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Storm Tide Frequencies
on the South Carolina Coast

VANCE A. MYERS

JUNE 1975

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NWS 15   Some Climatological Characteristics of Hurricanes and Tropical Storms, Gulf and East Coasts of the United States. Francis P. Ho, Richard W. Schwerdt, and Hugo V. Goodyear, May 1975.

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Silver Spring, Maryland·
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STORM TIDE FREQUENCIES ON THE SOUTH CAROLINA COAST

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ABSTRACT. Methods are described for estimating
hurricane tide frequencies on a coast by apply-
ing the National Weather Service hydrodynamic
storm surge model to a full set of climatologi-
cally representative hurricanes. For illustration
the methods are applied to the coast of South
Carolina, obtaining tide levels of annual frequency
from 0.10 to 0.002. The motivation for this work
is the Flood Insurance Program which uses the
results to define flood risk zones.

CHAPTER 1: INTRODUCTION

National flood insurance program

The "National Flood Insurance Act of 1963" (Public Law 448, 90th Congress,
Title XIII) provides for a national program for insuring residences and
small businesses against damage or destruction by floods. The law is
administered by the Secretary of Housing and Urban Development (HUD) through
the Federal Insurance Administration (FIA) and is cooperative between the
Government and private industry. Other Federal agencies assist HUD in
implementing this law by making technical studies.

Essential to establishing the flood insurance program in any community,
whether on the coast or in a river valley, is a flood frequency analysis.
Flood levels of certain probabilities of occurrence are the guides to
delineating flood risk zones within the community, to calculating flood
insurance rates, and to formulating local zoning and flood plain occupancy
ordinances. Such ordinances are required by the Act of 1968 as a condition
of community eligibility for federal sponsorship of flood insurance. The
FIA has requested the National Oceanic and Atmospheric Administration (NOAA)
to make water level frequency analyses and construct flood hazard zone maps
for the National Flood Insurance Program along various coastal reaches
where the principal flood hazard is inundation from storm tides. The National
Weather Service, NOAA, makes the basic coastal tide frequency determinations
and the National Ocean Survey translates these values into flood hazard maps.

Purpose of report

Assignments from the FIA to NOAA for coastal tide frequency determination
and flood zone mapping have included all of the coast of South Carolina.
The first purpose of this report is to provide technical documentation of
the coastal tide frequency determination for this area, which includes:
the five maritime counties of South Carolina; Beaufort, Colleton, Charleston,
Georgetown, and Horry; the cities of Charleston, Beaufort, Georgetown, and
Myrtle Beach; and a number of townships and towns. The second purpose is
to describe and illustrate by example the methods used by NOAA for tide
frequency determination along any hurricane-prone coastal reach.

Scope of report

This report provides and explains the basis for hurricane tide frequencies
for all of the open coast of South Carolina from an annual probability of
occurrence of 0.10 to an annual probability of 0.002 (mean recurrence inter-
val 10 yr to 500 yr). Not included in this report, but also necessary
for complete flood hazard assessment, are the destructive effects of waves
on the ocean front, the decrease (or increase) of ocean front storm tide
levels along estuaries and over land, and rainfall-induced flooding of
streams. These factors are included in other reports by NOAA or other
agencies.

Other severe storms at sea besides hurricanes create high waves and erode
the South Carolina beaches from time to time but are not known to produce
tide levels that of themselves pose a serious threat south of Cape Hatteras,
N.C. Thus, to assess storm tides on the South Carolina coast with a mean
recurrence interval of 10 yr or more, attention can be limited to hurricanes.
The historical record of hurricanes in South Carolina with particular
reference to the effects of the storm tide is summarized in Chapter 3.

The tidal waves or tsunamis of the Pacific Ocean are caused by severe
earthquakes. There has been no known occurrence of a damaging tsunami on
the mainland Atlantic coast of the United States, and they are not consider-
ed in this report.

Relationship to other reports

After hurricane Hazel severely damaged the coasts of the Carolinas
in October 1954, and two earlier hurricanes had struck New England
in the same season, the Congress directed the Corps of Engineers to
make a survey of the eastern and southern seaboard of the United States
with respect to hurricanes to assess the risk and survey the feasibility
of remedial measures (Public Law 71, 84th Congress). The Corps of
Engineers in response prepared comprehensive survey reports. These have
been very useful to the present study in providing data and background and

are the predecessors of the present report in giving frequency analyses of tide levels in Charleston Harbor and the South Carolina coast as a unit. The report, "Other Coastal Beaches, South Carolina," by the Corps of Engineers, Charleston District (U.S. Congress 1966) contains these frequency analyses and catalogues the several other reports prepared by the Charleston District in response to the law.

The report, "Carolina Beach and Vicinity, North Carolina," Corps of Engineers, Wilmington District (1961) provides information for a locale close to the South Carolina-North Carolina line. Adjacent to the other State boundary, the report to HUD, "Report, Flood Insurance Study, Chatham County, Georgia," by NOAA (1971), gives tide frequencies for contiguous Chatham County. That report was coordinated with the Savannah District of the Corps of Engineers, which has made and is making various Flood Plain Information studies for the area. The relationship of the tide frequency levels determined in the present report to the values in these earlier studies is discussed at the appropriate point later in this report.

The first comprehensive report by NOAA on methodology for coastal tide frequency analysis is "Joint Probability Method of Tide Frequency Analysis Applied to Atlantic City and Long Beach Island, New Jersey," ESSA Technical Memorandum WBTM HYDRO-11 (Myers 1970). The same information is contained in "Coastal Flooding, Long Beach Island and Adjoining Mainland, Ocean County, N.J.," a study by Environmental Science Services Administration for the Federal Insurance Administration (Environmental Science Services Administration 1970). (ESSA is a predecessor organization of NOAA). The present report is a sequel to these with respect to methodology and presents the refinements that have been made over the intervening several years.

The three main technical aspects of the joint probability method of tide frequency assessment (described in Chapter 2) are determination of the climatology of hurricane characteristics, development of a hydrodynamic model to calculate tide levels induced on the coast from hurricane atmospheric parameters, and calculation, assembling and synthesizing such information into tide frequency analyses. Ho, Schwerdt, and Goodyear (1975) have assessed the climatology of hurricane characteristics along all of the east and gulf coasts of the United States for the flood insurance program and other purposes. The needed data for South Carolina were taken from their worksheets prior to publication and are summarized in Chapter 4. For the techniques and details of developing this climatology, the reader is referred to the original report. The hydrodynamic surge model that is a vital component of the tide frequency analysis process is described in another NOAA publication, "SPLASH (Special Program to List Amplitudes of Surges from Hurricanes). I. Landfall Storms," NOAA Technical Memorandum NWS TDL-46 (Jelesnianski 1972), and in earlier scientific journal articles (Jelesnianski 1966, 1967). We will refer to the first as "The SPLASH Report." A summary of the characteristics of the model is contained in Chapter 5 of the present report.

The present report provides the technical basis for the revised flood hazard boundary maps and flood insurance rate maps published by the FIA in the Federal Register on May 25, 1973, for the township of Folly Beach, the city of Isle of Palms, the township of Sullivans Island, the town of Edisto Beach, the city of Charleston, and the unincorporated areas of Charleston County; and for the other maritime flood insurance maps for South Carolina that have been or will be released at later dates.

Definitions

The astronomical tide is the normal twice-daily oscillation of the height of the ocean surface occasioned by the gravitational attraction of the moon and sun acting on the rotating earth. The height and time of the high and low points of this astronomical tide is precomputed and published in tables by the National Ocean Survey (annual volumes). The astronomical tide is also called the gravitational or predicted tide.

The highest high astronomical tides during the 29-day lunar month occur when the lunar and solar tide producing forces are in phase. These are called spring tides. Neap tides occur during the part of the lunar month when the lunar and solar forces are in opposition. Neap tide range is usually 10 to 30 percent less than the mean tide range.

Storm tide is the name applied in this report to the total height of the ocean surface above local mean sea level in storms. In historical storms the highest storm tide is the highest water level observed at a tide gage or indicated by a reliable high-water mark at a location where wave effects would not be prominent. In future or postulated storms the maximum storm tide is the maximum of the hour by hour sum of predicted astronomical tide and predicted surge.

The surge is the name given to the increase or decrease of the height of the ocean surface due to storms and wind. The surge at a particular time is calculated by subtracting the height of the precomputed astronomical tide for that particular time from the observed height of the water surface. The surge has also been called the "meteorological tide."

Mean sea level (MSL) throughout this report refers to the mean observed water level at a point during the 19-yr epoch 1941-59, unless another reference plane is specifically stated. Datum planes are discussed in Chapter 6.

Bathymetry--the form, variation, and magnitude of water depth; corresponds to the "topography of a landform."

Marigram--plot of tide or surge height vs. time.

Shoaling factor is a term used to describe the relative potential for hurricane surges on a given coastal reach. It is related to the slope of the continental shelf and to the water depth, and is the dimensionless ratio of the maximum surge height that would be produced by a standard hurricane

moving normal to the coast at a standard speed, to the maximum height of the surge from the same storm if approaching over a continental shelf with standard slope and depth. These standards are recapitulated in Chapter 5.

A hurricane is a severe wind storm of tropical maritime origin. Hurricanes develop over the ocean and at tropical latitudes, but once formed may move over land areas and to more northerly latitudes. The winds at the lower levels spiral in toward the center in a counterclockwise direction (Northern Hemisphere). Hurricanes affect the United States primarily from mid-June to mid-October. A maximum sustained surface wind speed of 64 kt (75 mph) is the conventional dividing line between the hurricane and the lesser tropical storm. The name "hurricane" is derived, via Spanish, from a West Indian word for the storms (Millas 1968).

Central pressure—the lowest value of sea level pressure at the center of a hurricane at a particular time. The central pressure is an index of the overall intensity of the storm.

Radius of maximum winds—radially outward from the center of a hurricane the wind increases rapidly from slight values to hurricane force and then decreases more gradually. The distance from the hurricane center to the wind velocity maximum is called the radius of maximum winds. The radius of maximum winds is not identical in all quadrants and is generally most symmetrical in mature small hurricanes. The radius of maximum winds is used as a numerical index of the size or lateral extent of hurricanes.

Mean recurrence interval and return period are synonymous and are the reciprocal of frequency. "100-yr flood" is an abbreviation for "flood with mean recurrence interval of 100-yr." Repetition at a fixed regular interval is not implied. The primary significance of the "100-yr flood" is that it has a 1 percent chance of being attained or exceeded in any particular year.

A distinction is made for convenience in this report between frequency and probability. The term frequency refers to how often some natural phenomenon occurs on the average, and has units of time^{-1}. Example: "Hurricane storm center tracks cross the coast between points x and y with a frequency of 0.01 per year." The term probability when applied to hurricane characteristics refers to a fraction of some whole and is dimensionless. For example, the probability distribution of hurricane central pressures in a given region indicates the fraction of all the hurricanes of the region—however numerous they may be—that have central pressures below certain values.

Notation

Most of the symbols in this report are defined in the legend to table 4-1 on page 38. Others are defined in the text where used.

Authorization

Annual agreements between the FIA and NOAA Nos. IAA-H-29-70, IAA-H-20-71, IAA-H-19-72, IAA-H-5-73, and IAA-H-21-74 in fiscal years 1970 through 1974, respectively provide the general authority for the work described in this report. Project Orders from FIA under each annual agreement define specific studies needed. This report is applicable to all Project Orders pertaining to South Carolina. Appropriate portions have been abstracted for individual Project studies.

CHAPTER 2: JOINT PROBABILITY METHOD OF TIDE FREQUENCY DETERMINATION

Introduction

The goal of this chapter is to convey understanding of the joint probability method of coastal tide frequency analysis, both the "how" and "why" NOAA has selected this method for coastal tide frequency analyses for the Flood Insurance Program.

Assessment of future storm tide frequencies ultimately is based on the experience of the past. There are several approaches to interpreting past experience. They are catalogued here for the purpose of clarifying concepts. The sequence is organized accordingly and is not intended as a chronology of practices. In general, each method brings more information to bear on the assessment than the preceding methods, but at the expense of more exacting demands for data and more complex analysis. The main assumptions and data requirements of each method are stated. Several of the methods are illustrated by data at Charleston, S.C. The final method is the joint probability method.

Method 1—Highest of record

The first instinct in dealing with a natural hazard is to ask, "What is the worst that has happened here?" "Has happened" generally means either within the memory of the present generation of inhabitants, or as revealed by numerical records. The highest hurricane tide of record in Charleston Harbor is 8.5 ft above mean sea level in the hurricane of Aug. 28, 1893 (U. S. Congress 1966). A description of the effects of this famous hurricane is given in Chapter 3.

Data required: Highest of record.

Assumption: Past storms can be repeated.

Method 2--Statistical analysis of single-station data

The next questions one could pose are, "What is the general trend of high storm tide levels at the place in which we are interested? Is the highest known storm tide an outstanding solitary event far greater than the next highest--in which case it would be presumed to be very rare--or has it been nearly equalled several times--suggesting it is not so rare?" The formal approach to considering the entire period of record at a single observing point is to perform a statistical frequency analysis of the highest events. The data required for this are maximum tide levels in every storm during some definite period of years (preferably consecutive) that produced a tide higher than some stated base.

It is assumed that the "population" of all past, present and future storm tides--of which the recorded tides are but a sample--fits a specific mathematical probability distribution. The validity of this assumption is judged subjectively by noting how closely the graphed individual data points fit a curve or straight line fitted from the theoretical distribution. A good fit justifies cautious extrapolation of the curve from the region of the data to longer return periods. A data point far from the curve--an "outlier"--makes extrapolation difficult. Much of statistical theory applies to the annual series, that is, to the list of the largest flood in each consecutive year. Statistical methods are less developed for handling intermittent events like hurricanes, called by the statistians a partial duration series. The statistical analysis of maximum hurricane tides at Charleston from the Corps of Engineers 1966 report is reproduced in the Appendix.

> Data required: Highest tide level in each storm during
> some definite period of years.

> Assumption: Storm tides fit assumed distribution.

Method 3--Random timing of hurricanes with respect to astronomical tide

Gracie, a moderately strong hurricane, struck the lower South Carolina coast on Sept. 29, 1959. The maximum storm surge was almost coincident with astronomical low tide. The highest surge (defined in Chapter 1) was 8.3 ft, but since this peaked at the time of astronomical low tide the maximum total tide was only 5.6 ft MSL at the Charleston gage. The respective time graphs are shown in figure 1. Suppose the storm had arrived 6 hr later with exactly the same surge. The maximum water level at Charleston gage would have been 11.2 ft MSL, enough to flood the Battery ("HYPO 1" in lower panel of fig. 1). Or suppose that Gracie had arrived coincident with spring high tide. This would have yielded a peak of 12 ft MSL ("HYPO 2" of the figure).

In contrast to Gracie, hurricane Hazel in 1954 struck Myrtle Beach at the time of high astronomical tide, resulting in an inundation about 3 ft worse than if coincident with an average astronomical tide level and about 6 ft worse than if coincident with low tide.
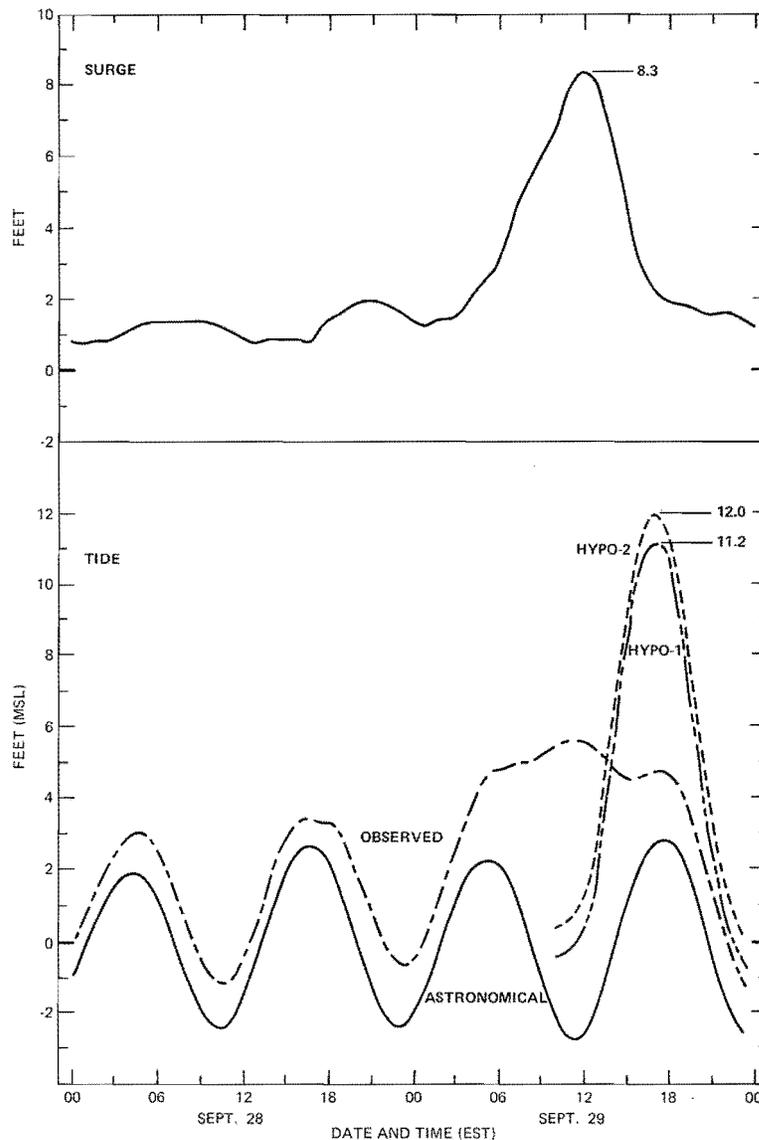
Figure 1.--Tides and surges in Hurricane Gracie at Charleston, S.C.,
   Sept. 28-29, 1959. Hypo 1: coincidence of surge with high astronomical
   tide. Hypo 2: coincidence with spring high tide.

The time of arrival of a hurricane is completely independent of the
phase of the astronomical tide or date in the lunar month. One way, then,
to extend the inferences from the past records is to assume that each
past storm could have arrived at various stages of the astronomical
tide. This is done by subtracting the astronomical tide from each total
tide marigram to obtain the surge, then recombining the various surge
marigrams with various astronomical tide marigrams to obtain hypothetical
total tide marigrams. Sufficient combinations should be used to encompass
both differences in phasing of the two and also variation in amplitude of
the astronomical tide during the lunar month. HYPO 1 in figure 1

illustrates the effect of change in phasing while HYPO 2 illustrates change
in both phase and amplitude. All combinations should be considered, less
severe as well as more severe than the actual event. In making these
inferences a scheme of assigning probabilities to the different hypothetical
combinations is needed, since they are not all equally likely. For example,
coincidence of a given hurricane surge with maximum spring tide is more
rare than coincidence with an average high tide for the simple reason that
the maximum spring tide occurs less often. Finally, the maximum tide levels
from these synthetic combinations are statistically analyzed.

The hydrodynamics of both astronomical tide and hurricane surge in shore
regions depend on water depth. Since both affect depth they are slightly
inter-dependent and affect each other. However, this is a small effect
that may be ignored except when the astronomical tidal range is a large
fraction of the water depth.

Data required: a) This method puts additional demands on the
storm data compared to method 2. Now are
needed not only the highest tide level
during each storm but also the time varia-
tion of the tide level, either observed or
approximated in some manner.

b) Frequency distribution of amplitude of
astronomical tide--readily obtained from
tide computation computer programs.

Assumption: Hurricane surge and astronomical tide are
independent and additive.

Method 4--Variation of strike point of hurricanes on coast

When Hazel struck the northern part of the South Carolina coast in 1954
the water level rose to 15.5 ft MSL at Myrtle Beach. Clearly, there is
nothing unique about the exact landfalling point of the hurricane;
contiguous coastal areas are exposed to a repeat of Hazel. Similarly,
the catastrophic Aug. 27-28, 1893 hurricane (description in Chapter 3)
entered the coast just south of Savannah. A slight displacement of the
track to the north would have resulted in an even higher inundation in
Beaufort and Charleston Counties, S.C., than occurred. In storm tide
frequency analysis the approach to the presumption that the exact coastal
strike point of a hurricane from the statistical point of view is accidental
is to assemble the hurricane storm tide history throughout a region, then
apply the total experience to the entire region. The region must be
homogeneous with respect both to climatology of hurricanes and to bathymetry
defined in Chapter 1). To do this in a formal probabilistic way now places
an additional demand on the data. Needed are not only the storm tide
heights at points but the profile of highest tide height attained along the
coast similar to figure 2 for Hazel. A "wide" profile translates to a
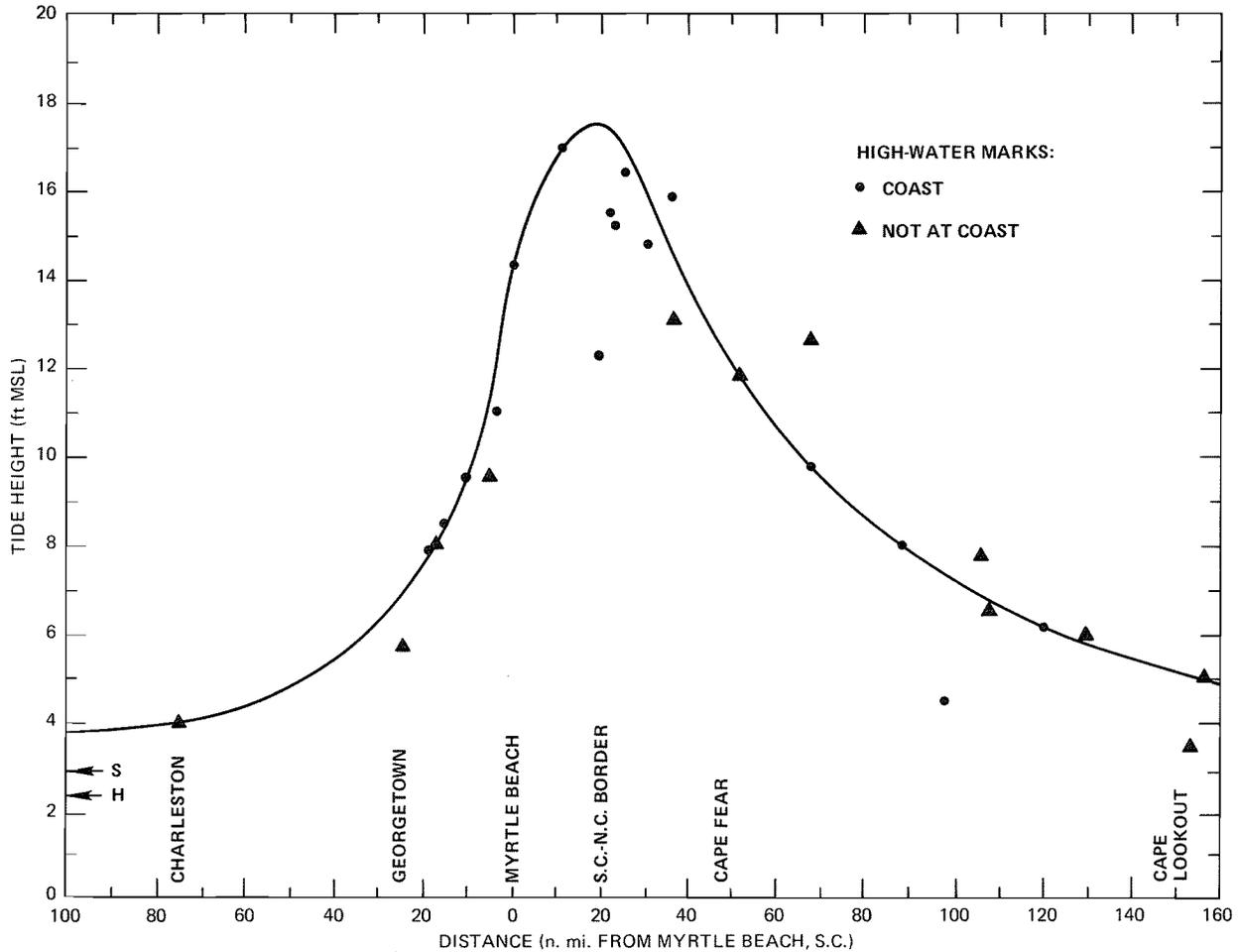
Figure 2.--Maximum tide along coast in Hurricane Hazel, Oct. 14-15, 1954, based on high-water marks. For comparison: S--mean spring high tide, H--mean high tide, at Charleston.

higher probability of given tide levels at individual points within that region than a "narrow" profile because it inundates a larger area to a given level.

