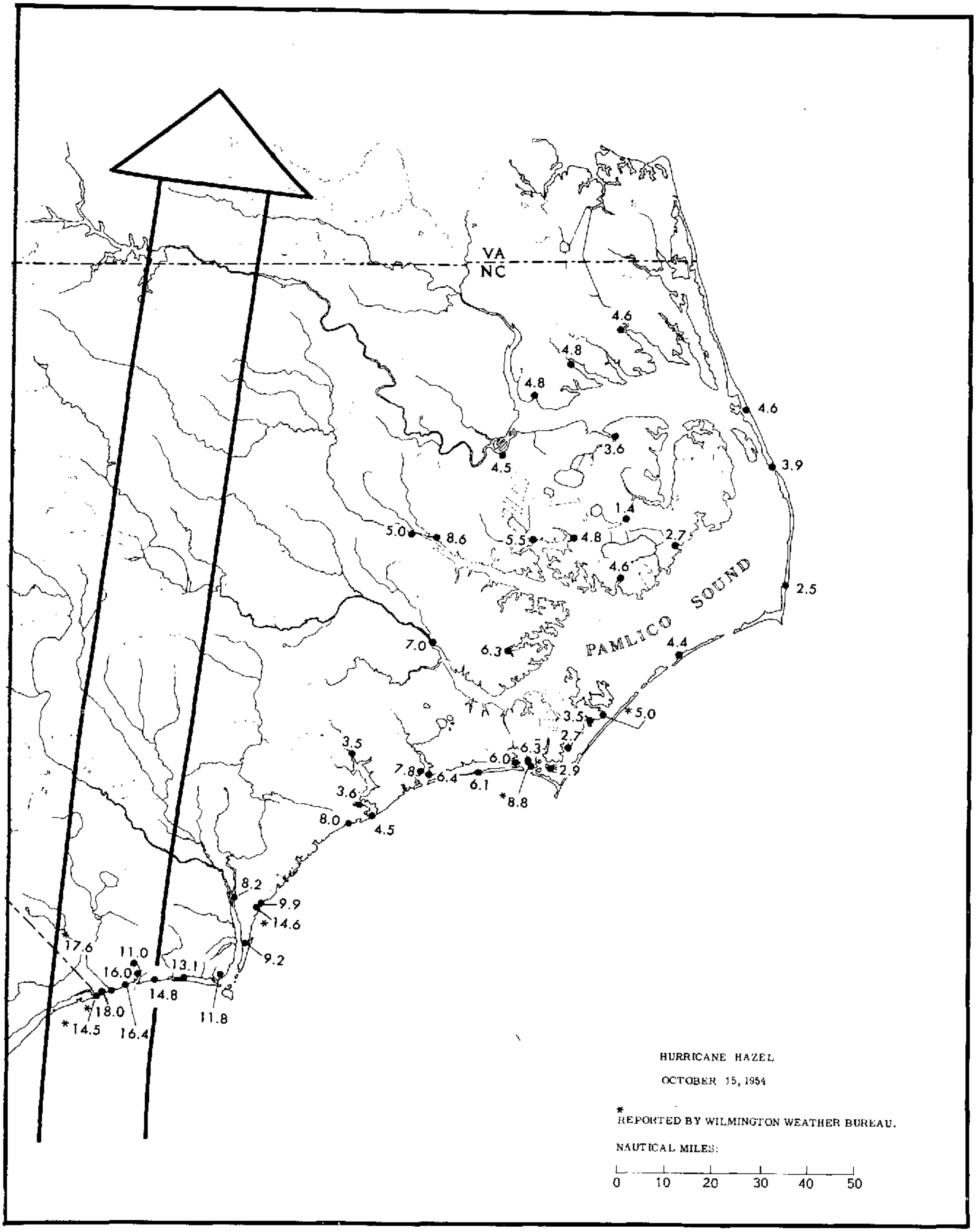


FIGURE 19.3.—Hurricane Hazel 1954, October 14–15. High water mark chart for North Carolina. (Based on data obtained from the Wilmington District of the U.S. Army Corps of Engineers.)

STORM NOS. 20, 21, AND 22.—HURRICANES OF 1955, CONNIE—AUGUST 11–13, DIANE—AUGUST 16–19, IONE—SEPTEMBER 18–20

These three hurricanes are being discussed together, for all had similar trajectories and many of the remarks which may be made about any one apply to one or both of the others.

Historical accounts of all three storms are given by U.S. Weather Bureau [112] and by Dunn, Davis, and Moore [23]. Additional meteorological data concerning Connie and Diane are given by Namias and Dunn [70] and Chapman and Sloan [4]. Special features of Ione are discussed by Jordan and Stowell [50]. Bretschneider [1] discussess the storm surges in Chesapeake Bay. Supplementary high water marks for all three storms have been collected by the Wilmington, N.C. District Office of the U.S. Army Corps of Engineers and are shown separately in the third figure for each storm. The data do not appear to present any new features but they give additional evidence of several of the surge producing processes discussed previously.

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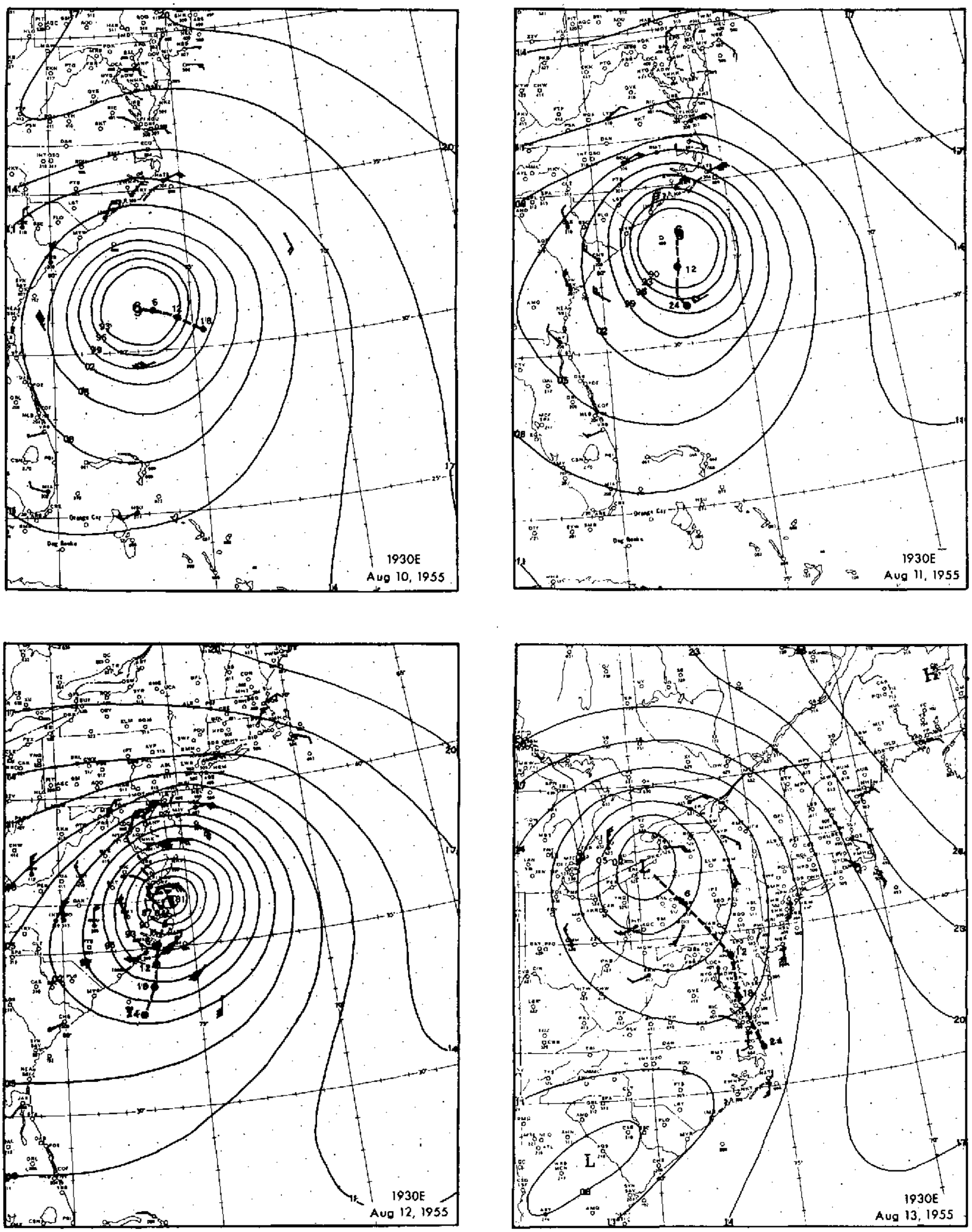

FIGURE 20.1.—Hurricane Connie 1955, August 11–13. Synoptic charts.

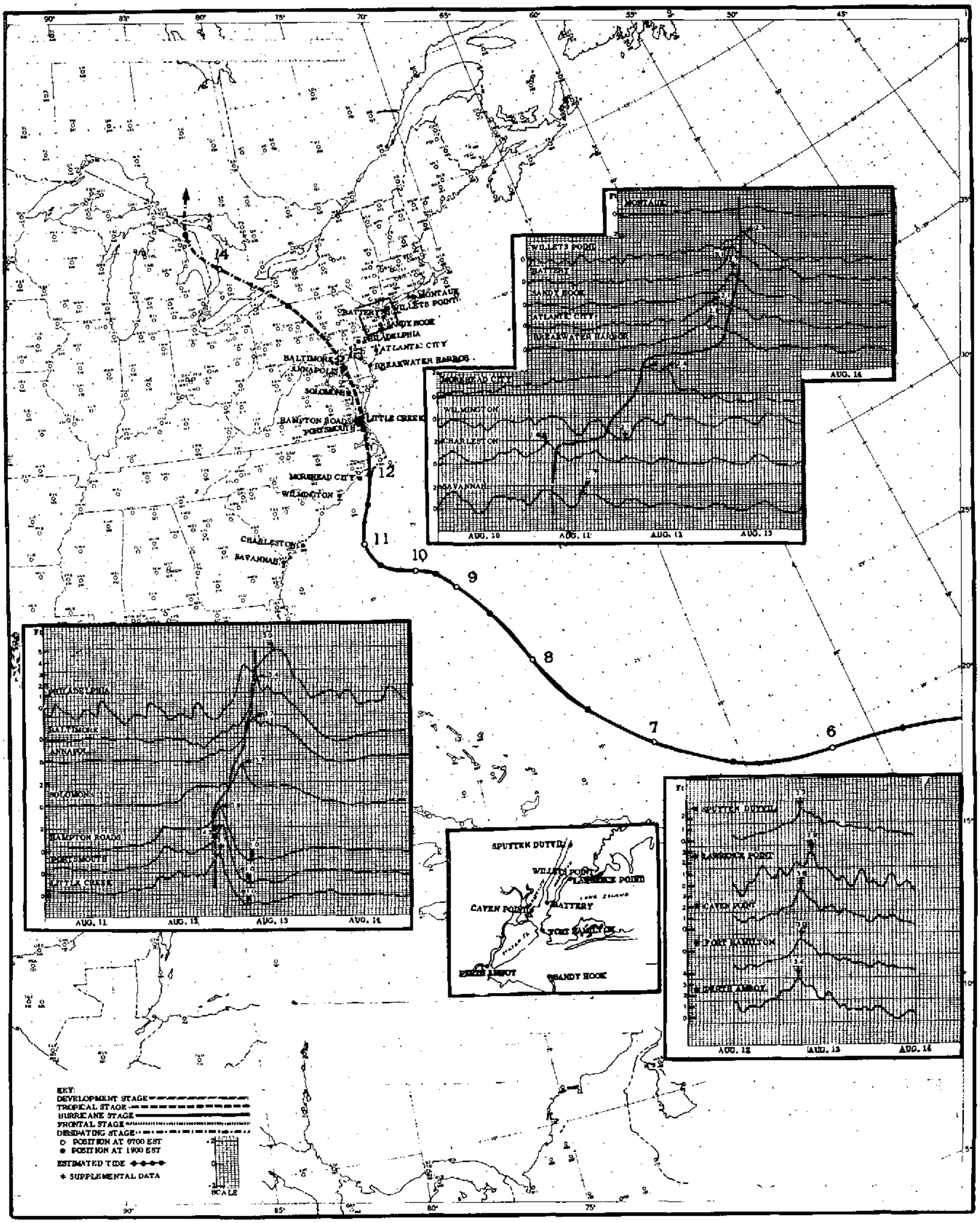

FIGURE 20.2.—Hurricane Connie 1955, August 11–13. Storm surge chart. Insert map for New York Harbor.

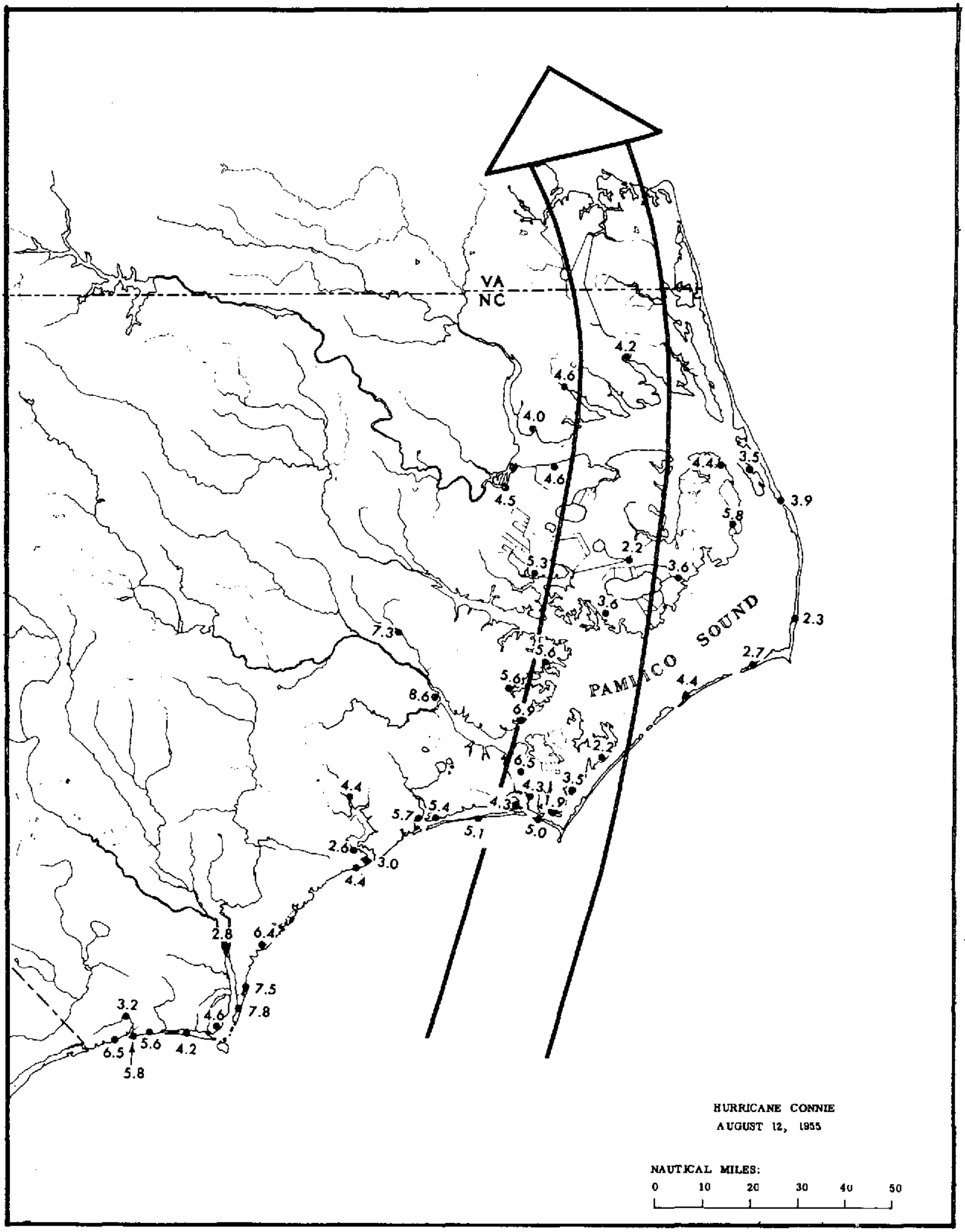

FIGURE 20.3.—Hurricane Connie 1955, August 11–13. High water mark chart for North Carolina. (Based on data obtained from the Wilmington District of the U.S. Army Corps of Engineers.)

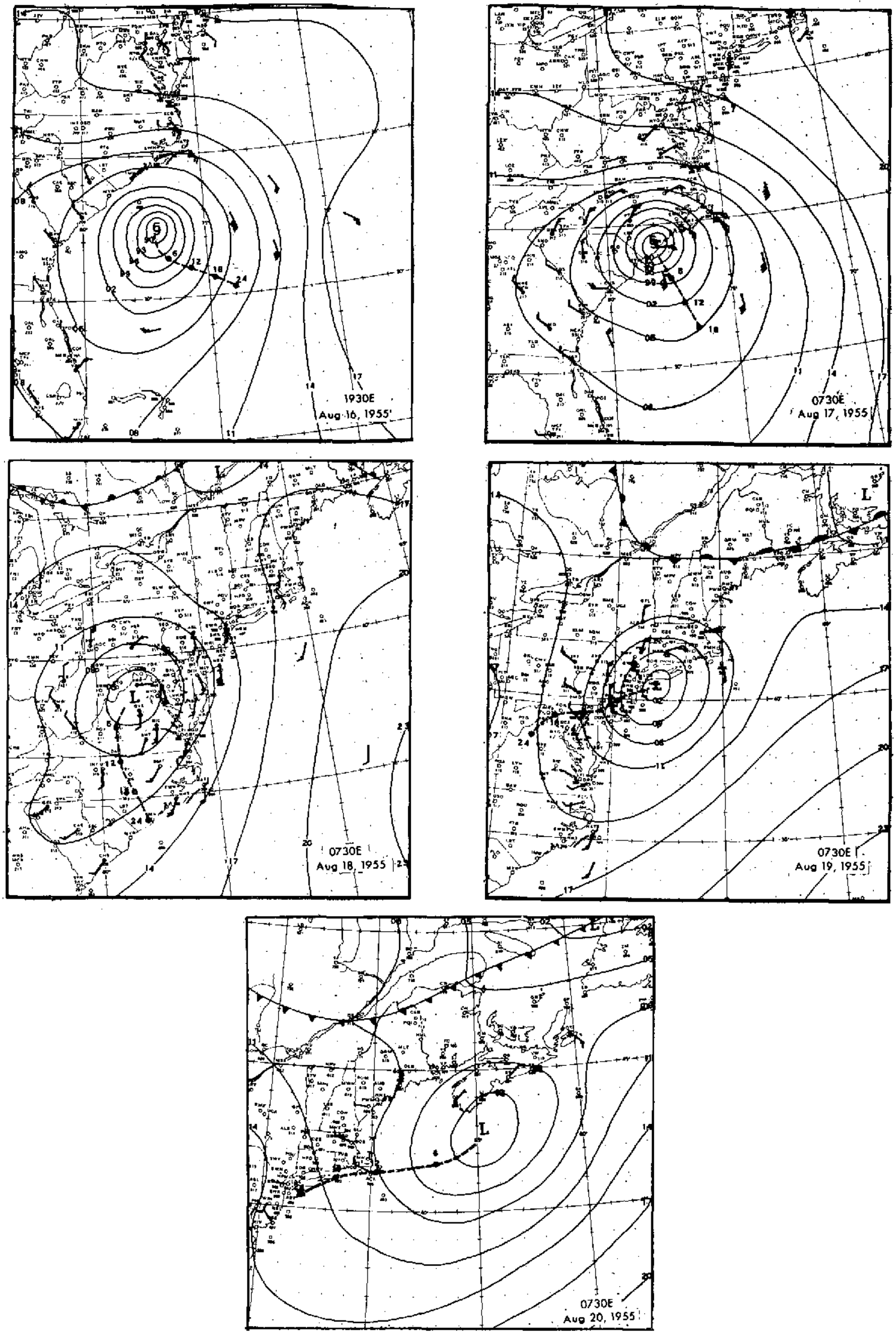

FIGURE 21.1.—Hurricane Diane 1955, August 16–19. Synoptic charts.

