CHAPTER 5

THE HURRICANE SURGE

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ABSTRACT

The landfall of a hurricane is generally accompanied by an increase in the tide level by four to fifteen feet above the normal value for the time and place at which the storm crosses the shoreline. This difference between the observed tide and that predicted from astronomical considerations is called the storm surge. The hydrodynamic theory of these disturbances has not been worked out in sufficient detail to permit a satisfactory theoretical approach to the storm surge prediction problem. Hence, the best guide to the probable behavior of future hurricane surges is believed to be the study of the effects of past hurricanes on sea leve

A gradual rise in tide level above predicted values may begin more than 24 hours before the storm makes its nearest approach to the station. Occasionally, the tide falls below normal for many hours during the approach of the storm. A rapid rise generally begins about the time gale winds associated with the hurricane are first experienced. The peak surge at any location along the shore usually occurs within an hour or tw after the nearest approach of the storm to the station. The maximum surg generally occurs somewhat to the right of the storm track, and the zone o extremely high water usually extends further to the right than to the lef of the storm track. The fall in water level after the storm is more rapi than the rise in areas with good drainage, but in marshland a week or mor may be required for the water level to return to normal.

The maximum height of the storm surge along the open coast is clearl a function of the storm intensity, but this factor alone is not sufficien to explain more than half of the observed variance in the reported peak storm tides. Topographic effects, such as the funneling of water in converging bays can alter the amplitude of the surge by a factor of two in a distance of only a few miles. This fact, together with the tendency of severe hurricanes to destroy the tide gages near their centers, and the difficulty of eliminating the effects of surface wind waves in interpreti high water marks, make it difficult to determine exactly the nature of pa storm surges.

THE HURRICANE SURGE

1. INTRODUCTION

The approach of a hurricane to the shore is accompanied by an increase in the tide level above the normal value. For storms which barely qualify as hurricanes, or which do not cross the coast, this increase may be no more than four feet. For the more intense hurricanes the tides may rise more than fifteen feet above normal.

The effects of storms and normal tides on sea level are almost independent along the open coast. Thus, it is convenient to consider these two effects separately. The storm surge is defined as the difference between the actual tide as influenced by a meteorological disturbance and the tide which would have occurred in the absence of the meteorological disturbance. The term storm tide is used to describe the observed tide at a time when this is significantly affected by meteorological factors.

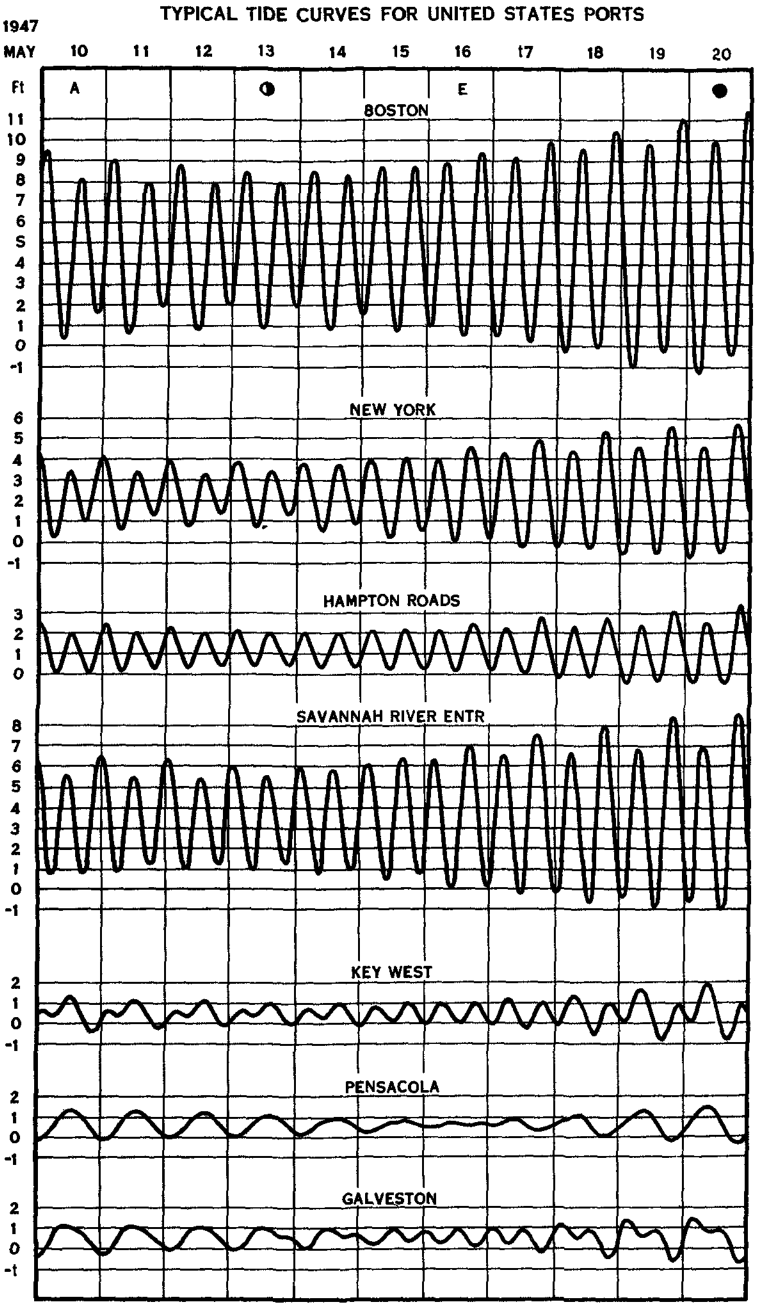
The practical importance of a given storm surge will depend on the stage of the normal tide at the time of the storm tide and on the elevation of the land in the region of the storm. Waves and swell, with periods of only a few seconds, add greatly to the damages caused by flooding in regions that are inundated by storm tides. The effects of these short-period waves also interfere with the collection of data on the actual tide elevations during a storm and considerably handicap all studies of actual storm tides. Thus, it is necessary to consider the normal tides, the short-period waves, and the elevation of the land near the coast in any discussion of the practical importance of storm surges.