Data required: Alongshore profiles of maximum storm tide heights.

Assumption: Hurricane strike point, within a climatologically homogeneous region, is accidental.

Method 3 assumes hurricanes are random with respect to coincidence with astronomical tide and method 4 that they are random with respect to exact coastal strike point. Clearly, the two methods can be combined if appropriate data are available.

Method 5--Shoaling factor adjustments

The limitation in method 4 that hurricane tide profiles may be transposed only within a region that is homogeneous with respect to bathymetry is rather restrictive along some stretches of the coast. The surge height that a given hurricane will produce on the shore depends on the slope and contour of the ocean bottom. A given storm will produce a higher surge where the water is shallow and has a gentle bottom slope than where the water is deep and the bottom slopes off sharply from the shore. A larger body of hurricane tide information can be treated as a whole if adjusted for this bathymetry effect. For this purpose, Jelesnianski (1967) devised the "shoaling factor" defined in Chapter 1 and has published (Jelesnianski 1972) profiles of the shoaling factor for certain important classes of hurricanes along the Gulf and Atlantic coasts, based on computations that will be described under method 6. On the South Carolina coast the shoaling factor is lowest at Myrtle Beach, higher at Georgetown, lower at Charleston, and then higher again at Hilton Head with a total range of about 15 percent.

Strictly, the shoaling factor applies only to the surge component of the total tide. Bathymetry effects on the astronomical tide component of the total tide are already included in the published astronomical tide values. However, total storm tide profiles may be adjusted by the shoaling factor as an approximation if two conditions are fulfilled, namely that the shoaling factor range is not large and that the hurricane surge is large compared to the astronomical tide range.

The procedure to apply method 5, using the approximation just stated, would be: adjust each coastal storm maximum tide profile from method 4 to a shoaling factor of 1.0 by dividing the tide height at each point on the profile by the corresponding local shoaling factor; perform the statistical analysis on the tide profiles normalized in this way; then adjust the composite results to a local point of interest by multiplying by the local shoaling factor. In applying methods 3 and 4 in combination, separation of surge and astronomical tide is made anyway and the shoaling factor can then be properly applied to the surge only.

Method 5 is a concept, and is presented here for its conceptual content. In practice, this method has not been used alone but has been incorporated into method 7.

> Data required: Shoaling factor profile for region of interest.
>
> Assumption: Surges from a given hurricane are proportional to the shoaling factor.

Method 6--Hydrodynamic synthesis

In applications of geophysical data of many kinds, models are used to transform available data to a needed but not directly available form. These models approximate real natural processes by equations. For example, on weather maps, winds are estimated from the horizontal component of the atmospheric pressure gradient or else the pressure gradient is estimated from the wind, where one but not the other is available, by certain relatively simple equations that take into account the predominant real factors interrelating wind and pressure gradient. A more complex example is rainfall and streamflow. Either may be synthesized from the other, provided a sufficiently detailed hydrologic model of the particular basin is available. In many hurricanes, the path, forward speed, wind field, and pressure field are known or can be fairly well approximated, while coastal tide level data are scanty or lacking. For these, a synthetic storm tide can be added to the past record if a hydrodynamic model is available that will calculate the storm surge from the atmospheric inputs. The change in ocean and lake water levels induced by wind storms is a serious engineering question for a wide variety of applications, and models to make the wind-to-water-level conversion have been given attention for decades. A hydrodynamic model for calculating the surge produced by a hurricane moving over the continental shelf has been developed by Jelesnianski (1967, 1972) and is now used operationally by the National Weather Service for predicting storm tides when a hurricane approaches. The same model can be used to reconstruct the storm tide from past storms. Doing so extends the inferences that may be made from the past record.

Method 6 includes such reconstruction, followed by application of methods 3, 4 and 5.

Data required:	Atmospheric parameters for hurricanes.
Technique required:	A hydrodynamic model that will calculate coastal storm surge profiles with an acceptable degree of reliability from atmospheric data.
Assumption:	That the model replaces the natural processes.

Method 7--The climatological-hydrodynamic (joint probability) method

In the final method, each of the more significant hurricane parameters--central pressure, radius of maximum winds, directional approach to coast, and forward speed--is viewed as a climatological variable that has a probability distribution at each coastal point and exhibits a smooth variation in these probabilities from point to point. This hurricane atmospheric climatology is estimated from the past record of the relevant

variables in individual storms and a reasonable geographic variation of each variable is worked out. The atmospheric climatology is then converted to storm tide "climatology" by running a number of hypothetical hurricanes representing the atmospheric climatology through the hydrodynamic model and assembling the resulting computed storm tide envelopes. More details of this process are given in a later chapter. The tide envelopes are synthesized from a variety of hurricanes—severe and not so severe, slow moving and fast moving, large and small, with different directions of approach, arriving at high astronomical tide and at low tide, etc. In doing this, it is necessary to keep careful track of the likelihood, or probability, of each characteristic of each hypothetical storm and by combining these to obtain the "joint probability" of the particular storm tide replication. Details of this are expanded in a later chapter.

This procedure provides a powerful tool in treating sporadic events like hurricanes. Under method 4 transposing storm experience was limited to the region that was "climatologically homogeneous." By taking into account the climatological gradients, the quantity of data available for making inferences for a particular region is increased and every coastal point is covered whether it has any direct data from measured hurricane experience or not. Obvious requirements for application of this method are a hydrodynamic model that will make the atmospheric parameter-to-surge-height conversion with acceptable reliability and a specific and reliable climatological portrayal of the hurricane variables. The tie-in to storm tide experience is the testing of the model.

Data required: a) Quantitative climatological specification of atmospheric hurricane parameters, stated in probabilistic terms.

b) Bathymetry, smoothed in a form acceptable to the model.

c) Shoaling factor curves.

Technique required: The hydrodynamic model from method 6.

Assumptions: The assumptions of methods 3, 4, 5, and 6.

Application of Method 7 to the South Carolina Coast

Assessing tide frequencies on the South Carolina coast by method 7 is the subject of the remainder of this report. The hurricane parameter probabilities used as the starting point are given in Chapter 4. This is preceded by a description of historical hurricanes in Chapter 3.

The hydrodynamic model used to compute coastal surges from representative hurricane parameters is the subject of Chapter 5. More complete description is found in the papers by Jelesnianski (1966, 1967, 1972) and Jelesnianski and Taylor (1973).

Needed data on astronomical tide levels and datum planes are assembled in Chapter 6.

Chapter 7 completes the computation of coastal tide frequencies.

All chapters include major procedural details, including changes from the 1970 procedure (Myers 1970).

CHAPTER 3: HISTORICAL HURRICANES ALONG THE SOUTH CAROLINA COAST

Hurricane effects

Coastal effects

Over the years, hurricanes have produced many disasters along the South Carolina coast. The loss of life and damage to property by these storms is primarily the result of the hurricane storm tide and, on the immediate coast, high waves. The hurricane winds are also a danger. The more destructive hurricanes of the past vividly illustrate the potential danger of life and property along the South Carolina coast.

Rain floods

Hurricanes also produce rain. The intensity varies from storm to storm. Hurricane rainfall of moderate intensity can be beneficial to agriculture, but the more extreme hurricane rains produce disastrous floods. One flood-producing hurricane is described in the next paragraph as a reminder of this danger. The remainder of the chapter is restricted to a survey of coastal effects from hurricanes. The reader is referred to Purvis and Landers' (1973) report for more details on rainfall-producing hurricanes in South Carolina.

A rain-producing hurricane

A relatively small hurricane of moderate intensity passed inland on the mid South Carolina coast near Bulls Bay on July 14, 1916. Before it had expended itself in the North Carolina-Tennessee Mountains to the northwest, it had produced floods on some South Carolina streams that (in 1975) still stand as records. Most effected were the Saluda River and its tributaries, the Broad River and the Wateree. The peak discharge on the Wateree River reached 400,000 cfs (cubic feet per second) near Camden, S.C. This is the highest known since records began in 1886. Downstream, Malta, S.C., experienced its highest stage of record in the same flood. On the Broad River in the 1916 stage of 37.8 ft (local datum) has been equaled once since (in the August 1940 hurricane) but has not been exceeded (Speer and

Gamble 1964). The rainfall at Kingstree, S.C., on July 14-15 totaled
16.77 in., the South Carolina 24-hr record to this day. Property and crop
loss due to flooding has been estimated at between $10 and $11 million
(1916 prices).

Sources of hurricane descriptions

A comprehensive descriptive listing of tropical cyclones that have affect-
ed South Carolina by National Weather Service authors was published by the
South Carolina Disaster Preparedness Agency in 1973 (Purvis and Landers 1973).
Historical sources including newspapers were pursued. The American Meteor-
ological Society (Ludlum 1963) has published a comprehensive volume on "Early
American Hurricanes, 1492-1870." Sugg and coauthors (1971) have written on
"Memorable Hurricanes of the United States since 1873." Tannehill (1956) in
his famous treatise on hurricanes, includes a chronology of North American
hurricanes. Original tide level information is found in several reports of
the Charleston District of Corps of Engineers (1957, 1964, 1966). The
Monthly Weather Review since its inception has included detailed descriptive
accounts of hurricanes either in the volume pertaining to the month of occur-
rence or in an annual summary. The remainder of this chapter draws from the
above sources, especially Purvis and Landers (1973) and Ludlum (1963), to
describe the most famous or infamous hurricanes that have affected coastal
South Carolina. For a complete chronology of the more than 168 tropical
cyclones, including those that reached South Carolina by the inland route
from the Gulf of Mexico, from 1686 to 1972, the reader is referred to Purvis
and Landers. Not all of these were of hurricane intensity.

Most of the older hurricane data refer to Charleston. This is not because
Charleston is more susceptible to hurricanes than other points along the
South Carolina coast, but because that is where records were kept.

Hurricane season

The hurricane season on the eastern seaboard is from late June to mid-
October. The incidence of these storms is greatest in late August and
September. According to Purvis and Landers, early residents of South Carolina
referred to hurricanes as the "September gales." It was said to be every
farmer's goal to get the cotton picked before the "gales."

Major storms of the 17th century

Sept. 4-5, 1686

A hurricane struck the Charleston area causing severe destruction to the
new colony, but it also benefited the colony by disrupting a Spanish attack
on the lower Carolina settlements. The Spanish landed near North Edisto
Island and struck toward Stuart Town near Beaufort on September 4th. That
evening the wind picked up to a gale, driving two of the Spanish galleys so
high on land that they had to be abandoned and the attack called off (Ludlum
1963).

Sept. 16 (or 14), 1700

A hurricane wrecked the ship "Rising Sun" (in Charleston Harbor) with the loss of all on board. Streets were flooded in Charleston. There was damage but no loss of life ashore (Ludlum 1963).

Major storms of the 18th century

There were several major hurricane disasters during the 18th century. Damage descriptions are available from Purvis and Landers, and Ludlum who in turn quote earlier sources. These are excerpted here.

Sept. 16-17, 1713

A great storm attended by an immense inundation from the sea drove many vessels ashore. -Seventy persons were drowned along the coast north of Charleston (Ramsay 1858, Ludlum 1963).

Aug. 13, 1728

Charleston, S.C. A tropical cyclone overflowed the town and all low lands, doing great damage. The inhabitants of the town were obliged to take refuge in the upper stories of their dwellings. Twenty-three ships were driven ashore, and many thousands of trees were leveled (Mills 1826).

Sept. 15, 1752

With respect to the general intensity of this storm Ludlum says: "Little doubt existed among the early writers on the subject that the hurricane of 1752 was the most severe in the Charleston area in colonial times. Ramsay (1809) declared: 'This was the greatest and most destructive hurricane that has ever taken place in Carolina.' Dr. Prioleau, who made a study for the Medical Society about 1805, thought 'the hurricane in the year 1752 far, very far exceeded, both in violence and devastation, the one in 1802....' Dr. Thomas Logan, writing in the Southern Literary Journal (1836), also repeated the above, saying that a 'partial inundation' occurred in 1752, but that no complete inundation had ever taken place. In modern times at Charleston only the hurricane of 1893 could be placed in the same class with that of 1752."

Descriptive details from Mills: "A large ship off Sullivan's Island was driven six miles north of Charleston into Clouter's Creek. Another vessel was driven with anchor ahead from White Point through Vanderhorst Creek. In passing, she carried away the southwest corner of the new Baptist Church and grounded on the west side of Meeting Street. A ship with a cargo of palatines, anchored in Ashley River, was with anchors driven on the marsh near James Island where she tossed so violently as to cause the death of 12 of them. The Hornet sloop-of-war, with 7 anchors, drifted ashore where Gadsden's Wharf now stands. She was the only vessel in the harbor which rode out the storm. The Pest House on Sullivan's Island, built

of wood, with 14 persons, was carried up Cooper River several miles, and 9 of the 14 were drowned. At 11 o'clock the wind shifted and in 10 minutes the tide fell 5 feet. Nearly all the slate and tile-roofed houses were uncovered, many persons hurt and some drowned."

Sept. 30-Oct. 1, 1752

"A severe tropical cyclone affected the South Carolina coast with the most destruction reported along the northern South Carolina coast. Governor Tryon of North Carolina says 'The hurricane is attributed to the effect of a blazing planet.'" (Purvis and Landers 1973).

Aug. 10, 1781

A tropical cyclone during the British occupation caused damage, sinking two British ships (Purvis and Landers 1973).

Oct. 7-8, 1783

A hurricane caused considerable damage to wharves and shipping in the harbor at Charleston. Dr. Samuel Latham Mitchell referred back to "the great storm of 1783" when writing his account of the 1804 hurricane, indicating that the storm was considered a major storm in South Carolina (Ludlum 1963).

Sept 19, 1787

Charleston, S.C. A very high storm tide is said to have drowned 23 people (Dunn and Miller 1964).

Oct. 19-20, 1797

A tropical cyclone affected the South Carolina coast and overflowed the wharves at Charleston. According to the Charleston City Year Book, 1880, the storm occurred on Sept. 5, 1797. Ludlum (1963) however, states that this is in error and that the tropical storm's correct date was Oct. 19-20, 1797.

Major storms of the early 19th century

Sept. 7, 1804

A severe hurricane moved inland between Savannah and Charleston and caused immense damage on the coasts of Georgia and South Carolina, then moved to sea again. The center of this storm skirted the coastline, passing over St. Simon Island, Ga., just east of Savannah over Beaufort, S.C., and then to the west of Charleston and Georgetown. This storm is said to have caused more than 500 deaths by drowning in South Carolina. The hurricane also caused major damage to the South Carolina economy. Historical notes contain no data on the height of the storm tides or strength of the winds. The Charleston City Gazette(Ludlum 1963) in describing the storm included the following:

"On Friday night last, about 11 o'clock, a dreadful gale of wind
came on this harbor, and continued to blow with the most extreme
violence until Saturday morning, 1 o'clock: The wind at first was
at N.E., in the course of Saturday morning, it changed to east,
and in the afternoon the southeast. It is impossible at this time
for us to describe accurately the destruction caused by this gale;
the whole of the wharves from Gadsden's on Cooper River, to the
extent of South-Bay have received very considerable damage, the
head and sides of most of them are washed away. Of the vessels
in the harbor, but 3 or 4 escaped without injury, several are
totally lost and many more are much damaged."

Aug. 27, 1813

A tropical storm came near Charleston causing a large loss of life and
property. The hurricane of 1813 rates a position close to the top of
Charleston's meteorological list for its combination of severe winds,
heights of flood tide, and general destruction. Probably those of 1752
and 1893 were of greater physical force and more lives were lost in each,
but 1813 must be considered among Charleston's major disasters (Ludlum 1963).

According to the Charleston Courier (Corps of Engineers 1957), here is
a description of the storm at Charleston:

"On Friday night last we experienced one of the most tremendous gales
of wind that ever was felt on our coast. The horrors of that awful
night we shall not attempt to portray, but the particulars of its
desolating effects, so far as they have come to our knowledge, will
be given with as much accuracy as the nature of the case admits.
For some days previous to Friday last, the unsettled state of the
weather was such as to indicate a gale; the uncommon roaring of
the sea upon the bar, the unerring indication of such an event,
was noticed by many. On Friday forenoon the wind was S.E. About
3 o'clock p.m., the wind began to blow very fresh at N.E. by E;
between 5 and 7 o'clock it had increased to a strong gale, and
at 9 o'clock it was a complete hurricane, prostrating in its
course houses, chimneys, fences and trees. It continued to blow
with equal violence until about 1 o'clock in the morning, when
the wind having shifted to the westward, it lulled considerably,
but still blew with much force until daylight, when it became
moderate. Torrents of rain accompanied the gale, and the tide which
should have been high before 10 o'clock continued rising until
near 12, at which time it was about 18 inches higher than in the
great gale of 1804. The rising sun, notwithstanding it disclosed
to us the ruins produced by the storm, was cheering to the eye; after
such a night of uncertainty the return of day was hailed with joy.

"Many families, whose dwellings are in low situations, were
driven from their houses through the pelting of the pitiless storm,
to seek a shelter among the more fortunate neighbors. Others again,
particularly in that part of the city fronting the N and N.E. had

the lower rooms of their houses completely inundated, and were
unable to leave them, unless indeed in boats, which was done in
some instances; while others were in vain crying for assistance,
expecting every moment when the vessels which were thrown upon the
wharves near them would crush their houses and bury them in their
ruins.

"More than half of the new bridge over Ashley River was swept
away by the violence of the storm, the great rise of water must
have floated the top from the piers, and the fragments in large
bodies drifted with the tide and lodged upon South Bay and elsewhere.

"At Fort Johnson much injury has been experienced. A part of
the battery is undermined, as are also the bake house and the
blacksmith's shop; the soldiers' barracks are partly destroyed,
the wharf washed away, and much other injury done. The whole
garrison was overflowed, but no lives lost. On Sullivan's Island
the storm proved most awfully destructive. All the houses in the
vicinity of the Cove have been demolished, and there can have been
but a very small part, if any, of the island which has not been
covered with water. It was infinitely distressing to hear the
shrieks of the sufferers, whose houses had been swept away, and who
were struggling for life, and with winds and waves driving them they
knew not whether. The extreme darkness of the night rendered it
almost impossible to afford any assistance to the unhappy sufferers
from those who were so fortunate as to be comparatively secure.
The tide was 2-1/2 feet high in the Officers' Quarters, and about
4 feet on the parade. In the morning the island exhibited a most
melancholy picture; fragments of houses, furniture, boats, etc.,
were thrown promiscuously over it, and the bodies of 9 persons, 4
of them females, lay among the ruins, an awful remembrance to the
survivors of the horrors they had escaped. It is supposed that as
many as 15 have perished."

Sept. 10, 1820

A destructive hurricane passed inland just north of Georgetown, S.C. The
tide in the bay at Georgetown rose 4 ft above a normal spring tide, to about
the height reached in the Great Gale of 1804. The Winyah Intellingencer of
Sept. 13, 1820, gives this account (Ludlum 1963):

"On 10th wind blew tempestuously all day fluctuating between
points ENE and NE, but more generally blowing from NE. About
sunset the scene became truly awful, the wind increasing in
violence, and the tide running with frightful impetuosity.
About this period, the church was blown from its foundations,
and many of the inhabitants were seen removing from such houses
as appeared most exposed to the dangerous tide and wind. After
dark the gale continued to increase, and about 10 or 11 o'clock
there raged one of the most violent hurricanes that has ever been
experienced here. At this hour the wind began to back (as it is
called) to the N, blowing at times in squalls of incredible violence,
bringing with them such floods of rain, that there was not a house

in the village could entirely resist their fury. The wind about
1 o'clock appeared to have backed as far as NW from which quarter
it continued to blow, but with decreasing violence until morning."

Sept. 27, 1822

The Georgetown area was struck again. A small but severe hurricane
entered the coast between Georgetown and Charleston, causing unprecedented
tides at Georgetown, and several hundred deaths (Ludlum 1963). From the
Charleston Gazette, September 30, (Corps of Engineers 1957):

"Friday. Violent tempest; heavy rain gale commenced 10 p.m. and
continued until 3 a.m. next day; many houses blown down; storm
tides very high; 8 persons drowned in Charleston, 4 at Sullivan's
Island. Georgetown and North Island suffered very much from the
effects of the storm; 4 drowned at Georgetown; Dr. Myer and family
of 15, and 18 others drowned at North Island."

Storms of the middle 19th century

The middle 19th century is remarkable more for the frequency than severity
of hurricanes in South Carolina. During the 55 years from 1825 through
1879, according to the Purvis-Landers chronology, at least 25 Atlantic
hurricanes had some effect on South Carolina. (Gulf of Mexico hurricanes
approaching the State from the landward side are not included in this count.)
Descriptions are quoted here of the 1834 storm at Georgetown, a graphic
description of the rice plantation inundation, and of the 1854 storm, the
worst of the period at Charleston. The hurricane of Aug. 19, 1871, is said
to have caused very high tides in the Cape Fear river in North Carolina.

Sept. 4, 1834

Ludlum and the Georgetown Union give a graphic description of the flooding
of the rice plantations and the river front in the vicinity of Georgetown:

"The storm flood at Georgetown was of record proportions. The
rice in the fields was under water for a period of about 12 hours.
The water rose 12 to 15 inches above the floors of the warehouses
along the river, and all of the wharves were flooded and suffered
some injury with the exception of those which had recently been
repaired. The editor of the Georgetown Union compared the
event with past occurrences:

'In fact the tide did not fall preceptibly before one
o'clock. It is said by one of our respectable and oldest
citizens to have risen higher than in the gale of 1804. The
fatal storm of 1822 was of short duration; and by a sudden
change in the wind the water was driven back and did not rise
near as high as in 1804--while at North Inlet the tide, impelled
by a tornado, rose to unparalleled heights, and destroyed 7 dwell-
ing houses, one church and 37 lives. The storm of 1822, for
strength and mischief done while it lasted, certainly claims
preeminence above any known or recorded to have occurred in this

neighborhood; but for duration and loss of every sort, except life, this gale of 1834 is unequalled. We have already said no wharves were to be seen. This cannot be said of any gale since 1804, and then the water was not so high. Far as the eye could reach, the fields were covered, and but for the appearance here and there of a tree or cluster of bulrushes, vines, etc., we should not have known that valuable plantations lay under the overwhelming waters.'"

Aug. 7-8, 1854

This hurricane approached the United States from the south-southeast after moving through the northern Bahamas. Again, quoting Ludlum, "The south-easterly blasts along the South Carolina coast drove the waters of the Atlantic Ocean into all the bays and inlets that abound there, over some of the low-lying islands, and into the tidal lowlands that fringe all the rivers and streams. Edisto Island near Charleston suffered severely, as did Port Royal and Beaufort to the south. The massive extent of the disturbance is indicated by the vast inundations that took place in the Winyah Bay area of Georgetown County. At Georgetown, according to the Pee Dee Times, though the tide was as high as in the disaster of 1822, the wind was thought to have been lower. The storm at that northeastern South Carolina location commenced on Thursday the 7th, and did not end until Saturday night; 'being the longest continuous blow in the remembrance of any inhabitant.' A graphic description of the inundations attending the hurricane has been preserved in the correspondence of Adele Petigru Allston:

'Since I wrote you last we have had a great blow, Storm. It commenced on the 7th inst and lasted until the night of 9th. The tide was higher than has been known since the Storm of 1882. Harvest had just commenced generally and the damage to the crops is immense. From Waverly to Pee Dee on the 8th not one head of rice was to be seen above the water, not a bank or any appearance of the land was to be seen. It was one rolling dashing Sea, and the water was Salt as the Sea. You will see at once that the crops must have been terribly injured. Many persons had rice cut and stacked in the field, which was all swept away by the flood. Your papa had none exposed in that way for he apprehended high tides from the state of the moon, and prepared as far as possible for it. Mr. J. J. Middleton had 40 acres of very superior rice swept away, a total loss, and many others have suffered in the same way, tho' not to the same extent.'"

Major late 19th century hurricanes

Tracks of hurricanes described in this section are shown in figure 3.