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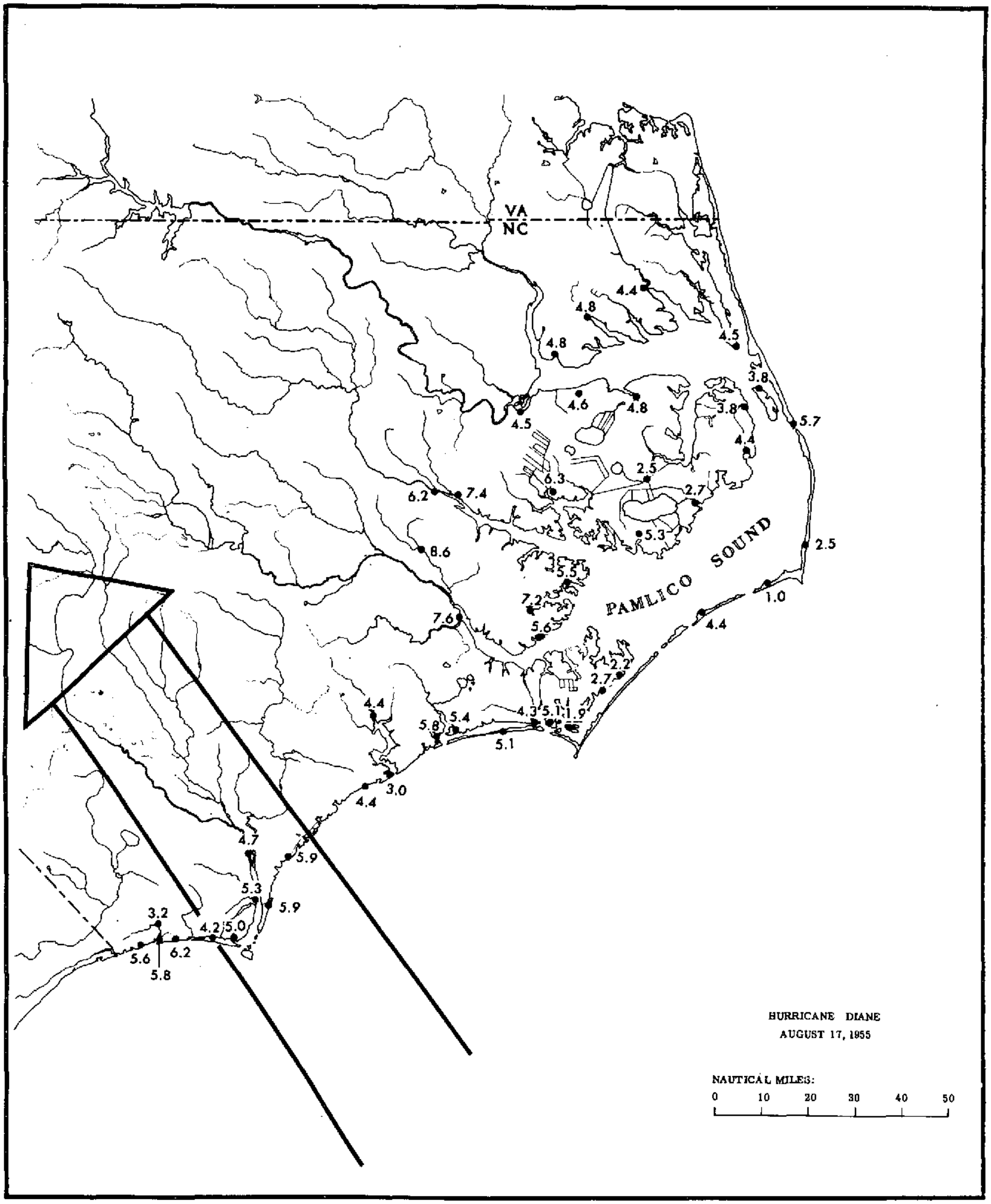

FIGURE 21.2.—Hurricane Diane 1955, August 16–19. High water chart for North Carolina. (Based on data obtained from the Wilmington District of the U.S. Army Corps of Engineers.)

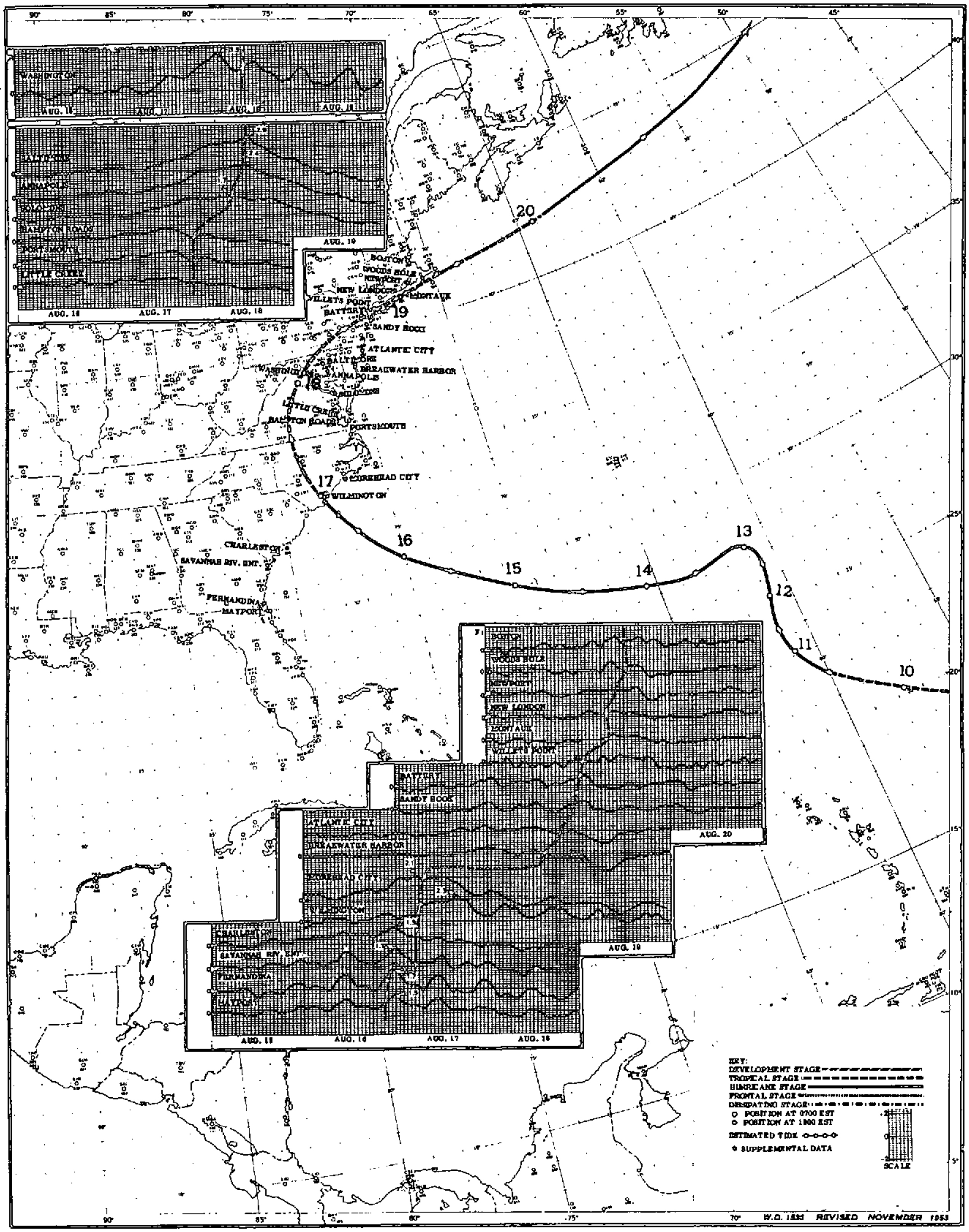

FIGURE 21.3.—Hurricane Diane 1955, August 16–19. Storm surge chart.

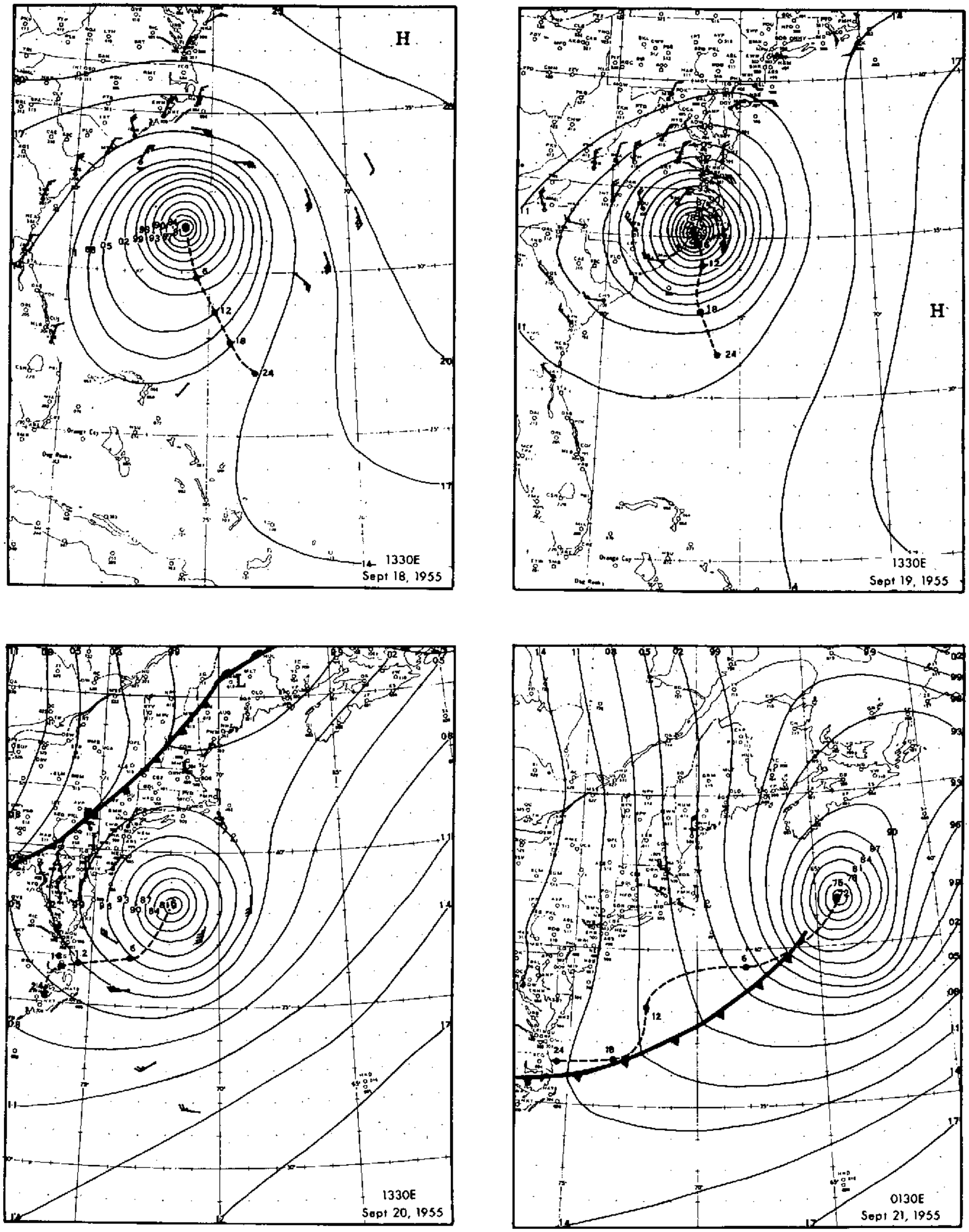

FIGURE 22.1.—Hurricane Ione 1955, September 18–20. Synoptic charts.

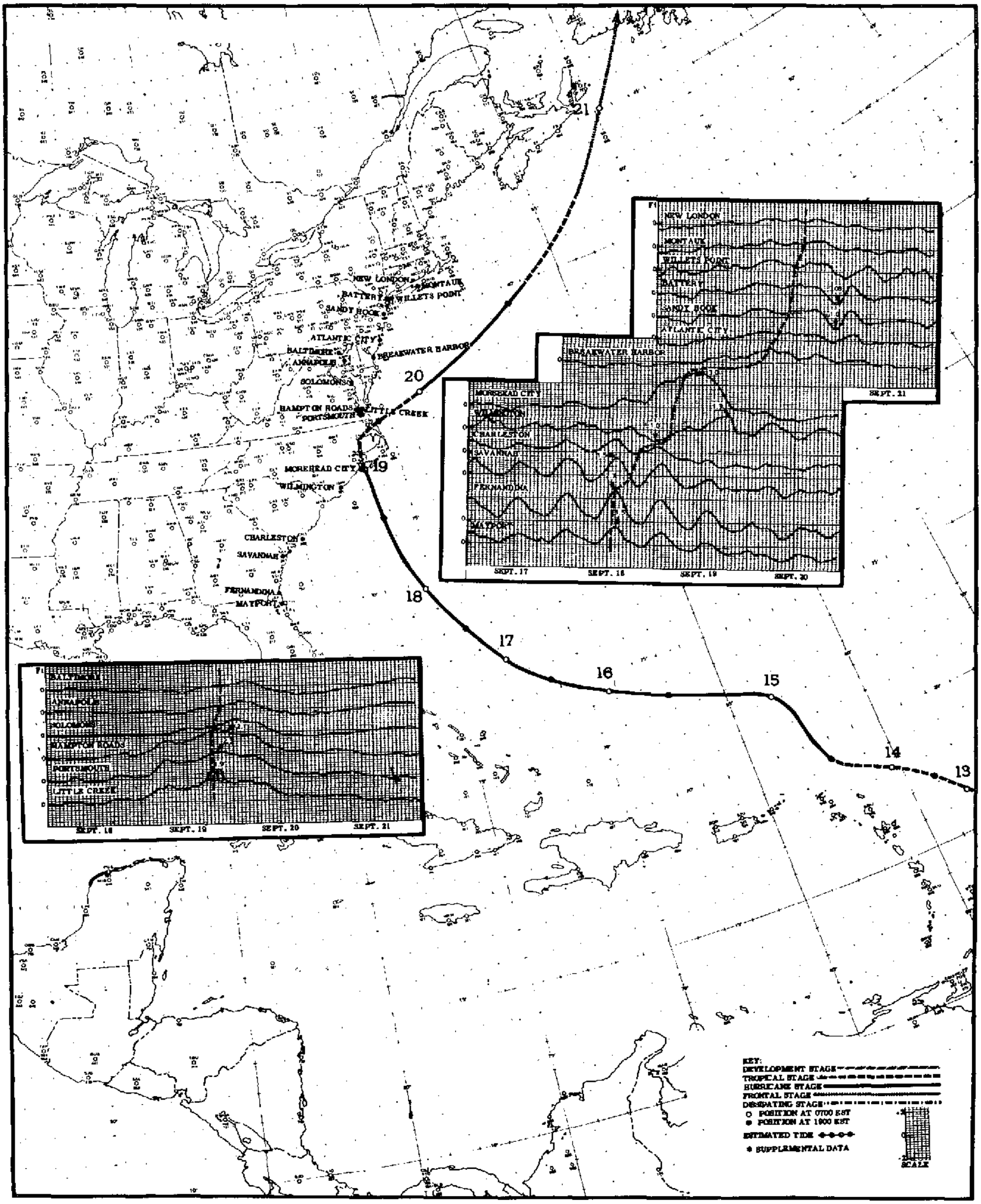

FIGURE 22.2.—Hurricane Ione 1955, September 18–20. Storm surge chart.

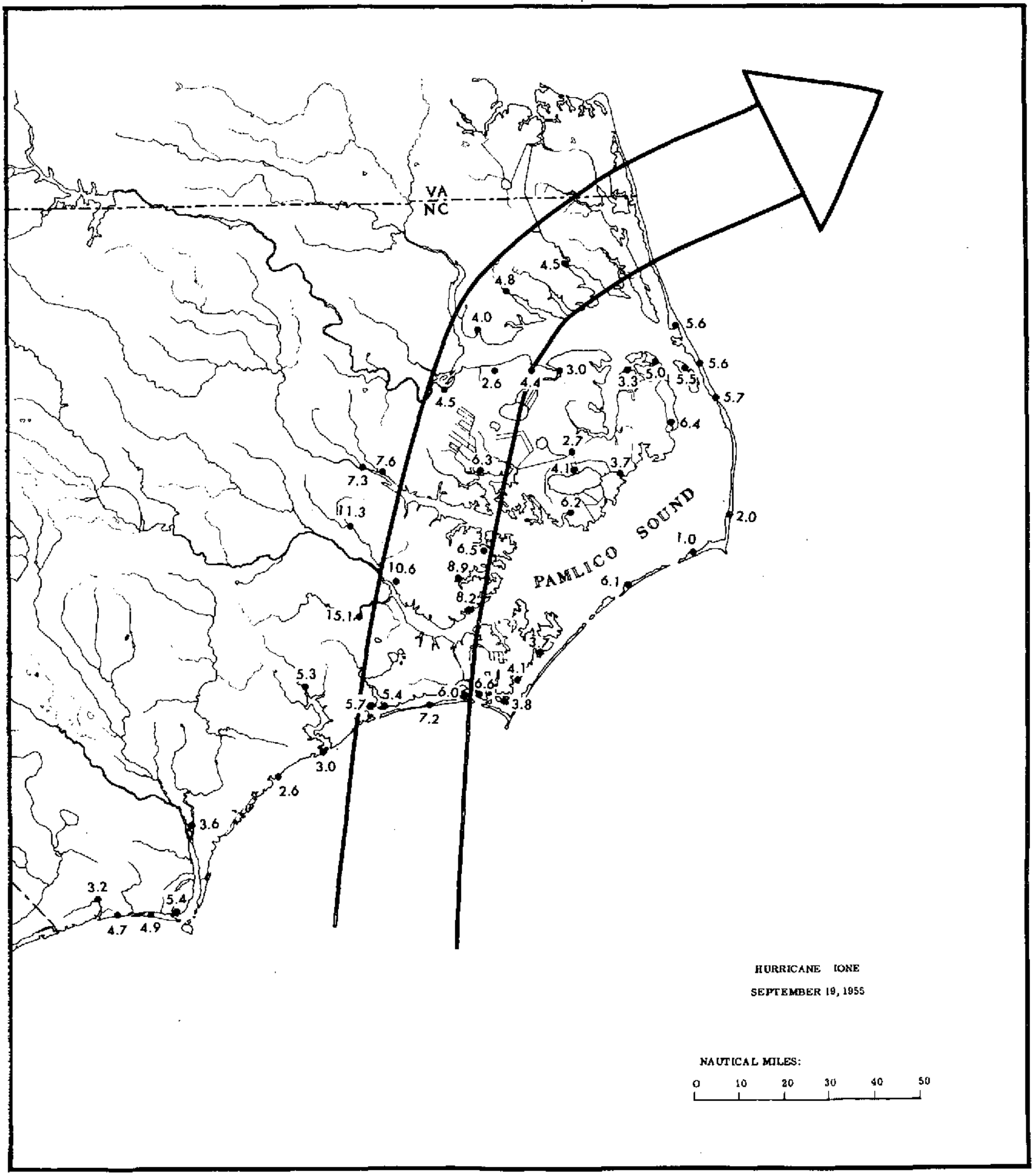

FIGURE 22.3.—Hurricane Ione 1955, September 18–20. High water mark chart of North Carolina. (Based on data obtained from the Wilmington District of the U.S. Army Corps of Engineers.)

A description of this storm including preliminary reports of high water elevations at several locations is given by U.S. Weather Bureau [111]. The meteorological aspects of the storm have been discussed by Hawkins [45], Richter and DiLoreto [85], and Dunn, Davis, and Moore [24]. Additional high water mark data have been collected by the New Orleans and Norfolk Districts of the U.S. Army Corps of Engineers and the Coast and Geodetic Survey. These are shown in figures 23.3 and 23.4.

The track of this storm and the synoptic charts given in figure 23.1 would lead one to expect the maximum on-shore surface waves to be those generated south of Louisiana. The detailed analysis of the wind field presented by Graham and Hudson [33] and a plot of all the ship observations recorded in this storm confirm this supposition. It is worthwhile to note that the variability in the high water marks collected in this storm is greatest near the Mississippi Delta region, where the surface wave activity was at a maximum. This is consistent with the hypothesis that surface waves are responsible for much of the variability in peak-tide heights.