2. THE NORMAL TIDE

Before entering into a discussion of the tide abnormalities caused by hurricanes, it is worthwhile to describe the major features of the normal behavior of the tide.

The normal tide is a regular quasi-periodic rise and fall of the level of the sea having periods of approximately 12.5 and 25 hours. The principle cause of the tide is the difference between the gravitational attraction of the sun and moon for the waters of the earth and for the solid earth. Meteorological factors such as land and sea breezes, the annual cycle of atmospheric pressure and wind systems also play a role in the normal tide. Tidal theory can describe completely the nature of the astronomical forces producing the tide. Theory cannot predict the manner in which the sea will respond to these forces. Practical tide predictions are based on an analysis of observed water level variations in the region for which the tide predictions are desired. Consequently, the published predictions of the normal tide include climatic as well as astronomical effects on sea level.

The amplitude of the diurnal and semidiurnal oscillations of sea level and the interval between successive high and low waters vary with the phase and declination of the moon, and the distance between the moon, the sun, and the earth in such a way that it is not satisfactory to think of the tide



Lunar data max S declination, 9th, apogee, 10th, last quarter, 13th, on equator, 16th, new moon, 20th, perigee, 22d, max N declination, 23d

Fig. 1. Typical tide curves for United States ports., (from U.S.C. & G.S. Tide Tables East Coast).

as a regular periodic oscillation having some mean range. Figure 1, taken from the Coast and Geodetic Survey Tide Tables, shows a number of typical tide curves. In general, the tide range is greatest at about the time of full moon and new moon and least at the time of first and third quarters, and greater at perigee when the moon is nearest the earth than at apogee when the moon is at its greatest distance from the earth. In the Gulf of Mexico the greatest range occurs when the moon is near maximum declination and the least range occurs as the moon crosses the equator.

In the United States, and in most other countries, tide predictions are usually made by using an analog computer to sum the series:

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

where: h is the predicted sea level at any time.

$\bar{h}$ is the height of mean sea level above the datum plane. The datum plane used along the Atlantic and Gulf coasts of the United States is mean low water.

B_n is the amplitude of the n'th constituent of the tide. (Determined from observations and modified by theory).

A_n is the speed of the n'th constituent of the tide, usually expressed as degrees per hour. (Determined from theory).

D_n is the phase displacement or epoch of the n'th constituent as of 0000 January 1 of the year of the predictions. (Determined in part from theory and in part from observations).

M is the total number of constituents considered.

t is the time, usually expressed in hours since 0000 January 1.

Equation (1) is designed for the computation of the effect of astronomical forces in causing the sea level to rise above or fall below its long term mean value. Local mean sea level varies from year to year because of changes in the proportion of onshore and offshore winds, (DeVeaux - 1955), and perhaps also because of crustal movements of the earth, the melting and reformation of glaciers, the average temperature of the water, and a host of other causes. If an adjustment is made to the constant term, $\bar{h}$ so that it equals the observed mean sea level for the year of predictions, the predictions will usually agree with observations within about 0.2 ft. at the times of high and low tide. Equally good agreement will be found at any phase of the tidal cycle at most stations along the open-coast. At inland stations, the agreement will not be as good near mid-tide as at the time of high and low tide.

Hurricane Surge

The 1958 Tide Tables, East Coast North and South America, contains daily predictions of high and low water for 28 locations along the Atlanti and Gulf coasts of the United States. A satisfactory estimate of the astr nomical tide at any time for many of the tide stations near the open coast can be obtained by fitting a sine curve to the published predictions of hi and low water as described in Table 3 of the Tide Tables. This procedure is often unsatisfactory in rivers, canals, and long bays such as Long Isla Sound. In such regions the tide curve may depart markedly from a sine cur A direct summation of equation (1) will improve the predictions in such cases, but even this will not always be satisfactory.

Most users of the tide tables are primarily interested in the time an height of the tide at high and low waters. An approximation to this data, valid for almost all purposes, can be determined for several hundred additional locations by using the table of differences published in the Ti Tables. It must be remembered, however, that these differences are average and that some of them are based on much less than the optimum amount of da Consequently, the approximate prediction of high and low water elevations obtained in this manner may sometimes differ from the true astronomical ti by several tenths of a foot, and the time may differ by as much as an hour This difference in the time of high and low water may lead to a difference of one or two feet in the estimated height of the tide at some specified time between high and low water.

