CHAPTER 52

HURRICANE TIDE FREQUENCIES ON THE ATLANTIC COAST

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I. INTRODUCTION

HISTORICAL BACKBROUND

Hurricane surge is a serious and not uncommon event along the Gulf of Mexico and Atlantic coasts of the United States. The most disastrous display of hurricane forces in recent decades was by Camille, which struck the Mississippi coast in 1969. The storm tide reached 24.6 ft MSL. Reported storm tides on the Atlantic coast have reached elevations of 15 to 20 ft in Florida, Georgia, the Carolinas and New England.

One of the latest coordinated efforts to alleviate losses from hurricanes -- supplementing warning services, community preparedness, and evacuation plans-- is the Flood Insurance Program.

NATIONAL FLOOD INSURANCE PROGRAM

The National Flood Insurance Act of 1968 provides for a cooperative program between the United States Government and private industry for insuring residences and small businesses against floods. The program is administered by the Federal Insurance Administration (FIA). Other federal agencies assist by making technical studies.

Essential to establishing flood insurance rates in any community, whether on the coast or an inland valley, is a flood frequency analysis. Flood frequencies are also used as guides in formulating local zoning and flood plain occupancy ordinances. The 100-yr level (1% chance of being exceeded in any year) is the main criterion for this. The 10-, 50-, and 500-yr levels are also required by FIA regulations.

II. JOINT PROBABILITY METHOD OF THE TIDE FREQUENCY ANALYSIS

Hurricane tide frequency analyses have been made by the National Oceanic and Atmospheric Administration (NOAA) for the open coasts of the states of Florida, Georgia, the Carolinas, Virginia, Maryland, and Delaware, and also Puerto Rico (Fig. 1). The method that NOAA has developed for coastal tide frequency analysis, has come to be known as the joint probability method, and was first applied to Atlantic City, N.J. (13). Refinements of this method have been made over several years and the method extended to other sections of the Atlantic coast (e.g., 1, 14).

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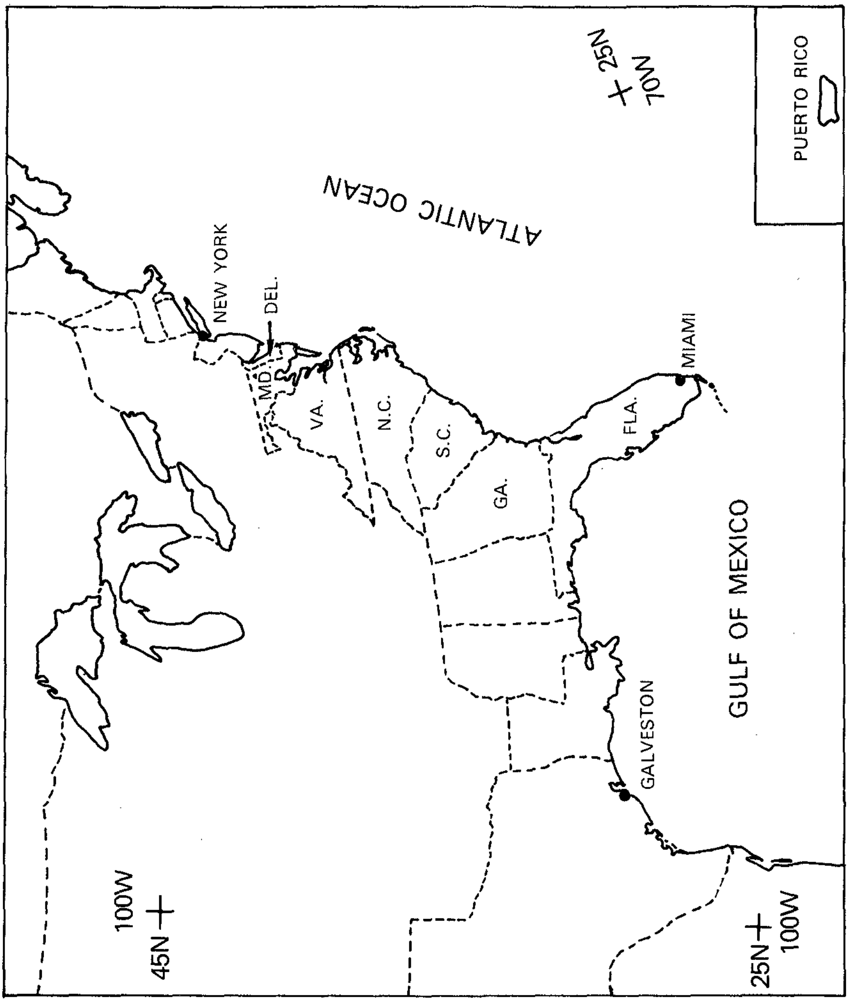

Figure 1.--Location map.