The tide gage at Bayou Rigaud is near the northeastern tip of Grand Isle, that is, near the southwestern corner of Barataria Bay. It has not been determined whether the surge recorded here is a result of set-up within the Bay, some process effective in the open Gulf, or both. The Humble Oil Platform is located about 10 miles from Bayou Rigaud, about 6 miles from shore. The peak surge at the platform was only 1.7 ft., approximately half of the 3.3 ft. observed at Bayou Rigaud. The synoptic chart for 1330 EST September 23, in figure 23.1, shows a pressure deficiency of about 21 mb. The hydrostatic elevation of the water surface due to this reduction in pressure would be about 0.83 ft. or about half of the observed storm surge at the platform. Several hypotheses can be produced to account for the differences between the surge records at these two stations but the available data are insufficient for a unique explanation.

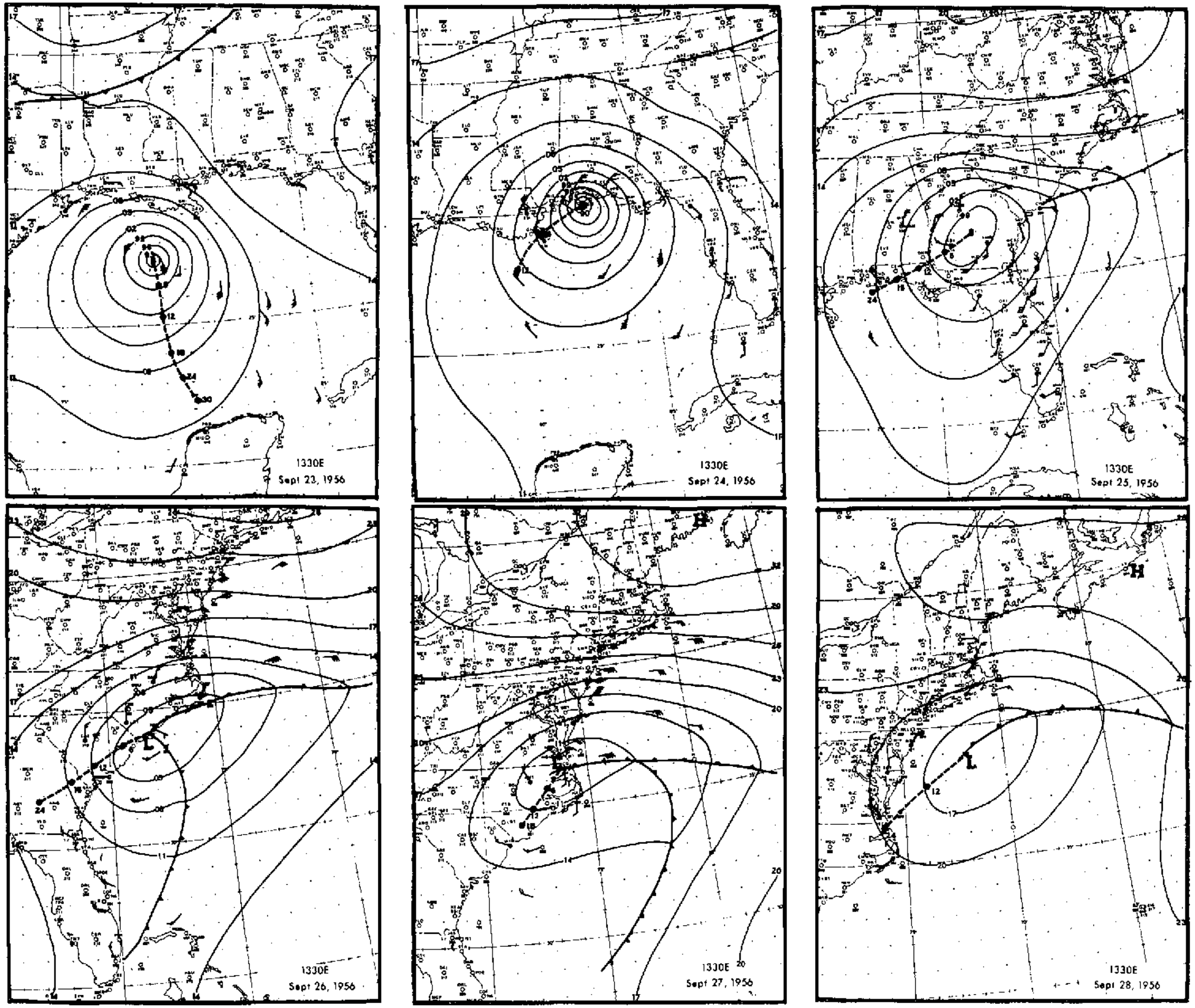

FIGURE 23.1.—Hurricane Flossy 1956, September 23–28. Synoptic charts.

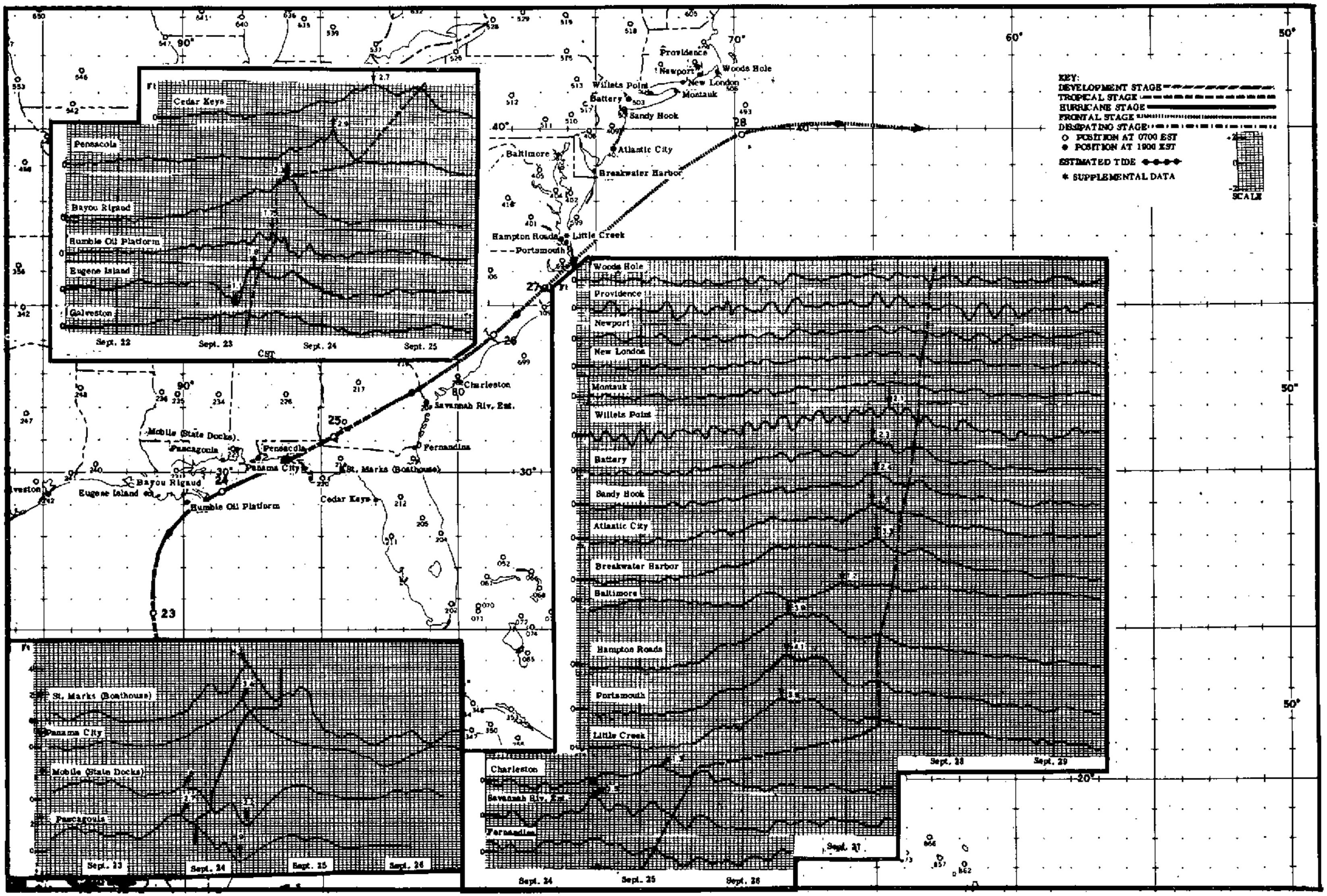

FIGURE 23.2.—Hurricane Flossy 1956, September 23–28. Storm surge chart.

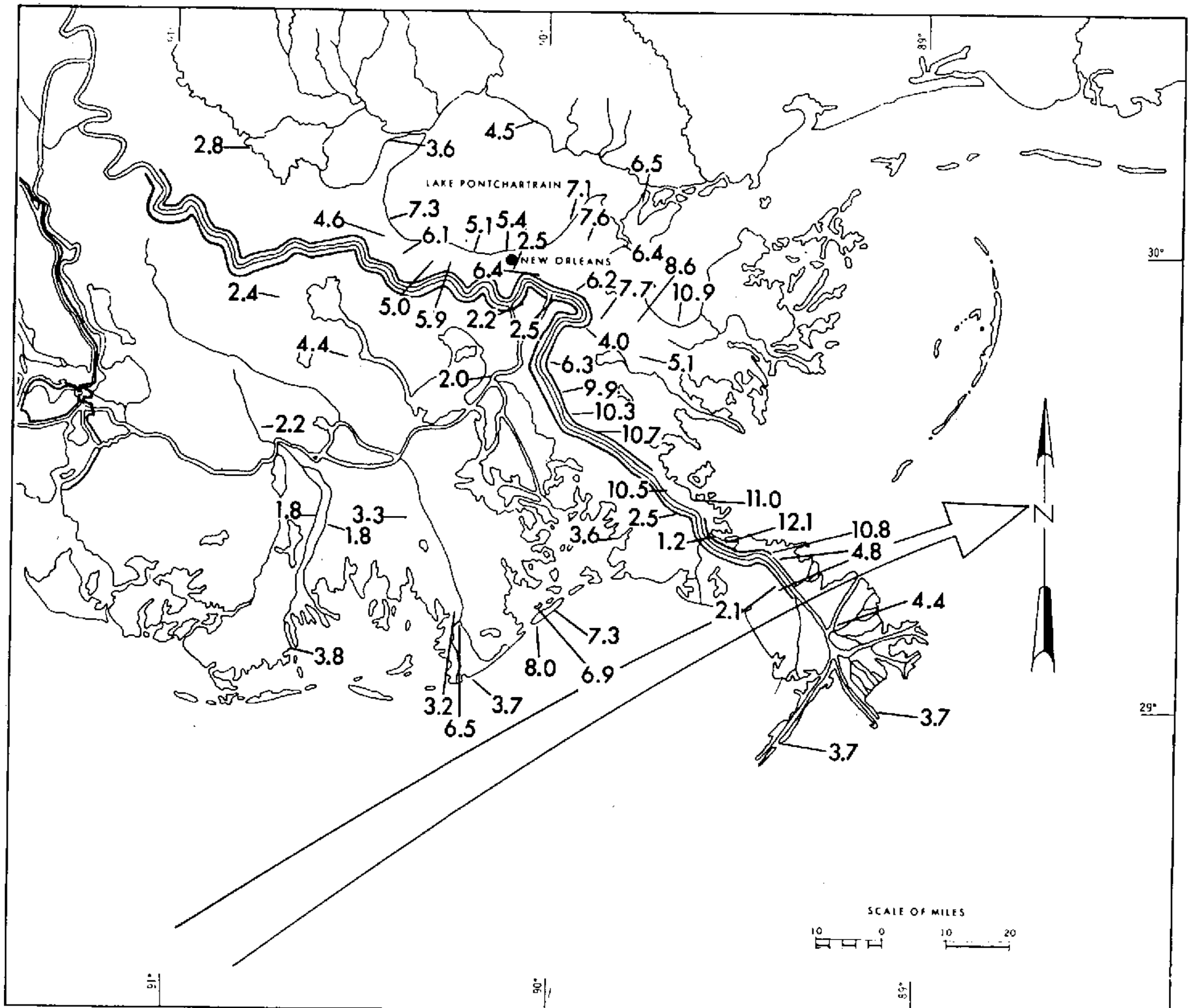

FIGURE 23.3.—Hurricane Flossy 1956, September 23–28. High water mark chart for Lousiana. (Based on data obtained from the New Orleans District of the U.S. Army Corps of Engineers.)

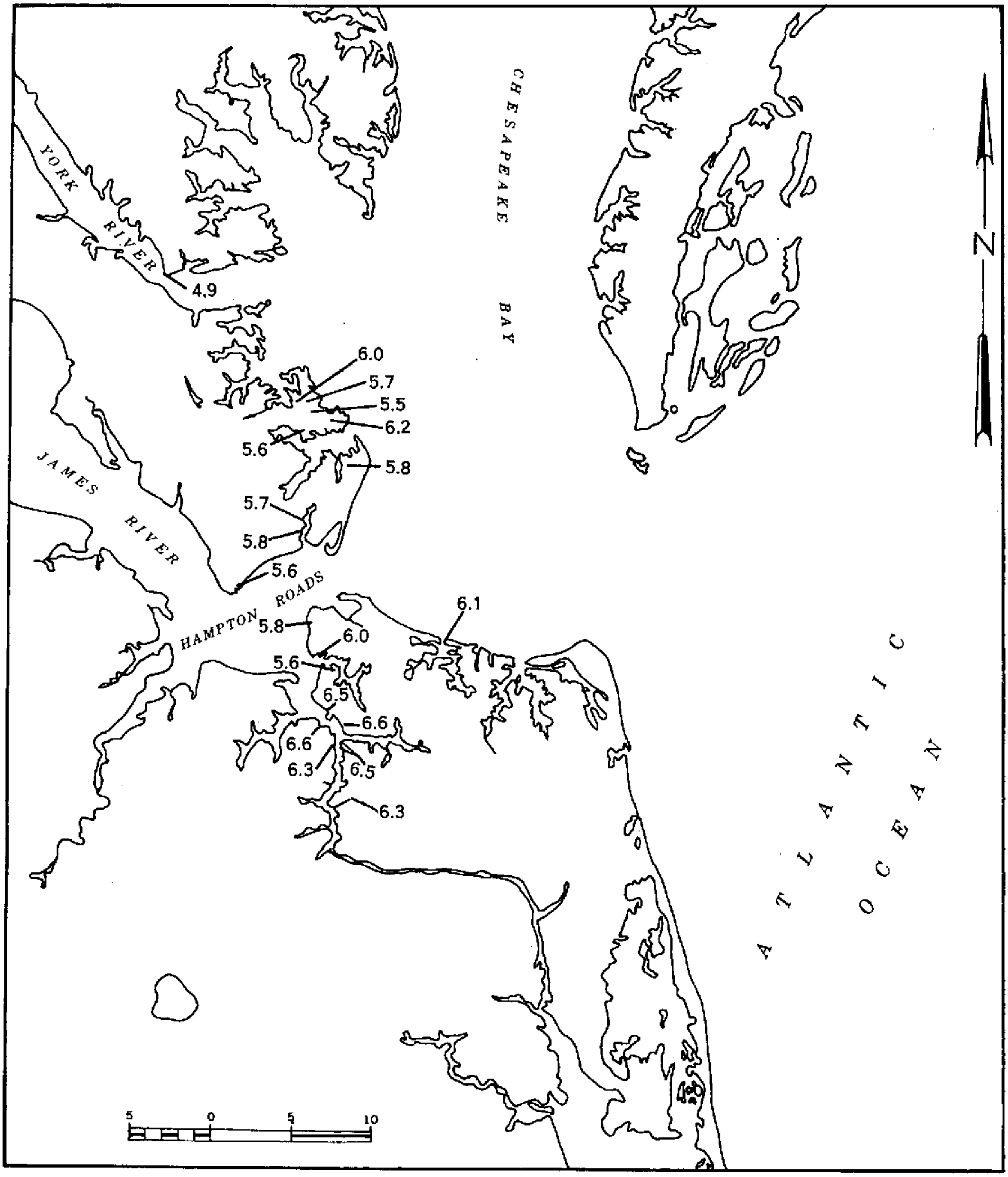

FIGURE 23.4.—Hurricane Flossy 1956, September 23–28. High water mark chart for the Norfolk, Va. area. (Based on data obtained from the Norfolk District of the U.S. Army Corps of Engineers.)

Historical data for this storm are given by Sumner [102, 103]. A meteorological discussion of the storm was given by Ross and Blum [86], and a meteorological discussion of the entire 1957 hurricane season by Moore and staff [64]. Graham and Hudson [33] have made an analysis of the detailed wind field in the storm as it crossed the coastline. The relation between this storm and the general circulation has been discussed by Klein [51]. Morgan, Nichols, and Wright [65] have given an account of the morphological effects of the storm on the Louisiana coast. Many additional manuscripts and working papers dealing with the various aspects of this storm have been prepared by several different organizations and given limited distribution. Much of the data presented here was given earlier by Harris [38].

STORM TIDE RECORDS

Time History of the Storm Tide

Figures 24.3 (a and b) show the observed storm tide at more than 30 recording tide stations affected by hurricane Audrey. These graphs have been plotted from hourly readings from the continuously recorded tide graphs. This was necessary in order to reproduce data from a wide range of chart scales on a common basis for visual comparison. The effects of oscillations with periods of less than 1 hour cannot be determined from the record. The extreme tide heights have been shown in all cases. These records have been divided into a number of panels each showing the behavior of the storm tide in a different waterway. The extreme high water due to the storm tide is shown for each curve unless the gage became inoperative before the extreme high water was reached. The extreme high water at a few stations resulted from rainfall runoff, and in these cases an effort has been made by the New Orleans District of the U.S. Army Corps of Engineers to indicate the peak water level due to the storm tide.

Records were obtained for three stations near Galveston, Tex., and one at Morgan Point in northwestern Galveston Bay, and one on the Intracoastal Waterway between Galveston Bay and Sabine Lakes, close enough to the southern end of the canal to suggest that it reflects conditions in East Bay. (These are labeled E through I.) At all three stations near Galveston the water level increased due to the storm while the storm was southeast of Galveston and the wind was blowing from land to sea. The out-of-phase relationship between the records at Station E (High Island) and F (Morgan Point) and records for stations near Galveston (G, H, and I) suggests that the high tide near Galveston was due to a transport of water from the northern portion of the Bay to the Galveston area by the northerly winds which blew over the Bay during the period of rising tides. It is possible that not all of the water carried from the northern portions of the Bay was able to escape through the entrance of Galveston Channel as fast as it was carried southward by the wind. The release of this mound of water, as the winds decreased in intensity and shifted toward the southwest after the passage of the storm, induced a secondary oscillation as shown by the second peak in the afternoon of June 27 at stations G, H, and I. The peak at Station E may have resulted from the first portion of this oscillation. This oscillation could have led to some flooding all around the Bay even without any increase in the amount of water in the Bay.

However, this explanation is not entirely unique. A tide gage was activated on the gulf side of Galveston Island shortly after hurricane Audrey. In hurricane Carla, 1961, the record from this gage is highly correlated with the records for the tide gages in Galveston Bay. This fact implies that some dynamic effect such as a storm-driven current along the shore and the rotation of the earth must have been the dominant cause of the rising water level with off-shore winds.

The record from Morgan Point (F) supports the second hypothesis. A time history of the water level during the storm from the northern shore of Trinity Bay, and for the tides on the open coast of Galveston Island would be useful.

A similar explanation may be applied to the records for the vicinity of Freeport, Tex., stations A, B, C, and D. Here it appears that some rise in sea level must have occurred on the open coast but this may have been modified by resonance or convergence in the channels. Information on the height of the storm tide at locations with a direct exposure to the open sea is needed to be sure of this.

Although the tide gage near Cameron, station N, was destroyed by the storm, a portion of the record was reconstructed from the log of the nearby Coast Guard Station on Monkey Island, and is shown as a dashed line in figure 24.3a. Other data were obtained from eye witness accounts. The tide was abnormally high on the coast south of Cameron and more than 130 people had evacuated their homes to the court house by midnight. By 0200 LST, the water was in the streets of Cameron. By 0245 LST it was above the runningboards of automobiles in the court house square. By 0430 LST the water was waist high in some streets of Cameron.