3. THE STORM SURGE

The high winds and low pressures associated with hurricanes usually lead to significant anomalies in the tide. A gradual rise in the tide level often begins more than 24 hours before the storm makes its nearest approach to the station. Occasionally, the tide falls below normal for many hours during the approach of the storm. A rapid rise generally begir about the time gale winds associated with the hurricane are first experienced. The peak storm surge usually occurs within an hour or two after tl storm makes its nearest approach to the station. In areas with good drair age conditions, the fall in the tide level is generally more rapid than tl rise and the tide often drops below normal for a few hours after the storr passes. In marshlands and other areas with poor drainage, many days may l required for the water levels to return to normal. The first storm surg peak is sometimes followed by a series of resurgences. The second storm surge peak, occurring several hours after the storm has passed, may be as high as the first. If the first storm peak occurs near the time of norma low water, and the second coincides approximately with normal high water, this second peak will be the more important (Redfield and Miller - 1955, Munk - 1955). Fortunately, the resurgences are not prominent in the regi of hurricane landfall but they may be important along the east coast of United States for storms moving approximately parallel to the coast.

The storm surge moves through long bays, such as Long Island Sound, as a progressive wave. Consequently, the peak surge at the head of the b may occur many hours after the peak storm conditions(Harris, 1957a). The storm surge as a function of time at the tide station nearest the point of landfall is shown for four hurricanes in Figure 2, taken from Harris (1957b).

Analogues showing the effects of past storms are essential to an understanding of the hurricane surge. Several papers of this type have been published within the past few years.

Cline (1920 and 1926) gives a record of the observed tide at one or more stations and the highest observed tide or storm surge at a number of points for many Gulf of Mexico hurricanes. Redfield and Miller (1955) give similar data for several Atlantic Coast storms. Hubert and Clark (1955) give data on the peak storm tides or peak storm surges associated with 16 Atlantic and Gulf hurricanes, including most of the data previously published by Cline. Zetler (1957) has given an exhaustive tabulation of the peak storm surge recorded by the Coast and Geodetic Survey tide gage in Charleston,S.C., during a great many hurricanes. Harris (1957a) gives the time history of the surge at all Coast and Geodetic Survey tide stations affected by eight hurricanes. Additional data on past storms are being collected by the United States Army Corps of Engineers and many coastal Weather Bureau offices as well as the Central Office of the Weather Bureau. It is hoped that a more exhaustive collection of the records of the tides during the past hurricanes can be published within the next few years. The data contained in the above reports indicate that maximum storm surge heights usually occur somewhat to the right of the storm center and the region of above normal tides generally extends farther to the right of the storm center than to the left. Profiles of the storm surge along the open coast, for four hurricanes taken from Harris (1957b) are shown in Figure 3. Deviations in this pattern are occasionally produced by local topography.

4. HYDRODYNAMIC THEORY OF STORM SURGES

The complete equations of motion governing storm surge generation have never been solved in closed form. The existing solutions have all been derived by idealizing the problem in some way. An analytic solution can be obtained most readily by assuming that the sea is a rectangular lake of constant depth on a non-rotating earth, and the solution obtained in this way will have a close resemblance to the true solution in a great many cases. For other problems it may be better to assume that the sea is unbounded, or that the sea has only one boundary and the depth increases at a constant rate as one leaves the shore. The simplest solutions are obtained by assuming that flow can take place in only one horizontal direction. Solutions obtained in this way sometimes give excellent results for the storm surge generated in a long narrow lake or for the advection of a storm surge in a river or other narrow channel. Even in the great majority of cases in which flow is not one-dimensional, the one-dimensional equations reveal many of the major factors involved in storm surge generation.

If a steady wind blows parallel to the axis of a narrow channel long enough for equilibrium conditions to develop, the differential equation fo the slope of the free surface may be expressed as

$$\frac{\partial h}{\partial x} = \frac{\rho_a}{\rho_w} \frac{\gamma^2 V^2}{g(H+h)} \qquad (2)$$

where: h is the height of water surface above the equilibrium plane.

x is the distance along the axis of the channel, with the wind blowing toward positive x.

ρ_a is the density of the air.

ρ_w is the density of water.

γ^2 is the wind stress coefficient, approximately 2×10^{-3}.

V is the wind speed.

H is the equilibrium depth of the water when no wind is blowing.

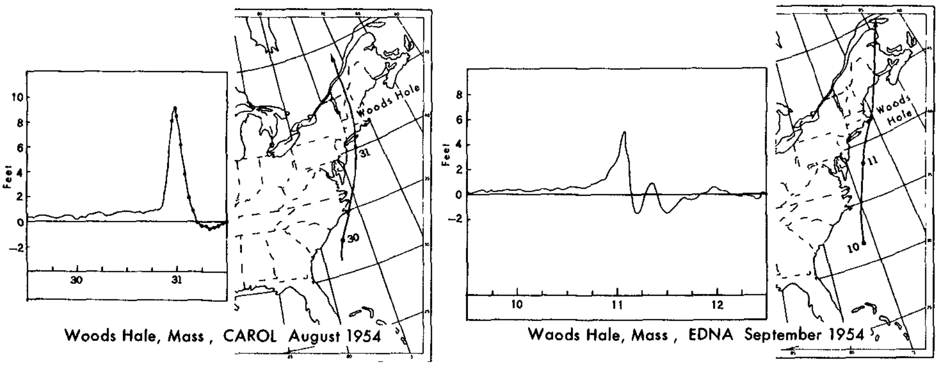
g is the acceleration of gravity.

A derivation is given by Keulegan (1953).

The total storm surge height, frequently called set up, in this sim case can be obtained by integrating equation (2) from a fixed boundary, o from a position at which, due to a low value for V or a high value for H the slope is virtually zero.

Although this simple situation rarely exists in nature, this equatio does serve to show that the slope of the free surface is related directly to a power of the wind speed and inversely to the total depth of water. This suggests that a given wind condition will produce a slightly lower s surge if it occurs at high tide than if it occurs at low tide. This dedu ion is supported by observations, Schalwijk (1947). Equation (2) also indicates, that when other conditions are equal, the highest surges will occur in regions in which the wind has a long fetch over relatively shal water. This also is generally supported by the observations, but suffici data to establish this empirically for hurricane conditions over open wat are not available.