With geophysical data of all kinds, models are used to convert available information to other forms needed but not directly available. The application here is to derive storm tide data from hurricane atmospheric parameters. The first step is to assess from past records the magnitude and frequency distribution of hurricane parameters that are related to surge generation along the coast. The second step is to calculate the coastal surge levels that each of a number of combinations of the hurricane parameters would produce. For this, a dynamic calculation method is used that has been demonstrated to reproduce hurricane surges within an acceptable tolerance. Enough combinations are used to represent the entire range of possibilities. Third, the computed hurricane surges are each combined with the astronomical tide with various time displacements between surge peak and high and low tide. The range of the astronomical tide is also varied.

The frequency of each computed storm tide is worked out from the hurricane parameter and astronomical tide probabilities in a manner briefly described later. Winter coastal storm tide frequencies are estimated at tide gage sites by a statistical analysis. Finally, the hurricane and winter storm tide frequencies are summed to yield the total tide frequencies from all storms.

HURRICANE PARAMETERS

There are four parameters used to compute the surge associated with a hurricane. The first of these is the central pressure, a universally used index of hurricane intensity. The radial profile of sea-level pressure vs. distance from storm center (panel A of Fig. 2) shows a sharp increase within the first few miles with the curve flattening out at greater distances. The distance from the storm center to the area of maximum winds is symbolized by R (schematically shown on B of Fig. 2). R is used as the index of the lateral extent of the storm and referred to as radius of maximum winds. The third and fourth parameters are the forward speed of the storm and the direction of the storm motion. These parameters can be scaled from a hurricane track as illustrated in panel C of figure 2. The lower righthand panel (D) illustrates the dimensions of a hurricane tide. This is a profile of hurricane Hazel's tide observed along the coast. The coastal distance is measured from the point of landfall of the storm center near the North Carolina - South Carolina border.

PROBABILITY DISTRIBUTION OF HURRICANE PARAMETERS

Figure 3 illustrates the climatological analysis of these hurricane parameters. The data sample is collected from all hurricanes exceeding a certain intensity and striking or passing close to the coast within a prescribed span of years. The data are plotted on accumulated probability diagrams as shown in the figure for coastal segments approximately 400 n.mi. in length, for each of the four hurricane parameters. Similar graphs are obtained for the entire coast, for about 60 overlapping zones centered at 50-n.mi. intervals.