The records for stations M, L, and K farther inland show that the tide did not become abnormally high at these locations until after 0300 LST. The time of the peak water level was also progressively delayed as the distance from the open coast increased.

At Creole, about 10 miles east of Cameron and a half-mile farther inland, indicated by an asterisk on this map, eye witness accounts report that the roads, elevation about 6 ft., were still passable at 0500 LST, but became impassable by 0600 LST. The peak water levels observed at Creole were higher than in Cameron and the peak reported storm tide from this hurricane occurred about 3 miles east of Creole.

The water level records for the Mermentau River, stations O through S in figure 24.3a, closely paralleled the records for the Calcasieu River. The fragmentary record for station S supports the reports of abnormally high water on the coast by midnight.

The record for Pecan Island, station T in figure 24.3b, is especially interesting. The gage is located on a canal leading to White Lake and is on the north side of a ridge which varies from 7 to 9 ft. in elevation in this vicinity. Here the water level dropped until 0800 LST and then rose rapidly to an elevation of 6.9 ft. by 1100 LST. The water level increased more than 6 ft. between 0800 and 1000 LST.

A comparison between the tide recorded several miles from the coast and on a coastal island is shown at the extreme right side of figure 24.3b. Station L is located on an oil drilling platform of the Humble Oil Company. Station K is located about 10 miles away on the northeastern tip of Grand Isle, La. These stations were on the periphery of the storm and may not be representative of conditions near the center of the storm. However, it is noteworthy that the effect of the hurricane on sea level was much greater at Grand Isle on the coast than at the oil platform in open water. This is consistent with the similar relationship observed in hurricane Flossy, 1956.

The other sets of records indicate the same general features, a progressive delay in both the onset and peak of the storm tide as distance from the open coast increases, and will not be discussed in detail.

Extreme Storm Tide Elevations

Figures 24.4a and 24.4b show the extreme storm tide elevations at more than 100 locations in Louisiana and Texas. Variations in the extreme tide elevation amounting to several feet in a distance of less than one mile can be noted at several locations on the map. It is believed that these differences near the coast are due principally to local variations in exposure to wind and waves. Farther inland the variations are apt to be due to the presence of control structures, the high values being reported on the seaward side of dikes and levees. At many places, the spoil banks resulting from canal dredging formed levees which impeded the flow of the storm tide. The water level on nominally dry land was higher than that in nearby canals for several days after the storm at many places. The shaded area on this map indicates the limit of widespread inundation as taken from a report prepared by the New Orleans District of the U.S. Army Corps of Engineers.

These data have not been analyzed to show specific depth-of-flooding contours because it is believed that such an anlysis would imply a degree of regularity not present in nature.

EFFECTS OF LOCAL TOPOGRAPHY

To understand the variations in peak water level and in the timing of the storm tide, it is necessary to consider the topography of the region affected. This is illustrated in figure 24.5, based on the latest available U.S. Geological Survey Topographic Charts. The figure shows the major topographic features in the region most severely inundated by this storm. The coastline in southwestern Louisiana consists of narrow ridges frequently no more

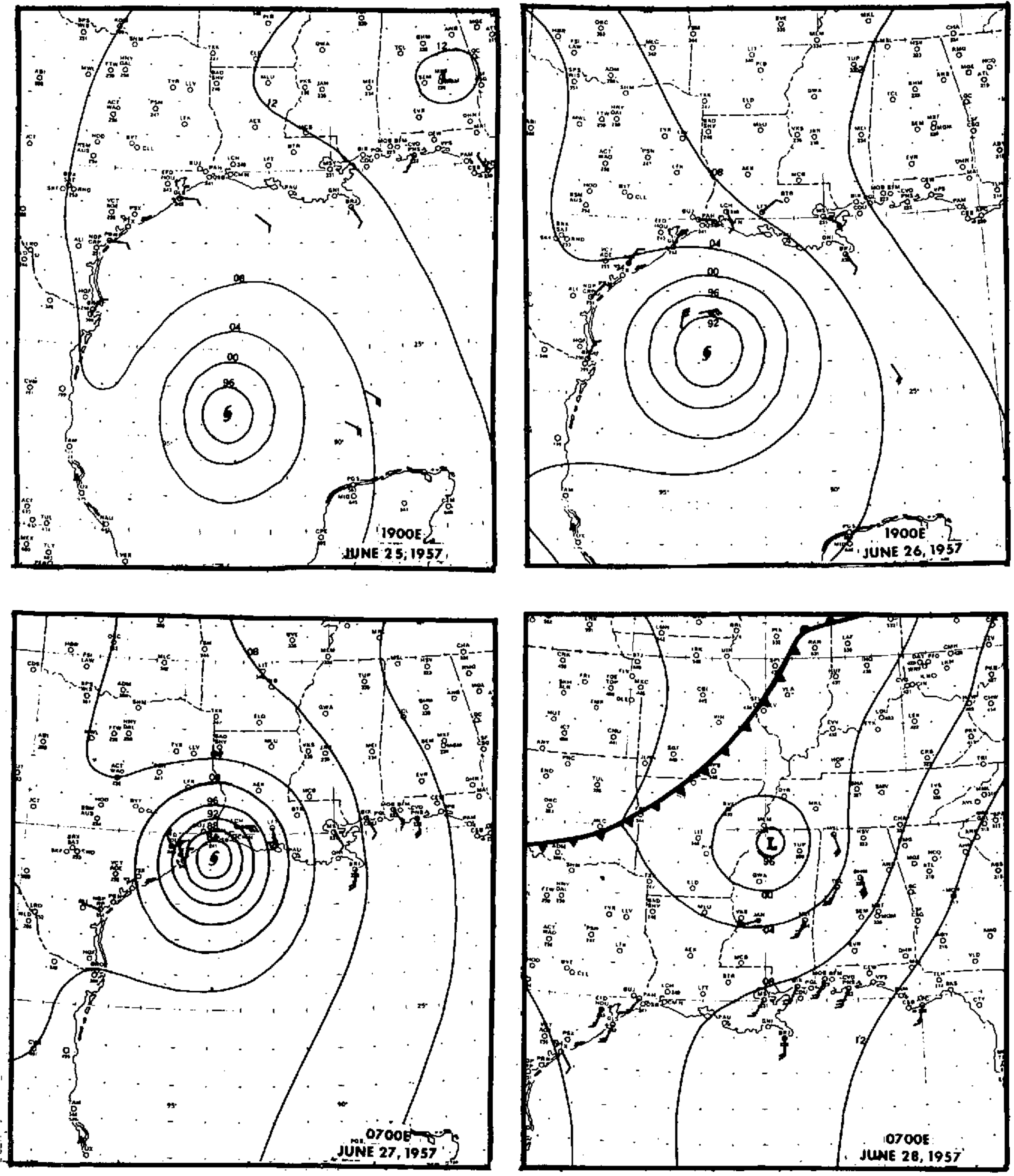

FIGURE 24.1.—Hurricane Audrey 1957, June 26–27. Synoptic charts.

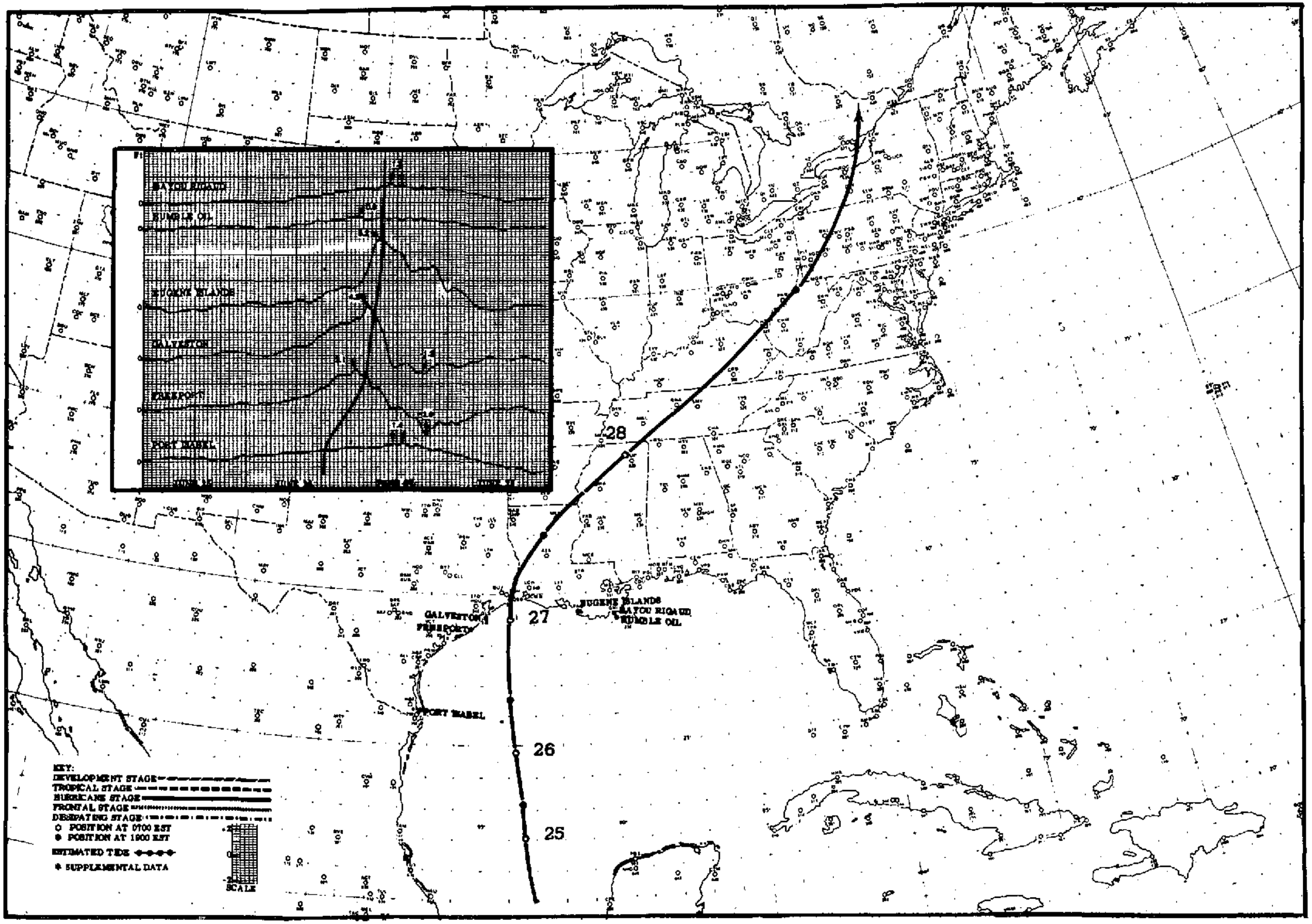

FIGURE 24.2.—Hurricane Audrey 1957, June 26–27. Storm surge chart.

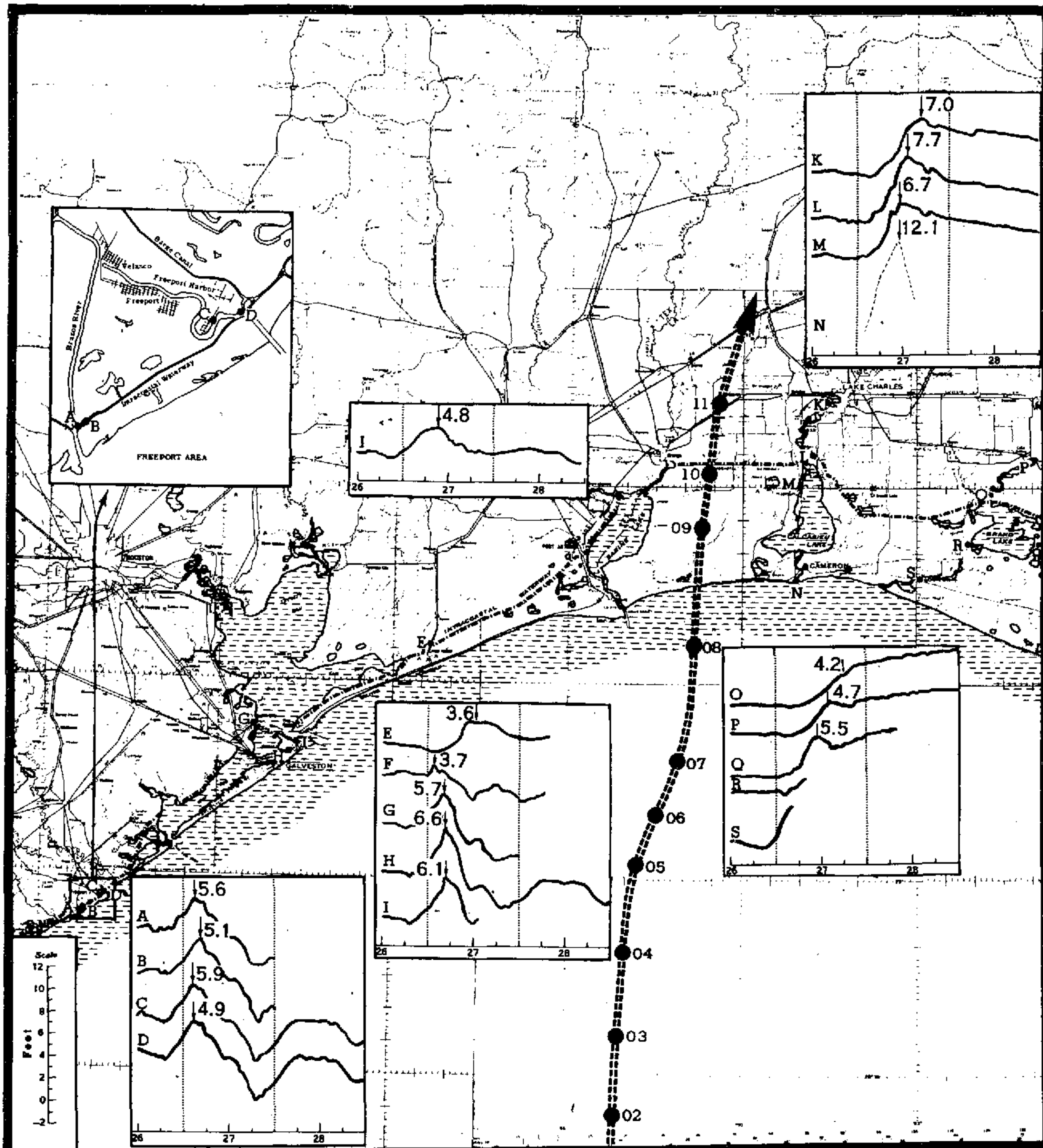

FIGURE 24.3a.—Hurricane Audrey 1957, June 26–27. Observed tides, Texas and western Louisiana. Insert map of Freeport, Tex.

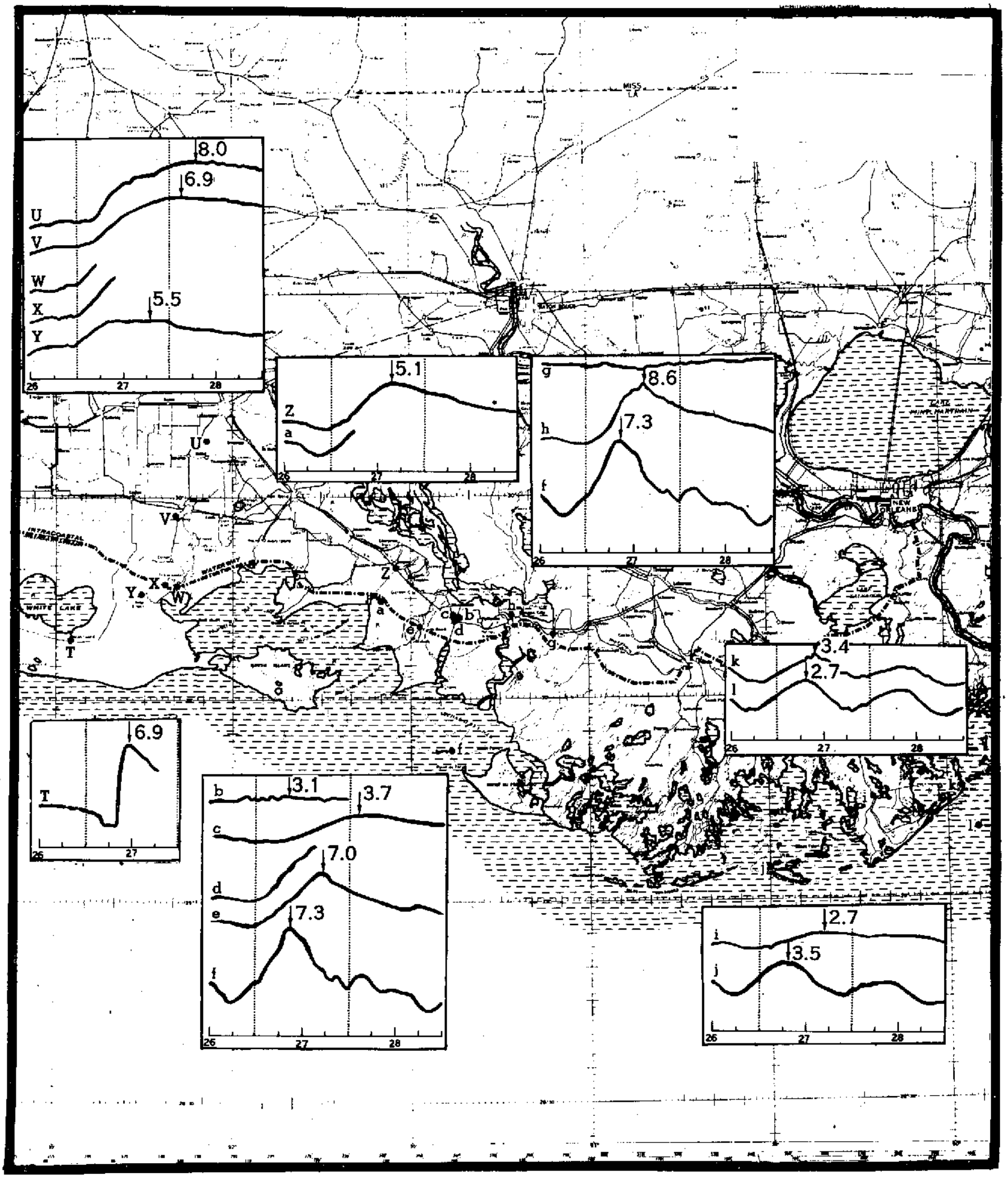

FIGURE 24.3b.—Hurricane Audrey 1957, June 26–27. Observed tides, eastern Louisiana.