Several empirical studies have shown a reasonably good fit between t slope of the water surface and some power of V different from 2 (Hellstr 1953, Darbyshire and Darbyshire 1956). The factor γ^2 is related to surfa roughness of the water; that is, to the wave height and wave velocity re tive to the wind. Neumann (1948) has suggested that this would lead to a decrease in γ^2 with increasing wind velocity and therefore to an expone



Woods Hole, Mass , CAROL August 1954

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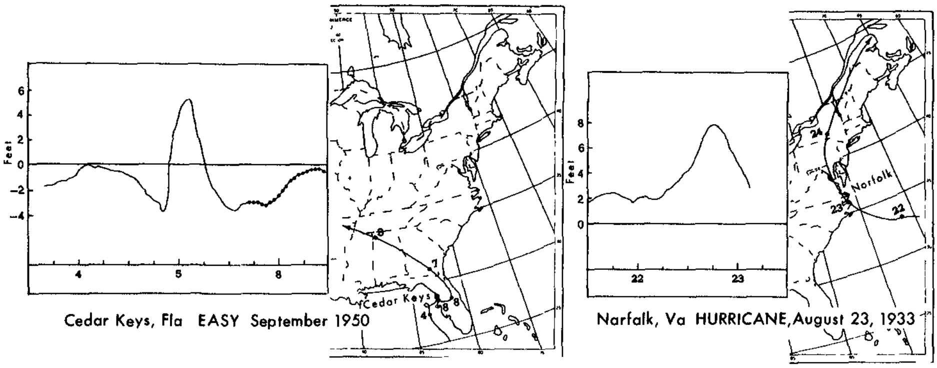
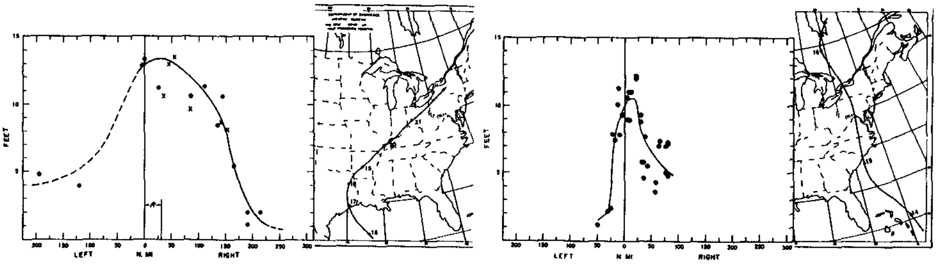


Cedar Keys, Fla EASY September 1950

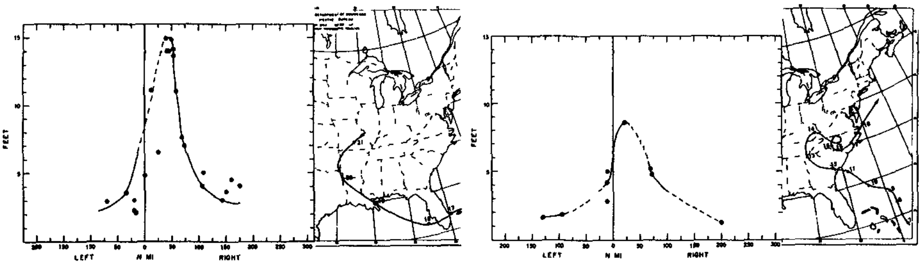
Narfalk, Va HURRICANE,August 23, 1933

Fig. 2. The storm surge, as a function of time in the region of hurricane landfall.



Hurricane Aug 16 17 1915

HAZEL Oct 14 1954



Hurricane Sept 17 19, 1947

Hurricane Aug 10 12 1940

Fig. 3. Storm surge profiles along the coast.

of less than 2. Reid and Wilson (1954),in a study relating surge height to wind speed, have shown that an exponent dirrerent from 2 may arise, even though γ^2 is assumed to be constant, because of the laws governing V and H in the particular case. It is also likely that the data developed in man empirical studies, involving only a few cases and a restricted range of velocities, will fit a linear law as well as a square law.

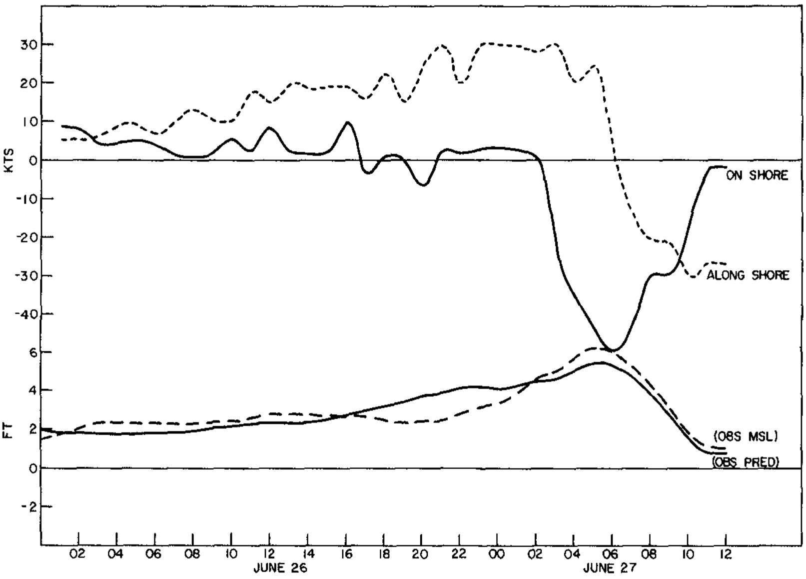
Although equation (2) sometimes gives a valid representation of the storm surge on a lake or bay, it is necessary to consider several other factors in order to explain the storm surge which develops along the open coast. The finite size of the storm is clearly important. If the storm were stationary and no flow parallel to the shore were possible, the wind effect at any point on the shore would be a function only of the wind stres seaward of that point, and the profile of the peak storm surge values woul approximately coincide with the profile of the wind stress component perpendicular to the shore. If flow parallel to the shore should occur, the peak would be somewhat flattened. These alongshore currents due to the gradient in the water elevation, brought about by variations in wind stren would reduce the water level below its equilibrium value near the peak and lift it above its equilibrium at some distance to either side of the peak.