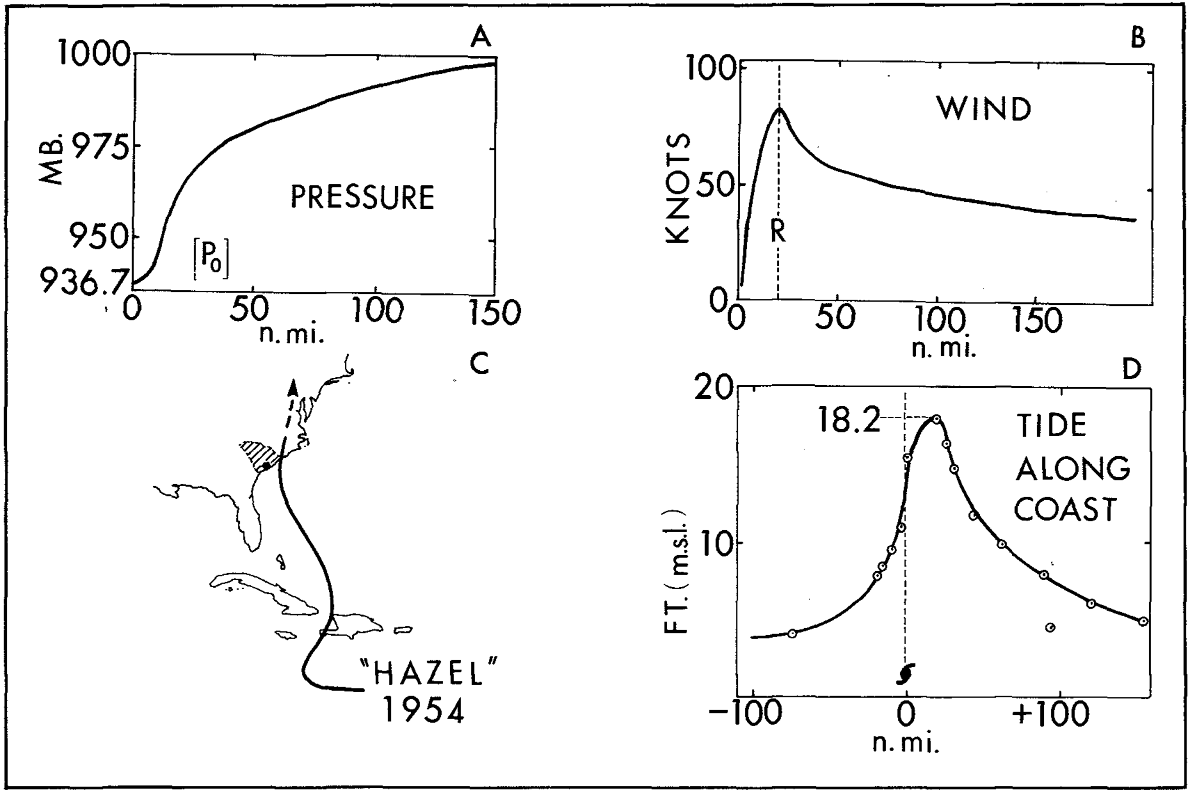

Figure 2.--Examples of basic characteristics of hurricanes from Hurricane Hazel.

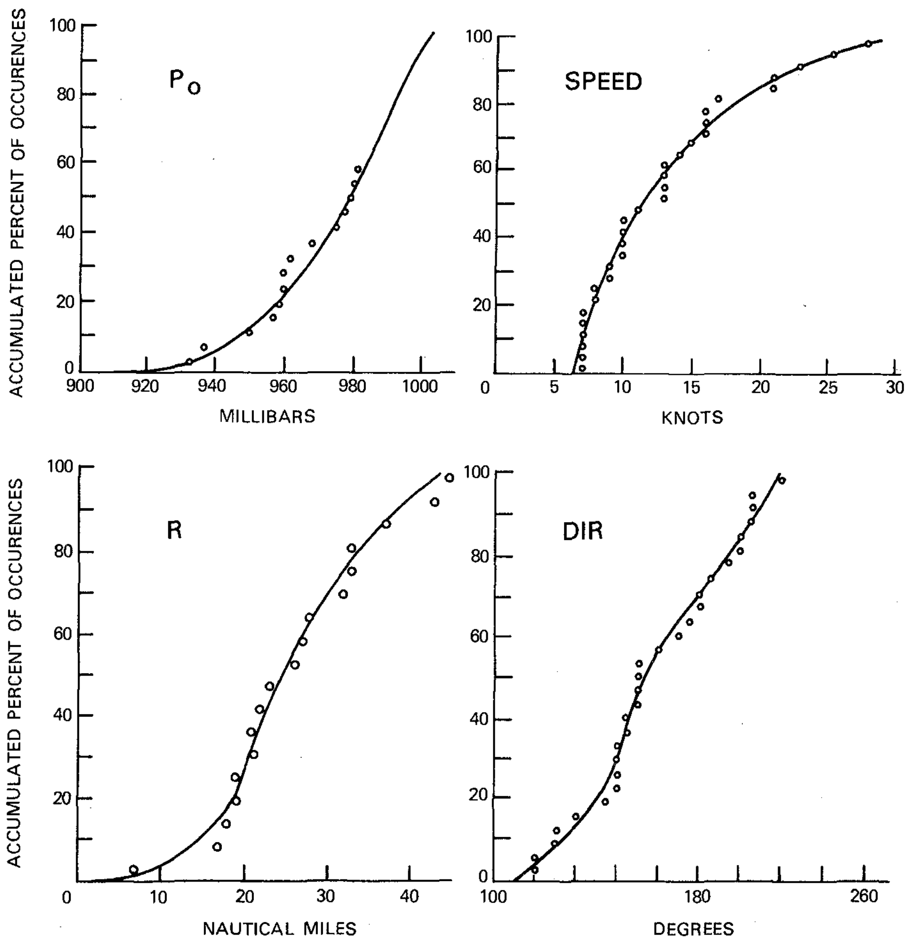

Figure 3.--Hurricane parameters -- data and probability distribution curves for a coastal zone.