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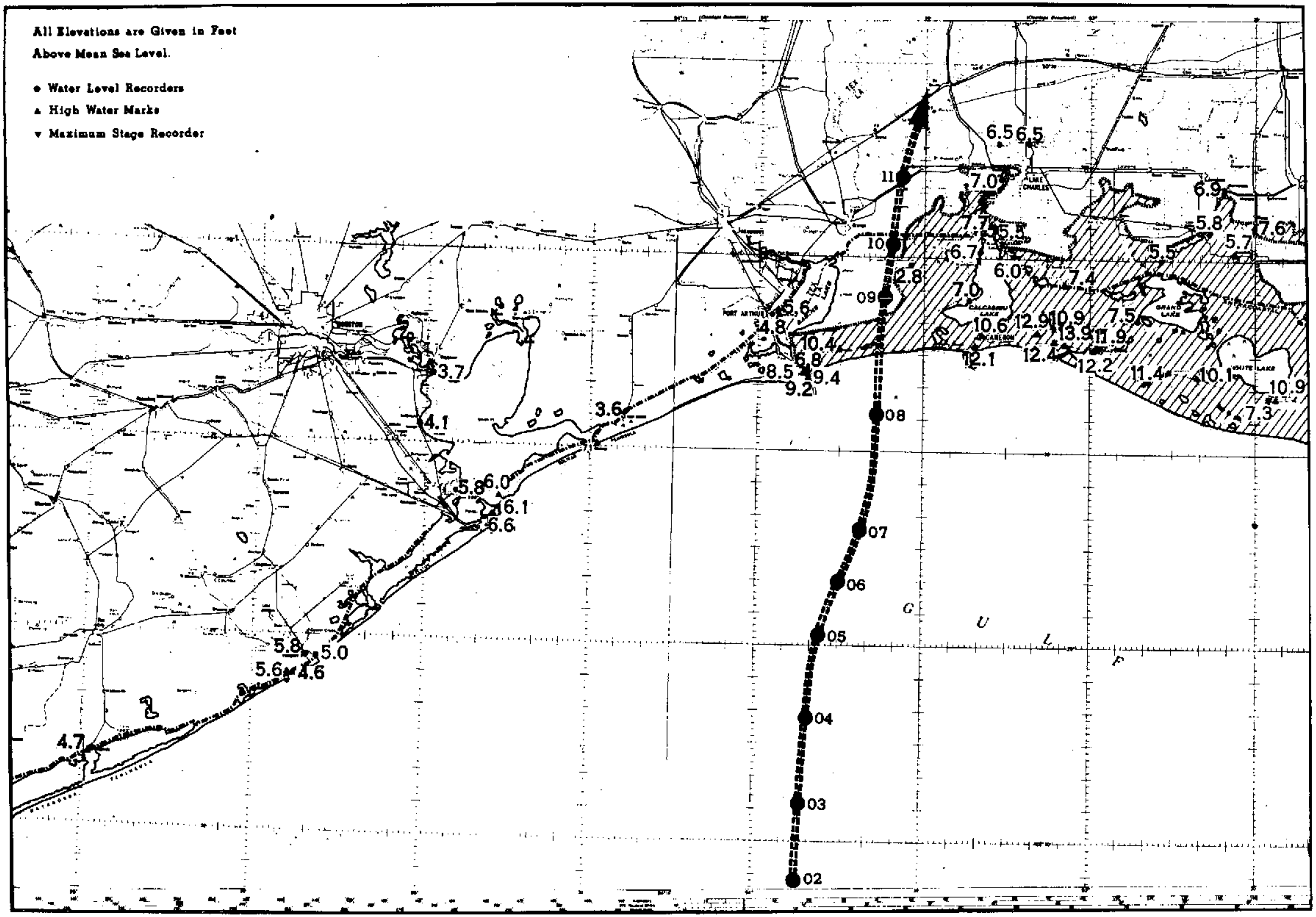

FIGURE 24.4a.—Hurricane Audrey 1957, June 26–27. High water mark chart for Texas and western Louisiana. Hatched area gives limit of inundation in Louisiana.

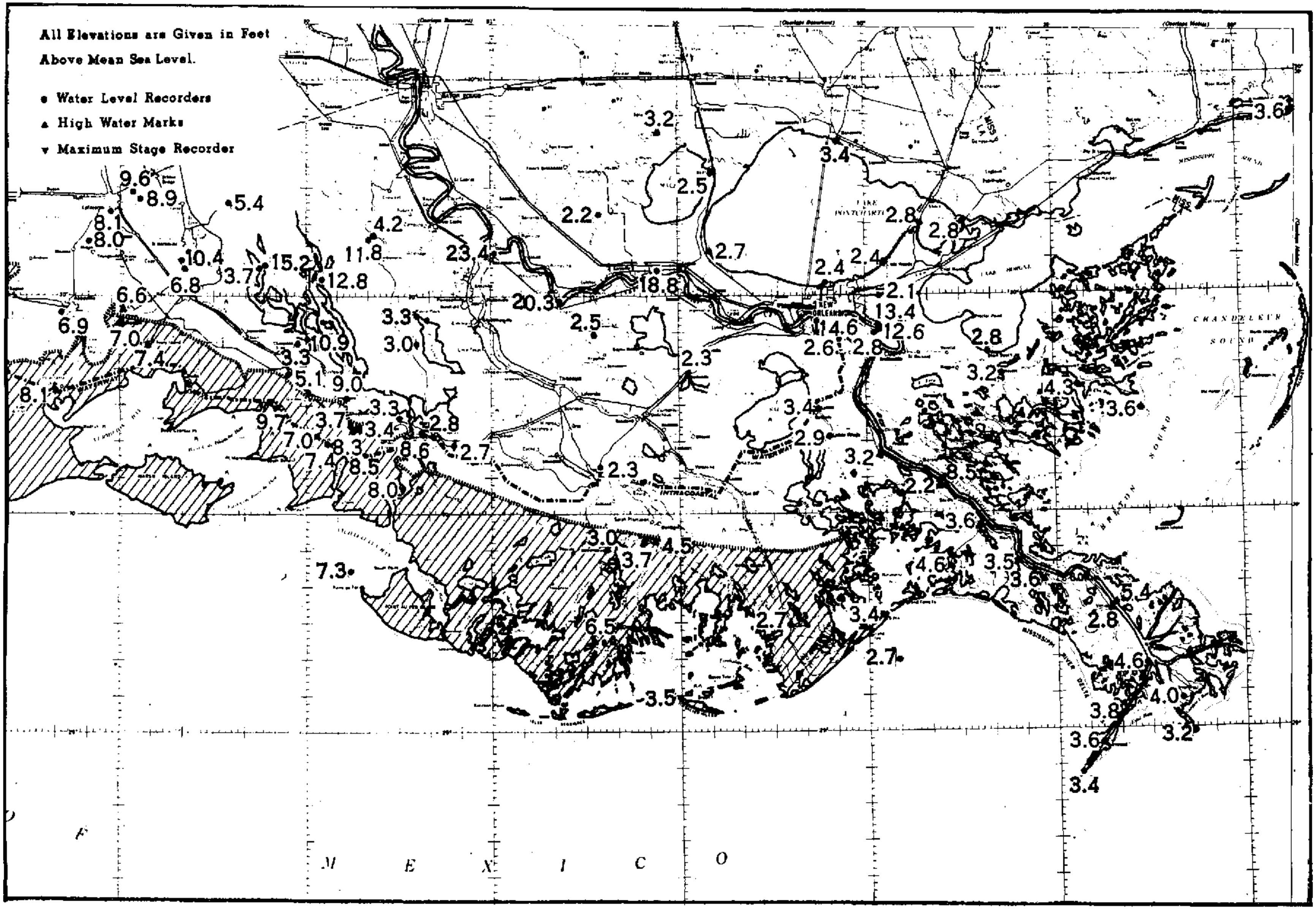

FIGURE 24.4b.—Hurricane Audrey 1957, June 26–27. High water mark chart, eastern Louisiana. Hatched area gives limit of inundation in Louisiana.

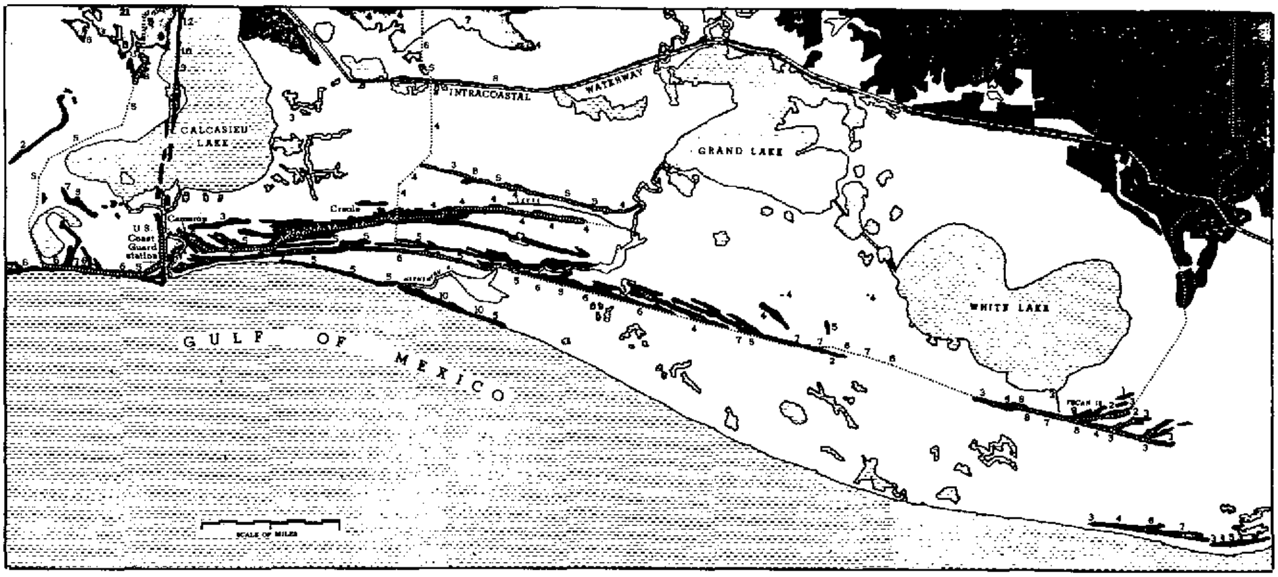

FIGURE 24.5.—Hurricane Audrey 1957, June 26–27. Topography of southern Louisiana.

than 100 ft. across and less than 3 ft. above mean sea level. North of the ridges, the land quickly drops to approximately sea level or below. In many locations the first continuous 5-ft. contour is 15 to 20 miles inland from the coast. Several other ridges with elevations varying from 2 to 10 ft. are found more or less parallel to the coast. Representative elevations are shown at intervals along the ridges.

It appears that the easterly wind ahead of the storm drove the water from the eastern end of White Lake and produced the fall in water level at the Pecan Island gage. Later, as the water south of the Pecan Island ridge became high enough to flow over the ridge, the water level at this gage rose rapidly to approximately the height of the ridge. It could not go much higher because the large pond north of the ridge would have to be filled to support any higher elevation.

The 10.9-ft. storm tide reported south of the ridge may have been due to a perturbation in the flow formed because of the presence of the ridge.

The same sequence of events appears to have been followed near Cameron and Creole. The ridges south of Cameron were lower. Both the center of the storm and the maximum wind speeds were nearer. This led to higher tides on the open coast. Consequently, the ridges were topped earlier than at Pecan Island. The ridge south of Creole is higher than that south of Cameron and this appears to account for the delay in the development of serious flooding, and perhaps for the higher peak tide elevation ultimately observed. This hypothesis can also explain the many eye witness reports of tidal waves at inland locations.

ORIGINAL TIDE RECORDS

Most of the preceding discussion has been based on hourly or extreme tide observations. This does not tell the full story, for oscillations with periods much shorter than an hour are frequently apparent in the tide records of a hurricane. Copies of several Coast and Geodetic Survey tide records are shown in figures 24.6 and 24.7. These are typical of all the gage records examined. The Coast and Geodetic Survey records were chosen for this display because of their near uniform scale. The left end of the short horizontal mark indicates the hour. Data read at these points have been used in plotting the curves of hourly readings. Hour numbers for even-numbered hours are given above the curve. A vertical scale is given on each figure. Figure 24.6 is a photograph of the original tide gage record for Galveston. This is one of the gages equipped with two recording pencils so as to extend the range over which the tide can be recorded without having to use any reversing mechanism. The second pencil began to record shortly before 0100 CST and the first pencil went off scale a little after 0200 CST. An oscillation with a period of 20 to 30 minutes is clearly indicated in this record. The extreme high tide of 6.6 ft. m.s.l. occurred at the peak of such an oscillation shortly before 0500 CST. The high water for the day (used in most tidal analyses), 6.3 ft. was obtained by drawing a smooth curve though several hourly values near the time of the extreme high water.

The records for four stations in Louisiana are combined in figure 24.7. The recording pencil at Eugene Island went off scale shortly after 0600 CST, came back on scale briefly between 0700 and 0800 CST, and went off scale again after 0800 CST. A new and higher base line was established as the recording pencil returned permanently to the recording position shortly after 1000 CST. The peak tide height had to be inferred from the data on the chart and may be in error by a few tenths of a foot. The short-period oscillations seen in the records for Galveston are also apparent in all of the records shown here. If one were to look at the records for Galveston and other landlocked harbors, he might suspect that these oscillations are due to an oscillation of the harbor. However these oscillations are also present in the records from the Humble Oil Platform. These cannot be due to harbor conditions. Since these oscillations can occur in open water, it is not safe to regard all such oscillations observed in harbors as being due to conditions within the harbor.

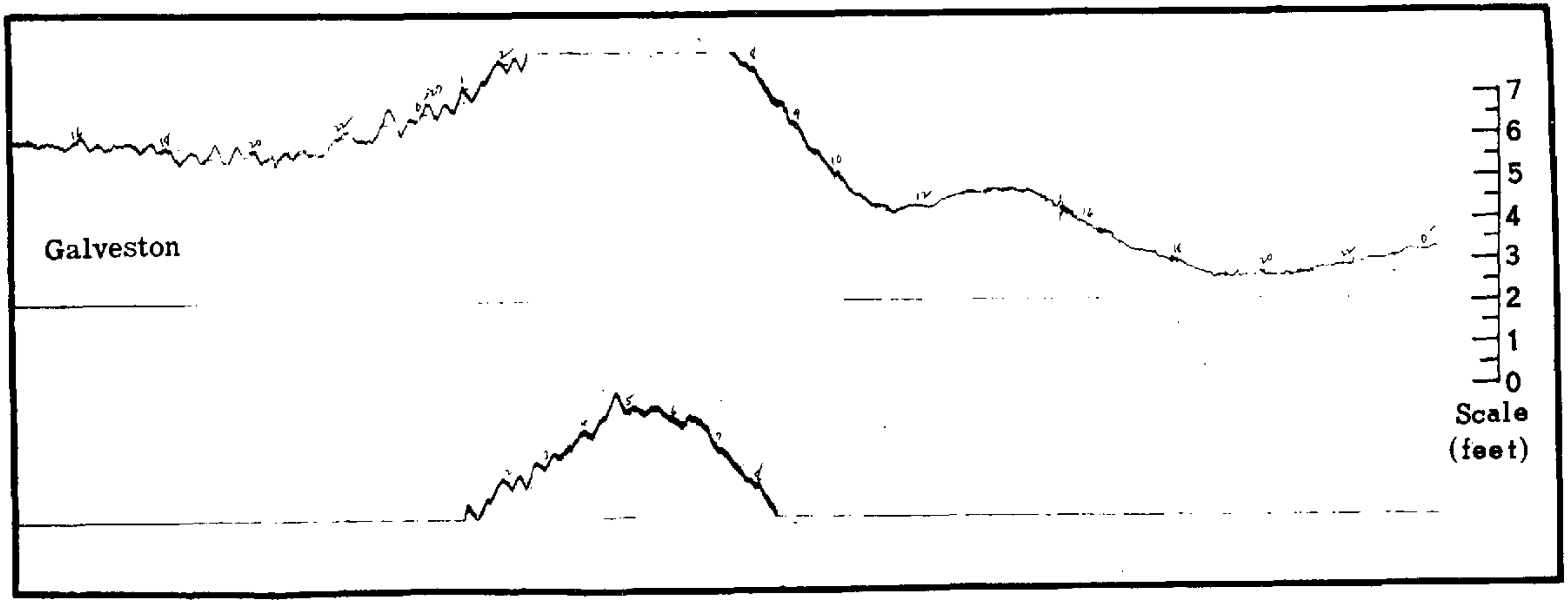

FIGURE 24.6.—Hurricane Audrey 1957, June 26–27. Observed tide records for Galveston, Tex., Coast and Geodetic Survey tide station.

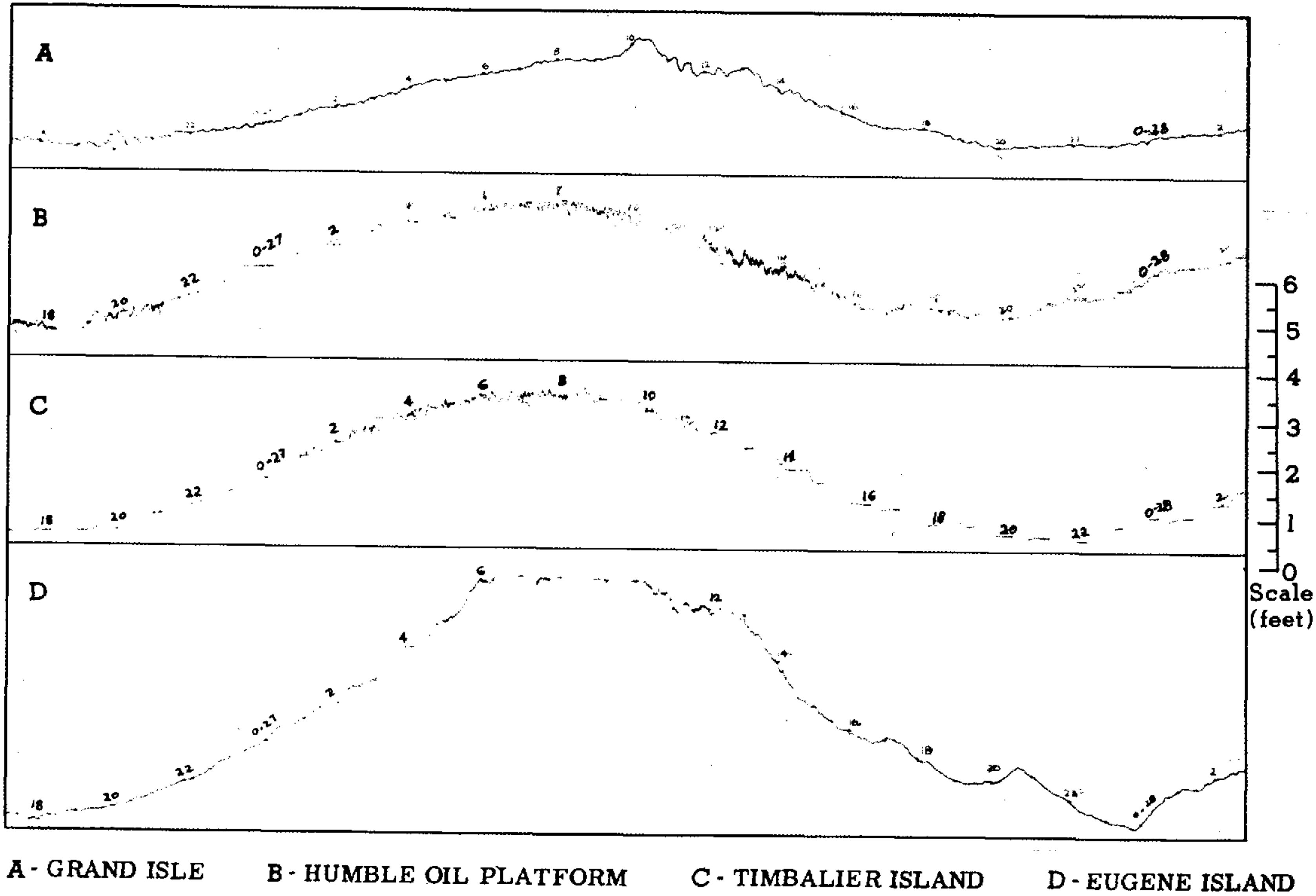

FIGURE 24.7.—Hurricane Audrey 1957, June 26–27. Observed tide records at Coast and Geodetic Survey tide stations in Louisiana.