Aug. 27, 1881

This hurricane of major proportions swept ashore just south of Savannah, Ga. Many lives were lost on the lower South Carolina coast, and 335 people were reported dead in the Savannah area. Overall, this storm took about

700 lives. Damage was very heavy on Tybee and other coastal islands near Savannah. Nearly 100 vessels were wrecked along the coast. The highest tide at Savannah Beach, Ga. was estimated at 16.5 ft above mean sea level. Hurricane winds did not reach as far north as Charleston where the highest wind was 54 mph (Purvis and Landers 1973; Dunn and Miller 1964; Corps of Engineers 1968).

Aug. 25, 1885

This hurricane is said to have damaged 90 percent of the houses in Charleston and swept some away completely. This extreme hurricane moved inland near Savannah on a northerly course and passed to the west of Wilmington, N.C. All of the South Carolina coast was severely damaged. Damage in Charleston alone was $1.7 million (1885 prices). As a result of this destructive storm, it was proposed that a weather reporting network be set up in the West Indies and Mexico. Twenty-one lives were lost in Charleston (Purvis and Landers 1973).

Aug. 27-28, 1893

A severe hurricane penetrated the Georgia and lower South Carolina coastline, submerged the coastal islands, and devastated the coast. An estimated 2,000 people lost their lives on the coastal islands and in the lowlands between Tybee Island, Ga. and Charleston, S.C. (Purvis and Landers 1973). The highest tide in this storm was estimated to have ranged from 17.0 to 19.5 ft MSL at Savannah Beach, Ga. (Corps of Engineers 1968). At Charleston the tide was 8.5 ft above local MSL (table A-1), the highest of record, even though the storm center was some distance away. At Edisto Beach 10.9 ft was attained (U.S. Congress 1966). Property damage along the coasts was enormous. Nearly every building on Tybee Island was damaged and the railroad to the island was wrecked. The storm moved through central South
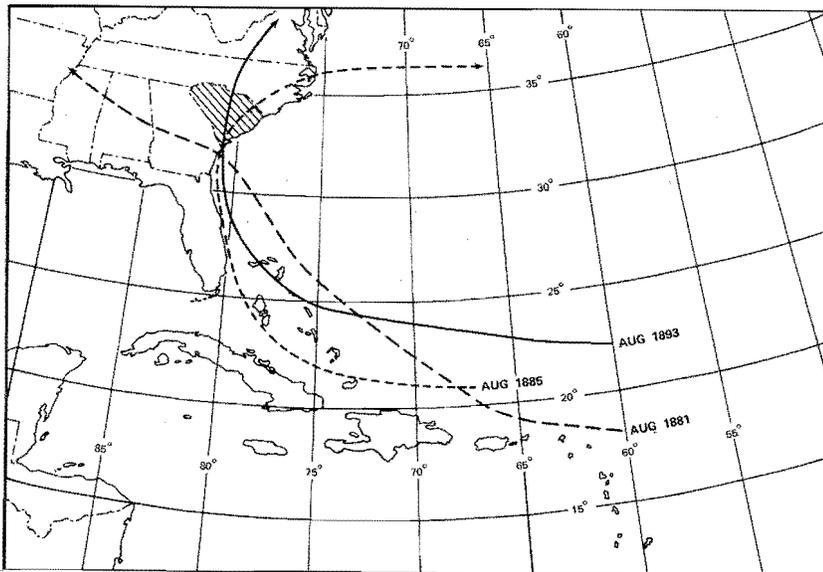
Figure 3.--Tracks of major late 19th century hurricanes affecting South Carolina.

Carolina on a northerly heading passing from about Savannah to a little west
of Charlotte, N.C.

The most damaging hurricanes of the 20th century

Tracks of hurricanes described in this section are shown in figure 4.
Storm tide levels in this section are heights above either the 19-yr local
mean sea level, or the zero of the "National Geodetic Vertical Datum of
1929," depending on the location and source. These are identified as "MSL"
and "1929 datum," respectively. These datum planes are defined in Chapter 6
and differ by 0.4 ft at Charleston.
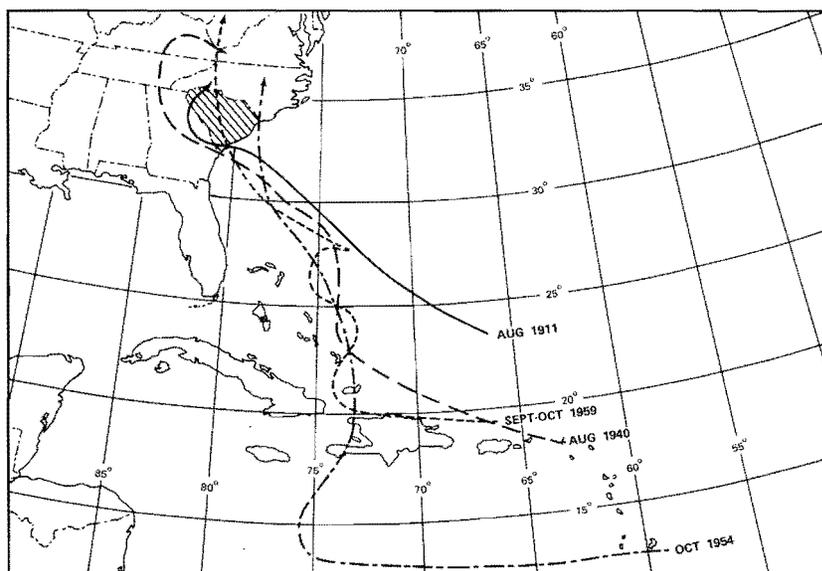
Figure 4.—Tracks of damaging hurricanes of the 20th century affecting South
  Carolina.

Aug. 28, 1911

A severe hurricane that caused great damage to property due to winds and
high tides, moved inland between Savannah, Ga., and Charleston, S. C. This
storm is considered in the same category as the storm of 1940, described in
the next paragraph. At Charleston, the barometer fell to 992 mb (29.30 in.)
The wind at the Weather Bureau office reached 81 mph from the southeast
[fastest single mile, U.S. Weather Bureau, Charleston (1949)]. Anemometer
corrections have been applied from Harrison (1963). This is the highest wind
of record since establishment of the station in 1871, possibly excepting
Gracie of 1959. Seventeen lives were lost, and damage totaled about $1 mil-
lion (1911 prices). The storm passed into the Piedmont section of South

Carolina and then recurved to the northeast (Sugg et al. 1971). At Charleston the tide reached 7.5 ft MSL, the third highest of record (table A-1).

Aug. 11, 1940

This is the best documented of major hurricanes that occurred up to that date. The storm entered the coast from the southeast, striking between Savannah, Ga., and Beaufort, S.C. at about 4 p.m. on August 11. Near Beaufort, S.C., the tide is estimated to have reached 14.2 ft MSL (fig. 5). The tide overtopped the sea wall along Beaufort River, destroyed or ripped every wharf from its piling and flooded the entire business area of Beaufort to a depth of 2 to 3 ft. Eight people died on Ladies Island, near Beaufort. On Lemon Island, in the Broad River, the tide rose to 16 ft, 1929 datum (fig. 5). The outlying islands of St. Helena, Hilton Head, Doufuskie, and Pinckney suffered considerable damage due to the storm tide with inundations up to 10 ft MSL. Many small homes were destroyed or severely damaged. Wells, the only water supply, were flooded with salt water. Several hundred people were left homeless and 25 people died on these outlying islands. At Hunting Island the beach scarp receded 75 to 100 ft, and several sand bars fronting the beach were washed away. Near the southern tip of Edisto Island a high-water mark indicated a tide of 13.6
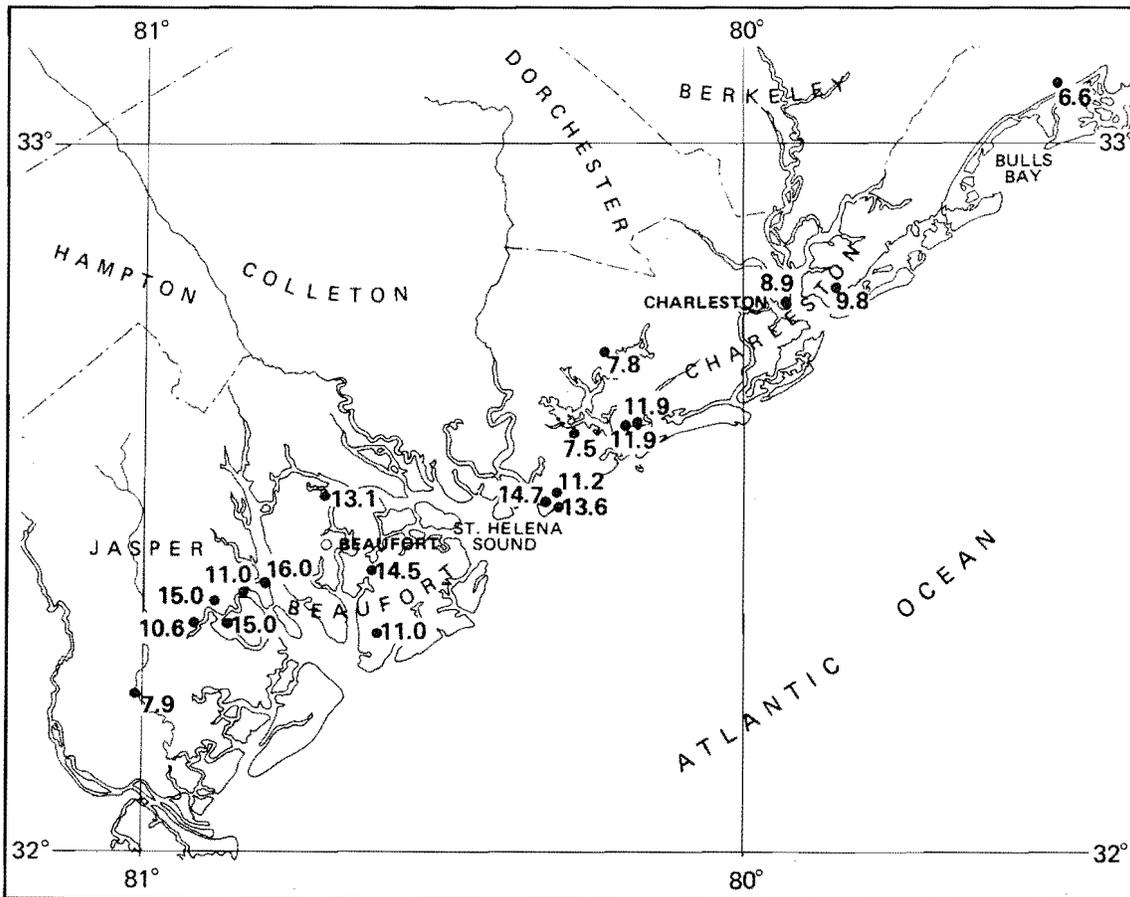
Figure 5.—High-water marks, hurricane of Aug. 11, 1940, obtained by National Ocean Survey field party in 1971 (ft above National Geodetic Vertical Datum of 1929).

ft, 1929 datum (fig. 5), on the open coast near Edisto Beach. After the hurricane, the beach appeared to have a flatter slope. About 175 cottages were destroyed on Edisto Island. On Folly Island, the maxium tide, determined from a National Ocean Survey (NOS) bench mark, was 8.3 ft MSL. The entire beach front eroded an average of 75 ft and there was considerable damage to property. At Charleston, S.C., most of the damage was done to buildings, wharves and boats along the waterfront. Large areas of the city's low waterfront perimeter were inundated and many automobiles were damaged by the storm tide. The tide reached its maximum height at about 3 p.m., and high-water marks recovered by NOS in 1971 indicated this height to have been 8.9 ft 1929 datum. Estimated damage to the city was $1.5 million (1940 prices). Sullivan's Island, Isle of Palms and Lawleys Island suffered minor damage. Myrtle Beach escaped with no noticeable damage. Overall, this hurricane killed 34 people and caused damage estimated at $6.6 million (Corps of Engineers 1957).

As part of the overall assignment to assess tide frequencies on the South Carolina coast, the National Ocean Survey, NOAA, sent survey parties into the field to locate high-water marks of historical hurricanes and level these to bench marks where feasible. The Aug. 11, 1940 hurricane is not included in Harris' (1963) compendium of hurricane tide values, and high-water marks from this storm, which produced the highest tides of record in parts of Beaufort County, have not been published before. The high-water marks obtained by the NOS party in 1971 for this hurricane are shown in figure 5. The reference datum is the National Geodetic Vertical Datum of 1929, defined in Chapter 6.

Oct. 15, 1954

Hurricane Hazel entered the coast just north of Myrtle Beach, S.C., and was one of the most destructive hurricanes, in terms of property damage. Hurricane winds hit the Atlantic Coast between Georgetown, S. C., and Cape Lookout, N.C., and storm tides devastated the immediate ocean front of this stretch of coast. Every fishing pier from Myrtle Beach to Cedar Island, N.C., a distance of 170 mi, was destroyed. High tides of 16.6 ft MSL were observed at Holden Beach Bridge and Calabash, N.C. The lowest recorded barometric pressure of 938 mb was reported at Little River Inlet on the South Carolina-North Carolina border. At Cherry Grove Beach, a 17-ft MSL tide destroyed all front-row houses and washed some second-row houses from their foundations. At Tilghman Beach, Ocean Drive, Crescent Beach, Atlantic Beach, and Windy Hill, S.C., practically all front-row houses were destroyed or damaged, with waves breaking at housetop heights along some of the beach front. At Myrtle Beach, high-water marks at "Edgewater Apartments" near 16th Avenue South indicated a tide height of 15.5 ft MSL. The highest wind gust at Myrtle Beach AFB was 106 mph. It is estimated that wind and water combined badly damaged or destroyed about 80 percent of the beach front property in the Mytle Beach area. At Surfside and Garden City, S. C., hundreds of houses were destroyed by tides in excess of 13 ft MSL. On Pawleys Island, S. C., 75 percent of the houses on the beach were badly damaged and 10-ft waves covered the northern and southern ends of the island, as well as low-lying areas in the middle. At Georgetown, sections of the streets were inundated. Folly Island, Sullivans Island, and Isle of Palms suffered

light property damage and slight beach erosion. No serious damage was
done at Charleston. Total property damage was estimated at $34 million
in North Carolina, $27 million in South Carolina. Advance warnings
enabled people to evacuate the threatened areas and only one person was
killed in South Carolina as a result of this storm. After devastating
the coast, hurricane Hazel moved across North Carolina with diminish-
ing winds, passing through Virginia and heading northward toward Lake
Ontario and Canada (Corps of Engineers 1957).

The coastal tide profile for Hazel is plotted in figure 2. Wind charts
and other meteorological data on this storm have been published by Graham and
Hudson (1960, pp 85-103).

Sept. 29, 1959

Hurricane Gracie entered the Beaufort County coast about 11:30 a.m. The
eye of the hurricane passed over St. Helena about 10 mi east of Beaufort.
Damage of disaster proportions occurred in the coastal region from Beaufort
to Charleston, S.C., and considerable additional damage occurred in the
Walterboro-Bamberg sections. An enormous number of trees were felled, causing
considerable random damage, and there was a great deal of crop damage,
especially to unpicked cotton. Seven fatalities are attributed to the storm,
but only two injuries. Beaufort MCAAS reported lowest pressure of 950 mb.
Gracie followed a path northwestward to Bamberg, then changed to north-north-
westward and passed west of Columbia (Purvis and Landers 1973).

"Hurricane force" winds struck Charleston on the morning of the 29th. It
is not known if the wind exceeded the previous record in the 1911 hurricane.
Power failed when the wind had reached 48 mph from the northeast and was
still increasing at the Weather Bureau Office (U. S. Weather Bureau,
Charleston, S.C., 1959).

The storm arrived at low tide at Charleston but still produced the sixth
highest storm tide of record (tables A-1 and A-2). Charleston marigrams
for the storm are shown in figure 1. Low areas of the city were flooded with
from 1 to 2 ft of salt water (U. S. Weather Bureau, op.cit.)

CHAPTER 4: CLIMATOLOGY OF HURRICANE CHARACTERISTICS

Introduction

To calculate tide frequencies on the South Carolina coast by the joint
probability method we need an appraisal of

   a) how often hurricanes pass
   b) their direction of motion
   c) their speed of motion
   d) their central pressure (an index of the intensity of the storm)
   e) the radius of maximum winds (an index of the lateral extent of the
       storm).

The significance of each of these parameters and its appraisal for the South Carolina coast is the subject of this chapter. The data are taken from the original work of Ho, Schwerdt, and Goodyear, who made a climatological analysis of hurricane parameters along all of the Atlantic and gulf coasts of the United States. Their final report [Ho et al. 1975] includes a few revisions and adjustments not carried back to the present work. These revisions do not siginificantly affect computed storm tide heights on the South Carolina coast. A sumary of the climatological analysis methods is given here. The reader is referred to the cited report for additional details.

Frequency of landfalling hurricanes and tropical storms

A key parameter is the frequency with which hurricane storm tracks intercept the coast. Figure 6 shows a count of landfalling hurricanes by 50 n.mi. coastal

HURRICANES	Brunswick, Ga.	Ga.-S.C. border	Charleston	Myrtle Beach	S.C.-N.C. border
88-year track count (1886-1973)	1	3	6	3	2	4
Yearly average from count	.011	.034	.068	.034	.023	.046
Smoothed yearly average	.023	.028	.035	.040	.044	.046

HURRICANES AND TROPICAL STORMS

Smoothed yearly average	.051	.058	.064	.066	.070	.072

-100   -50   0   50   100   150   200

Distance from Ga.-S.C. border (n.mi.)
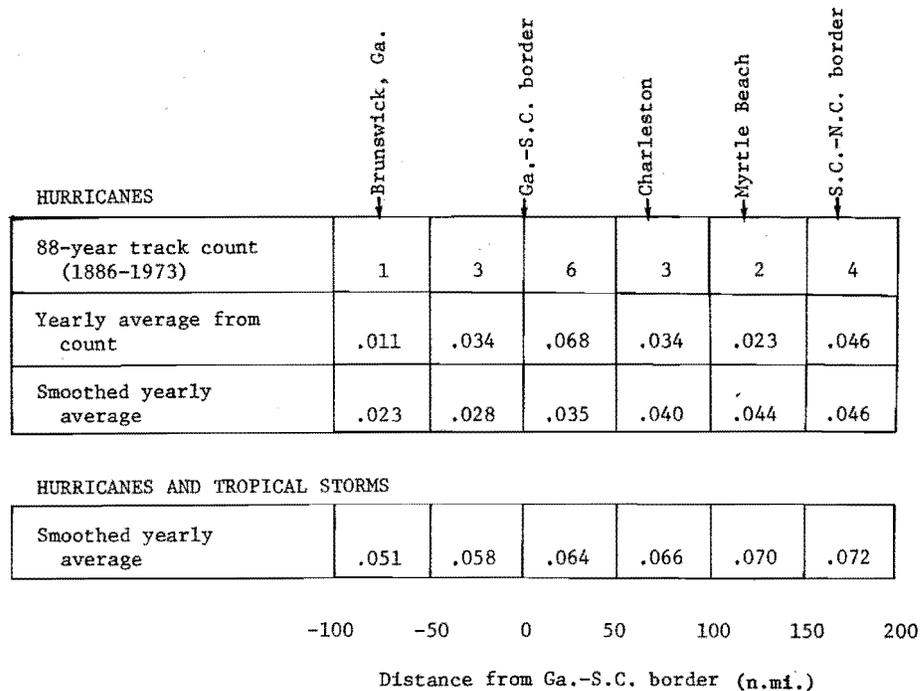
Figure 6.--Landfalling frequency of hurricanes and tropical storms per 50 n.mi. of coast. Track count from track maps by Cry (1965) and the Monthly Weather Review. Smoothed averages from graphs by Ho et al. (1975).

segments from Cry's track charts (Cry 1965), Monthly Weather Review articles the last few years, and the smoothed frequency from the Climatology Report based on the same track charts. Comparing line 2 and line 3 in the figure, the past hurricane experience has been smoothed down in Beaufort County from 0.068 to 0.035 hurricanes per 50 n.mi. per yr, but has been smoothed up in the Charleston and Myrtle Beach areas. The smoothed frequency of hurricanes plus tropical storms, used later, is also shown.

Frequency of alongshore hurricanes and tropical storms

Many hurricanes in the Atlantic recurve from their low-latitude east-to-west track and veer off north-northeastward or northeastward. Some of these pass parallel to the South Carolina coast. Those that are close in contribute to high tides on the coast. To assess these, track crossings of increments of lines perpendicular to the coast were counted and smoothed. The smoothed frequency of alongshore hurricanes plus tropical storms opposite Charleston is 1.6 tracks per 100 yr over the first 10 n.mi. from the coast, then 2.1, 2.7, 3.3, 3.4, and 3.4 crossings per hundred years per 10 n.mi. normal to the coast out to 60 n.mi. These frequencies increase slightly along the South Carolina coast from south to north.

Probability distribution of hurricane central pressure

The driving force in producing hurricane winds is the horizontal pressure gradient driving the air toward low pressure at the center. The depression of the hurricane central pressure below ambient surrounding pressure is the universally used index of hurricane intensity. The square of the maximum wind speed is roughly proportional to this pressure depression. The average radial profile of sea-level pressure in Hurricane Hazel of October 1954 about the time of landfall of the storm center is shown in figure 7, from Graham and Hudson (1960).
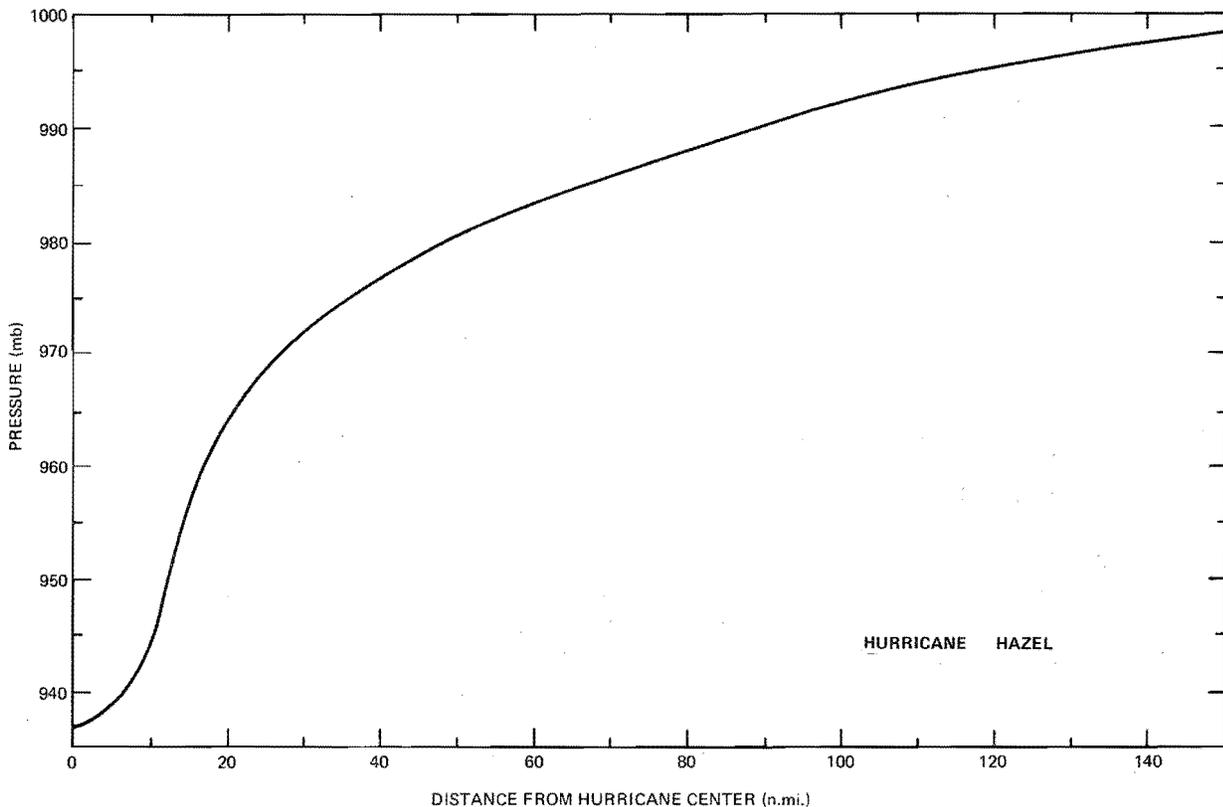
Figure 7.--Radial sea-level pressure profile, Hurricane Hazel, Oct. 15, 1954, at landfall. Adapted from Graham and Hudson (1960).