Next, values at certain probability levels are read from each of these graphs and smoothed along the coast by applying a weighting function. The resultant coastal profiles for the central pressure are shown in figure 4 (reproduced from Fig. 11 of ref. 4), depicted as lines joining values at the percentiles indicated inside the right margin. The distance scale for the abscissa is measured along a smoothed coastline running from Texas to Maine. The diagram indicates that the minimum central pressures are expected in the Florida Keys, where the most intense hurricane in the western hemisphere, with central pressure of 892 mb, was reported. The trends in the curves reflect the fact that hurricanes tend to become less intense with increasing latitude.

The R 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. Forward speeds were scaled from track charts and a probability analysis made as with the other parameters, except that hurricanes landfalling on the coast and those bypassing the coast (alongshore hurricanes) were analyzed separately. The direction of forward motion analysis was restricted to landfalling storms. For this, all tracks of tropical cyclones since 1871 were used. For numerical calculations of surges, alongshore hurricanes are treated as if they were moving exactly parallel to the coast.

Hurricane Frequency

In addition to the distributions of these hurricane characteristics, the overall frequency of hurricane occurrences is basic to calculating hurricane tide frequencies. The frequency of occurrences is assessed by counting tracks (separately for landfalling and alongshore) and smoothing the counts along the coast, similar to the other parameters.

Figure 5 shows the frequency of landfalling hurricanes (from ref. 4). The frequency varies from a minimum of 0.1 storms per 10 n.mi. of smoothed coastline per 100 years near Boston, to maxima of 2.2 in the middle of the Gulf coast and in the Florida Keys.

Similar analyses were made for alongshore hurricanes, and for hurricanes that exited the coast after an earlier entry of the coast elsewhere. Because of hydrodynamic factors, exiting hurricanes give half or less the surge heights as landfalling hurricanes of the same intensity. Exiting hurricanes also tend to have weakened while passing over land and contribute little to the frequency of high storm tides.

Winter Coastal Storms

From time to time, winter coastal storms originating in mid-latitudes also cause millions of dollars of damage along the northern part of the Atlantic coast. At the 100-yr return period storm tide magnitude the activating storms are hurricanes and the additional contribution by winter coastal storms is generally small. The contribution to storm tide frequency of the latter may be evaluated with sufficient precision by direct analysis of long period tide gage records, and interpolation along the coast. These storms are taken into account in coastal storm tide frequency analysis north of Cape Hatteras, but their frequency of occurrence and characteristics are not discussed further in this paper.