The component of wind stress parallel to the shore would also generat an alongshore component of the ocean current. The Coriolis force acting o an alongshore current would cause an increase in water level to the right of the current.

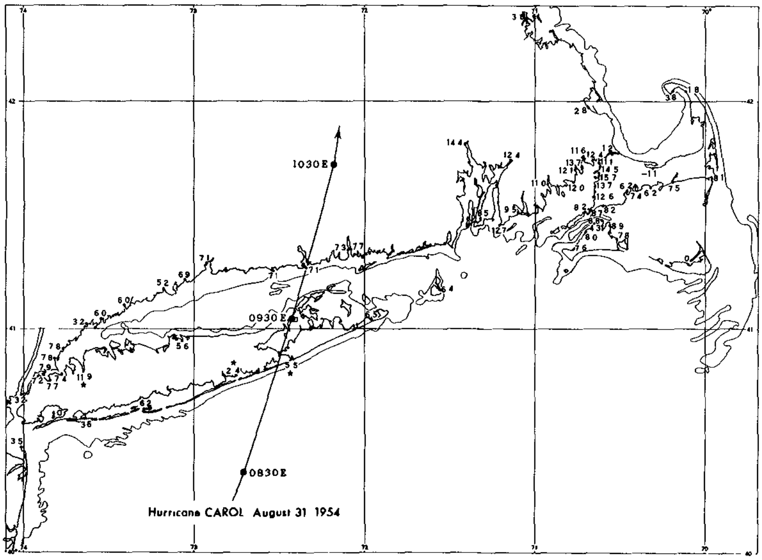
The decrease in pressure in this stationary storm will be exactly com- pensated for by an increase in water level of 13.2/12 ft. of water for eac inch of mercury.

All of the above effects will also be present in a moving storm, but in many cases the disturbing forces will not last long enough to permit th equilibrium value to be obtained. In others, the effects of resonance wil lead to the development of heights above the equilibrium value.

The presence of these dynamic factors is well illustrated in Figure 4 the storm surge curve for Galveston, Texas during hurricane AUDREY, June 1 The dashed line in the bottom of the figure gives the observed water level obtained by plotting hourly values. The solid line gives the storm surge obtained by subtracting the predicted tide height from the observed values The onshore component of the wind is shown by the solid line in the upper part of the figure, and the component of the wind parallel to the shore is shown by the dashed line. This component is considered positive when the shore is to the right of the wind vector. Notice that the wind had an off shore component during most of the period of increasing storm surge. Alth the wind data used here are those observed at the Weather Bureau Airport station in Galveston, they are representative of the true winds for at lea 50 miles on either side of Galveston during this storm. This figure indic



igure 4. Tide and wind records at Galveston, Texas during hurricane AUDREY, Bottom: Dashed line - tide height above mean sea level, solid line - difference between observed and predicted tide height. Top: Dashed line - alongshore component of wind velocity, solid line - onshore component of wind velocity.



igure 5. The storm surge associated with the landfall of Hurricane CAROL, 1954. The storm surge, observed minus predicted tide, is shown in feet and tenths. The peak storm surge coincided in time with the normal high tide at most recording tide stations. It is assumed that this also holds true for high water data. It was not possible to obtain tide predictions for a few locations. The peak storm tide above mean sea level is shown for these stations, and they are indicated by a star.