The central pressures at landfall of the storm center of all hurricanes
intercepting the United States east and gulf coasts since 1900 with central
pressures 982 mb or lower are listed by Ho et al. (1975). The central pres-
sures of hurricanes passing within 150 n.mi. at sea are also included in this
basic body of hurricane central pressure data. The central pressures from
this list within 200 n.mi. of Charleston, S.C. are plotted in figure 8 and an
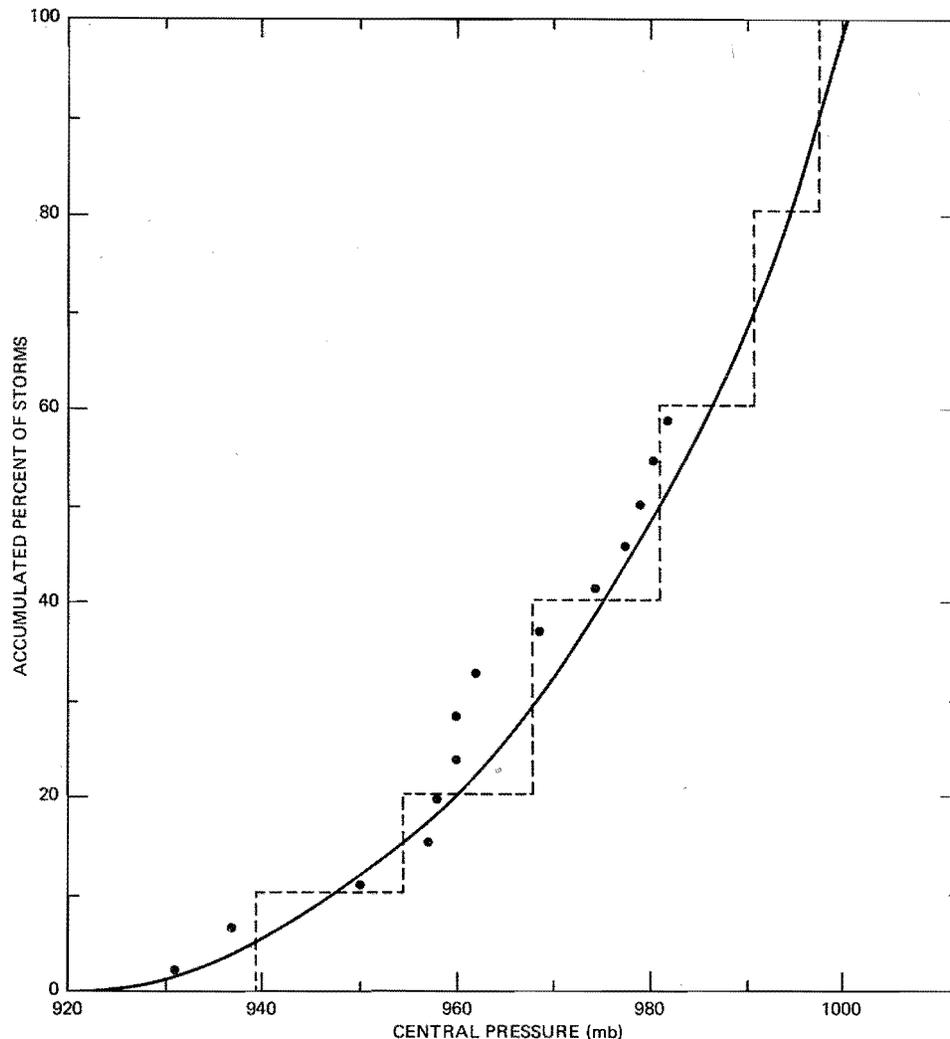
Figure 8.--Probability distribution of central pressures of hurricanes and
    tropical storms in Charleston, S.C., zone, 1900-1973.

accumulated frequency curve fitted by eye. The curve is extrapolated to
central pressures weaker than 982 mb to include the weaker storms statis-
tically.

The plotting position formula in this diagram and in similar diagrams for
other hurricane parameters is p = (m-0.5)/n, where p is the probability, m
the rank of an event from most severe to least severe, and n the total number
of events. From the curve it is seen that 10 percent of hurricanes in the

vicinity of Charleston have central pressures lower than 948 mb, 30 percent lower than 968 mb, etc.

For tide frequency analysis we divide this continuous distribution into six class intervals and let the central pressure at the middle of each class interval represent that class. This substitution is indicated by the dashed curve on the figure. For computation purposes the hurricanes are treated as if the most severe 10 percent all had central pressures of 939.5 mb, the second 10 percent 954.5 mb, then 20 percent with 968 mb, etc. These class interval representative values and their corresponding probabilities are listed in table 4-1.

Similar analyses were made for 400 n.mi.-long zones with a new over-lapping zone every 50 n.mi. and the resulting frequency curves adjusted for a smooth progression along the coast. By interpolation from this full set of frequency curves, the accumulated central pressure distribution applicable to any coastal point is obtained. The accumulated probability of hurricane central pressures obtained in this way applicable to the coast at the Georgia and the South Carolina-North Carolina borders is given in tables 4-2 and 4-3.
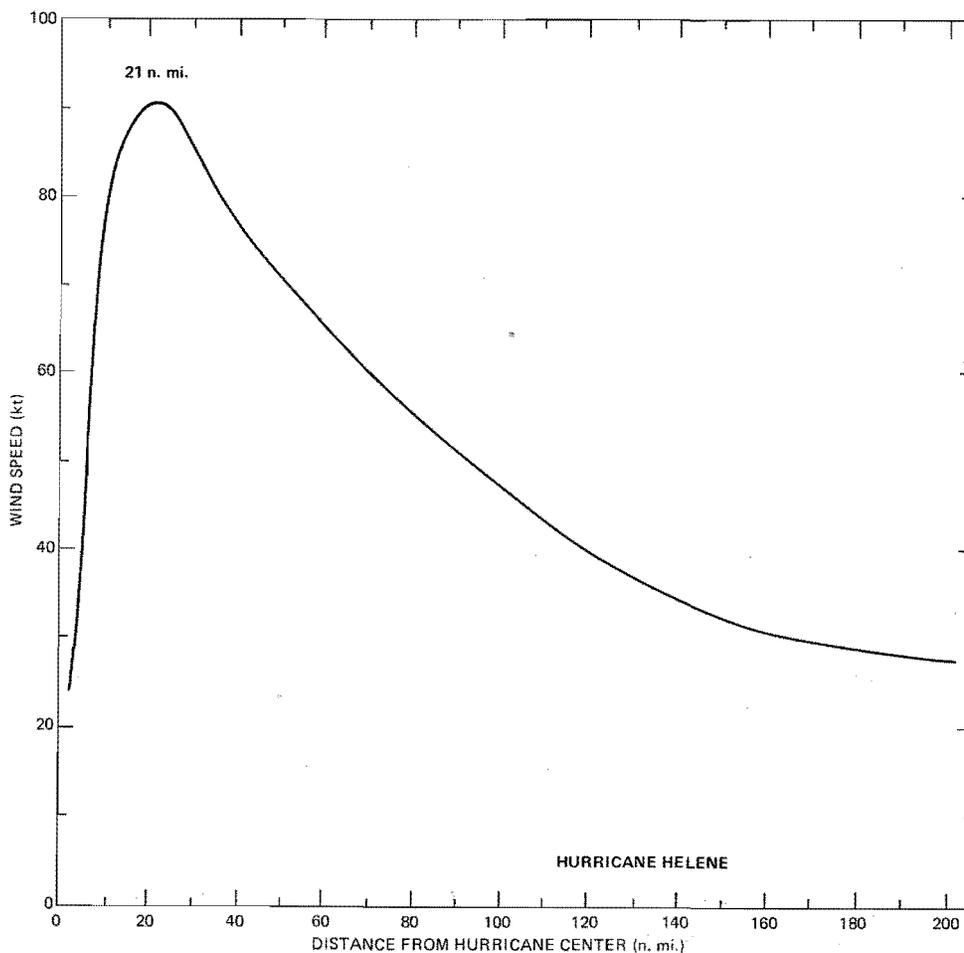
Figure 9.--Radial wind profile, Hurricane Helene, Sept. 27-28, 1958. Adapted from Schauss (1962, fig. 11a).
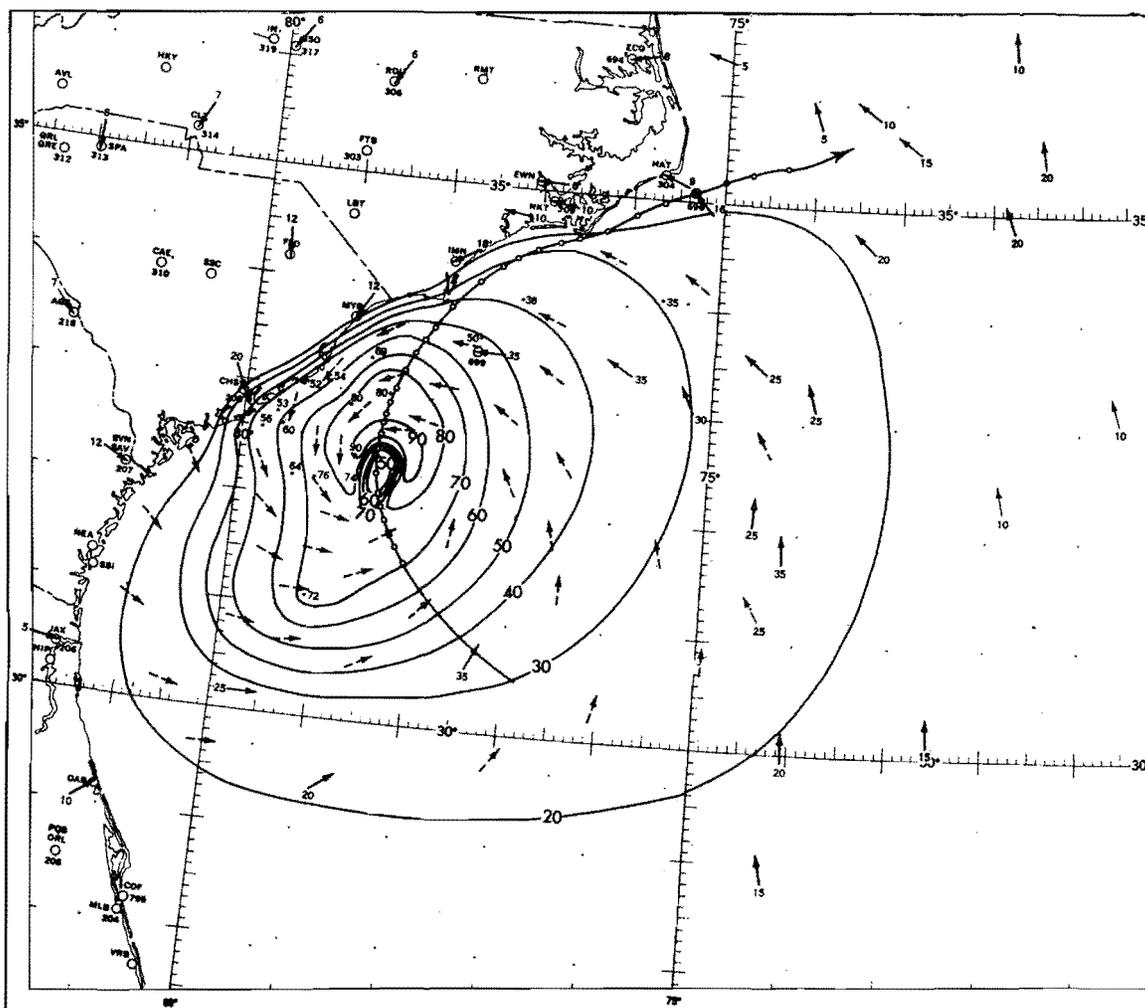
Figure 10.--Wind field (kt) of Hurricane Helene, 1100 EST, Sept. 27, 1958, from Schauss (1962, fig. 12a).

Probability distribution of radius of maximum winds

The radial wind profile in the right front quadrant of hurricane Helene of September 1958 about the time the storm was closest to the South Carolina coast is depicted in figure 9. This is from a detailed estimate by Schauss (1962). The shape of this profile is characteristic of well-developed hurricanes, rising rapidly from low wind speeds at the storm center to the maximum speed at the radius of maximum winds, R, then decreasing more slowly outward. The plan view of the wind speeds in this storm at the same time as estimated by Schauss is reproduced in figure 10. These winds are to be interpreted as averages over several minutes at 30 ft above the surface.

The radius of maximum winds in hurricanes affecting the United States coast since 1900 was subjected to a frequency analysis in overlapping zones in the same manner as central pressure. The plot for the zone centered on Charleston is shown in figure 11. There are fewer points on figure 11
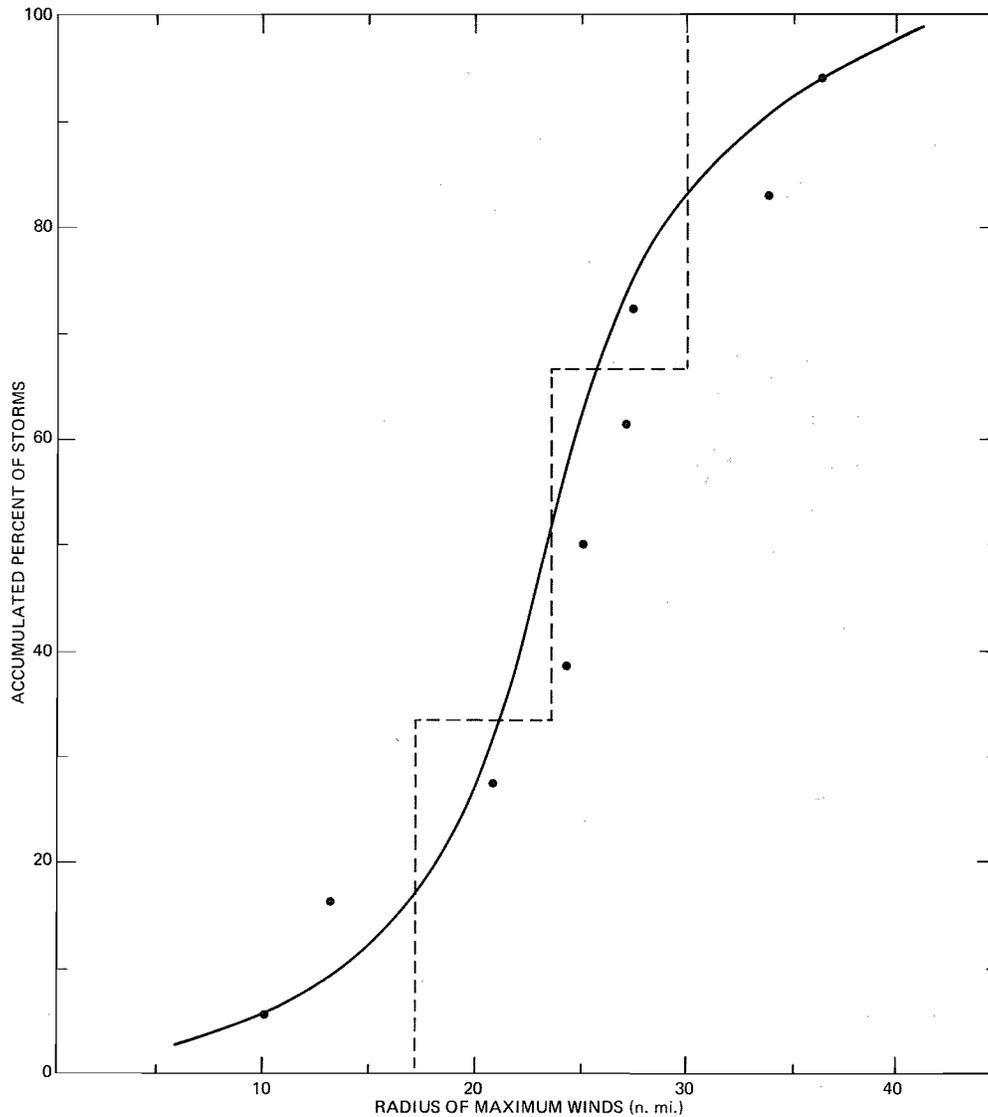
Figure 11.—Probability distribution of radius of maximum winds of
hurricanes, Charleston, S.C., zone, 1900-1973.

than on the corresponding central pressure diagram because reliable R
values could not be obtained for some storms.

For surge computations, the radii of maximum winds for landfalling
hurricanes are grouped into three classes represented by the midpoint
values indicated by the dashed curve on figure 11 and listed in table
4-1. Alongshore storms are less influential on overall storm tide
frequencies and only two R classes are used.

Probability distribution of hurricane forward speed

Forward speeds were scaled from track charts and a probability
analysis made as with the other parameters, except that landfalling and
alongshore storms were analyzed separately. The plots for the zone
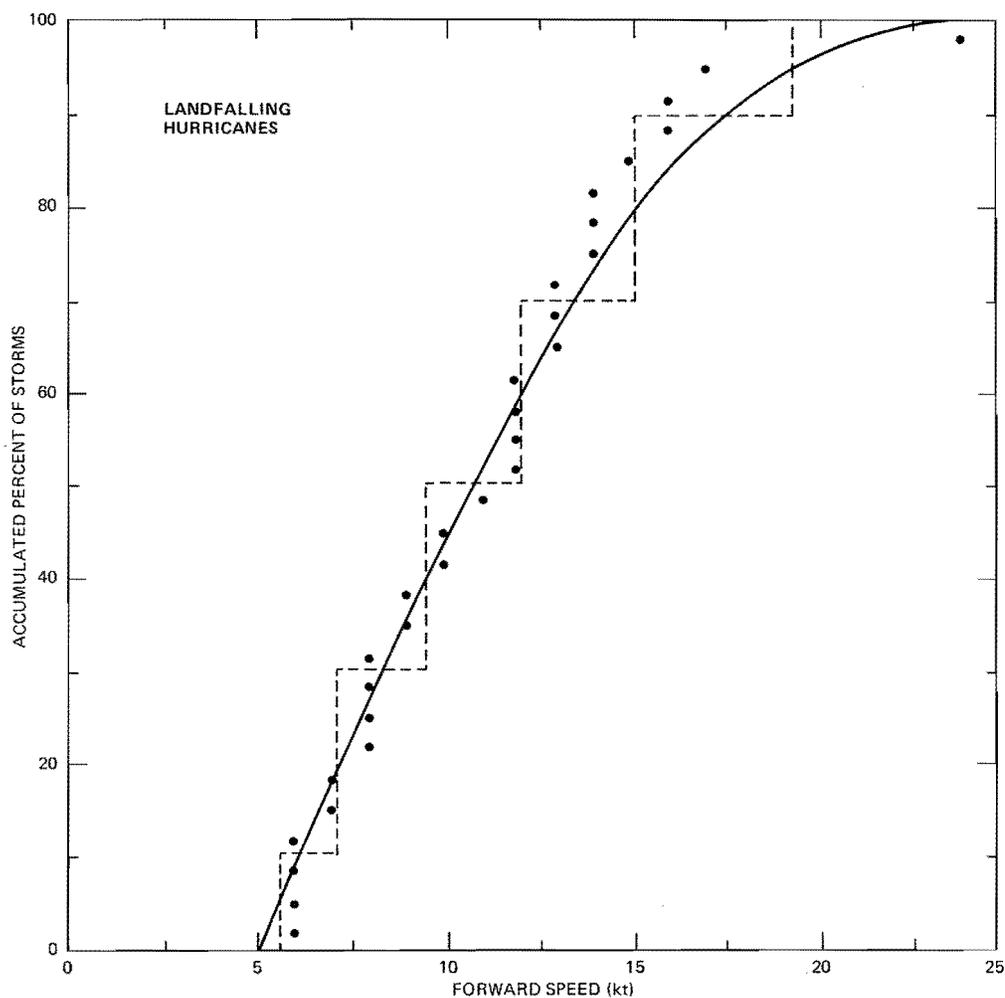
Figure 12.--Probability distribution of forward speed of landfalling
hurricanes, Charleston, S.C., zone, 1886-1973.

centered on Charleston are shown in figures 12 and 13. The points are
more numerous than for the central pressure distribution because the
record has been extended back from 1900 to 1886 and includes all hurri-
canes classed as such by Cry (1965) without any limitation on the
central pressure. The alongshore storms move slightly faster than the
landfalling storms as would be expected. The grouping into class
intervals for surge computation is shown by dashed lines as before and
is listed in table 4-1.

Probability distribution of direction of forward motion

An analysis was made of direction of forward motion, restricted to
landfalling storms. For this, all tracks of both hurricanes and tropi-
cal storms since 1871 were used, it being assumed that the direction-of-
motion behavior of tropical storms differs little from that of hurricanes.
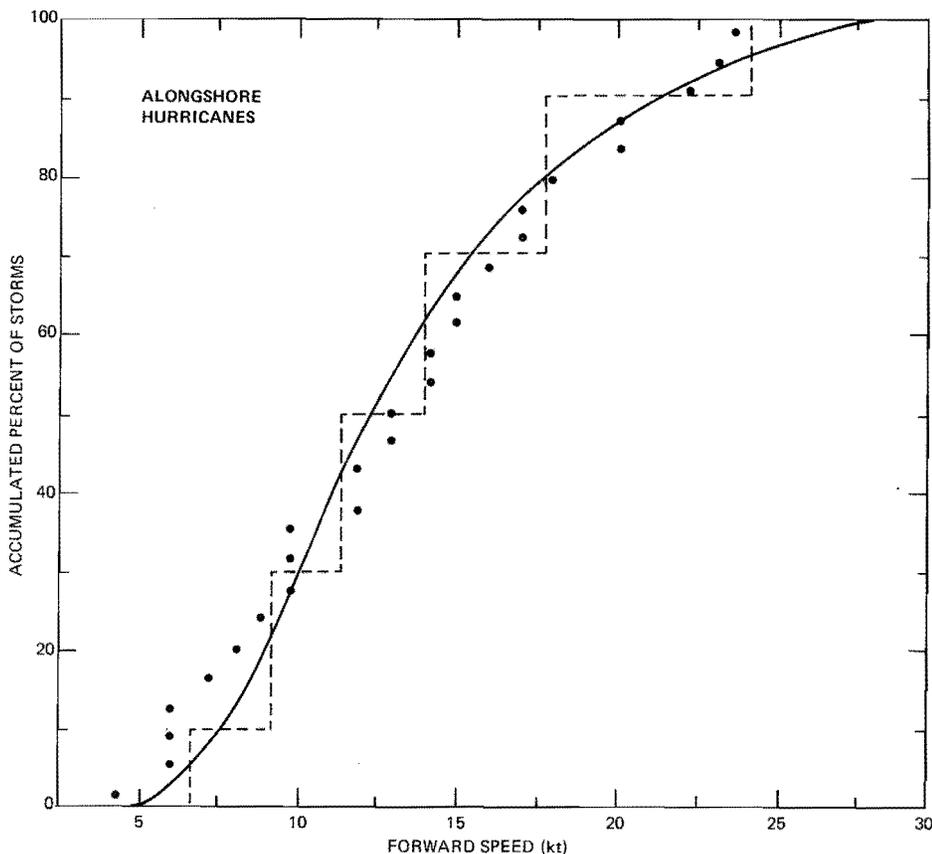
Figure 13.--Same as figure 12 for alongshore hurricanes.

The corresponding accumulated probability plot opposite Charleston is depict-
ed in figure 14. The grouping by class intervals is depicted by a dashed
curve on the figure and listed in table 4-1 as before.

For dynamic calculations of surges, alongshore storms are treated as if
they were moving exactly parallel to the coast.