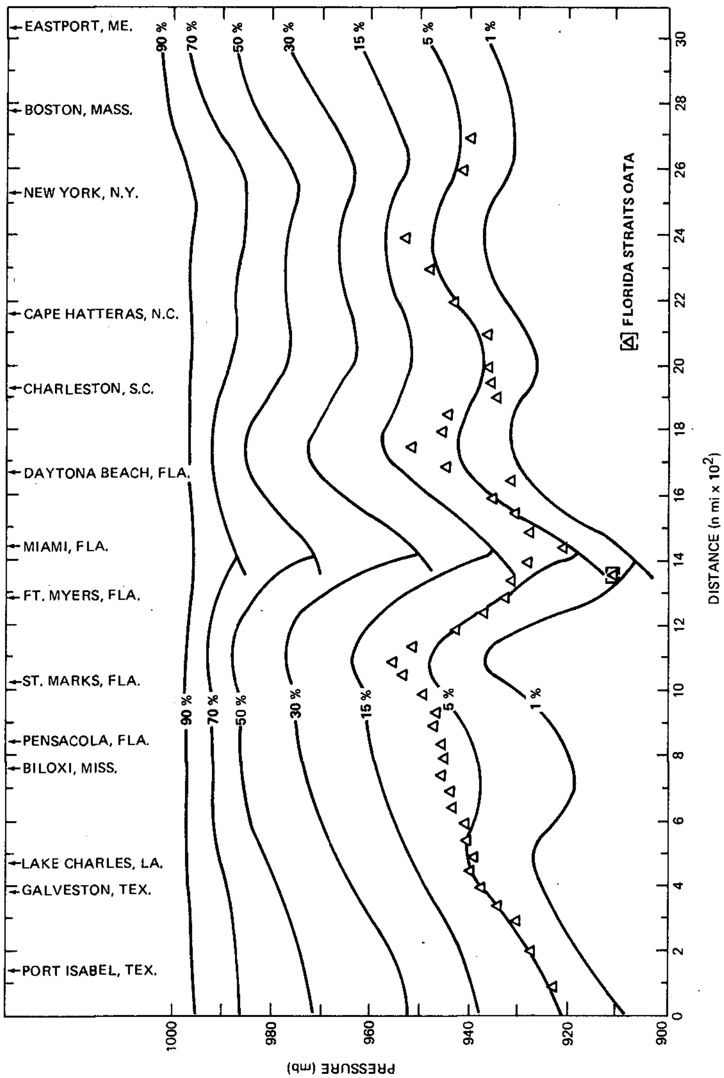

Figure 4.--Hurricane parameter probability profiles along coast -- central pressure. Based on 1900-74. Plotted points (Δ) are taken from frequency analyses at 50-n.mi. intervals for the 5th percentile.

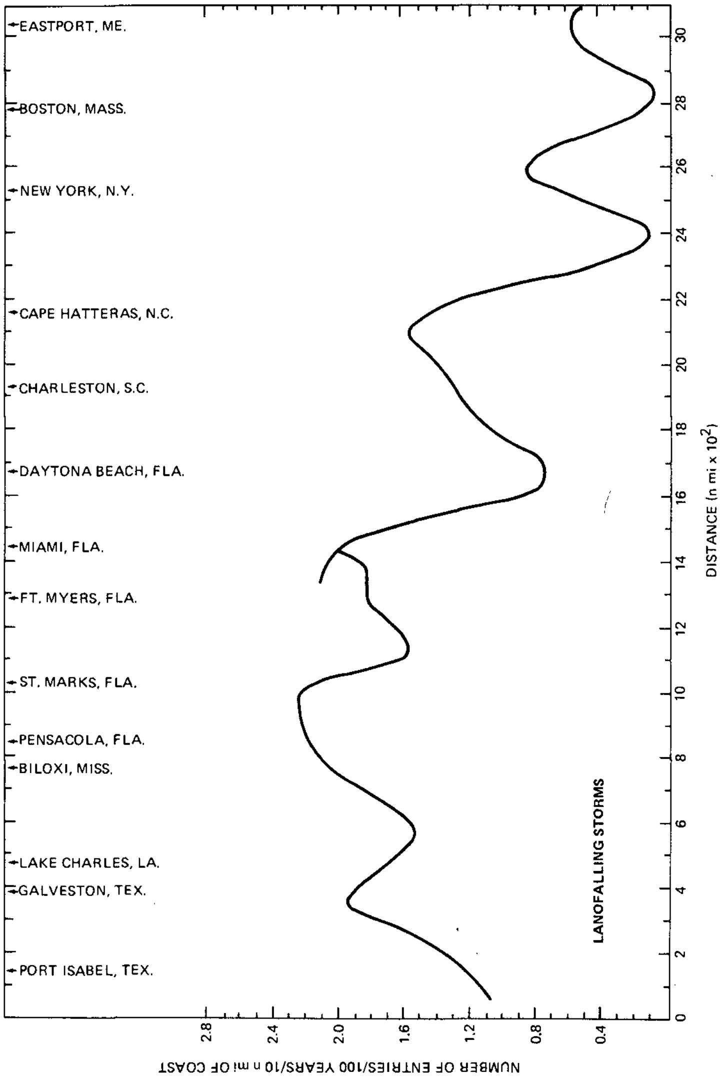

Figure 5.--Frequency of landfalling hurricanes and tropical storms based on 1871-1974.

Hydrodynamic Synthesis

Having defined the hurricane climatology, the next step in the tide frequency analysis is the simulation of hurricane surges. A hydrodynamic-numerical model, called SPLASH, has been developed by Jelesnianski (9, 10) for calculating the surge produced by a hurricane moving over the continental shelf. The model simulates the moving wind and pressure fields over the sea from the basic parameters described above, then computes the surge produced by these fields. This model was developed to predict storm tides when a hurricane approaches, as part of the public warning service of the National Weather Service. The operational application of this model is described in separate reports (11, 12). The same model is used here to compute storm surges from climatological possibilities for frequency analysis.