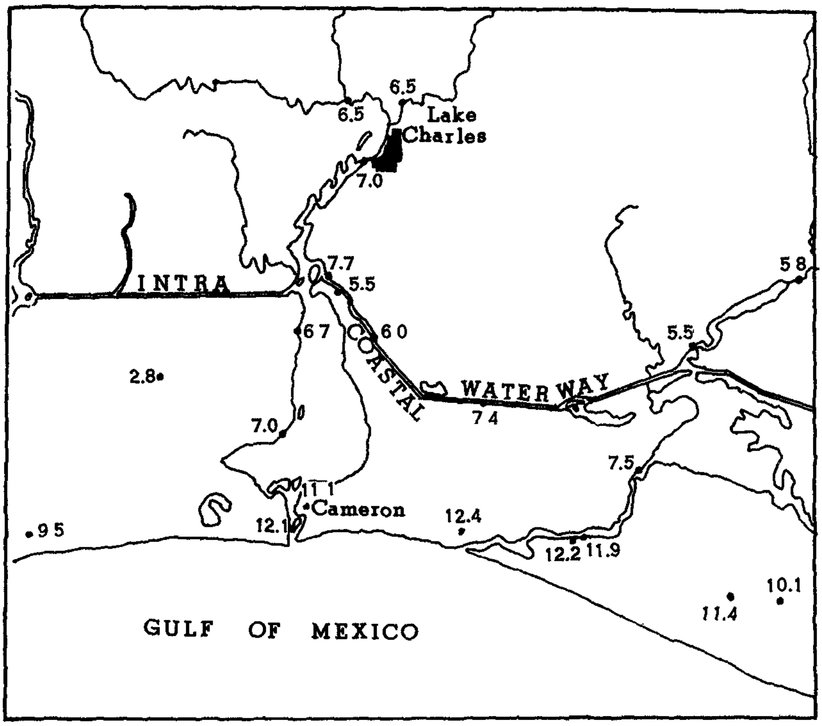


Fig. 6. Storm tide elevations in the vicinity of Cameron, La., produced by Hurricane AUDREY, June 1957. All elevations are expressed in feet above mean sea level. Data obtained from U. S. Army Corps of Engineers, New Orleans District, and State of Louisiana, Department of Public Works.

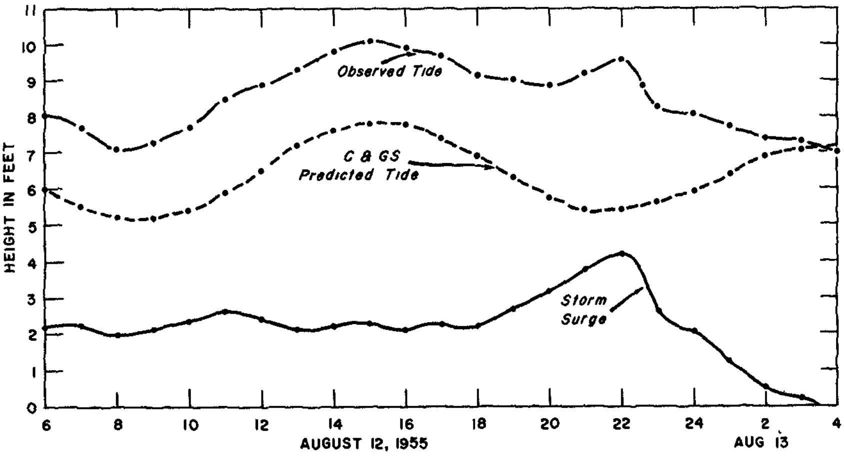


Fig. 7. Observed, predicted, and meteorological tides at Little Creek, Norfolk, Va., for Hurricane CONNIE, August 1955.

clearly that the water level at Galveston was not controlled by the onshore winds. The increase in water level may have been due to the Coriolis force or to the boundary effects of the Louisiana and Texas coasts, or to a combination of these effects.

Freeman, Baer, and Jung(1957) have proposed a system for computing the effects of the Coriolis force due to the alongshore component of the wind, and the direct effect of the onshore component of the wind in piling up water against the shore. This system, which is based on fundamental principles, does predict surge heights which are well within the proper order of magnitude. However, it does not take into account all of the dynamic effects which we believe to be important and requires a more detailed specification of the wind field while the storm is still at sea than is possible to give at the present time.

5. THE EFFECTS OF LOCAL TOPOGRAPHY

It is often useful to think of the storm surge as a wave-like disturbance of the sea surface in which the wave length is of the order of a hundred miles and the period between 8 and 24 hours. Considered in this way, it is easy to see that the surge height experienced on the open shore can be greatly modified as it moves through a bay or a river. The amplitude of the disturbance will frequently double within a distance of only a few miles as it progresses into a bay with converging shorelines. Likewise the height of the disturbance may be decreased near the middle of a wide bay with only a narrow connection with the sea. Figure 5, taken from Harris (1957b) shows the effects of local topography on the storm surge produced by Hurricane CAROL.

If the storm tide at the coast rises above the top of barrier islands, the water will flow directly inland with little regard to the natural drainage channels. In these cases the peak tide levels are to be expected a short distance inland from the natural coast, with levels sloping downward inland. This peak occurs landward of the natural shore because the presence of the submerged coastline has little effect on the slope of the free surface of the water. The slope downward at points farther inland occurs because the inertia of the water and the effects of friction as the water flows over vegetation prevents the transport of enough water inland to maintain an equilibrium between the moving storm and the slope of the free water surface. This effect is shown by the record of peak tides produced by Hurricane AUDREY, Figure 6. No land remained above water south of the intracoastal water at the height of the storm tide. In some areas the storm tide extended far beyond this canal and in others the spoil banks, formed in building the canal, served as dikes to impede the northward flow of water. These dikes had to be breached at several places to permit the land to drain after the storm.

The direct effect of wind stress over an enclosed or semi-enclosed body of water is to pile up water at the leeward end of the basin. The effect is nearly independent of the advection of the surge from the open sea into the basin. A wind blowing toward the head of a bay will serve to increase the surge height at the head of the bay. A wind blowing toward the sea wil tend to decrease the water level at the head of the bay but it may not ove come the effects of the progressive surge.

6. STORM SURGE OBSERVATIONS

The best storm surge records are obtained from a continuously recording tide gage at a site for which the observations have previously been analyzed for astronomical tide predictions, for it is only in this case th the storm surge can be accurately determined. Unfortunately, there are ma large gaps in the tide gage network and the peak storm tide is not often experienced at a recording tide gage. The peak storm tide can often be determined by an inspection of the coast soon after the passage of a sever storm. High water marks may be located inside buildings flooded by the storm, and sometimes in natural or artificial basins whose connections wit the sea are good enough to permit the passage of the tide but too tortuous to permit the passage of the high seas prevalent on the outercoast. The peak storm surge, however, cannot always be obtained from these data. The reason for this is shown in Figure 7 adapted from Hoover (1957). The peak storm tide occurred about 1500 EST, near the time of normal high tide, and indicated a storm surge of 2.3 feet, however, the peak storm surge of 4. feet occurred about 2200 EST, near the time of normal low water.