Interdependence of parameter probability

Storm surge frequency synthesis by the joint probability method includes
answering the question of whether the four distributions--central pressure,
radius of maximum winds, forward speed, and direction of motion--are suffic-
iently statistically independent that they may be considered so. Ho et al.
(1975) noted that, considering all of the hurricanes of the east coast, there
appears to be a negative correlation between central pressure, p_o, and radius
of maximum winds, R. A plot of p_o vs. R limited to South Carolina hurricanes
(not shown) however gives a random scatter. Figure 15 reproduces the relation-
ship curves from Ho et al. with assumed "no correlation" curves for the range
of South Carolina storms superimposed. In the tide frequency analysis for
South Carolina, p_o and R are treated as independent.
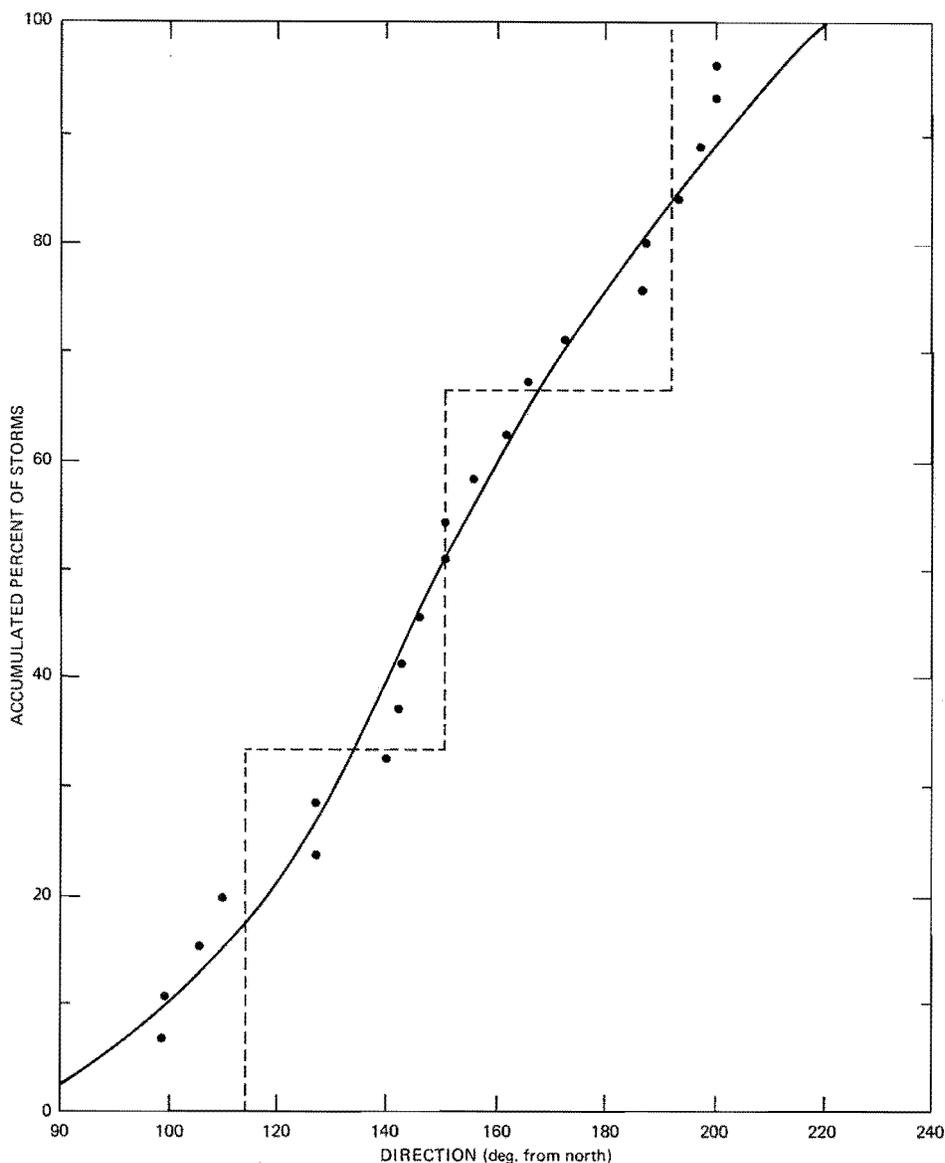
Figure 14.—Probability distribution of direction of forward motion of landfalling hurricanes and tropical storms in Charleston, S.C., zone, 1871-1973.

The other main joint probability question is whether direction of storm motion and forward speed are correlated. This is taken care of in part by providing separate forward speed probabilities for landfalling and along-shore storms, respectively. The difference in these probabilities is slight, suggesting further refinement of the interrelationship is unwarranted.

We assume that p_o and R are essentially independent of direction and speed of motion, over the ranges of these parameters on the South Carolina coast.
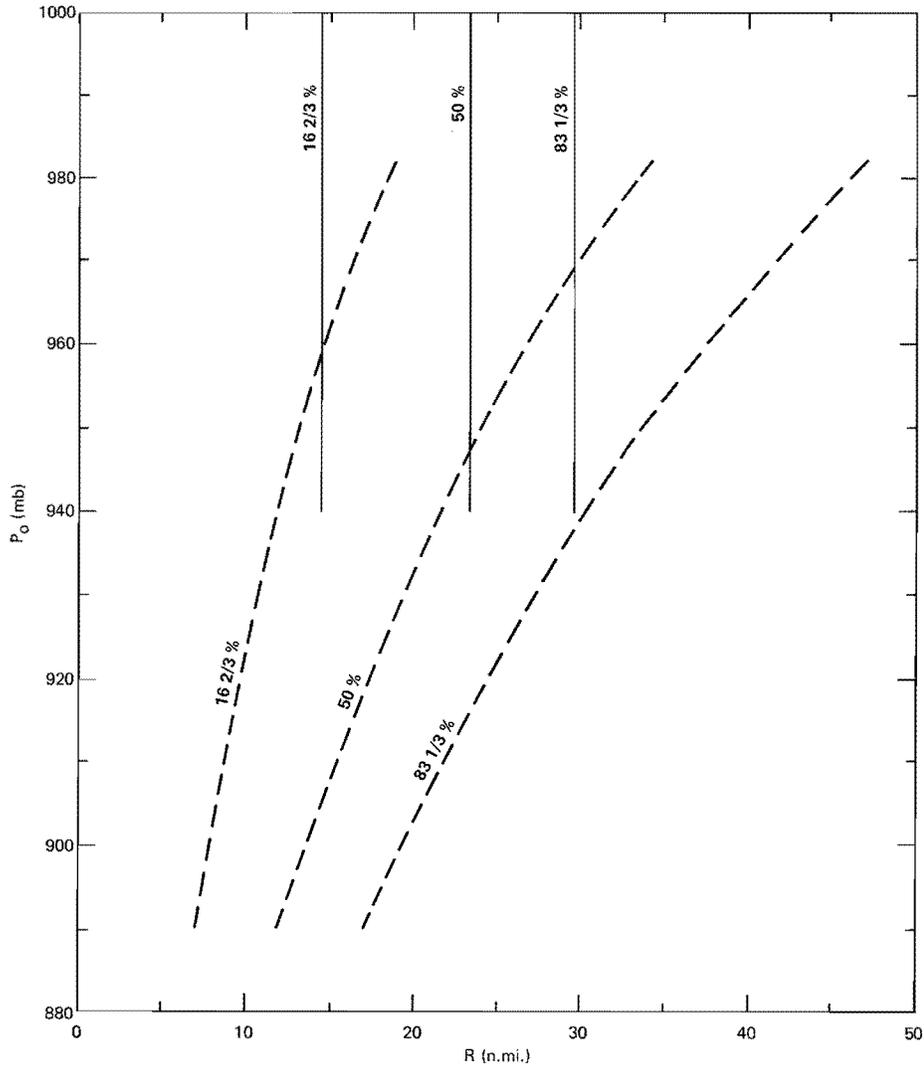
Figure 15.—Accumulated probability of hurricane R vs. P_O. Dashed,east coast of United States from figure 32 of Ho et al. (1975). Solid, assumed at Charleston, S.C., for tide frequency analysis.

Hurricane parameter tables

The process of analyzing hurricane parameters described for Charleston, S.C., was repeated for overlapping zones each 50 n.mi. along the coast. The respective curves were then adjusted for smooth progression along the coast. Interpolation between the curves gives the hurricane parameter prob- bability distributions corresponding to any coastal location. The hurricane parameters found in this way are listed in tables 4-2 and 4-3 for the Georgia-South Carolina-North Carolina borders. Such tables are included in all NOAA flood insurance reports.

Interpretation of hurricane parameter tables

The variety of hurricane and tropical storms that might some day enter the coast near Charleston, S.C., is infinite. The left part of table 4-1 approximates the infinite population of landfalling storms by a finite set 6 x 6 x 3 x 3 = 324 hypothetical storms (6 pressure depressions, 6 forward speeds, 3 Rs, 3 directions of motion, each moving at constant speed in a straight line). Each parameter represents a range. For example, the 10 percent of storms with largest pressure depression are assigned a "p_o" of 939.5 mb. The true range extends from 947.3 mb down to some unknown low value.

Each of the 324 storms represents a definite fraction of all storms, obtained by multiplying the four parameter probabilities. For example, moderately deep, moderately fast, moderately large storms approaching from the SSE are represented in table 4-1 by

$$p_o = 954.5 \text{ mb}$$
$$f = 15.1 \text{ kt}$$
$$R = 23 \text{ n.mi.}$$
$$\theta = 99 \text{ deg. to coast}$$

This member of the 324-member set has a probability of

$$.1 \times .2 \times .33 \times .33 = .0022$$

The sum of the 324 probabilities is 1.0.

Similarly, the alongshore storm population is represented by

$$6 \times 6 \times 2 \times 6 - 432 \text{ storms.}$$

A systems analysis might show that the resolution of one or more storm parameters into fewer class intervals would be permissible and adhere to the goal of holding numerical approximation errors in tide frequencies (errors from procedure only as distinguished from basic data and assumptions) to 0.1 ft. The saving in computer time by modifying the class interval would be modest and such an analysis has not been made.

The final key parameter in table 4-1 is the landfalling frequency, F_n, for all storms. To obtain the frequency of landfalling storms having characteristics within certain bounds, multiply F_n by the ratio of these storms to all storms.

Comparison with 1970 study

The basic approach to hurricane climatology is the same as in the earlier Atlantic City, N.J., report (Myers 1970, Chap. III). The refinements applied here, from the work of Ho, Schwerdt, and Goodyear (1975) include extension of the procedure to all of the coast, updating and revision of the basic data for individual storms, and careful attention to along-coast gradients. The count of landfalling storms is based on a more substantial sample than in the earlier study.

Legend

P_o = Central pressure in mb.

D = Central pressure deficit in mb. 1013.2 − P_o.

P_i, P_f, P_r, P_θ = Proportion of total storms with values centered at D, f, R, and θ_L, respectively.

F_n = frequency of landfalling storms, tracks per n. mi. of coast per yr.

f = Forward speed of storm in kt.

R = Distance from center of storm to principal belt of maximum winds, in n. mi.

θ_c = Directon of coast, clockwise from north, in deg.

θ_L = Direction of entry, measured clockwise from coast, in degrees.

L = Effective distance perpendicularly outward from coast, in n. mi. (mid-points for intervals 0 to 10 statute mi, 10 to 20 statute mi., etc.)

F_b = Average number of alongshore storms per yr that pass through the intervals centered at L.

Note: Alongshore storms have the same value of P_o, D, and P_i as landfalling.

Table 4-1.--Hurricane and tropical storm parameters -- Charleston, S.C.

				Landfalling storms F_n = .00130					
P_o	D	P_i	f	P_f	R	P_r	θ_c	θ_L	P_θ
939.5	73.7	0.1	5.6	0.1					
954.5	58.7	.1	7.2	.2	17	0.33		62	0.33
968.0	45.2	.2	9.5	.2	23	.33	49	99	.33
981.0	32.2	.2	12.2	.2	30	.33		144	.33
991.0	22.2	.2	15.1	.2					
997.2	16.0	.2	19.2	.1					

		Alongshore storms			
L	F_b	R	P_r	f	P_f
4	.015			6.6	0.1
13	.023			8.6	.2
22	.024	20	0.5	10.8	.2
30	.025	27	.5	13.5	.2
43	.054			17.6	.2
61	.064			23.5	.1

Legend - see page 38.

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Table 4-2.—Hurricane and tropical storm parameters —
South Carolina - Georgia border

Landfalling storms
$F_n = .00122$

P_o	D	P_i	f	P_f	R	P_r	θ_c	θ_L	P_θ
941.5	71.7	.1	5.2	.1					
956.6	56.6	.1	7.2	.2	16	.33		63	.25
971.0	42.2	.2	9.1	.2	22	.33	30	88	.25
983.7	29.5	.2	11.5	.2	29	.33		110	.25
992.1	21.1	.2	14.4	.2				134	.25
997.0	16.2	.2	17.6	.1					

Alongshore
storms

L	F_b	R	P_r	f	P_f
4	.0120			6.3	0.1
13	.0157			8.1	.2
22	.0174	19	.5	10.2	.2
30	.0216	26	.5	12.8	.2
43	.0561			16.7	.2
61	.0698			22.0	.1

Legend - see page 38.

Table 4-3.--Hurricane and tropical storm parameters --
South Carolina - North Carolina border

			Landfalling storms $F_n = .00142$						
P_o	D	P_i	f	P_f	R	P_r	θ_c	θ_L	P_θ
936.5	76.7	.1	5.6	.1					
951.3	61.9	.1	7.6	.2	19	.33		64	.33
965.1	48.1	.2	9.6	.2	25	.33	54	109	.33
977.8	35.4	.2	12.9	.2	31	.33		139	.33
987.9	25.3	.2	16.4	.2					
996.9	16.3	.2	21.7	.1					

		Alongshore storms			
L	F_b	R	P_r	f	P_f
4	.018			7.6	.1
13	.022			10.2	.2
22	.023	22	.5	12.3	.2
30	.027	28	.5	15.1	.2
43	.063			19.7	.2
61	.069			26.2	.1

Legend - see page 38.

CHAPTER 5:   HURRICANE SURGES FROM DYNAMIC MODEL

Description of model

As a hurricane moves over the continental shelf, a rotating mound of water develops under it, with scale size governed by storm size. It is imperceptible, of course, to the observer on a ship at sea. The main driving force in producing this mound is the wind of the storm. An important second force in deep water is the "inverted barometer" phenomenon; that is, the hydrostatic rise of the water surface in compensation for the lower atmospheric pressure. As the mound of water moves toward the shore it is amplified dynamically by the sloping ocean bottom and produces high tides. The inverted barometer effect no longer holds directly. If the wind is directed strongly toward shore, and if the mound of water does not lag the storm, the effect is accentuated. A model to calculate the height of such storm-induced water levels on the shore from hurricanes was alluded to in Chapter 2 (Methods 6 and 7). Simplified hurricane parameters of central pressure, radius of maximum winds, forward speed, and direction of motion, together with the bathymetry of the sea bottom and coastal orientation, are the only inputs. The model generates idealized wind and pressure gradient fields from these parameters; the winds and pressure gradients, in turn, are inputs to calculating the reaction of the water. This model, its theoretical basis, and its practical application and testing have been described in several reports (SPLASH Report, Jelesnianski 1966, 1967; Jelesnianski and Taylor 1973). The original motivation for this work was to predict coastal flood levels as part of the warning service of the National Weather Service when a hurricane approaches. This technique of surge computation has been found useful in calculating tide frequencies synthetically for flood insurance purposes from the climatological data on hurricanes.

The model, while complex, involves many simplifications of the real natural phenomena. These are discussed in the cited reports. Even if a perfect model were attainable, it would not make perfect surge predictions because perfect atmospheric input data are not available. The model has been named SPLASH, and we will refer to it by that name.

Distinction of surge and tide

The SPLASH model calculates the storm-induced portion of the rise of the water level—the storm surge. The normal astronomical tide is then added to this to obtain the total water level, as described in Chapter 7.

Bathymetry

In its present form, SPLASH makes calculations at successive time steps at a rectilinear grid of points and requires a straight coast as a boundary. To apply this model to real coasts, the coast is transformed to a straight line and corresponding adjustments made to the offshore water depth lines. This process has been described by Barrientos and Jelesnianski (1973). Briefly, the bathymetry lines are drawn such that they are at the same distance from the hypothetical straight coast that the real bathymetry lines are from the real curved coast. In this transformation, areas are conserved

but angles are distorted. Tangents have been drawn to the coast at 50 n.mi.
intervals, and the bathymetry out to 76 n. mi.from the coast, or to the
300-ft water depth, has been normalized to this tangent as just explained. In
doing this, features of the sea bottom of less than grid dimensions—4
statute mi.—are smoothed out because the dynamic model is designed to respond
to scales the size of small hurricanes and up. For illustration, the upper
part of figure 16 shows the ocean depth contours for an area centered on
Charleston, S.C., from nautical charts (National Ocean Survey, b,) while
the lower part of the figure shows smoothed bathymetry lines adjusted to
a straight coast as contained in the SPLASH input data.
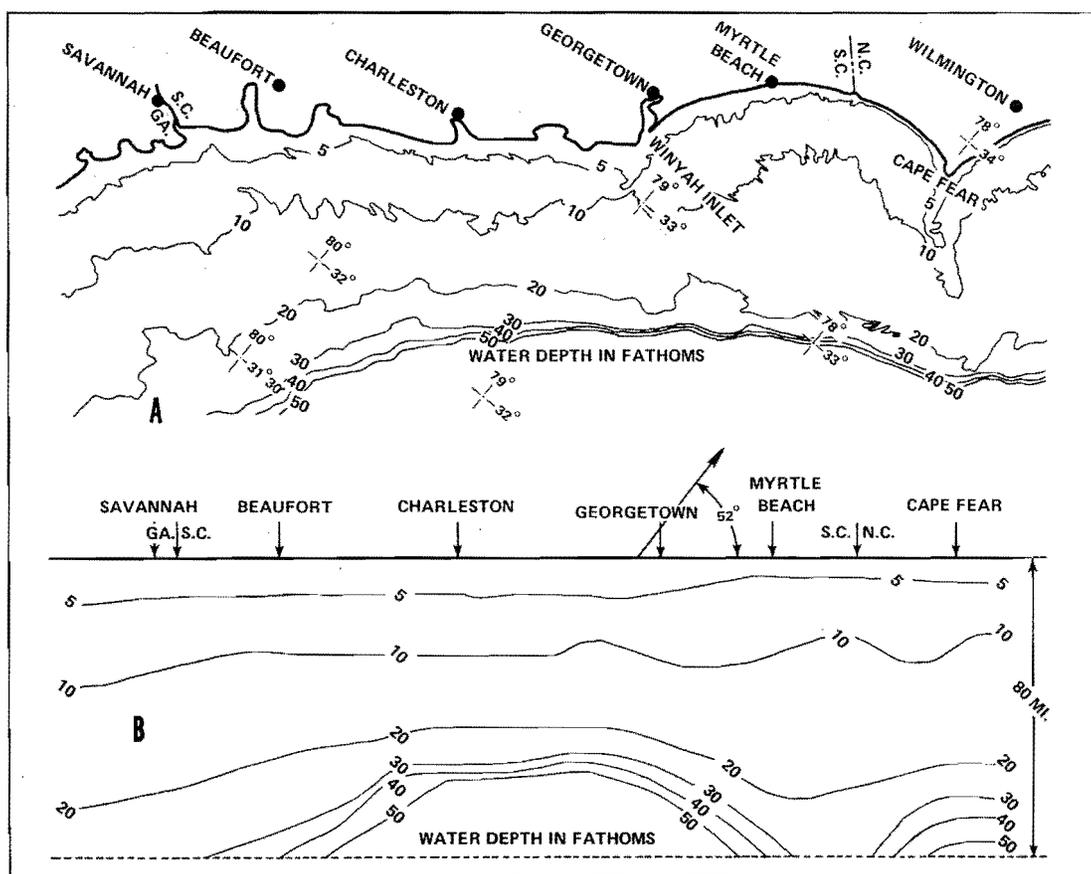
Figure 16.—Water depth off South Carolina. A. Actual from National Ocean
Survey charts. B. Smoothed and rectified to straight coast for surge
computations by SPLASH model. (From unpublished data by Barrientos and
Jelesnianski.)

Classes of hurricanes

The surge dynamics are different for hurricanes moving into the coast
over the continental shelf, and for storms moving essentially parallel to
shore. Therefore, "landfalling" and "alongshore" hurricanes are treated
separately in surge computations. Storms whose tracks make an acute angle
of 20 deg., or less, to the coast are treated as "alongshore." This
separation of hurricane classes by track direction has already been made in

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the compilation of climatological parameters (Chapter 4). The greatest risk
of inundations on the South Carolina coast is from landfalling hurricanes.
Alongshore hurricanes make an appreciable contribution to the 100-yr tide
level, though much less than landfalling storms. The overall storm tide
frequency curve is obtained by adding together at each tide height the fre-
quencies from each of the two classes. A third class of storms, "exiting,"
is discussed at the end of the chapter.

Coastal surge envelope—landfalling hurricanes

The SPLASH model with given hurricane input parameters (central pressure,
radius of maximum winds, track, speed, and landfall point) computes the
resulting surge height at a grid of points over the continental shelf every
2.5 min. One line of grid points at (at 8-mi intervals)represents the coast.
The main interest in SPLASH computations, both for hurricane warnings and
flood-frequency analysis, is in the highest attained water level at each
point on the coast. Therefore, at each coastal grid point the highest
attained level is saved in computer memory and printed out as the alongshore
envelope over time of highest surge. An example of such an envelope is
shown in figure 17.
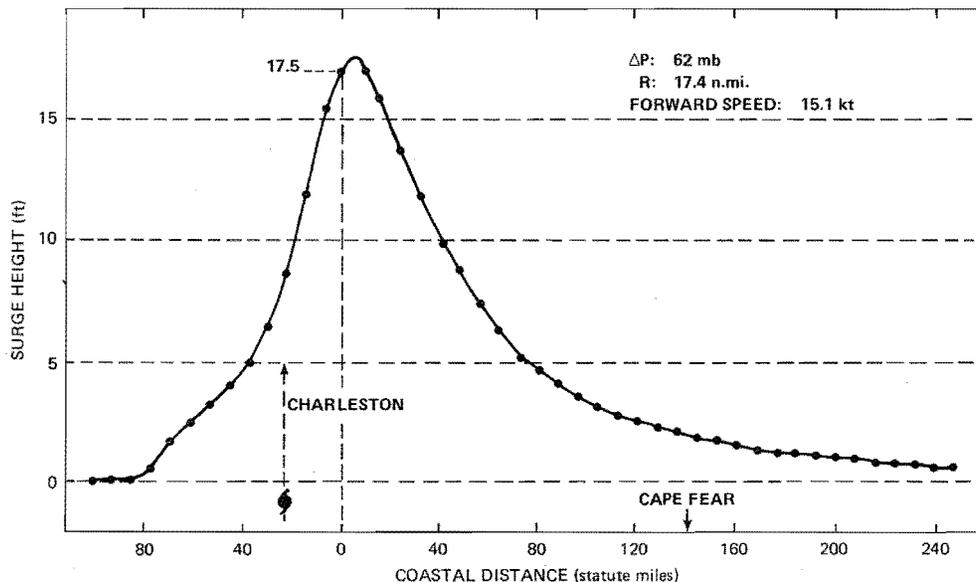
Figure 17.—Example of coastal maximum surge envelope computed by SPLASH
   model.

Short cuts in coastal surge envelope computations

In effect, a coastal surge envelope like figure 17 is obtained for each
of the hypothetical climatologically representative hurricanes, 324 hurri-
canes in the case of Charleston, table 4-1. However, these may be obtained
with greater economy of computer time than direct calculation of each one
separately. This is done by taking advantage of approximate linearities in
the variation of the surge height with the hurricane parameters. The
procedure followed for Charleston was as follows:

a. Make surge computations at a standard pressure depression of
    62 mb, 3 radii of maximum winds, a speed of 15 mph (12.8) kt),
    and 3 directions of approach (9 computations).

b. Compute surges at 62 mb pressure depression, median radius of
    maximum winds, median direction of approach, and 4 forward
    speeds (4 computations). Construct graph of maximum surge
    height vs. forward speed.

c. Extend the computations from a to other forward speeds by
    taking ratios from the curve constructed in b.

d. Adjust all computed surge profiles to each pressure depression
    in table 4-1 by assuming that the height of the entire surge
    profile is proportional to the pressure depression. This
    assumption is justified in the SPLASH report. (See fig. 1
    of that report).

e. In using the above procedure it is important to verify the
    assumption that the same relative variation of surge height
    with speed may be applied at different directions of approach.
    This should be used with caution and over limited ranges, but
    was considered valid for Charleston. Figure 3 of the SPLASH
    report, a nomogram of surge height variation with vector storm
    motion, gives guidance on the linearities involved. If the
    assumption is not adequate, graphs for each of the directions
    of approach can be computed as in step b.