Shoaling Factor

Because of dynamic effects, the surge height that a given hurricane will produce at the coast varies with the shape of the continental shelf. The bathymetry effect on storm surges is handled by the use of a shoaling factor[2]. The shoaling factor is the ratio of the peak surge height that a standard hurricane would produce in a given locale compared to the maximum surge height the same storm would produce over a "standard basin." Figure 6 shows the coastal profiles of the shoaling factor for two different radii of maximum winds. The application of this will be described later.

Astronomical Tide

Another feature of hurricane tides, shown in figure 7, is illustrated by observed tides at Charleston, S.C. in Hurricane Gracie. This diagram includes curves depicting three different water levels. The normal astronomical tide is shown by the solid curve. The dashed curve is the tide level actually observed during the storm. The difference between these is by definition the "surge." That is, the surge is the storm effect, and the graph of this is shown in the lower panel. The surge reached a magnitude of 8.3 ft MSL but, since this was coincident with low astronomical tide, the observed tide peaked at only 5.6 feet. If the same storm had coincided with the normal high astronomical tide, the hurricane tide would have reached 11.2 ft; if the storm were coincident with spring tide, the water level would have been 12 ft. This illustrates the fact that in a synthetic calculation of storm tide frequencies, the relative phasing of storm surge and astronomical tide should be taken into account.

Frequency Distribution of High and Low Tides

Most of the combinations of forces producing the astronomical tides are experienced during a 19-yr cycle. There is also a seasonal variation in the mean water level with the maximum in September-October in most of the study

[2]The same topic is also discussed by Barrientos and Jelesnianski: "A Numerical Model for Forecasting Hurricane Storm Surges," in the storm surge section of these proceedings.

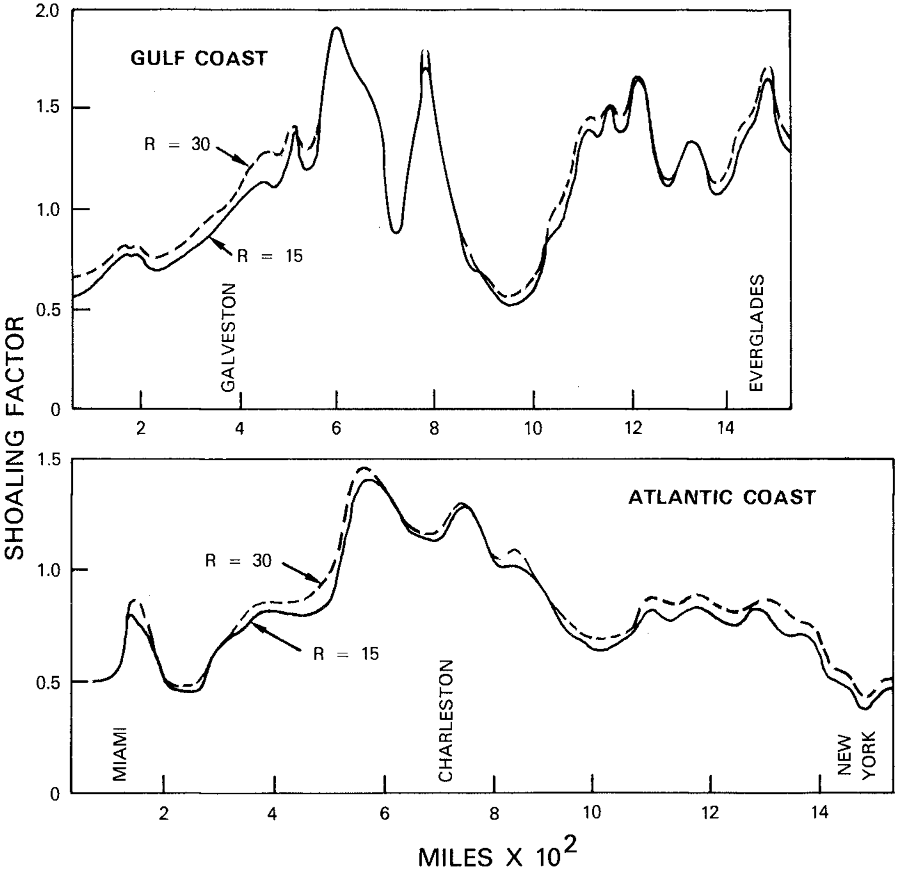

Figure 6.--Shoaling factor curves for Gulf of Mexico and east coasts. R in statute miles.