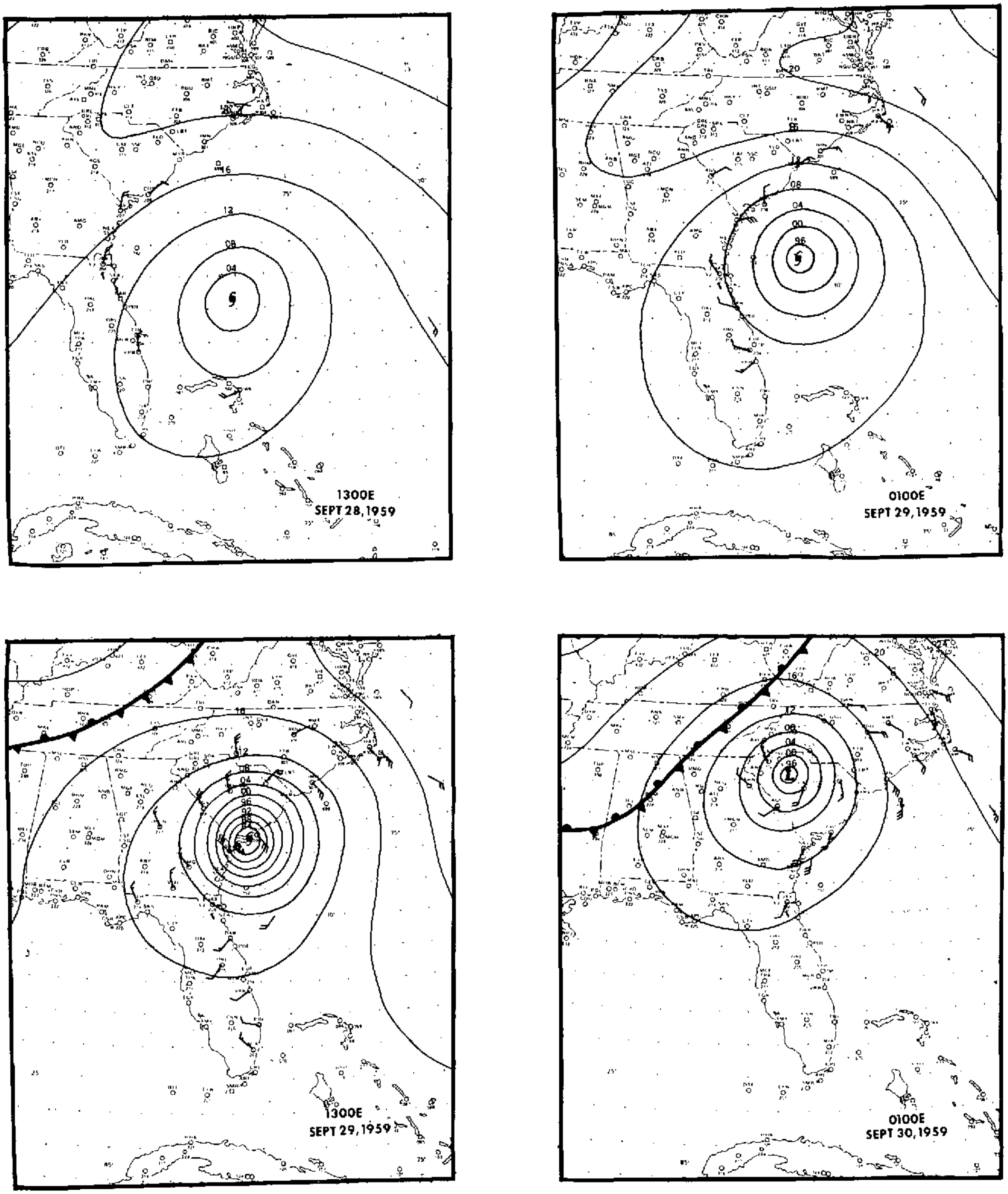

FIGURE 25.1.—Hurricane Gracie 1959, September 28–30. Synoptic charts.

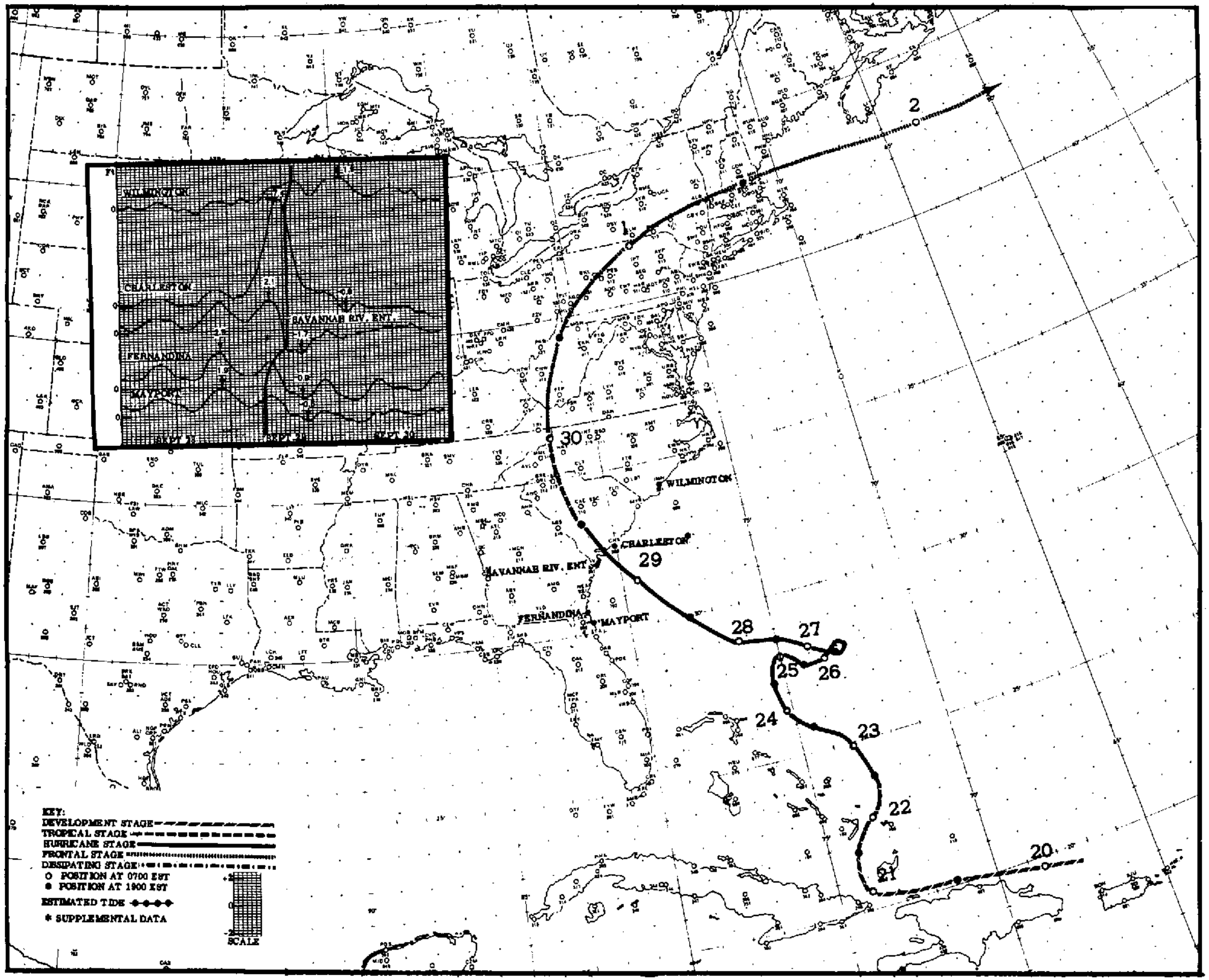

FIGURE 25.2.—Hurricane Gracie 1959, September 28–30. Storm surge chart.

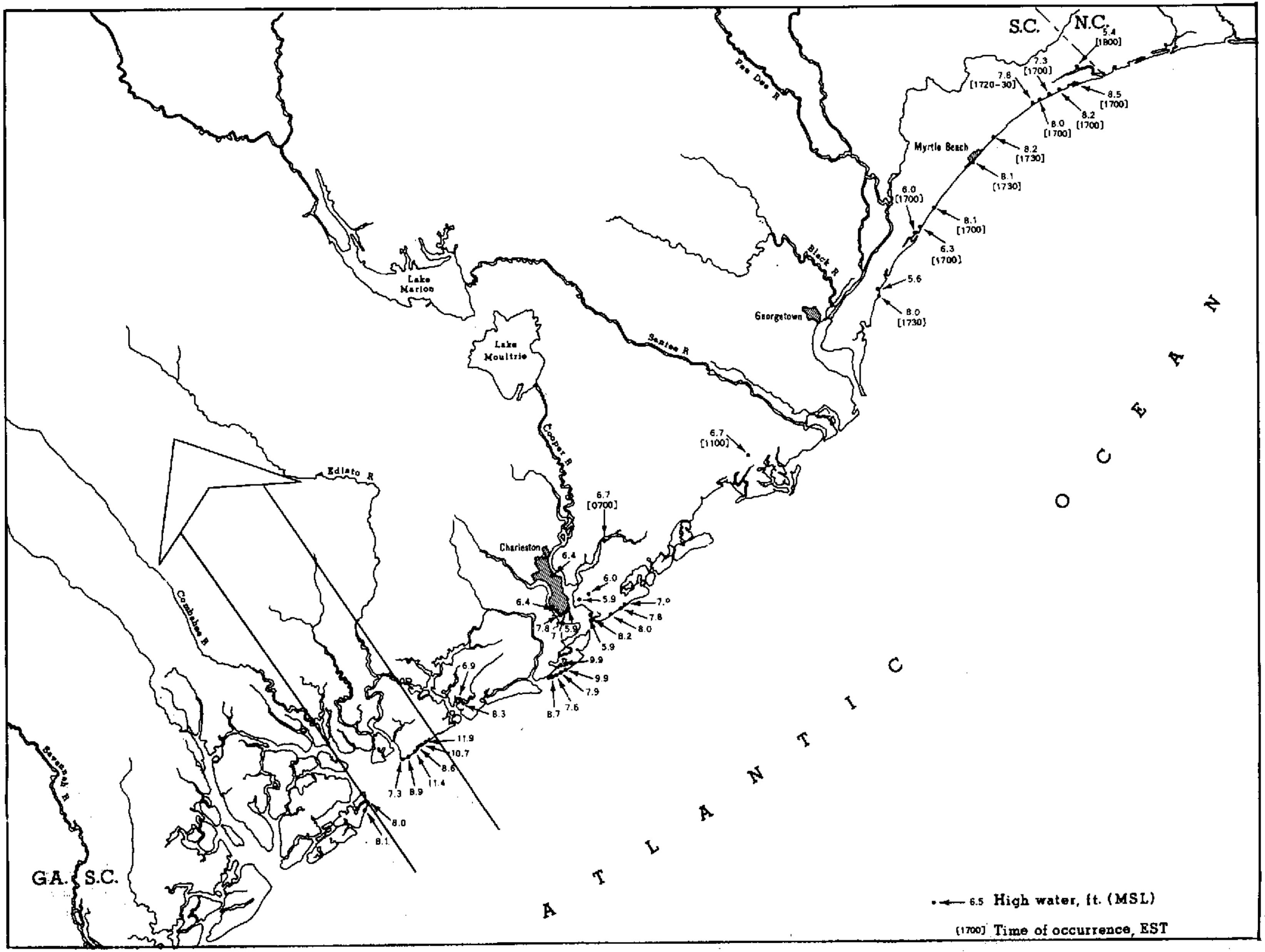

FIGURE 25.3.—Hurricane Gracie 1959, September 28–30. High water mark chart for South Carolina.

able for many of the high water marks in North Carolina but tide prediction constants are not available for many of the same locations. Fortunately, the tides are negligible in the sounds from which most of these data come and time of the maximum water level may be accepted as the time of the peak surge. The approximate width of the storm eye and the location of the center for 3-hour intervals are shown on this chart also. On the open coast the peak water level occurred shortly before the arrival of the storm center, that is, when the local winds were from the east to northeast. This is also true for the western portion of the estuaries. On the lagoon side of the barrier islands the peaks generally occurred after the passage of the storms while the winds were westerly. This suggests that most of the flooding along the shores of the sounds was due to movement of the water already in the sounds or added by rainfall with little additional contribution from the ocean. This view is supported by the observation that most of the peak water levels reported for the islands are lower than the crests of the islands. Additional data, not reproduced here, collected by the Wilmington District Office of the Corps of Engineers show this clearly. The storm passed this area during a period of rising tide, with the normal tide just a little above low water in the southern part of the region and near the normal high in the north.

The density of the high water marks recovered in Florida, shown in figure 26.6, is unprecedented in this region. The first survey crew entered the areas affected only a day or two after the storm to locate and identify as many high water marks as possible. Sometime later these were all connected by level lines to establish bench marks to obtain reliable estimates of the peak height of the storm high water. The great variability in the high water elevations shows the influence of small-scale dynamic processes in determining the maximum water level during a hurricane. This leads one to wonder about the representativeness of the rather small number of peak water marks shown in the same areas for many earlier storms. Several processes can be proposed to account for this pattern of high water marks but the present state of the theory and the available data do not permit a unique determination of any of them.

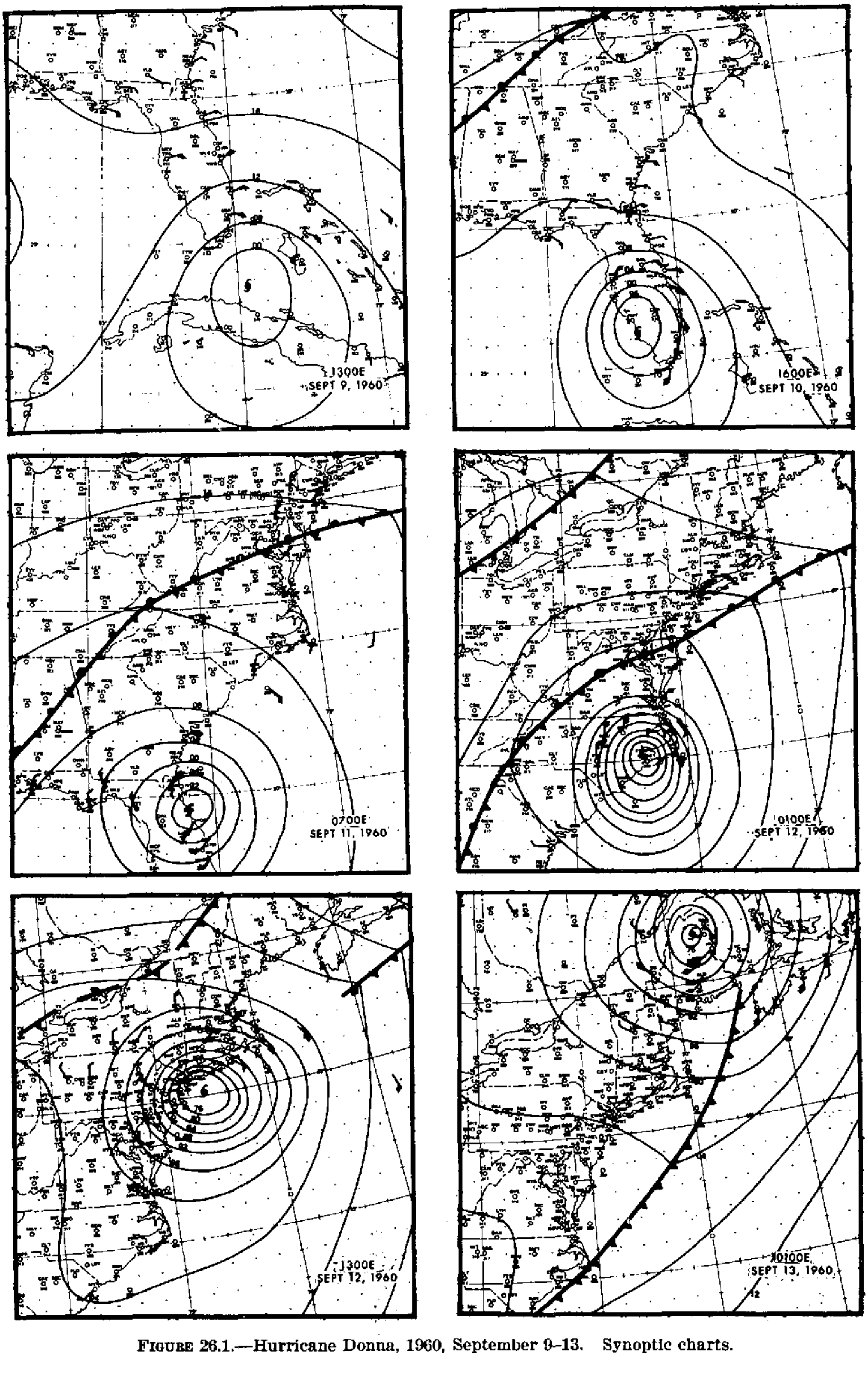

FIGURE 26.1.—Hurricane Donna, 1960, September 9–13. Synoptic charts.

STORM NO. 25.—HURRICANE GRACIE 1959, SEPTEMBER 28–30

The meteorological data for this storm have been discussed by Cry [9] and Dunn and staff [25]. The high water marks published by Harris [39] are repeated with a few corrections obtained after publication of the earlier note. Most of these high water mark data were furnished by the Charleston District of the U.S. Army Corps of Engineers.

The peak surge produced by this storm along the coast and in Charleston Harbor coincided approximately with the low astronomical tide. The storm surge graphs for this hurricane contain oscillations of approximate tidal periodicity. One would suspect that they result from some interaction between the storm effects and the astronomical tides, except for the fact that similar oscillations occur in the residual several times each year during periods of fine weather.

The local variability in high water marks reported for other hurricanes is in evidence here (fig. 25.3) but is not as pronounced as in many other regions.

The hurricane produced extensive coastal flooding in Florida, North Carolina, New York, and southern New England. An historical account of the storm is given by Dunn [22]. Various features of the storm have been discussed by many writers and it is certain that there are many more to come; however the writer of this report is unacquainted with any published papers which give more information pertinent to the storm surge problem than this brief note and the following figures.

The surge pattern along the Atlantic Coast from Cape May northward is similar in many respects to that generated by the storms of September 21–22, 1938, September 13–15, 1944, and Carol, August 30–31, 1954. Most of the features discussed with any of these storms are presented here in only slightly modified form. However, some of them can be better documented. The surge records for the Chesapeake Bay region were very similar for the storms of September 17–19, 1936, September 13–15, 1944, and August 13–15, 1953. The discussion given for the Chesapeake Bay region in connection with these storms applies to this one as well. The records for the west coast of Florida are very similar to those obtained in the storms of September 17–21, 1926 and September 15–20, 1945. Somewhat less pronounced similarities to other storms can be found in many of the records for other regions.

The data for New York and southern New England permit a more detailed analysis of the maximum surge and of the maximum water level than could be made for any earlier storms. This analysis is presented in figure 26.3 The travel of the maximum water level and of the peak surge up New York Harbor can be easily traced. The movement of the surge crest up through the Harbor was a little faster than that of the normal tide crest. This is consistent with the theoretical deduction that the wave speed should be greatest where the total depth is greatest. The progress of both tide and surge through Long Island Sound is even clearer than that through New York Harbor. At Willets Point near the western end of Long Island Sound, the surge from the south was slightly larger than that from the east, but the highest water levels were associated with the surge from the east. This is in contrast to the records for the other similar storms in this area in which both the maximum surge and the maximum water levels were associated with the surge which came from the east. However, the amplitudes of the two surges were nearly equal. It appears from this figure that the maximum surge at Lawrence Point came from the east in spite of the fact that Lawrence Point is nearer to New York Harbor than Willets Point. This discrepancy is believed to result from the inadequacy of the tide prediction for Lawrence Point. The structure of the normal tide is quite complicated in this region and the constants necessary for a fundamental prediction for Lawrence Point were not available. The uncertaintly of the predictions based on an analysis of the data for another location is greater than the difference between the two surges recorded for Willets Point. This storm and the three mentioned above as being similar to Donna in this area passed over Long Island. In New York City the peak surges, as well as the highest water occurred near the time of the normal high tide for the day. In southern New England they occurred slightly after the time of the normal high tide for the day, but while the normal tide was still above mean sea level. The one exception of note is Willets Point where the peak surge from the south coincided with the low tide for the day and the peak surge from the east coincided with the high tide.

A few additional high water marks collected in this region, for which the storm surge could not be computed, are shown in figure 26.4. In several cases high water marks were obtained from buildings on the beach near the tide gage location. In every case the second mark was higher than the tide gage reading, giving additional evidence of the tendency for breaking waves to produce higher high water levels on normally dry land than in the deeper water near the tide gage location.