Maximum surge height--alongshore hurricanes

A hurricane moving with uniform velocity strictly parallel to a hypothetic-
al straight coast with uniform slope of the bottom away from the coast,
produces the same maximum surge height everywhere along the coast once equi-
librium is reached. The height of this maximum surge, of course, depends
on the strength of the storm (indicated by central pressure), the radius
of the maximum winds, the forward speed, the distance of the storm track
from the coast, and the bathymetry. The computation of surges is more
troublesome than of landfalling storms; i.e., there is a greater tendency
for oscillations to develop that may or may not be spurious. This question,
including transient waves, is discussed by Jelesnianski (1967, 1972). At
the time the South Carolina tide frequency analysis, described here, was
made, the state of the art was to read out the maximum coastal surge as
a function of R, forward speed, and distance from coast at a standard pressure
depression from nomograms derived from a number of SPLASH runs. The
pertinent portions of the nomograms are reproduced in figure 18, with in-
structions. The results are adjusted for pressure depression by table 5-1
and are multiplied by shoaling factor from figure 19.
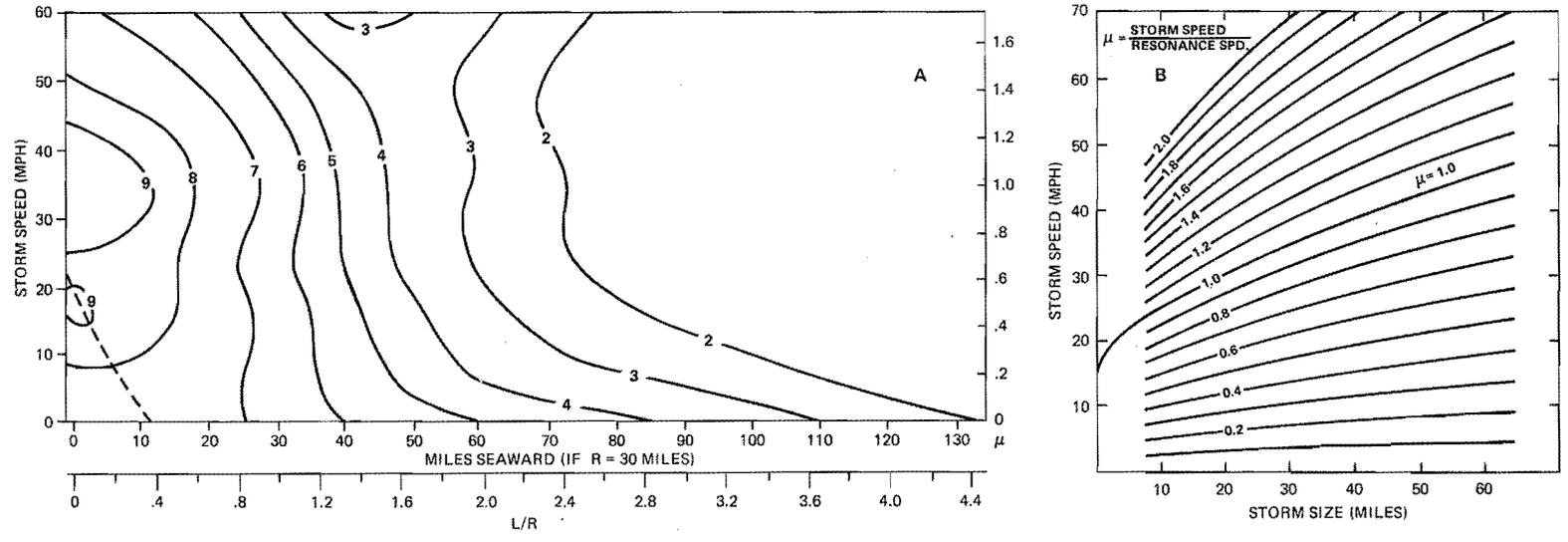
(a) For R = 30 statute miles (25.5 n.mi.) or close to this enter figure A with distance seaward, L, and storm speed, f, in units indicated. Read maximum surge (ft).

(b) For other R's enter figure B with R and f and read ratio μ. Enter figure A with μ and dimensionless distance from coast L/R on supplementary scales and read surge height.

Figure 18.--Maximum coastal surge height (ft) from alongshore hurricanes; standard basin, land to left of storm track, pressure depression 50 mb.

Table 5-1.--Adjustment of surge from alongshore hurricanes for pressure
depression.

D (mb)	Ratio to height from figure 18
10	0.16
20	.35
30	.56
40	.77
50	1.00
60	1.23
70	1.47
80	1.71
90	1.96
100	2.22
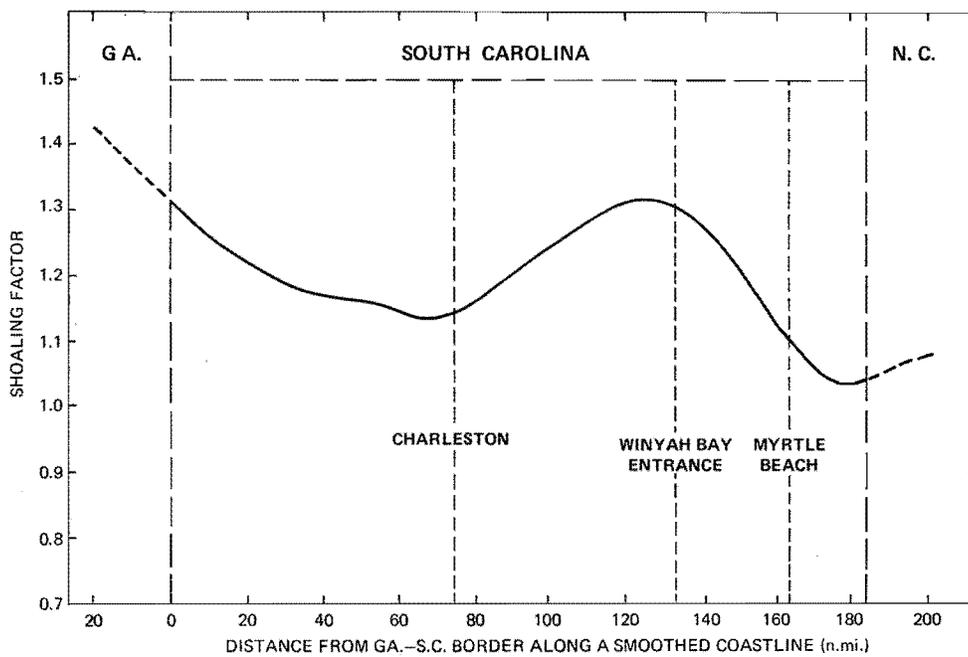
Figure 19.--Shoaling factor, South Carolina coast. Adapted from Barrientos
and Jelesnianski (unpublished).

Shoaling factor

The surge height that a hurricane of given intensity, size, and vector storm motion will produce on the coast varies with the bathymetry of the continental shelf. In general, the shallower the water, the higher the surge. The bathymetry effect on storm surges is handled by use of shoaling factors discussed under Method 5 in Chapter 2 and defined in Chapter 1. Profiles of the shoaling factor along the coast have been published by Jelesnianski (1972) with "standard hurricane" defined as a storm with a central pressure depression of 62 mb, and R of 30 statute mi, moving normal to the coast at 15 mph. The bottom of the "standard basin," from a 15-ft water depth at the coast, slopes downward at 3 ft per mi seaward. The portion of this shoaling factor curve for South Carolina is reproduced in figure 19. Unpublished shoaling factors for R = 15 mi were also available to us and confirmed that the relative shoaling factor is not significantly different from the figure.

The shoaling factor also varies modestly with angle of approach to the coast if the angle is not too acute (Jelesnianski 1972). The shoaling factor dependence of alongshore hurricanes is less certain and the landfalling shoaling factor is assumed to apply.

The procedure in NOAA's tide-frequency analyses, including the present one, is to compute the tide frequency at control points along the coast not more than 50 n. mi. apart and interpolated between, using the shoaling factor as a guide. Computations are made closer together where there is an abrupt change in the shoaling factor.

Time variation of surges

To combine calculated storm surges with the astronomical tide to find the maximum height of the combination, the time variation of both is needed as indicated by the example with hurricane Gracie in figure 1. The SPLASH program computes the surge height on the 4-mi grid every 2.5 min. The normal printed output includes only the enveloping values obtained by scanning the 2.5-min values at each coastal grid point for the maximum. For combining the surge profile and the astronomical tide for the indicated purpose of finding the maximum total, the assymetry of the rise and fall of the surge and the non-simultaneity along the coast of maximum surge height makes no difference. The only requirement is to know how long the surge remains above each height. A saving in computation time is made by precomputing the time variation from a number of SPLASH surge computations, then normalizing this to an approximation by two parameters. We carry forward the concept of "$t_{2/3}$" time variation index from the Atlantic City study (Myers 1970) but work up new nomograms to evaluate the index. In this concept, the time variation of the coastal surge is approximated by a Gaussian curve defined by two parameters: the maximum surge height S_x, (in ft)

and the duration that the surge exceeds 2/3 of S_x, $t_{2/3}$ (in hr). The surge, S, at time, t, is then given by

$$S = S_x \, e^{-.40547(2t/t_{2/3})^2} \tag{1}$$

where t is the time (in hr) after the occurrence of the maximum surge and $t_{2/3}$ is the time just indicated. This is illustrated in figure 20. For justification for this, the reader is referred to pp.31-32 and figure 3 of the earlier study.

Note that S_x in the equation is the time maximum at any coastal point. It is not the alongshore maximum, except at one point.

In the present study, the $t_{2/3}$ factor was scaled for each of the representative landfalling climatological hurricanes from figure 21, selecting the diagram with the closest R size. These nomograms are based on a number of SPLASH runs over a standard basin. For the alongshore hurricane $t_{2/3}$ was scaled from figure 22. This nomogram is a composite of a number of SPLASH runs at R = 30 statute mi. For Rs near this size the diagram is used directly. For smaller Rs the diagram is assumed to apply, using the two normalized scales.
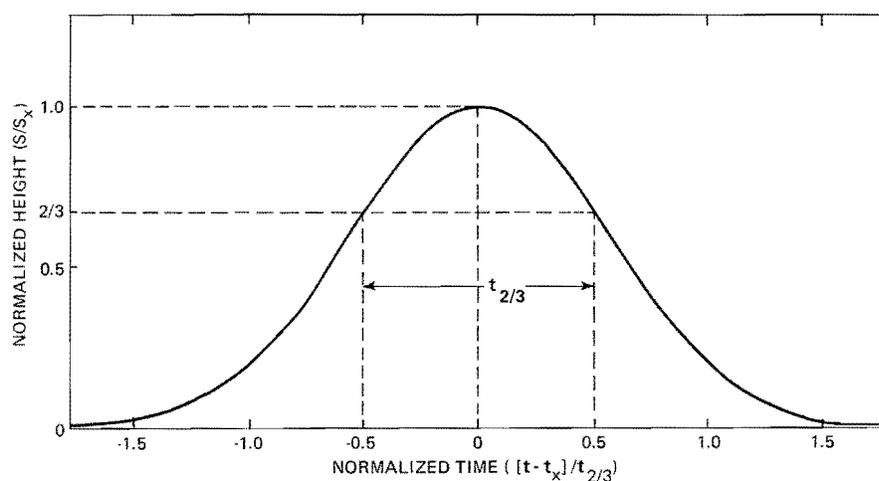
Figure 20.--Standardized time variation of hurricane surge.

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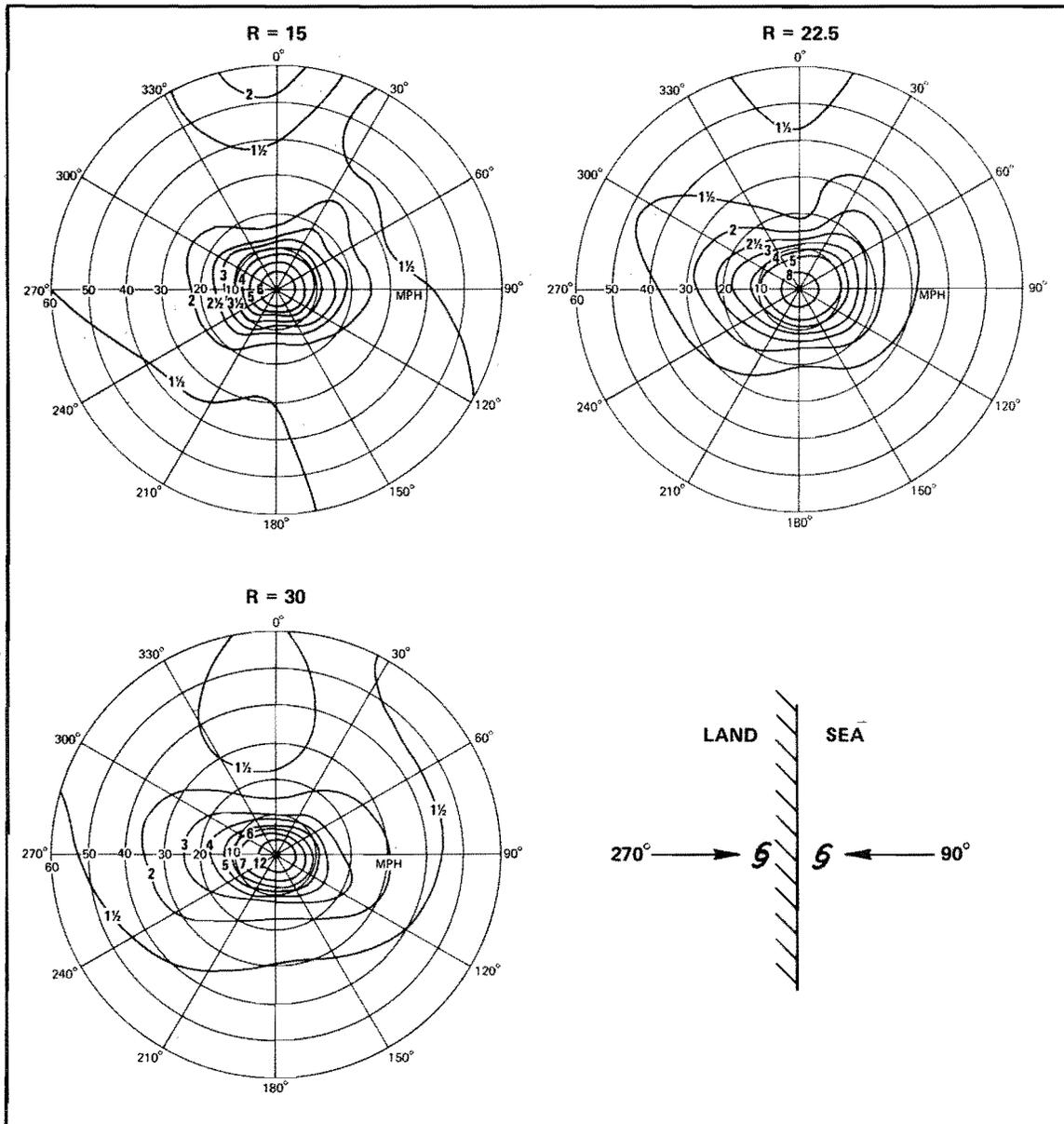
Figure 21.--Time scale factor ($t_{2/3}$ in hr) for storm surge, landfalling and exiting hurricanes, as a function of storm direction (degrees from coast), speed (mph), and radius of maximum winds, R (statute mi).
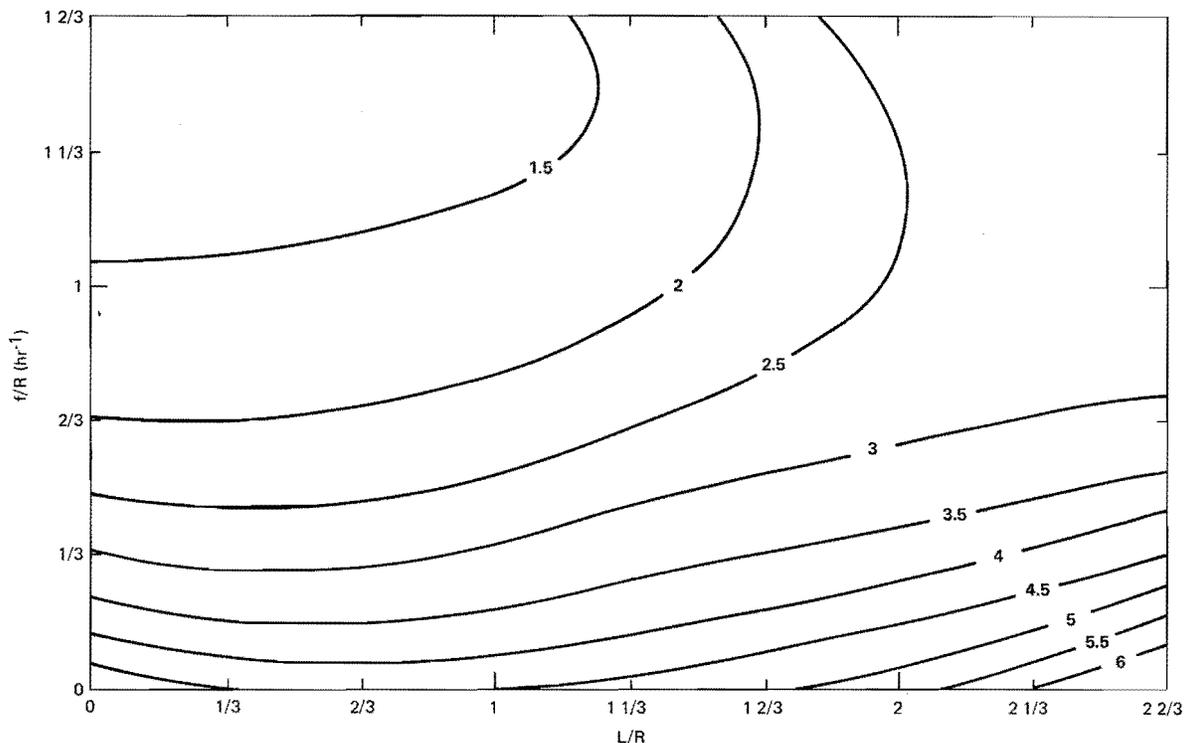
Figure 22.--Time scale factor ($t_{2/3}$ in hr) for storm surge, alongshore hurricanes, as function of storm speed, and distance of path from coast.

Exiting hurricanes

Hurricanes may leave a coast after entering at another point. Numerically, there are a considerable number of such storms that pass across South Carolina after having entered the coast on the northeastern shore of the Gulf of Mexico. A few storms also enter northern Florida from the Atlantic and then recurve over Georgia and South Carolina. Hurricane parameter statistics on these exiting storms are contained in the climatology report (Ho et al. 1975), and the surge resulting from these can be computed with the SPLASH model. These storms tend to have weakened, however. Their relative importance may be judged by obtaining maximum indicated surge heights from the nomograms in the SPLASH report in relation to p_o and R values. Doing this for the South Carolina coast suggests that the exiting storms are unimportant, and they are not considered further in this report. This exclusion applies to storms that exit the South Carolina or nearby Georgia coasts. Some of the storms tabulated as "alongshore" with respect to South Carolina crossed the Florida Peninsula earlier. An example is Donna of 1960, which "exited" to the Atlantic Ocean near Daytona Beach, Fla.

Difference from 1970 study

In the earlier study, surge profile envelopes like figure 17 were calculated by three steps: a) obtain peak of alongshore surge envelope as function of hurricane parameters, for a standard basin, by nomograms; b) adjust by Atlantic City shoaling factor [from Jelesnianski's earlier paper (1967)]; and c) approximate surge profile by a "$d_{2/3}$" distance scaling procedure analogous to the "$t_{2/3}$" time scaling procedure.

Beginning with the NOAA tide frequency studies made in 1973, the surge profile envelope is computed directly by a SPLASH computation rather than the "$d_{2/3}$" method. Local bathymetry is now available in input form for SPLASH along the Atlantic and Gulf coasts, for rectified basins centered every 50 mi (Barrientos and Jelesnianski 1973). Shoaling factor profiles based on this bathymetry are used to interpolate between tide frequency calculations at control points.

The nomograms for height of surge for alongshore hurricanes, figure 18, from Jelesnianski (1973), are improved in detail and theory and replace figure 4-8 of the Atlantic City report.

All "$t_{2/3}$" diagrams have been reworked. Figures 21 and 22 replace figures 4-4 and 4-10 in the old report.

CHAPTER 6: ASTRONOMICAL TIDE AND DATUM PLANES

Introduction

The state of the astronomical tide is an important factor in storm tide frequency analysis. This chapter summarizes the needed basic facts on the absolute level, range, reference datum planes, and trends in astronomical tide on the South Carolina coast.

Published values of astronomical tide

Astronomical tide levels are precomputed and published annually by the National Ocean Survey of NOAA in "Tide Tables, High and Low Water Predictions, East Coast of North and South America, including Greenland" (National Ocean Survey, a). These tables contain in the twice daily (in the study area) heights and times of high and low astronomical tide at certain reference stations and time and height differences to adjust these values to numerous subordinate stations. The reference stations for South Carolina are Charleston from Edisto Beach northward and Savannah River Entrance (Fort Pulaski, Ga.) south of this point. Difference constants for 100 subordinate stations in South Carolina are given in the 1974 volume. The rationale for the computation of the astronomical tide at the reference stations has been described in detail by Schureman (1958). The oscillation of the tide is regarded as the sum of a series of cosine wave constituents. The period of each constituent is calculated from astronomical geometry and depends on the relative position and motion of the moon, sun, and earth. The phase angle of each constituent is determined from the astronomical geometry and harmonic analysis of past tide records. The amplitude is derived from the harmonic analysis.

Tide observations

The National Ocean Survey maintains tide gages at the reference stations, abstract hourly tide levels, and makes these available to interested parties. The Charleston gage has been in operation since 1921 at the Customhouse, with an earlier record from 1900 to 1904, and the Savannah River Entrance gage since 1935. The adjustment constants to the subordinate stations are obtained by comparing simultaneous records from other gages, including special observations of at least one month from gages installed temporarily for this purpose. A catalog of the tide gages and tidal records on the South Carolina coast is contained in a report by Harris and Lindsay (1957). More recent information on control tidal stations may be obtained from the National Ocean Survey, Rockville, Md. 20852, Attention C331.

Astronomical tide range

The astronomical tide range increases from north to south on the South Carolina coast and is slightly greater in many estuaries than on the open coast. Mean and spring tide ranges from the published tide tables are:

	Tide range (ft)	
	Mean	Spring
Myrtle Beach	5.1	6.0
Charleston		
Sullivans Island	5.2	6.1
Customhouse Wharf	5.2	6.1
Ashley River, Greggs Landing	6.1	7.2
Edisto Beach	5.9	6.9
Savannah River Entrance	6.9	8.1

Datum planes

Several different references, or datum planes, are in common use for describing water and land elevations along the shore.

The National Geodetic Vertical Datum of 1929 refers to a particular geodetic surface determined by adjustment of selected leveling nets in the conterminous United States. Zero on this reference surface is close to but not identical with "local mean sea level" defined below. Land elevations on topographic maps are commonly referred to this datum.

Mean low water is the average height of all low waters over a 19-yr period. The principal tide generating constituents cycle through a complete set of combinations and variations during 19 yr. A particular 19-yr epoch is, therefore, adopted as a base period for tidal datum plane references (Marmer 1951, p. 63). All tide work under the jurisdiction of the National Ocean Survey is currently referred to mean water level planes

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during the epoch of 1941–59. "Mean low water" explicitly means the average
of all the low waters during that epoch, twice daily on the South Carolina
coast.   Nautical charts giving water depths, which are concerned with the
safety and convenience of boats, are commonly labeled as depth below mean
low water.

Local mean sea level is the average height of the surface of the sea,
usually observed at hourly intervals, during a base 19-yr epoch. This is
the primary reference datum for this and other NOAA tide frequency studies,
with the 1941–59 epoch as the base. Where the definition of "MSL" is not
stated this reference is understood. Where special sets of data are referred
to the National Geodetic Vertical Datum of 1929 or to mean low water, these
are explicitly identified.

Mean high water is the average height of the high tides during the base
19-yr epoch. Mean high water is a reference line with respect to riparian
land titles.

Gage zero is the point on a tide gage above which tide levels are measured
locally, then converted to one of the other datum plane references. The
gage zero is leveled to a fixed bench mark, thus gage zero has historical
continuity if the tide gage should be destroyed in a storm.