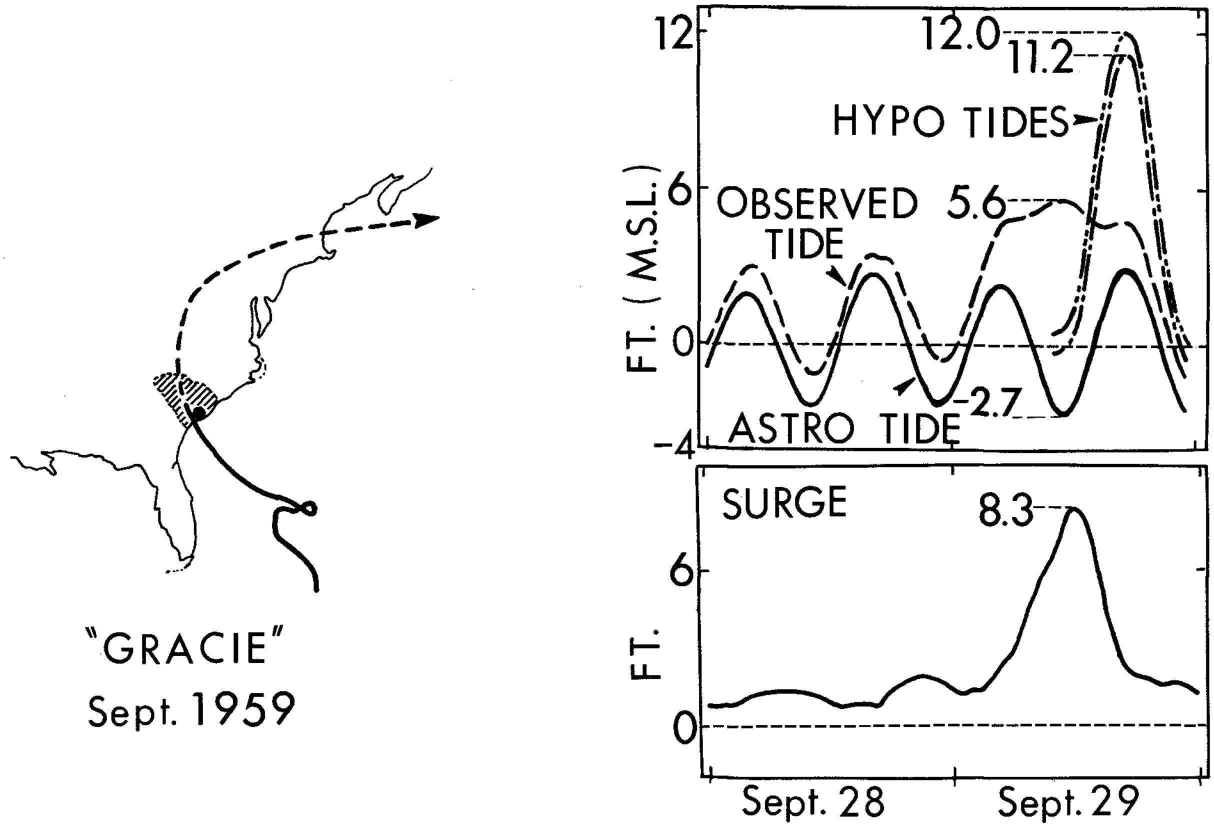

Figure 7.--Difference between surge, astronomical tide, and storm tide. Hypothetical combination illustrated by Hurricane Gracie of September 1959 at Charleston, S.C.

area. The months July, August, September, and the first half of October are taken to represent the hurricane season. Astronomical high and low tides for these representative months are recomputed for a 19-yr period with the standard tide computation program written by Pore and Cummings (18). The accumulated frequencies of the high and low tides are calculated separately by months, then weighted in proportion to hurricane occurrences in each month at a particular location. Each distribution is divided into four range class interval values. The representative astronomical tide marigrams needed to combine with each hurricane surge marigram are then approximated as cosine waves with a period of 12.42 hours oscillating between corresponding high tide and low class interval values. This assumes that the highest high tides occur with the lowest low tides, etc. The foregoing calculations are carried out at tide stations and then interpolated along the coast as needed.