High water mark data obtained from North of the islands. Additional data, not reproduced Carolina and coastal Virginia are presented in figure 26.5. The time of occurrence is also avail-

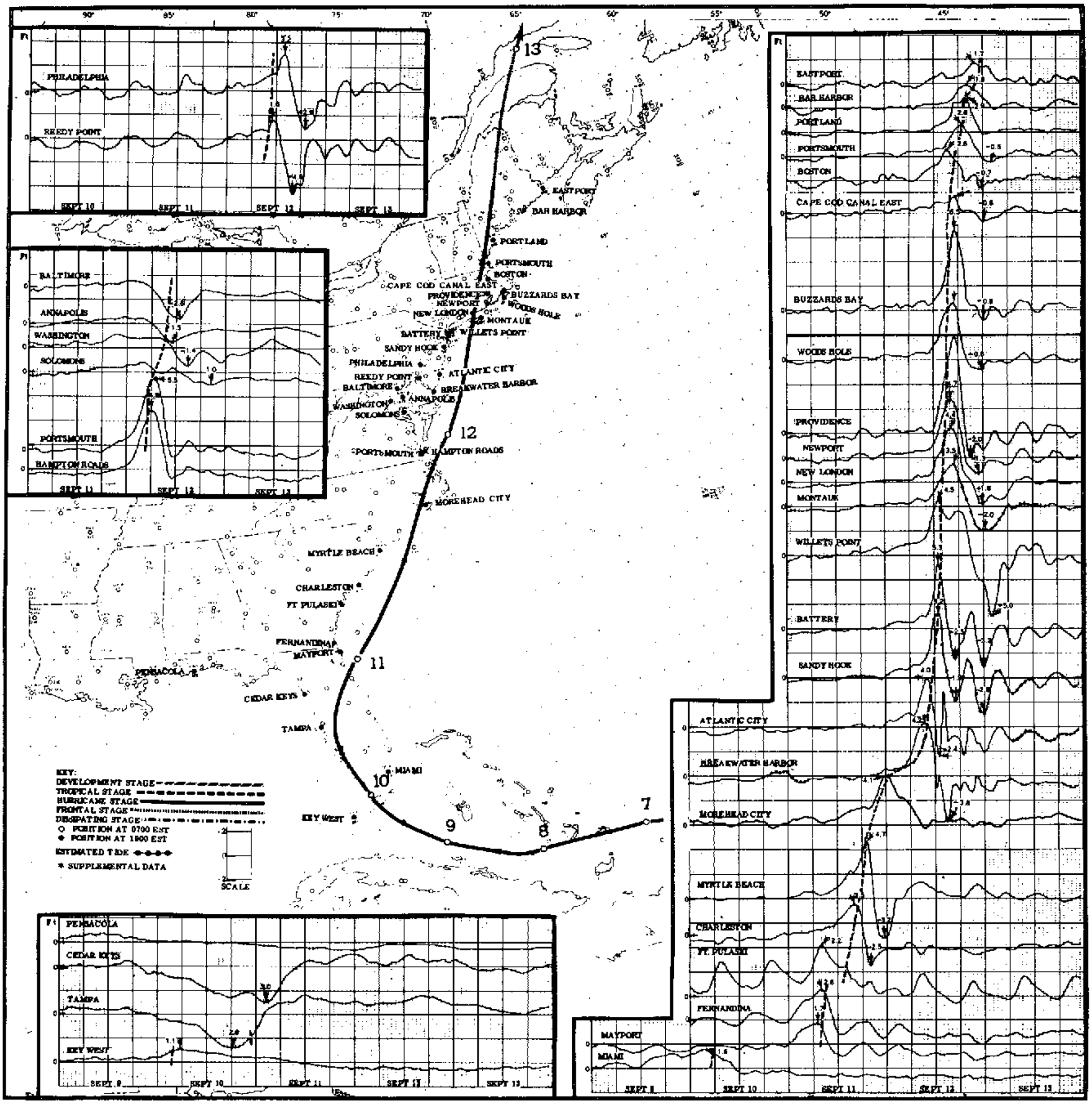

FIGURE 26.2.—Hurricane Donna 1960, September 9–13. Storm surge chart.

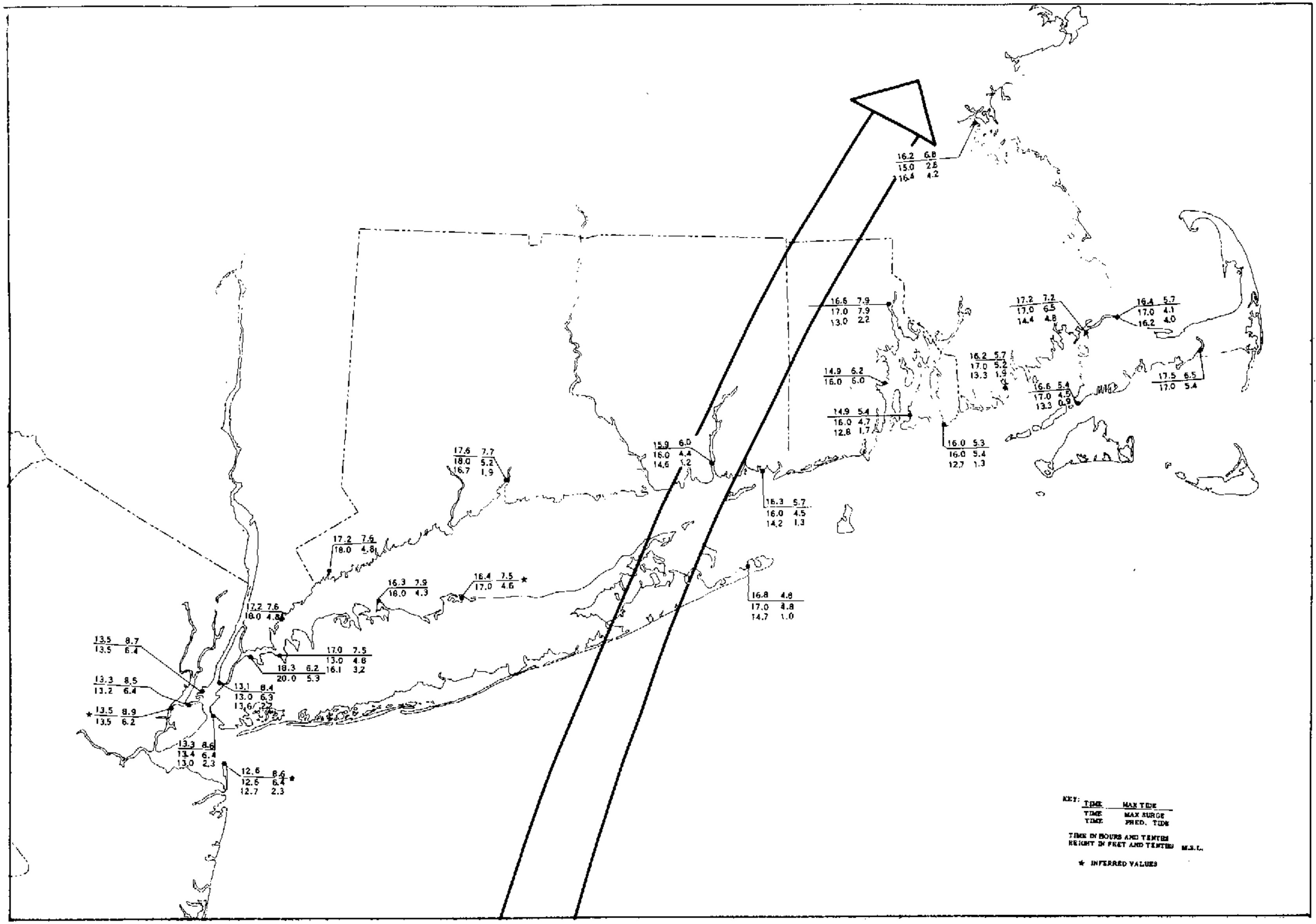

FIGURE 26.3.—Hurricane Donna 1960, September 9–13. High water levels, peak surges, and high tides in New York and southern New England. The two values indicated as inferred are based on high water marks obtained near the gage house when the gages failed for a short period near the time of high water.

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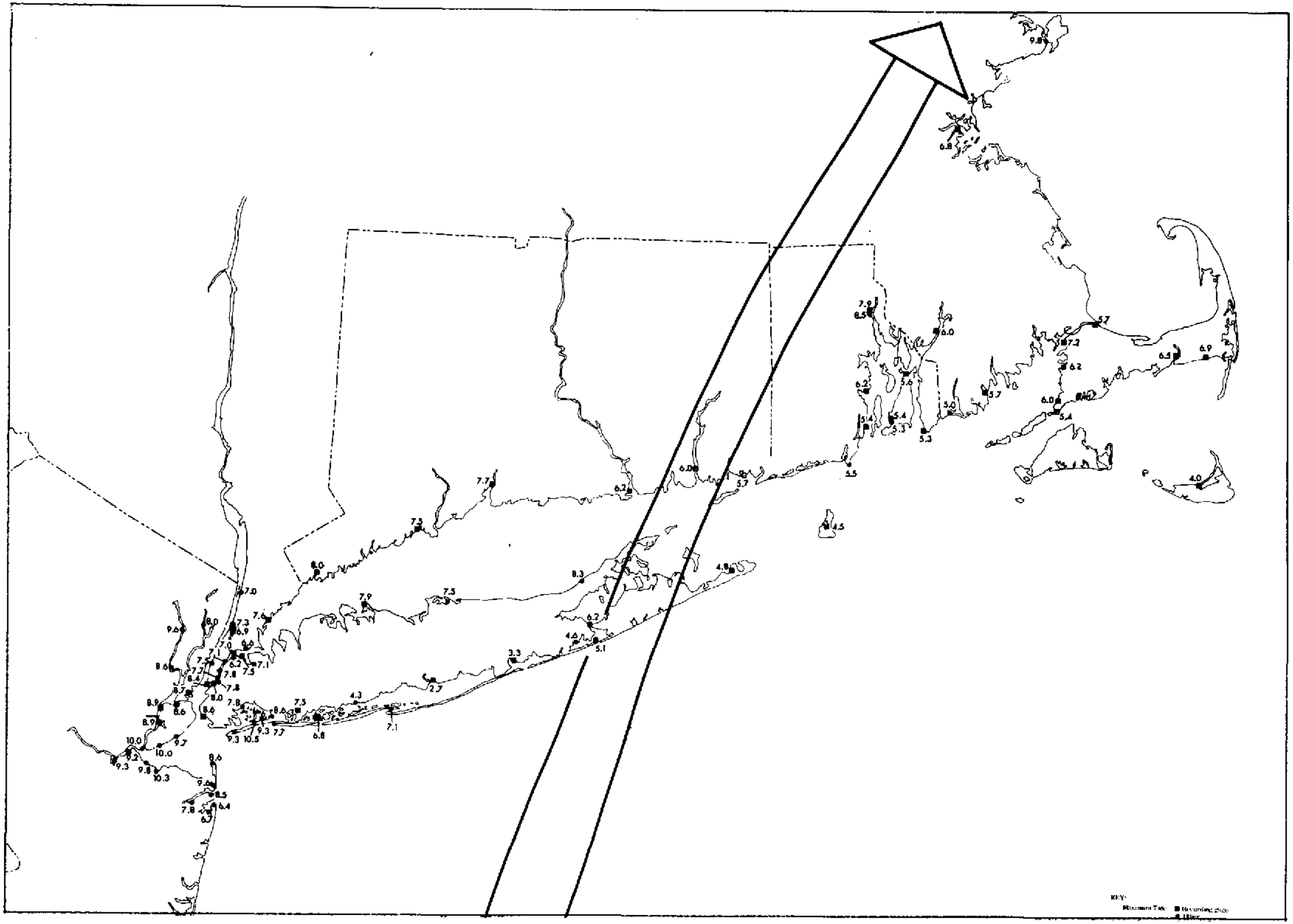

FIGURE 26.4.—Hurricane Donna 1960, September 9–13. High water mark chart for New York and New England. (Based on data obtained from the New England Division and New York District of the U.S. Army Corps of Engineers.)

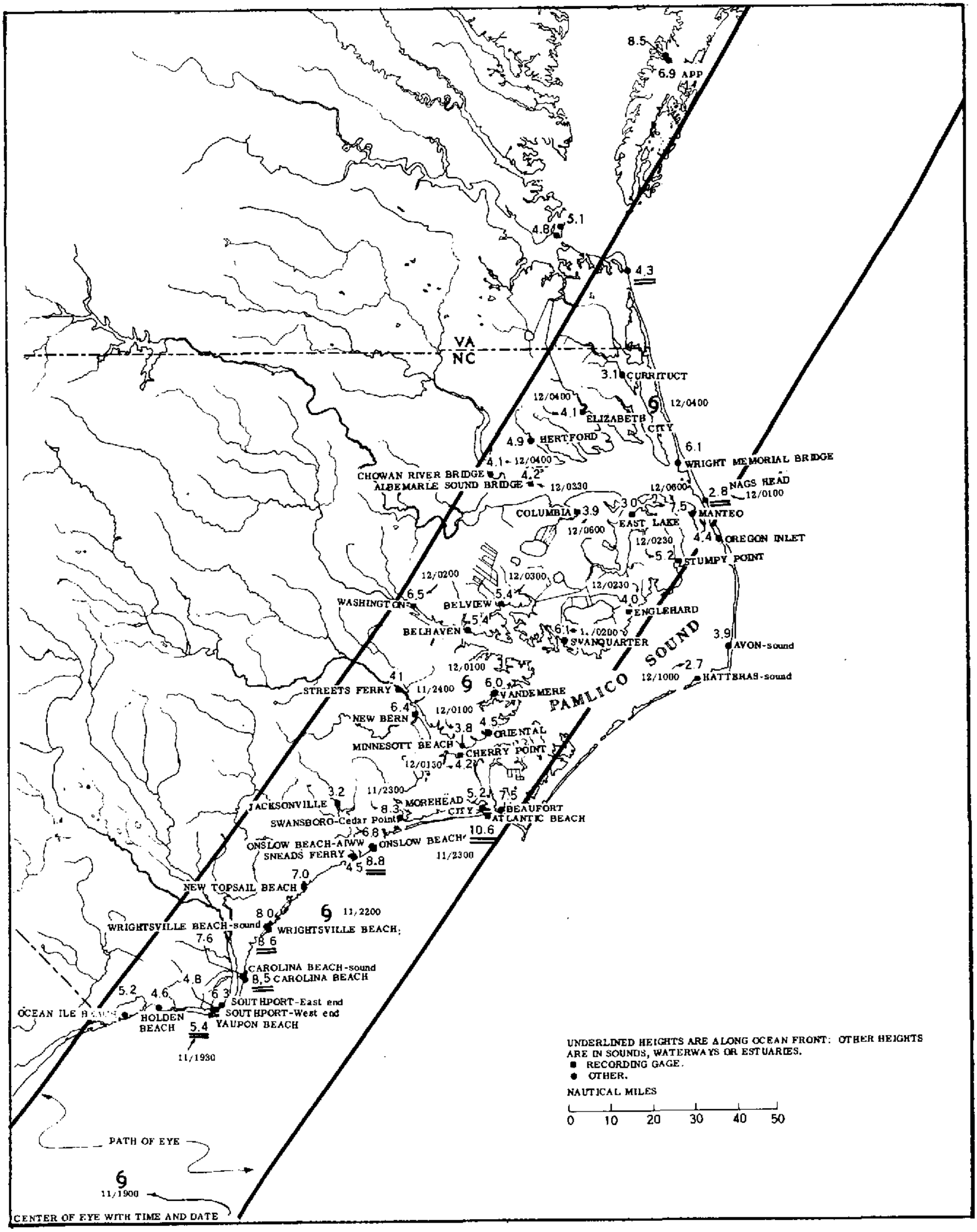

FIGURE 26.5.—Hurricane Donna 1960, September 9–13. High water mark chart for North Carolina and Virginia. (Based on data obtained from the Norfolk and Wilmington Districts of the U.S. Army Corps of Engineers.)

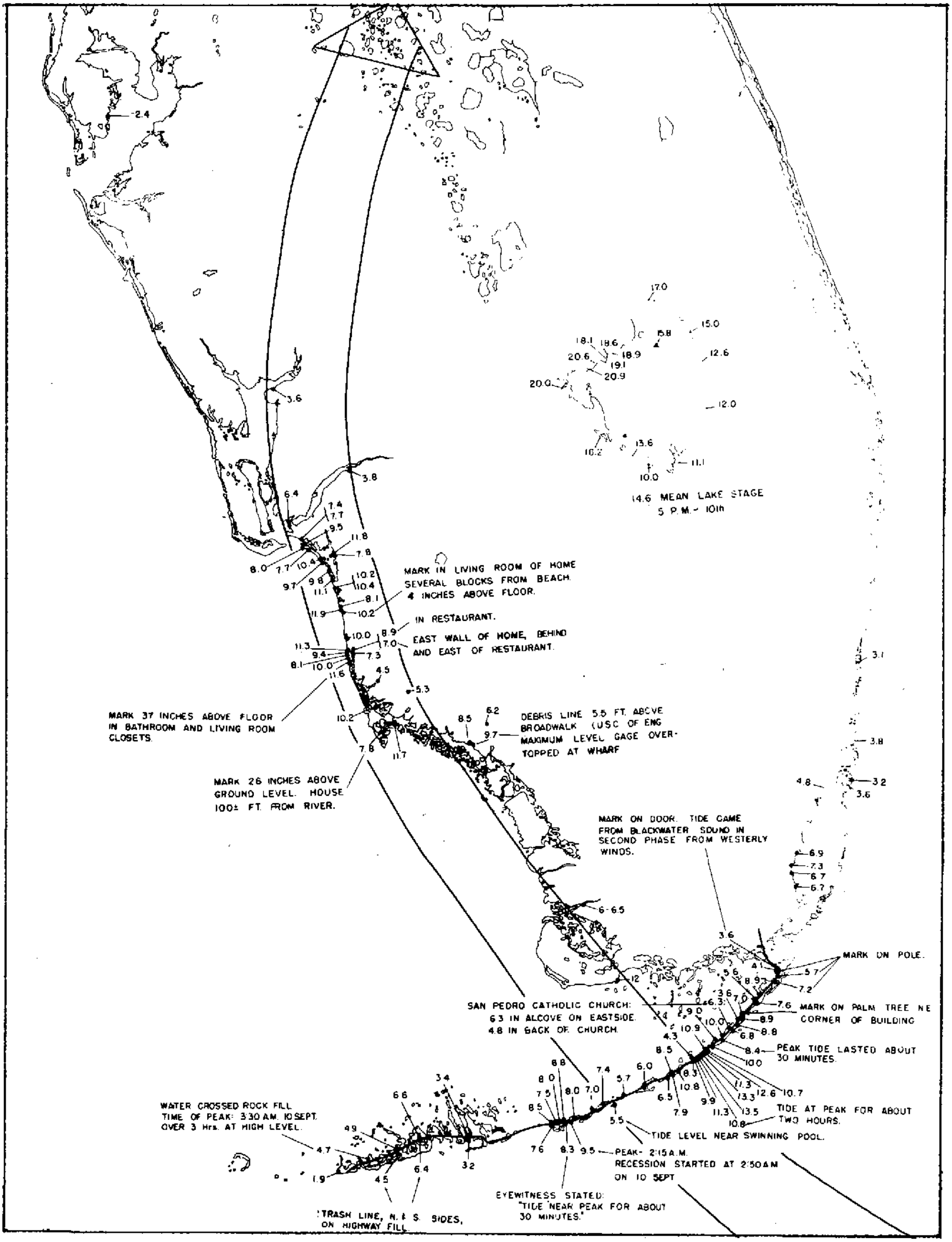

Figure 26.6—Hurricane Donna 1960, September 9–13. High water mark chart for Florida. (Based on data obtained from the Jacksonville District of the U.S. Army Corps of Engineers.)

The coastal flooding produced by this storm in Texas is the best documented and appears to have been the most extensive on record. The storm motion was unusually slow for so large a storm and the water levels remained within a foot or so of their peak values for nearly 24 hours.

Historical accounts of this storm and some preliminary storm surge data have been published by Cooperman and Sumner [8], Cry[10], and Dunn and Staff [26]. Detailed analysis of several aspects of this storm are now underway or planned for the near future, but the author is unaware of any completed investigation which has much bearing on the storm surge problem.

Because of the slow movement of this storm, it has been found desirable to include two pages of synoptic charts. The observed tide records for many locations in Texas and the expected astronomical tide for Galveston are included with the storm surge chart. The extent of flooding and many supplementary high water marks as obtained from the Galveston District of the U.S. Army Corps of Engineers are shown in figure 27.3. Supplementary high water mark data, as obtained from the New Orleans District of the U.S. Army Corps of Engineers are presented in figure 27.4. Continuous tide records for many locations in Louisiana were also examined but these give little additional insight not provided by the other data and are not published here.

The water level records for southern Louisiana are all rather flat. The storm effects were clearly evident as early as the afternoon of September 8 and continued through September 12 at most stations. East of the Mississippi River the effect was greatest on the afternoon of the 10th and appears to be associated with set-up in the sounds leading to Lake Pontchartrain. West of the delta the effect was greatest on the 9th when the wind was nearly parallel to the shore.