Differences between standard datum levels at the Charleston Customhouse
gage are given below:

	Ft above gage zero	Ft above local mean sea level
Mean high water (1941–59)	7.79	2.48
Local mean sea level (1941–59)	5.31	0.0
National Geodetic Vertical Datum of 1929	4.93	-0.38
Mean low water (1941–59)	2.59	-2.72
Gage zero	0.0	-5.31

Users of this report who need the difference between local mean sea level
datum and 1929 geodetic datum at various locations or bench marks can request
this information from the National Ocean Survey, Rockville, Md. 20852,
Attention C331.

Secular trend

Long period tide records on the east coast of the United States indicate
a general rise in sea level with respect to the adjacent land. The apparent
change in sea level has been ascribed to a combination of increase of
volume of water in the ocean from melting glaciers and to subsidence of
the land. We won't speculate here on the relative contribution of these
processes. Graphs depicting the variation in average annual sea level, rela-
tive to bench marks on adjacent land have been published by Hicks and Crosby
(1974). Their curves for Charleston, S.C., and Fort Pulaski, Ga., are

reproduced in figure 23. No adjustments are included in the present study for secular trend in sea level on the South Carolina coast. However, long-range planners should bear in mind that, extrapolating past trends on the east coast as a whole as well as at Charleston, sea level relative to the land is expected to continue to rise.
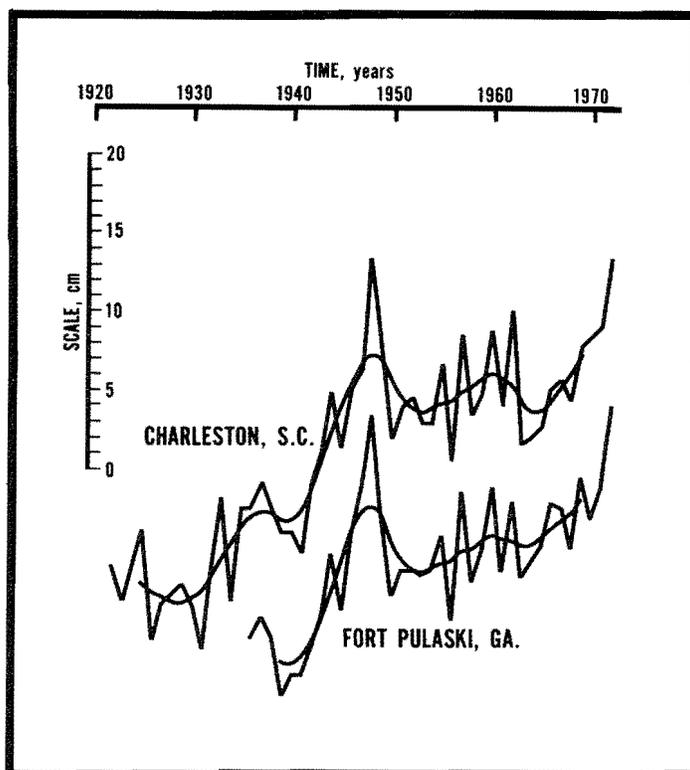
Figure 23.--Secular change in sea level with respect to adjacent land at Charleston, S.C., and Port Pulaski, Ga. [From Hicks and Crosby (1974)].

Annual trend

Local annual trend in average tide level at Charleston is depicted in figure 24. This is calculated from the semi-annual (SSA) and annual (SA) tide prediction harmonics (Schureman 1958) and is similar to the average observed curve published by Marmer (1951, p.53) for 1930-48. Similar annual trends are experienced along the rest of the coast and are presumably due to systematic annual variations in winds over the Atlantic Ocean. September tides are used as representative of the hurricane season.

Frequency distribution of high tides

The frequency distribution of astronomical high tide in September during the base epoch 1941-59 at the Charleston gage is shown in figure 25. This was computed for the present study by the National Ocean Survey by rerunning the standard tide computation program and forming a frequency distribution of the resulting high tides. For later computations the distribution is divided into four class intervals, as shown.
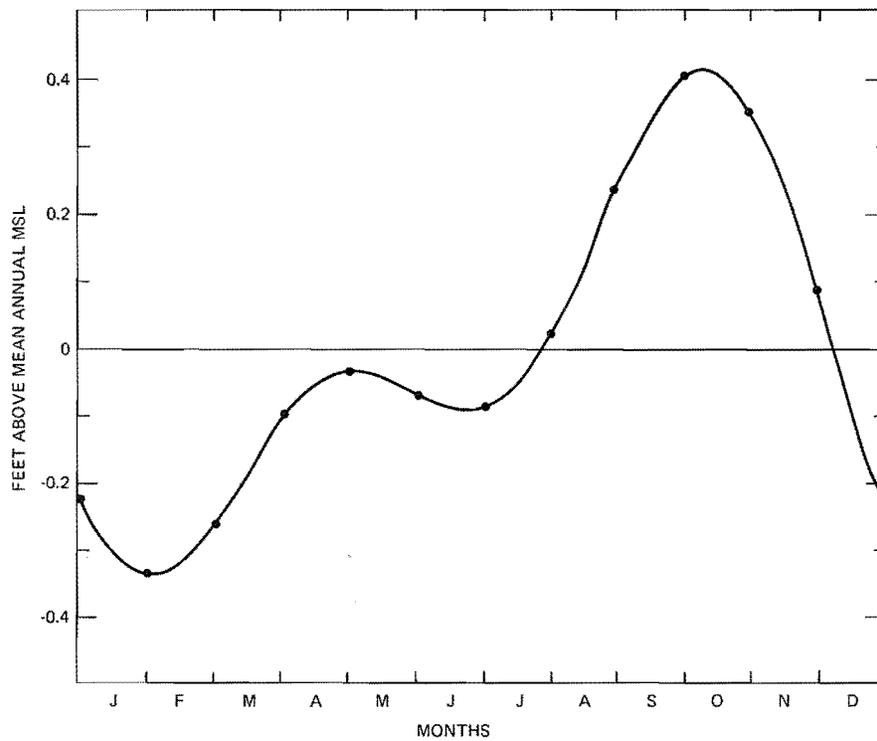
Figure 24.--Annual variation in sea level at Charleston derived from semi-annual (SSA) and annual (SA) tide prediction harmonics.
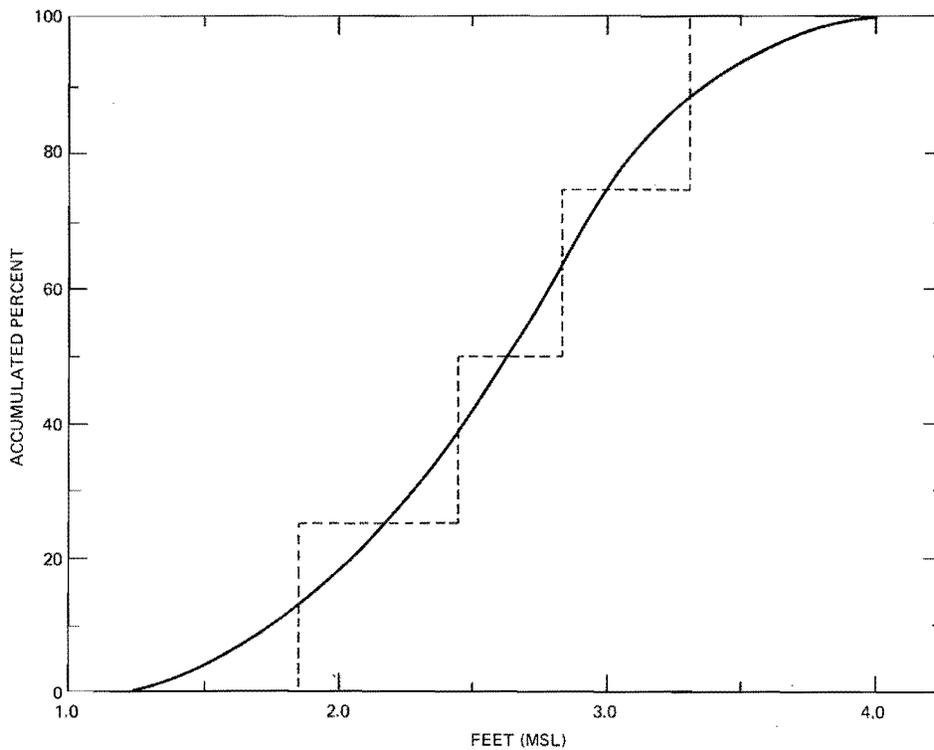
Figure 25.--Frequency distribution of astronomical high tide at Charleston, September 1941-59.

Time variation of astronomical tide

In the present study the representative astronomical tide marigrams needed for combination with each hurricane surge marigram were approximated as cosine waves with a period of 12.42 hr (one-half mean lunar day) oscillating about mean sea level, with the amplitudes scaled from figure 25 for the northern South Carolina coast. On the southern South Carolina coast, Fort Pulaski, Ga., data were used in a similar manner. This is the same procedure as in the Atlantic City study (Myers 1970). A planned refinement in future studies in regions of astronomical tide range of 5 ft or more is to start with the frequency distribution of low tides as well as high tides, instead of approximating low tide indirectly, as here.

CHAPTER 7: HURRICANE TIDE FREQUENCIES

Chapter 4 defined the climatology of key hurricane characteristics on the South Carolina coast in probabilistic terms. The calculation of the coastal surge from any particular hurricane, real or hypothetical, was the subject of Chapter 5. Chapter 6 summarized the basic facts needed with respect to the astronomical tide. The present chapter completes the task, combines the information from these three previous chapters, and completes the evaluations of the frequency of coastal storm tides.

Storm events and resulting tide

A "storm event" in this chapter is a particular hurricane with specified P_o, R, direction of motion, and speed. It landfalls at a specified coastal point or bypasses a specified distance at sea, at a specified time with respect to high and low astronomical tide, and at the time of the lunar month when the astronomical tide has a specified range. Each such storm event is at the middle of a class interval with respect to each of the seven specified characteristics and represents a definite fraction or probability of all possible storm events. This chapter illustrates how the maximum storm tide at Charleston, S.C., is calculated for two such storm events, one "landfalling" and one "alongshore," how the probability (fraction of all storm events) and frequency (expectancy per yr) is calculated, and how these frequencies from all storm events are combined into the frequency curve. NOAA has received a number of queries about this procedure. Details are illustrated in tables 7-1 and 7-2. The example storm event is specified in the first section of the tables.

Coastal surge envelope

The SPLASH computation prints out the highest surge value for a particular landfalling hurricane at 8-statute mi intervals along the coast. A smooth curve drawn to such output was depicted in figure 17. In computations only the discrete values at the 8-mi intervals are used. This is equivalent to approximating the smooth coastal envelope by a series of 8-mi long steps, as illustrated in figure 26. A stepwise profile like figure 26 is computed for each climatologically representative landfalling hurricane specified by the hurricane parameter table for the study point.

This is 6 x 6 x 3 x 3 = 324 profiles for landfalling storms influencing Charleston, table 4-1.
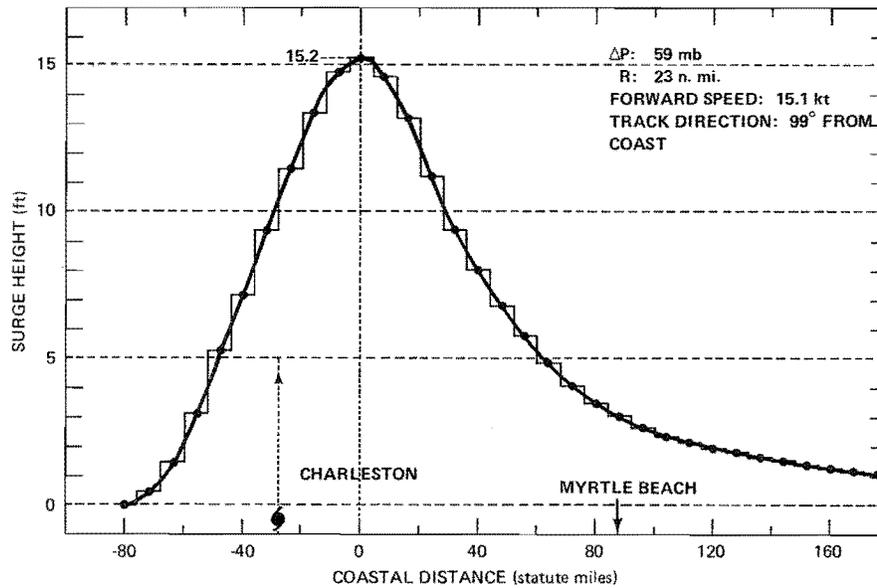
Figure 26.--Sample surge envelope for landfalling hurricane.

The coastal surge height is also computed at the point of interest for each climatologically representative alongshore hurricane--432 storms for Charleston. This is not a profile but simply the maximum surge height value. Conceptually, the only alongshore variation of the maximum surge from this type of hurricane event is the variation due to shoaling factor.

Variation of hurricane landfalling point

The maximum coastal surge from a landfalling storm is approximately at distance R to the right of the landfall point of the storm center. The SPLASH program will accept landfall points at fixed 4-statute mi intervals along the coast. In figure 26 the landfalling point was chosen 28 mi to the left of Charleston to maximize the surge at Charleston for the given storm. Other landfall points are equally likely. Rather than multiple SPLASH runs with varied landfall point, the variation is simulated by assuming that each of the 8-mi steps in figure 26 is a "surge event" that Charleston may expect, with proper adjustments. The two adjustments are: (a) Multiply the 8-mi segment surge height by the ratio of the local Charleston shoaling factor to the shoaling factor at the original point. This takes care of bathymetry variations. Shoaling factors are from figure 19; (b) the pressure depression probability may vary along the shore. To ensure that this is taken care of, multiply the surge height by the ratio of the pressure depression at the new landfalling point of the storm center to that at the original landfalling point. Approximate this ratio by comparing the central pressure depression at the 15 percentile level on curves like figure 8. Apply at all frequency levels. The illustrative example of this process is found in table 7-1B.

Time variation of surge

In order to combine hurricane surges and astronomical tide on a random basis as discussed under method 3 in chapter 2, the time variation of both is needed. It was explained in chapter 5 that, for computational purposes, the time variation of the surge would be assumed symmetrical about the time of maximum surge, according to equation (1) and related to the two parameters, S_x and $t_{2/3}$. This time variation applies to each of the coastal tide segments in figure 26, which is the time-maximum where it occurs, not just to the absolute time-and-space maximum. As an example, the time variation for the third segment to the left of Charleston in figure 26 is graphed in figure 27. The smooth curve shows the time variation from equation (1) with $t_{2/3}$ interpolated from figure 21. This is replaced by the step curve shown in the figure. The latter is stepped in equal time units of 1/80th mean lunar day, or 0.311 hr, to agree with the time division of the astronomical tide explained in the next paragraph.

Time variation of astronomical tide

The computational time variation of the astronomical tide was described in chapter 6 as a cosine curve with a wave length of one-half mean lunar day, 12.42 hr, and an amplitude twice that of the selected high tide. The time variation of the astronomical tide in our example "storm event" with upper quartile high tide from figure 25 is illustrated in figure 28 and the corresponding computational step representation in units of 1/80th mean lunar day. This provides 19 full steps from high tide to low tide and two half steps, at high and low tide, respectively.

Maximum storm tide

The next procedural step is to add the stepwise surge marigram like figure 27 and the stepwise astronomical tide marigram like figure 28 to obtain the stepwise total storm tide marigram. This process is illustrated in figure 29 and table 7-1C, for a particular time displacement. Scanning the total storm tide marigram of the figure yields the maximum tide for a "storm event" for which all seven variables have been specified.

The maximum combination of surge and astronomical tide always occurs when one is rising and the other falling, including the limiting cases of coincidence of maxima and/or minima (Myers 1970, p. 62). Since both are approximated by symmetrical waves, all possible combinations are recognized by combining only falling astronomical tide with rising surge, as depicted in figures 27, 28 and 29.

Frequency of landfalling storm events

The frequency of each landfalling storm event is calculated by the joint probability method, illustrated in table 7-1D. By our stepwise computational approximations, Charleson, S.C., will experience the same maximum storm tide probability method, illustrated in table 7-1D. By our stepwise computational approximations, Charleston, S.C. will experience the same maximum storm tide if the storm center landfalls anywhere within an 8-mi coastal span. To

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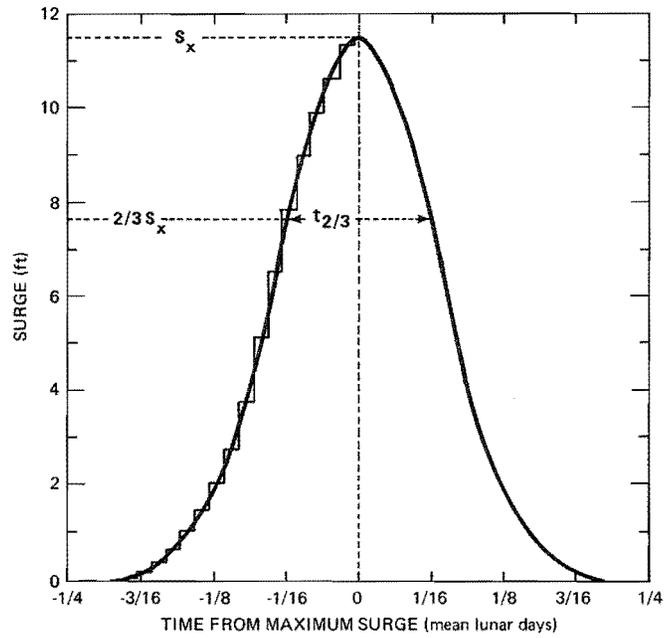
Figure 27.—Sample standardized time variation of hurricane surge.
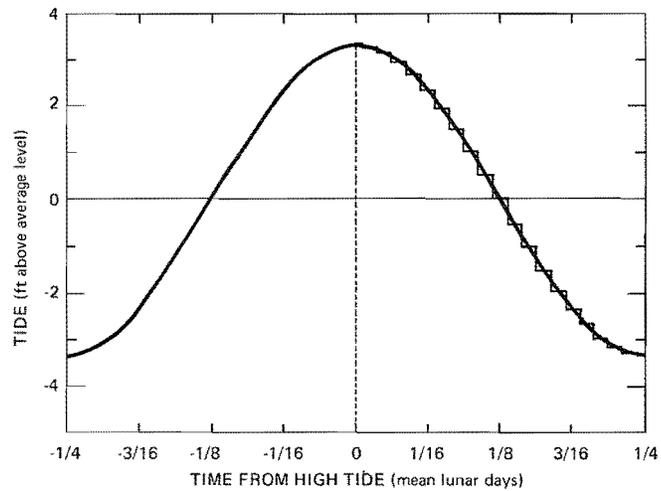
Figure 28.—Sample time variation of astronomical tide.
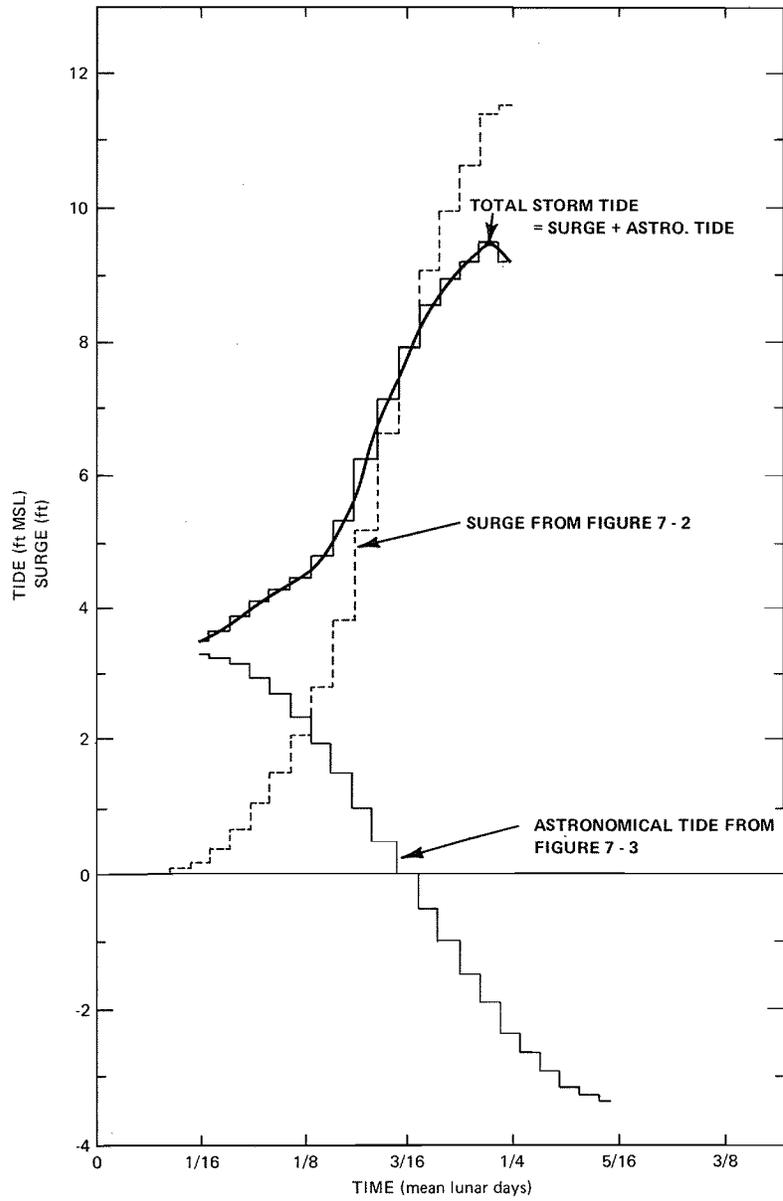
Figure 29.—Sample summation of astronomical tide from figure 27 and
hurricane surge from figure 28.

obtain the frequency of this hurricane landfall "event," multiply F_n, the landfalling frequency in storms per mi per yr, by the length of the segment. When a surge profile is shifted along the coast, F_n is adjusted also, step (b) in table 7-1D. The final step is to multiply this coastal segment landfalling frequency by the probability (fraction of all events) of the particular storm event. This is simply the product of the six individual probabilities, illustrated in the table.

Maximum storm tide for alongshore hurricane event

For alongshore hurricanes, the bypassing distance, L, is the significant parameter instead of the landfalling point. There are fewer computations because we are dealing with only six standardized distances from the coast (illustrated in table 4-1) rather than a multiplicity of 8-mi landfalling coastal segments. The maximum surge height for the given storm over a standard basin is scaled directly from figure 18 (which has been generated from a series of SPLASH runs) and then is adjusted for shoaling factor from figure 19 to the site, Charleston in our example, rather than making an explicit SPLASH calculation for the site. Alongshore adjustments are not involved. Having this maximum surge height for the storm event, the other steps--stepwise surge and astronomical tide marigrams, their summation, and extraction of the maximum storm tide--are exactly the same as for landfalling hurricanes except that a different diagram, figure 22, is used for obtaining $t_{2/3}$ scaling factor. This is illustrated in table 7-2, parts A - C.

Frequency of an alongshore hurricane event

The frequency of an alongshore hurricane event is handled in the same way as landfalling except that F_b is already specified in the table as storms per yr through an interval. It is the counterpart of the frequency per yr for landfalling storms after F_n is multiplied by the length of coastal segment. The probability of an alongshore hurricane event (fraction of all events) is the product of the same six probabilities as for landfalling storms. The process is carried out separately for each of the standardized distance-from-shore intervals. This process is illustrated in table 7-2D.