7. EMPIRICAL FORECASTING AIDS

Since the dynamic models of storm surge generation are either greatly oversimplified or too complicated for ready use in the field, and since i either case they are rather uncertain, it is necessary to consider empirical correlations between other, more easily observed, hurricane parameter and the associated storm surge. Accounts of two such studies, Conner, Kr and Harris (1957) and Hoover (1957), have been published in the *Monthly Weather Review* recently. Figure 8 shows the correlation between the minimum pressure, as determined by the methods described by Myers(1954), and the highest reported storm tide along the coast of the Gulf of Mexico or estimated highest storm surge along the coast of the Atlantic Ocean. Thi is a revision of a similar figure published by Conner, Kraft, and Harris (1957). Improved data were obtained for a few storms, and data have been added for many more storms. The change in the prediction equation is not believed to be significant. An effort was made to eliminate the effects of local topography, as discussed in section 4 above, as far as possible Some of the storm surge data may be subject to the uncertainty indicated in figure 7. The correlation between the central pressure and the peak

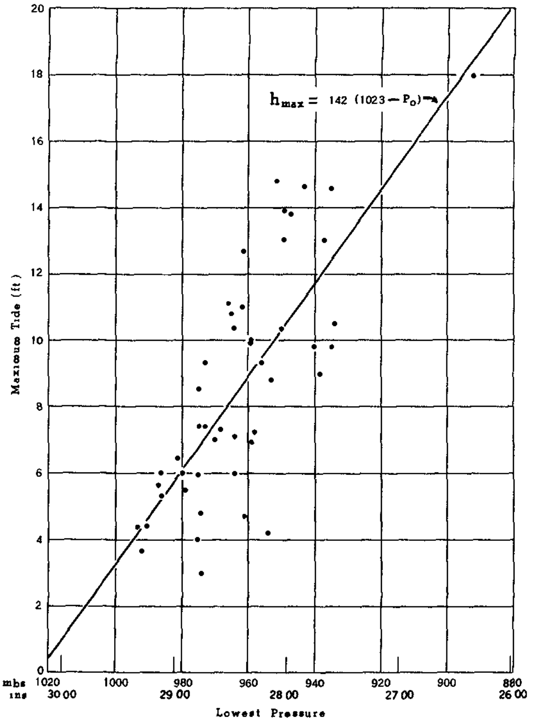


Fig. 8. Storm surge height, as a function of the central pressure in the storm.

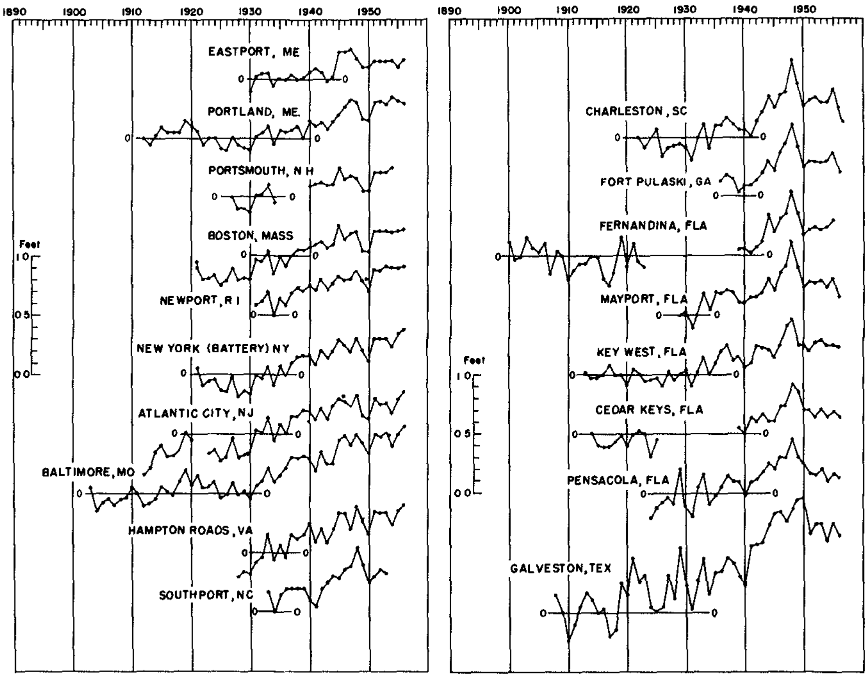


Fig. 9. Yearly sea level, Atlantic and Gulf Coast, (from NHRP Report 7)

storm surge on the Atlantic Coast, or the peak storm tide in the Gulf of Mexico, is about 0.75 indicating that approximately half of the total variability in the peak storm surge height on the open coast can be explained by variations in the intensity of the storm. A further analysis of the data, not shown here, suggests that the storm surge is higher in regions in which the continental shelf is flattest. The data do not indicate any clear cut relation between the peak storm surge and the speed of the storm or the pressure at the edge of the storm.