The storm surge along the entire Texas coast began to develop at a time when the winds were parallel to the coast for a distance of at least 100 miles from the coast and reached a peak when the winds at the coast were from the north and actually had a slight offshore component. This same phenomenon was pointed out in connection with the storms of July 25, 1934 and August 29–30, 1942 and hurricane Audrey, June 26–27, 1957. The data available for the other storms permit two possible explanations for this phenomenon. The high tides observed on the north side of Galveston could have been produced by a set-up within the Bay due to the northerly winds, or could be due to the dynamic effects of the earth's rotation and the current generated by the component of the wind parallel to the shore. The high correlation between the record at Pleasure Pier on the open Gulf and the other gages in the southern part of Galveston Bay show clearly that the disturbance in the open Gulf was dominant. The absence of any time history of the water level in the northern or northeastern parts of Galveston Bay prevents a satisfactory evaluation of the possible set-up within the Bay.

The pattern of high water marks near Port Lavaca, in figure 27.3, suggests that the maximum water level near the open coast was about 12 ft. above mean sea level. At this water level most of the barrier islands would have been under water and the ridges which are normally the highest parts of the islands would have acted as offshore bars. Waves breaking over these bars would add to the accumulation of water within the Bay. This and additional wind set-up over the Bay may account for the higher water levels on the landward side of the Bay. The peak value of 22.0 ft. at Port Lavaca may represent an additional increment due to the convergence of wind-driven water in a narrow part of the Bay.

Here, as always, it is important to remember that one can present only hypotheses. Neither the data nor the theory is sufficiently advanced to establish dependable explanations.

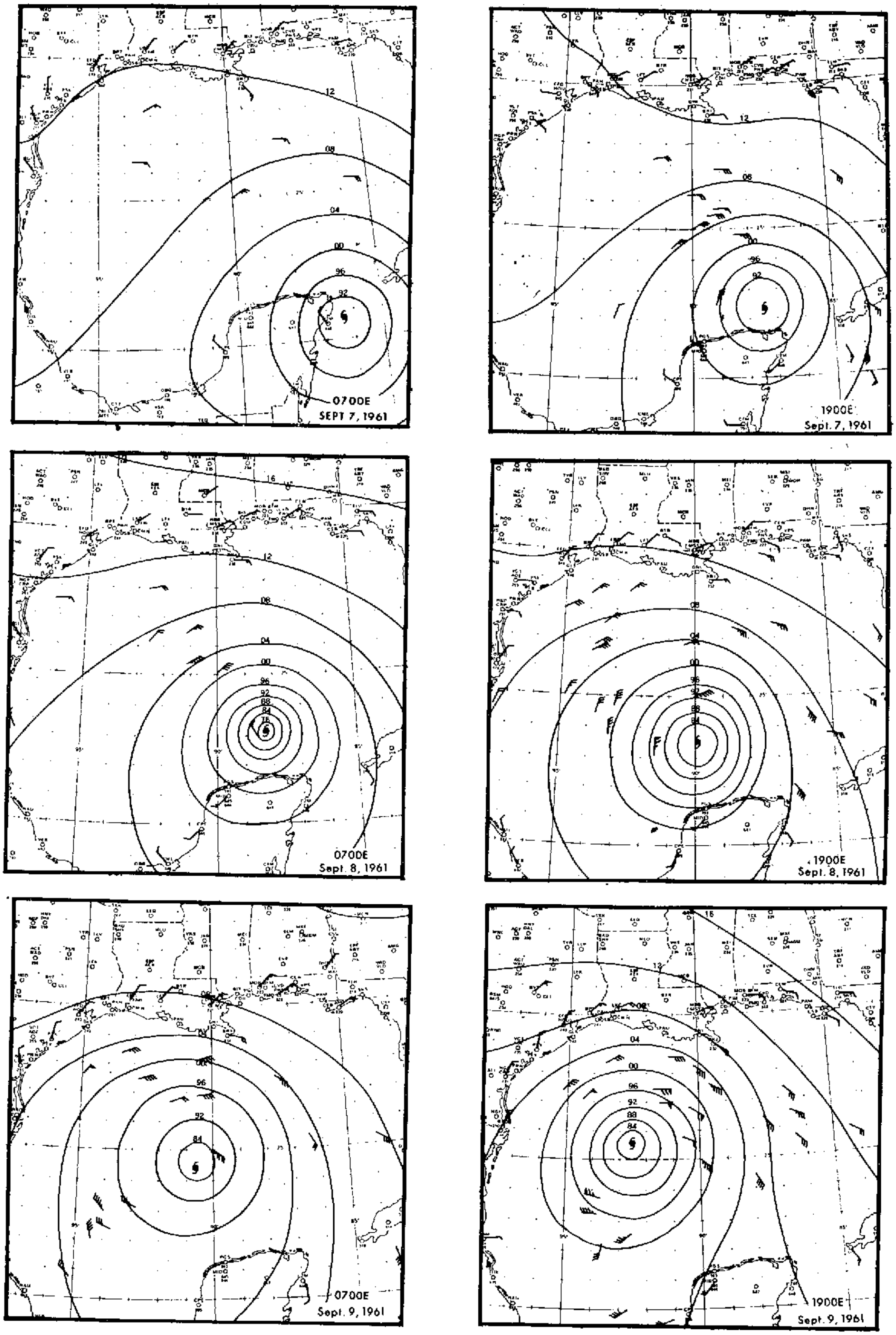

FIGURE 27.1a.—Hurricane Carla 1961, September 7–12. Synoptic charts, September 7–9.

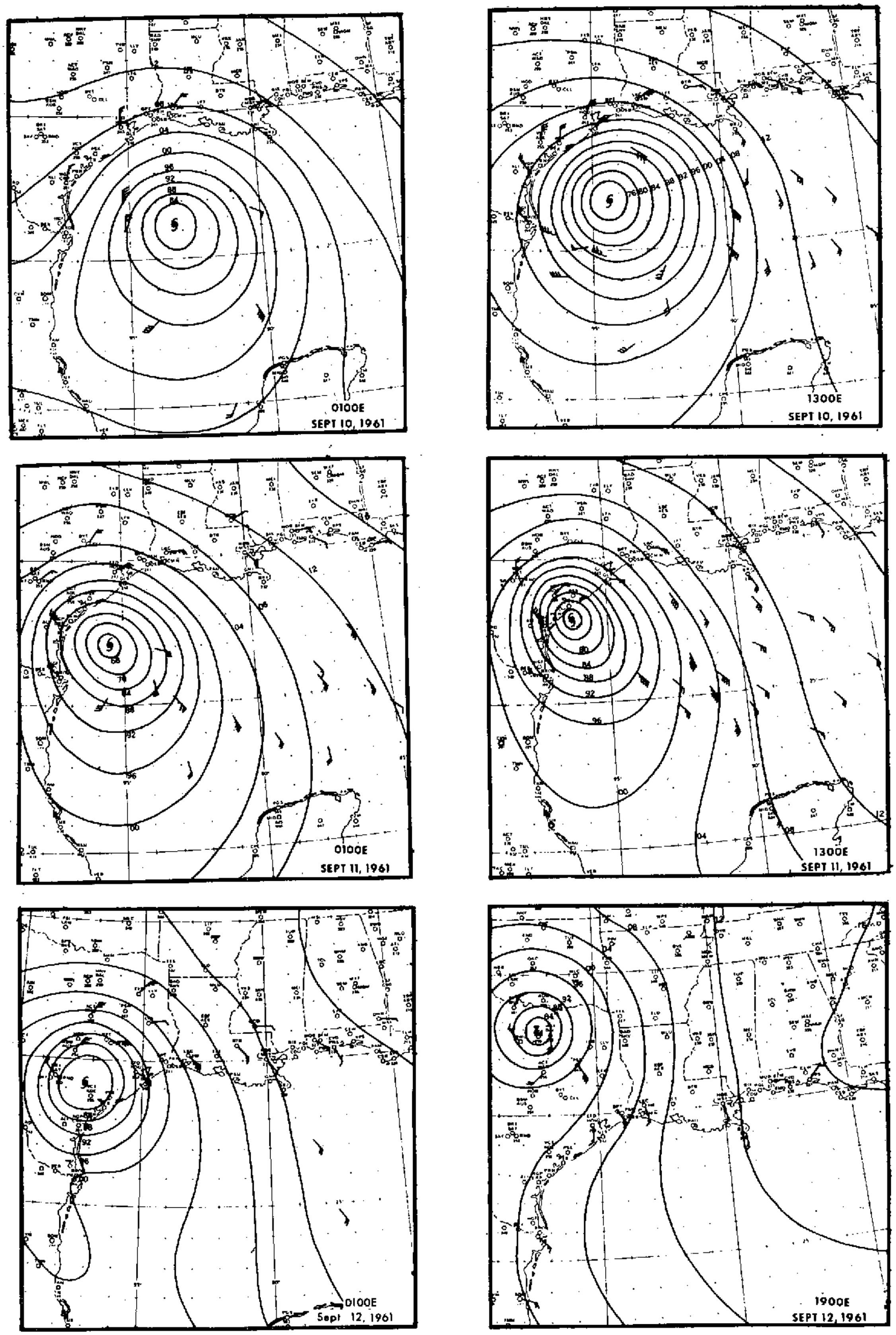

FIGURE 27.1b.—Hurricane Carla 1961, September 7–12. Synoptic charts, September 10–12.

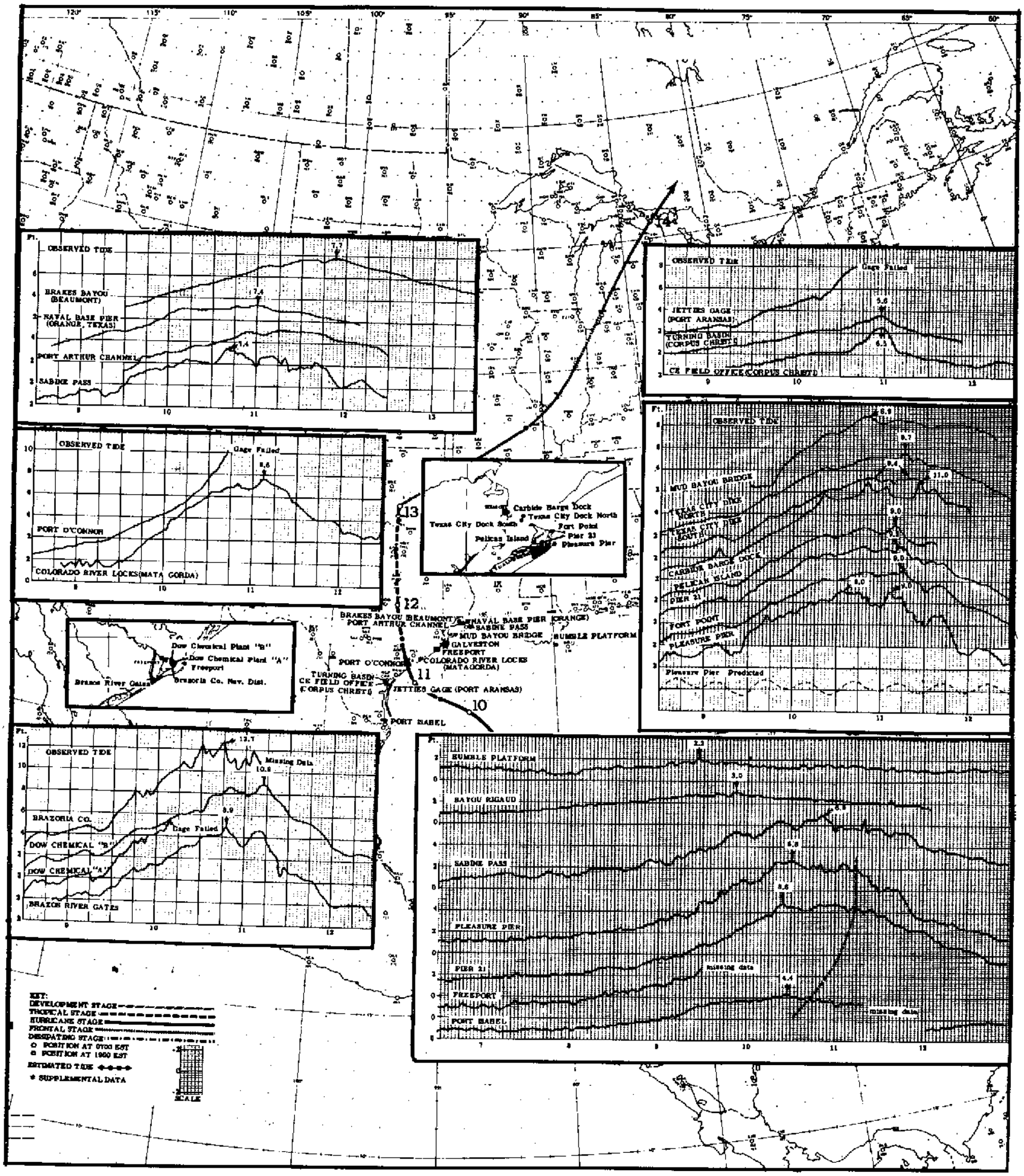

FIGURE 27.2.—Hurricane Carla 1961, September 7–12. Storm surge and observed tide chart. Insert maps for Freeport and Galveston, Tex., areas.

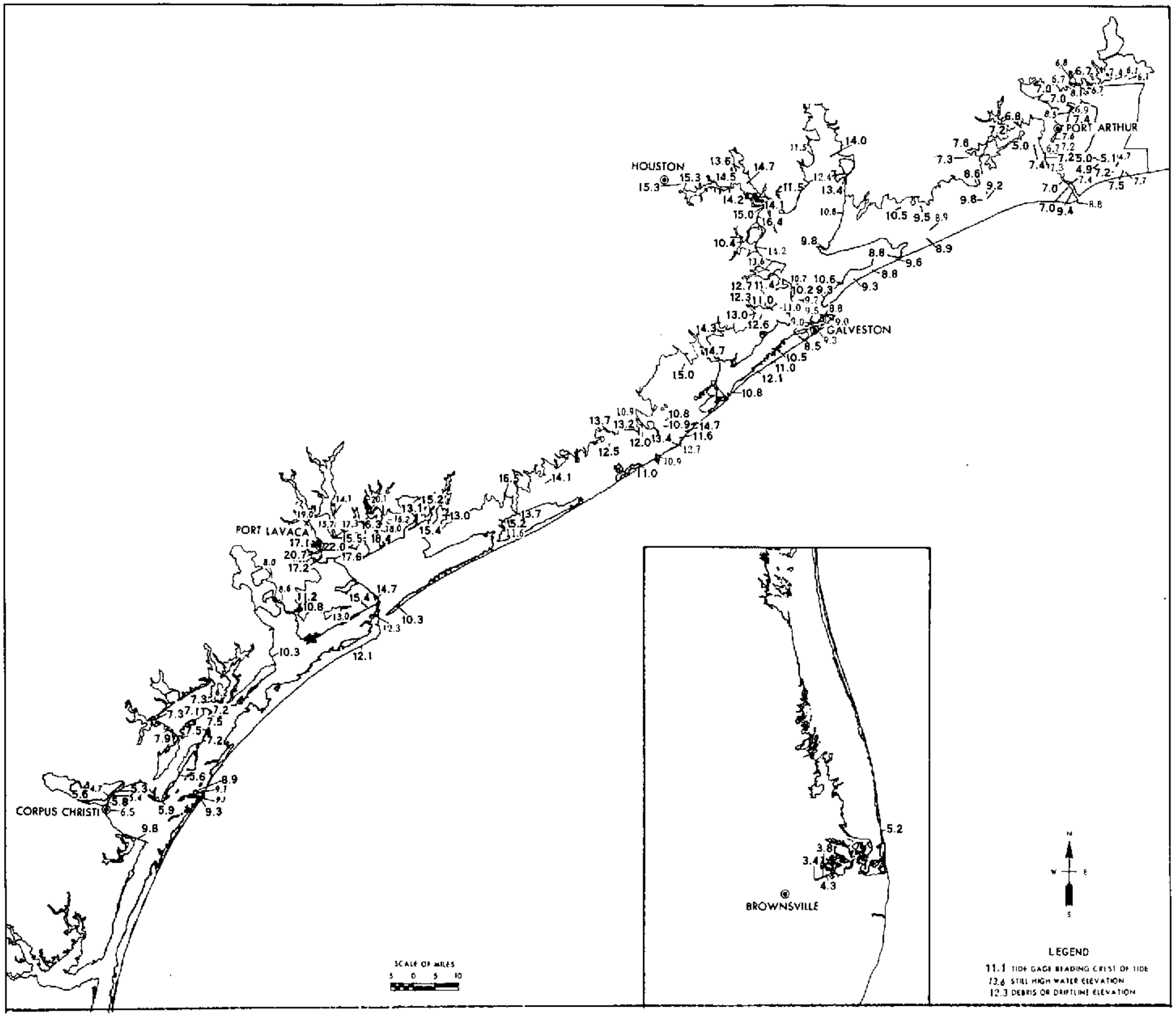

FIGURE 27.3.—Hurricane Carla 1961, September 7–12. High water mark chart for Texas. Shaded area indicates the extent of flooding. (Based on data obtained from the Galveston District of the U.S. Army Corps of Engineers.)

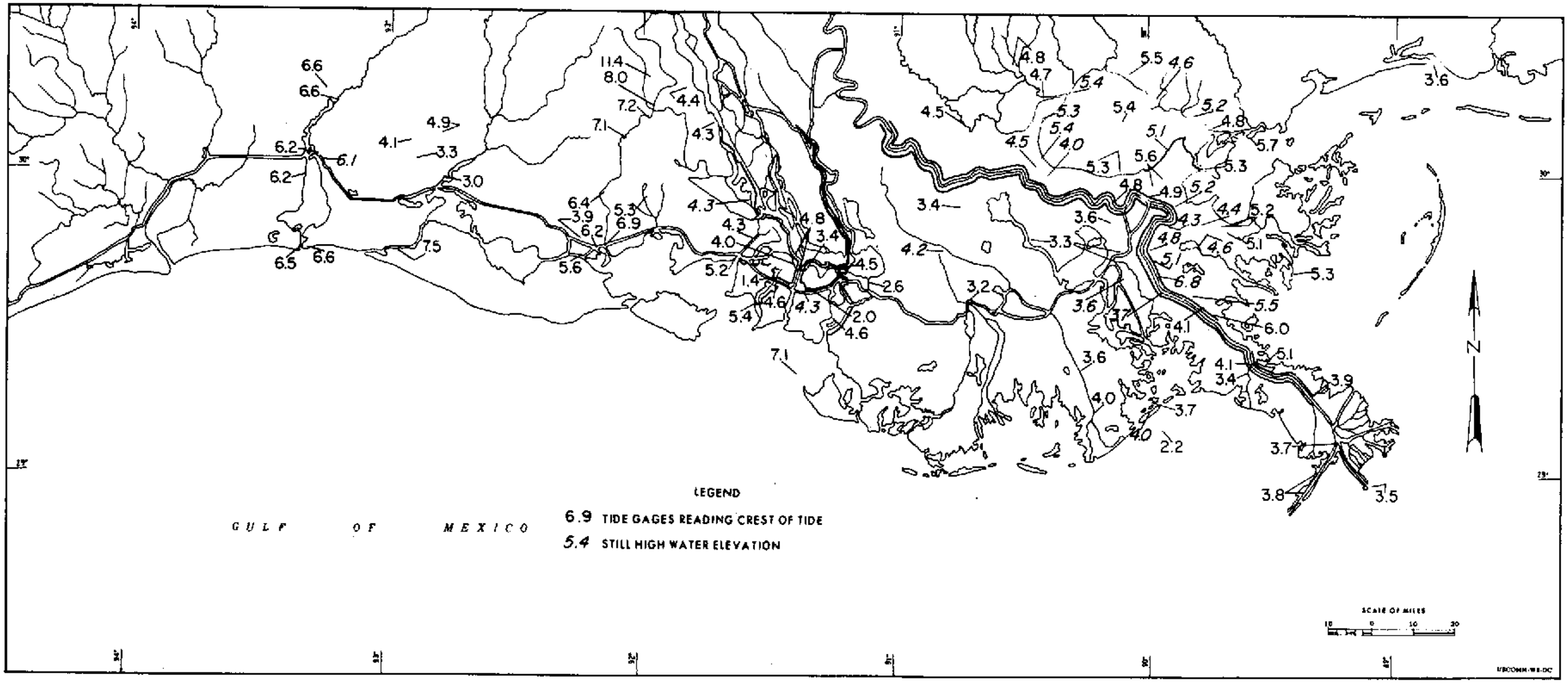

Figure 27.4.—Hurricane Carla 1961, September 7–12. High water mark chart for southern Louisiana. (Based on data obtained from the New Orleans District of the U.S. Army Corps of Engineers.)

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