Construction of tide frequency distribution

A series of "bins" are set up in the computer program for each one-tenth-ft interval, from 2 ft MSL to beyond the maximum tide height expected. Frequencies are to be accumulated in these bins and all frequencies are initially set to zero. As each individual storm event maximum tide is computed, it is rounded off to the nearest one-tenth of a ft. The frequency of that event, computed as just explained, is added to the accumulated frequency in the corresponding bin. Thus, when all storm event maximum tides and their frequencies have been computed, the results have been summarized in an incremental table of frequencies of storm tides at one-tenth-ft class intervals. Finally, the frequencies are accumulated from the highest tide value down to obtain the usual "equals or exceeds" frequency distribution. This evaluation is normally done separately for landfalling and alongshore hurricanes and then the two frequency curves are added together; conceptually, this is not a requirement, and all storm events could be treated alike. Finally, taking the
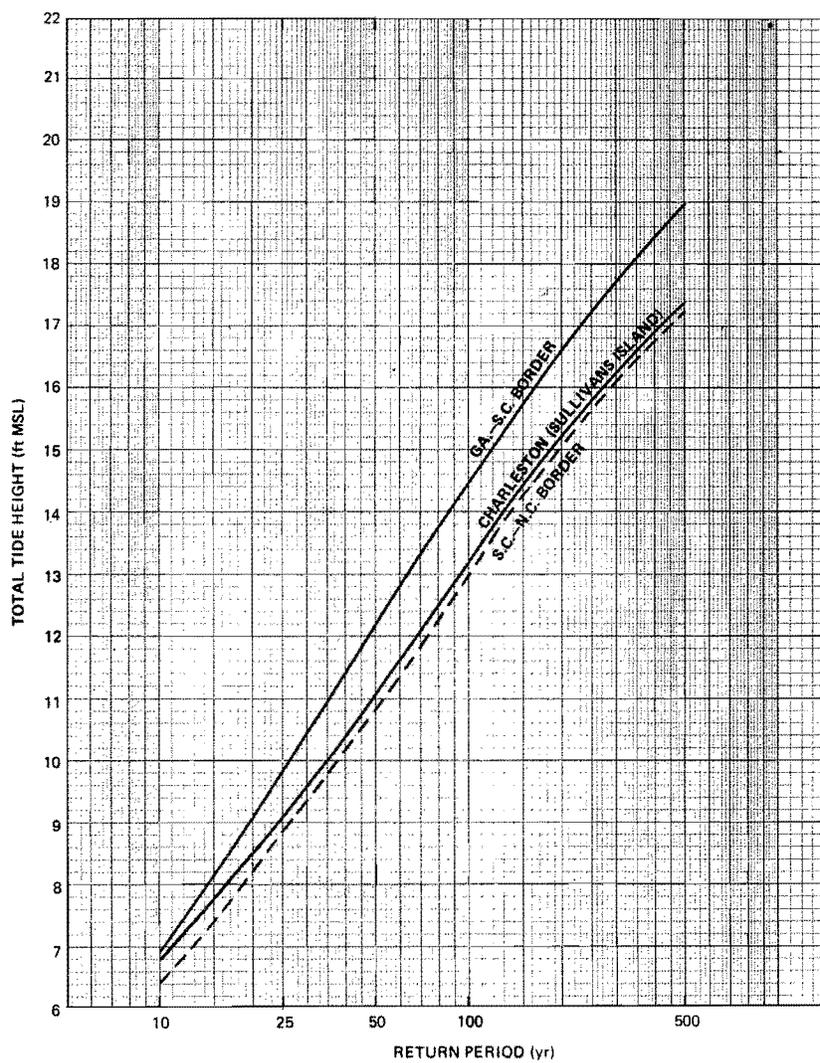
Figure 30.--Tide frequencies at selected points on the South Carolina coast, based on specification of hurricanes in tables 4-1, 4-2, and 4-3.

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reciprocal of the accumulated annual frequency at which each tide level is equaled or exceeded, gives the return period in yrs, defined in Chapter 1. The plots of open coast tide frequencies obtained in this manner, derived from the hurricane specifications in tables 4-1, 4-2 and 4-3, are depicted in figure 30 for Charleston, S.C., and for the northern and southern South Carolina boundaries.

Definition of "open coast"

The Charleston curve of figure 30 applies to the entrance to the harbor on the outer beaches of Sullivans Island and Morris Island. The 100-yr return period tide level is calculated at 13 ft MSL. The flood insurance maps, which depict "base flood elevation" (100-yr) to the nearest 1 ft, show 1 ft less flood elevation at the Battery and at the NOS Customhouse tide gage site in the City of Charleston than at these open coast locations.
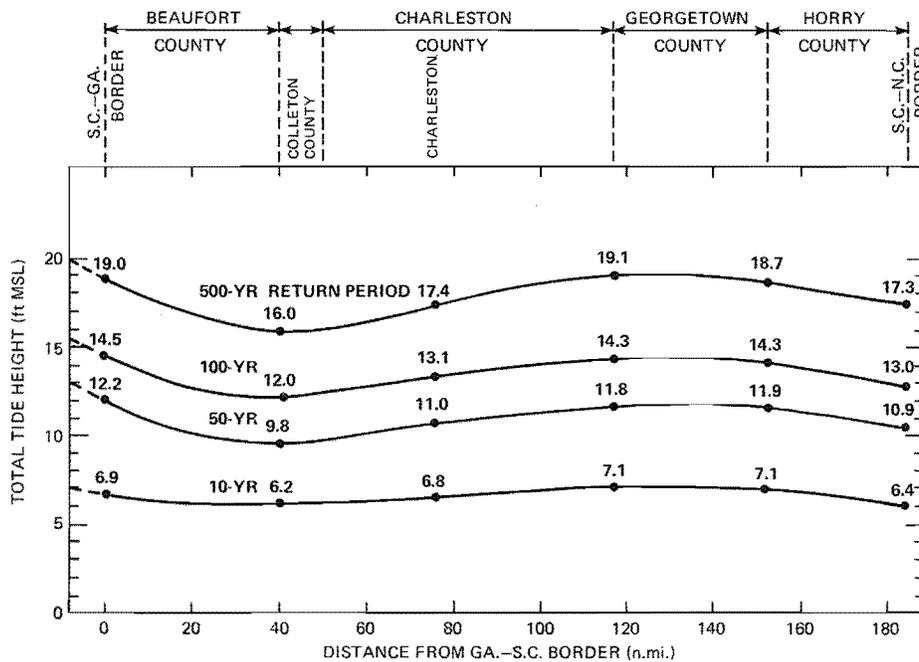
Figure 31.—Coastal tide frequencies, South Carolina.

Coastal profiles

Coastal profiles of tide frequencies, figure 31, are constructed by plotting the values from figure 30 at the control points for standard return periods and interpolating coastwise between by reference to the shoaling factor profile, figure 19.

A point to emphasize is that these are estimates of open coast tide levels that would be expected in a tide gage house or other stilling well designed to damp out the short-period oscillations of waves, if such a structure existed. Waves are an additional factor to be estimated separately. This added hazard is taken care of in flood insurance rating by designating a high hazard "special flood hazard" zone subject to waves (Federal Insurance Administration 1974).

Adjustment of these open coast tide levels to inland values along bays and estuaries or over land which is normally dry but may be flooded by a storm is not included in the present report.

Figure 31 depicts the alongshore variation of tide frequencies at a point, any point. The scale of hurricane storm surges is such that the whole South Carolina coast is not influenced equally and simultaneously. Thus, the annual frequency of a given storm tide level somewhere on the South Carolina coast is greater than the point values in the diagram. This needs to be taken into account by officials concerned with disaster planning for broad areas.

Comparison with observed tide

The most recent severe hurricane on the South Carolina coast was Hazel of 1954. The observed storm tide profile derived from high-water marks for this storm, from figure 2, is compared with the coastal tide frequency profiles in figure 32. This is to illustrate the point that tide levels in the upper part of the frequency range, for example at the "500-yr" level, are not merely hypothetical extrapolations but are real events.

Remarks on class intervals

The coastwise surge envelope is discretized into 8-statute mi intervals, figure 26, resulting in adjacent surge steps differing in height by 1 ft or more. The large number of climatological hurricane events processed smooths out the bumps that would result in the tide frequency curve if only a few storms were processed with this large interval. Tide frequency plots at a 0.1 ft interval are smooth enough that halving the coastwise step by outputting all SPLASH grid points instead of alternate points was not considered warranted. The discretization step for the surge and astronomical tide marigrams (figs. 27 and 28) must be the same and is controlled by the surge, which has the larger range. A Δt was chosen to give surge time-step differences no larger than the coastwise differences. Discretization of the astronomical tide and of the p_o, R, and f probability distributions is based on similar considerations. Discretizing the θ probability distribution is mainly a question of reducing a nonlinear relation between S_x and θ to linear steps. Guidance on this is obtained from figure 3 of the SPLASH report (Jelesnianski 1972).
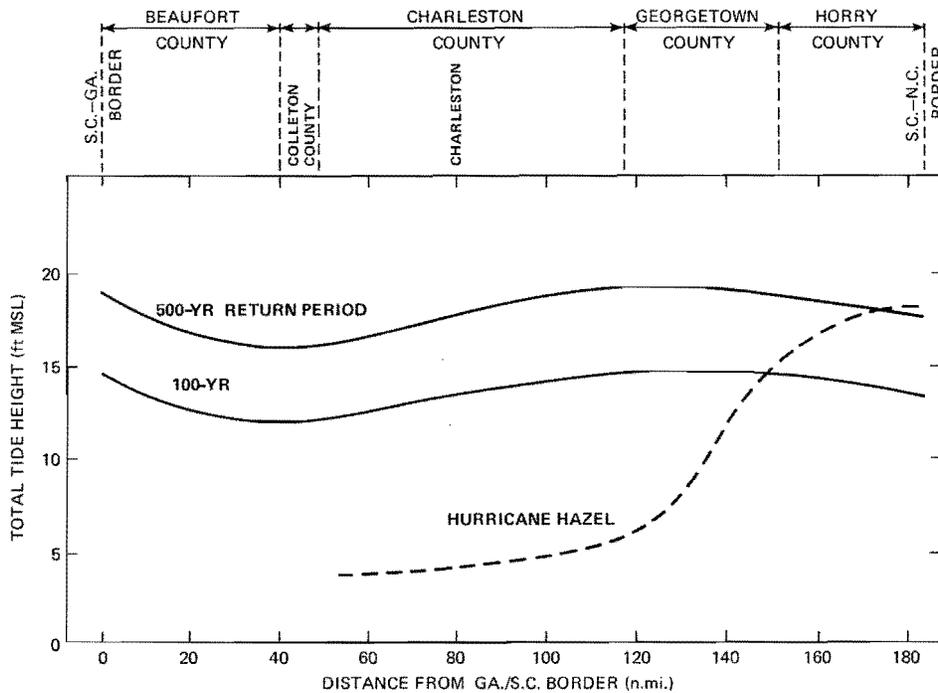
Figure 32--Comparison of Hurricane Hazel storm tide profile (fig. 2) with
coastal tide frequencies (fig. 31).

Differences from 1970 study

The main differences from the 1970 Atlantic City study are noted at the
ends of chapters 4 and 5.

Winter-type storms ("northeasters") are not considered in the present study
(see "scope of report" in chapter 1). They were a necessary adjunct of the
1970 study, at a more northerly latitude.

No analysis of land subsidence/sea-level rise was made in the present study
in view of the convenient availability of a recent paper that covers this
(Hicks and Crosby 1974).

Computer Program

For the calculations described in this chapter, SPLASH runs are made for the specified climatologically representative hurricanes to obtain coastal surge envelopes in the same manner (and on the same computer) as in weather forecasting operations of the National Weather Service.

Pertinent data from the resulting computer listings are punched on cards and become the input to a special computer program that performs the operations illustrated in tables 7-1 and 7-2 and also sums the individual storm frequencies (last lines of the two tables) into tide frequency relationships. A listing of the latter computer program in FORTRAN is available from the National Weather Service, Silver Spring, Md. 20910, Attention W21.

Table 7-1--Illustrative computation of the maximum storm tide at Charleston, S.C., produced by a climatologically representative landfalling hurricane and frequency of the event.

A. Specification of Event

p_o = 954.5 mb; D = 1013.2 - p_o = 58.7 mb

R = 23 n.mi.

f = 15.1 kt

θ = 99 deg. to coast

Landfalling point = 4 statute mi to left of Charleston

Astronomical high tide: upper quartile

Timing: Peak surge at Charleston 15 time units (15 x .311 = 4.66 hr) after astronomical high tide.

B. Maximum Surge Height at Charleston

(a) Surge height at mi -24 (fig. 26)   = 11.5 ft

(b)* $\dfrac{\text{Shoaling factor at mi } -0}{\text{Shoaling factor at mi } -24} = \dfrac{1.15}{1.17}$ = 0.98

(c)# $\dfrac{\text{Pressure depression at mi } -4}{\text{Pressure depression at mi } -28} = \dfrac{59}{58}$ = 1.02

Adjusted surge height:

(a) x (b) x (c) = 11.5 x .98 x 1.02   = 11.5 ft

C. Maximum Storm Tide at Charleston

Astronomical high tide, upper quartile, fig. 25:   3.3 ft MSL

$t_{2/3}$ fig. 21, hr (interpolate):   2.94 hr

in time units of 0.311 hr: 9.45 units

Maximum surge at Charleston, table 7-1B: 11.5 ft

time units after high tide	10	11	12	13	14	15
astro. tide (ft MSL) (cosine function)	0.0	-0.5	-1.0	-1.5	-1.9	-2.3

*This ratio is output from SPLASH, can be approximated from fig. 19.
#From p_o curves at 15-percent level, interpolated along coast.

Table 7-1--Continued

time units from max. surge	-5	-4	-3	-2	-1	0
surge (ft) (from eq. 1)	7.9	9.1	9.9	10.7	11.4	11.5
sum (ft MSL)	7.9	8.6	8.9	9.2	9.5	9.2

<u>Maximum tide</u>: 9.5 ft MSL

D. Frequency of Event

<u>Individual probabilities</u>

P_o	0.2	(table 4-1)
R	.33	(table 4-1)
f	.2	(table 4-1)
θ	.33	(table 4-1)
Astronomical tide:	.25	(fig. 25)
Timing displacement:	.05	(fig. 29)

<u>Joint probability</u>

0.2 x 0.33 x 0.2 x 0.33 x 0.25 x 0.05   = .000054

<u>Frequency per yr</u>

(a) Storm track frequency, F_n, at landfall
point for maximum surge at Charleston   = .00130 n.mi.$^{-1}$ yr^{-1}

(b) Ratio of F_n at shifted landfall point
to F_n at (a) (Interpolate from F_n's in
tables 4-1 and 4-3) = .00132/.00130   = 1.015

(c) Length of coastal segment (fig. 26)
8 stat. mi.   = 6.9 n.mi.

(d) Storm event joint probability   = .000054

(e) Frequency per yr at Charleston of
specified event: (a) x (b) x (c)
x (d) = .00130 x 1.015 x 6.9 x .000054   = .00000049 yr^{-1}
                                                     = .49 x 10^{-6} yr^{-1}

Table 7-2.--Differences from table 7-1 for alongshore hurricane

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A. Specification of Event

P_o, R, f, θ, astronomical tide -- same as landfalling hurricane in table 7-1A.

Distance of track from shore: 22 n.mi.

B. Maximum Surge Height at Charleston

(a) Units from shore, L/R = 22/23   = 0.96

(b) μ, (fig. 18B)   = .50

(c) Maximum surge, standard basin, (fig. 18A)   = 6.6 ft

(d) Shoaling factor (fig. 19)   = 1.16

(e) Maximum surge (c) x (d)   = 7.7 ft

C. Maximum Storm Tide at Charleston

(a) Distance from coast L/R = 22/23   = 0.96

(b) Normalized storm speed R/f = 23/15.1   = 1.52

(c) $t_{2/3}$ (fig. 22)   = 1.3 hr

(d) Maximum storm tide: 5.4 ft MSL
     (Same procedure as table 7-1C)

D. Frequency of Event

(a) Frequency of storm passages, F_b, table 4-1   = 0.024 yr^{-1}
     (thru segment 22 $\pm$ 4.25 n.mi. from coast)

(b) Joint probability from table 7-1D   = .000054

(c) Frequency: (a) x (b)   = .000001296 yr^{-1}
                                                     = 1.296 x 10^{-6} yr^{-1}

CHAPTER 8· SUMMARY

Summary

The frequency distribution of the magnitude of hurricane storm tides on the coast of South Carolina has been estimated for the National Flood Insurance Program and other planning purposes. This is accomplished by the climatological-hydrodynamic or joint probability method. The conceptual basis for this method was outlined and its accomplishment described. A descriptive summary of hurricanes on the South Carolina coast is presented to illustrate the point that these storms have ravaged the coast since colonial times. This behavior may surely be expected in the future.

The report illustrates the method used by NOAA for open coast tide frequency evaluations in hurricane areas as practiced through the end of 1973.

Disaster planning

The goal of this study is to make an actuarial evaluation of tide level frequencies for flood insurance rating and land zoning decisions. For disaster planning against severe storms, particularly involving evacuation and protection of life, very rare storms need to be taken into account. Hurricane Camille of recent memory, which devastated the Mississippi coast in 1969, has been used as a bench mark for this type of planning. Camille produced a maximum tide of over 24 ft near Pass Christian, Miss., (Hudson and Wilson 1969) and exceeded 20 ft MSL over more than 20 mi of beach front. Approximately these same levels would result on the South Carolina coast from a Camille-type storm. The shoaling factor is slightly less along most of the South Carolina coast than at the Camille site but the astronomical tide range, with the associated possibility of coincidence with high tide, is greater. The likelihood of a Camille-type storm is only slightly less on the South Carolina coast than on the Mississippi coast based on the central pressure probability profiles of the climatology report (Ho et al. 1975).

Regional study vs. local study

We close with remarks on differences in tide frequencies at Charleston in this study and in the earlier study by the Corps of Engineers (1966). Compare the Charleston (Sullivans Island) curve of figure 30 with figure 33 in the Appendix. The first is by the "joint probability" regional analysis the second from a reliable long-period record. In comparing the curves, allow 1-ft difference for location at the 100-yr return period (page 64) and 0.4 ft for datum.

It is futile to attempt to account for all the differences resulting from use of different approaches but some of them are evident. The regional analysis has used a higher overall frequency of hurricanes at Charleston than the last 88 yr alone suggests, as indicated in figure 6. This seems consistent with the regional experience during the same 88 yr and, qualitatively, with the overall severity of hurricanes at Charleston during 3 centuries (chapter 3). Another factor is that Charleston has been spared a direct strike by storms like Hazel at Myrtle Beach, the 1893 storm in Beaufort County, Camille on the Gulf coast in 1969, or even the 1940 storm at Beaufort, S.C. The possible

strike of a very severe storm in the future is taken account of in the joint
probability method and is the primary reason for the substantial difference
at the 500-yr return period (.002 annual probability) in figures 30 and 33.

If the regional approach is valid, then a few places will have had a more
severe recent measured experience than the climatological expectancy. This is
indeed found at Savannah Beach, Ga., where a regional analysis assigns a lower
frequency to the 1893 tide level than a plot of the local record alone would
indicate (Ho 1974).

APPENDIX: FREQUENCY ANALYSIS OF HURRICANE TIDAL ELEVATIONS AT CHARLESTON, S C.

Tidal elevations at the site of the NOS tide gage at the Customhouse,
Charleston, are listed in table A-1, reproduced from the Corps of Engineers
(1966) report. The reference zero datum in this table and table A-2 is the
National Geodetic Vertical Datum of 1929. The 1941-59 epoch local mean sea
level, used as the datum reference in the body of this report, is 0.4 ft
higher than this at the Charleston gage. The frequency plot from the cited
report is replicated in figure 33.

The plotting position formula is

$$p = \frac{n}{N} = (m - 0.3)/(n + 0.4)$$

where

    p = annual frequency
    N = years of record (72, 1893 - 1964)
    n = number of events (17)
    m = rank of event
from Beard (1962).

The plot assumes a log normal distribution. The original figure carries
this statement, which we endorse, "although the normal predicted astronomical
tide belongs, statistically, to another population, tide tables show that
astronomical highs of 4.2 ft above msl can be expected on the average of once
a year in Charleston harbor. This point has been plotted to show the behavior
of the stage-frequency data at such stages and below, where the stage-fre-
quency relationship is dominated by normal tidal harmonics."

One storm within the range of table A-1 has occurred since table A-1 was
assembled. This is listed for information in table A-2. Figure 33 was re-
plotted including this storm (not shown) and was not significantly changed.
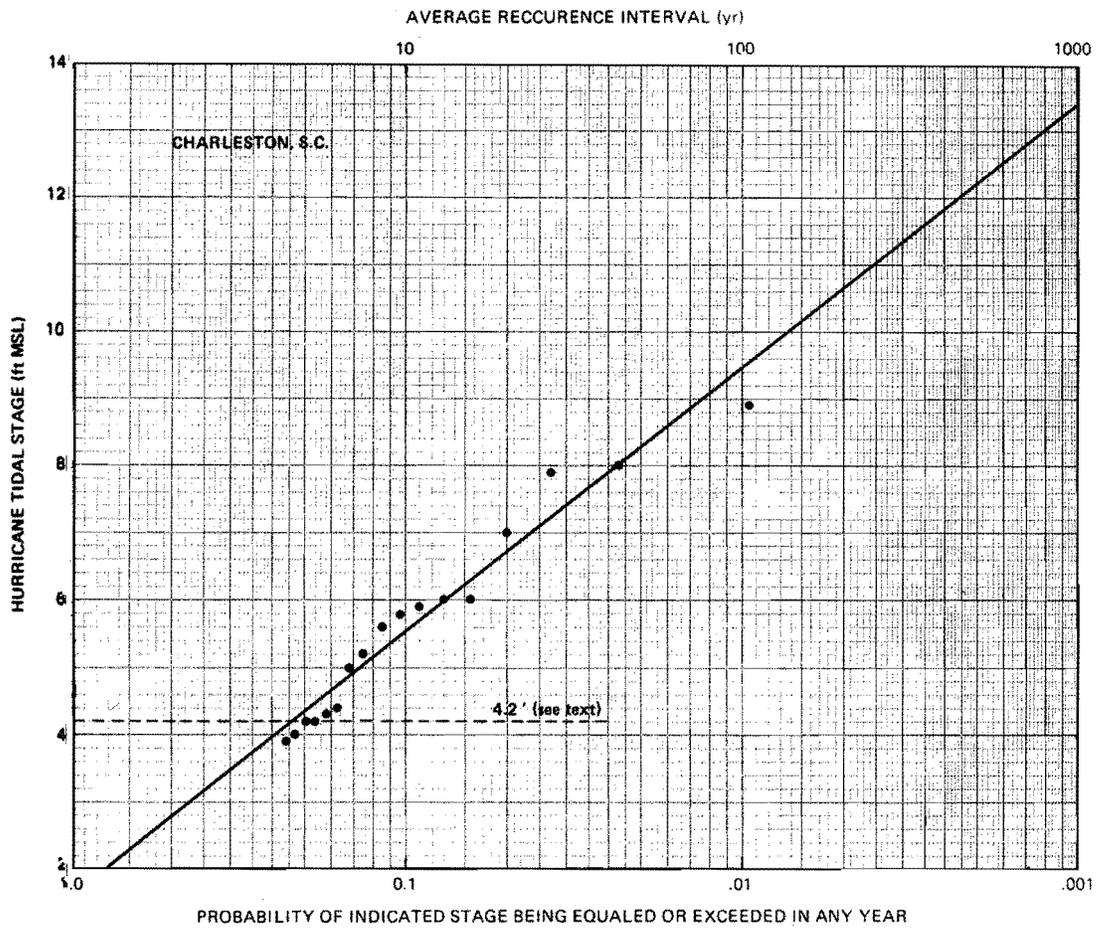
Figure 33.—Tide frequency relation, Customhouse gage, Charleston, S.C., based on 1893-1964 data. [From Corps of Engineers (1966)]. Datum reference: National Geodetic Vertical Datum of 1929.

Table A-1.--Frequency analysis of hurricane tidal elevations affecting
Charleston, S.C., 1893-1964*

Storm Date	Rank	Maximum Storm Tide Ft. #	Plotting Position
28 Aug. 1893	1	8.9	0.0094
11 Aug. 1940	2	8.0	.0231
27/28 Aug. 1911	3	7.9	.0366
27/28 Sept. 1894	4	7.0	.0500
29 Sept. 1959 (Gracie)	5	6.0	.0637
15 Oct. 1947	6	6.0	.0774
14 July 1916	7	5.9	.0909
20 Oct. 1944	8	5.8	.104
18 Sept. 1928	9	5.6	.118
17 Aug. 1955 (Diane)	10	5.2	.132
11 Sept. 1960 (Donna)	11	5.0	.145
18/19 Sept. 1955 (Ione)	12	4.4	.159
11 Aug. 1955 (Connie)	13	4.3	.172
15 Oct. 1954 (Hazel)	14	4.2	.186
29/30 Aug. 1954 (Carol)	15	4.2	.199
30 Aug. 1952 (Able)	16	4.0	.213
27 Sept. 1958 (Helene)	17	3.9	.227

*from Corps of Engineers (1966) Table 1

#National Geodetic Vertical Datum of 1929

Table A-2.--Storm not included in Table A-1:

25 Oct. 1963 (Ginny)   Maximum tide.....6.9'

Acknowledgments

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