8. WAVES AND SWELL

In the immediate neighborhood of the coast, and in the flooded region the most damaging aspects of the hurricane are the short-period waves and swell. These may be prominent along the coast many hundreds of miles from the storm. Quantitative forecasts of the waves associated with hurricanes and other storms are desirable. However, the character of the swell and breakers reaching the shore at any location depends to a great extent on t local topography and may vary widely over short distances. The wave heigh in the open sea is a function of the wind speed, the fetch (the length of the region in which the wind direction is essentially constant), and the duration (the length of time the wind blows over the fetch). Near the coa the bottom topography becomes important and may dominate the other factors in hurricane conditions. The most important factor limiting the wave heig in the flooded region may be the depth of the water. Studies of waves bre ing in shallow water indicate that the maximum wave height, trough to cres will rarely exceed 0.78 times the still water depth (Munk 1949). The stil water depth referred to here is the depth of water as averaged over severa wave periods. For example, if the storm tide reaches a level of 8.0 ft. in a region in which the land elevation is 3.0 ft. MSL, the water depth w be 5.0 ft. and the maximum wave height will be approximately 4.0 ft.

The wave run-up along a sloping beach may be somewhat higher than th indicated above. Detailed studies by coastal engineers show a lower limi ing wave height at many coastal locations. However, in the absence of su studies, it is recommended that waves of the limiting height shown above, be assumed in making plans for hurricane preparedness. Warnings of high waves should be included in warnings of hurricane storm surge conditions but quantitative forecasts of the wave height to be expected under these conditions are not warranted at the present time.

9. LAND ELEVATION AND DATUM PLANES

The end product of a storm surge forecast is the decision to recomme or not recommend special preparations for the safety of life and property in exposed places. This decision depends not only on the height of the water level, storm surge plus normal tide, but also on the elevation of t land and the type of exposure of the place in question.

The The most extensive collection of land elevation data available in the United States is that given in the quadrangle maps published by the United States Geological Survey. These maps, with a horizontal scale of from 0.5 to 2.6 inches to the mile, give contours of land elevations with intervals ranging from one foot in some parts of Texas to 20 feet in some sections of New England, and many spot elevations. The contour analysis is generally accurate to within 25 per cent of the contour interval at the time of preparation of the maps.

The datum of reference for elevations on most of the charts published since 1930, is the "Sea Level Datum of 1929". This datum plane is based on tide observations for periods of various lengths from 1875 to 1924 at 26 stations in the United States and Canada, (Harris and Lindsay-1957). The sea level datum used on the map may differ from the local mean sea level as obtained from local observations by as much as 0.5 ft. at many locations and by more than 1.0 ft. in a few places.

Additional land elevation data may be obtained from bench mark descriptions published by the Coast and Geodetic Survey, the Geological Survey,the Corps of Engineers, U.S. Army, state, city, and county engineering offices. The Sea Level Datum of 1929 is the most widely used plane of reference in these bench mark descriptions, but other planes are used by some agencies. It is generally possible to relate these local datum planes to the Sea Level Datum of 1929. The Coast and Geodetic Survey has established local tidal datum planes, based on local water level observations in many coastal regions. Spirit level connections have been made between many of these tidal bench marks and the geodetic lines of the Sea Level Datum of 1929.

The annual mean sea level is not constant, but varies from year to year. The actual sea level, relative to the land, along most of the Atlantic and Gulf coasts is higher now than when the 'Sea Level Datum of 1929" was established. However, the trend toward rising sea levels prominent between 1928 and 1948 appears to have been arrested along much of the coast. In many areas the current trend is toward lower sea level, see figure 9, taken from Harris and Lindsay. Since the cause of the rising sea levels of the first part of the century and of the falling sea levels of the past decade are unknown, extrapolation of the observed trends either forward or backward in time is not recommended. Hydrographic charts of the Atlantic and Gulf of Mexico waters are based on a mean low water datum. This is also the datum used in the published tide predictions in this area, and is the datum most widely used in many coastal communities.

Mean low water is defined as the average elevation of all low waters in the tide cycle. Hence it depends on both mean sea level and the tide range. The range of the tide is greatly affected by local topography and may change by several feet within a few miles. Navigation improvements and the reclamation of land also affect the range of tide. Since mean low water is subject to all of the factors which affect the range of tide as well as to those which affect mean sea level, it is not well suited as a reference plane for land elevations. Mean sea level will not often vary by as much as a tenth of a foot in a hundred miles along the open coast, but may vary by as much as a foot in a hundred miles in an estuary or river Sea Level Datum of 1929 will not vary by a measurable amount within a similar distance. Mean low water, on the other hand, may vary by more than 2.0 ft. within a distance of five miles.

If mean low water or any other datum is more widely understood locally than mean sea level, it may be desirable to use the local datum in local forecasts in order to be understood by the public. However, the use of mean sea level or Sea Level Datum of 1929 is to be encouraged whenever this is practicable.

10. SUMMARY

Tides as much as four to fifteen feet above normal frequently accompany hurricanes as they move inland. This difference between the normal and observed water levels, called the storm surge, is correlated with the central pressure of the storm. It is also greatly affected by local topography and by many other factors not yet well understood. The practical importance of the storm surge depends on the phase of the normal tide at the time of the storm surge and on the land elevations in the vicinity of the storm surge as well as on the magnitude of the storm surge itself.

Although present knowledge of the processes by which storm surges are generated by hurricanes is not great enough to permit forecasting the elevation of the storm tide with the precision desired, meteorologists, engineers, and other public officials can contribute greatly to public safety during hurricanes if they are able to combine a knowledge of local topography and normal tide characteristics with a familiarity of the effec of past hurricanes on sea level.

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