COMBINATION OF ASTRONOMICAL TIDE AND HURRICANE SURGE

To combine calculated storm surges with the astronomical tide in search of the maximum height of the combination, the time variation of both is needed. The SPLASH program computes the surge height at grid points every 2.5 minutes. For combining surge profiles and the astronomical tides for the indicated purpose of finding the statistical distribution of maxium total, the assymetry of the rise and fall of the surge and the non-simultaneity along the coast of the time of maximum surge height in a particular case make 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 representative SPLASH surge computations, then normalizing these by fitting to two parameters. The time variation of the coastal surge is then approximated by a Gaussian curve defined by the maximum surge height, S_x, (in feet) and the time that the surge exceeds 2/3 of S_x, $t_{2/3}$ (in hours). The time variation is then described by:

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

where t is the time (in hours) after the occurrence of the maximum surge and $t_{2/3}$ is the time duration indicated above. For the justification for this, the reader is referred to a previously cited report (13).

Each surge is combined with astronomical tide in 84 different ways. These are 21 phasing displacements from low-tide coincidence to high-tide coincidence and four amplitudes of the astronomical tide, ranging from neap tide to spring tide.

III. HURRICANE TIDE FREQUENCY

Hurricanes striking a point of interest are represented by all possible combinations of selected values of the hurricane parameters. This could be, for example, six different central pressures, three R's, three directions of motion, and six speeds, a total of 324 hurricanes. Surges are computed for the 324 storms, with both time and space variation defined. (A SPLASH computation yields surge heights at 8-mi intervals on the coast for specified time increments).

Allowing the same set of hurricanes to strike various points up and down the coast gives a multiple of 324 hurricanes. The surge height produced by each of these hurricanes can be approximated by shifting the surge envelope from a SPLASH computation and applying the shoaling factor adjustment mentioned earlier. Each surge is combined with astronomical tides in the ways described.

The frequency of each of these hurricane tides is the product of the storm parameter probabilities, the landfalling frequency, and the astronomical tide probability. The accumulative frequencies of all these hurricane tide events are plotted as a tide frequency curve for the landfalling hurricanes. Alongshore storms are treated in a similar manner and the two frequency curves summed.

Statistical interdependence of hurricane parameters is handled by assigning conditional probabilities. For example, the speed of storm motion is defined separately for landfalling and alongshore hurricanes. Similarly, a different central pressure distribution is used for small R storms than for medium and large R storms. Details are given in cited reports.

Figure 8 illustrates a typical tide frequency diagram -- a plot of storm tide level against return period, for Rehoboth Beach, Del. The landfalling hurricane tide frequency curve and the alongshore hurricane tide frequency curve are computed separately by the procedure just described. The tide frequency curve from winter coastal storms is obtained by direct statistical analysis of tide gage data.

Summing the frequencies (reciprocal of return periods) of these three classes of storms at each tide level gives the frequency that level of tide is equaled or exceeded, from all storm classes. The figure indicates the contributions made by the different classes of storms. The winter coastal storm is the major factor contributing to the lower end of the frequency curve. The alongshore hurricanes contribute significantly to the recurrence intervals of 100 - 200 years; the landfalling hurricanes contribute most to the more rare return periods. This is typical in the study area north of the entrance of Chesapeake Bay (8). For coastal areas to the south, the tide level produced by landfalling hurricanes is the prime factor in the total storm tide frequencies (e.g., 6, 7).

COMPARISON OF FREQUENCY CURVE WITH HISTORICAL HURRICANE TIDE DATA

Repeating the same process at another point on the coast, we obtain a tide frequency curve, as shown in figure 9 for Savannah Beach, Ga. (1). The 100-yr tide level reaches 14-1/2 ft MSL. It should be noted here that the computed tide frequencies are of still-water levels on the open coast that would be measured in a tide gage house or other enclosure, excluding wave action. The plotted points are the five highest observed high-water marks at Savannah Beach since 1854. This is to verify the correspondence of the computed frequency curve to the local historical record. Other localities with a long period of observed high-water mark records also indicate similar good fit to the computed tide frequency curves, but there are exceptions in some places. The indirect method described, of course, gives hurricane tide frequencies where there are no or few historical storm tide data.

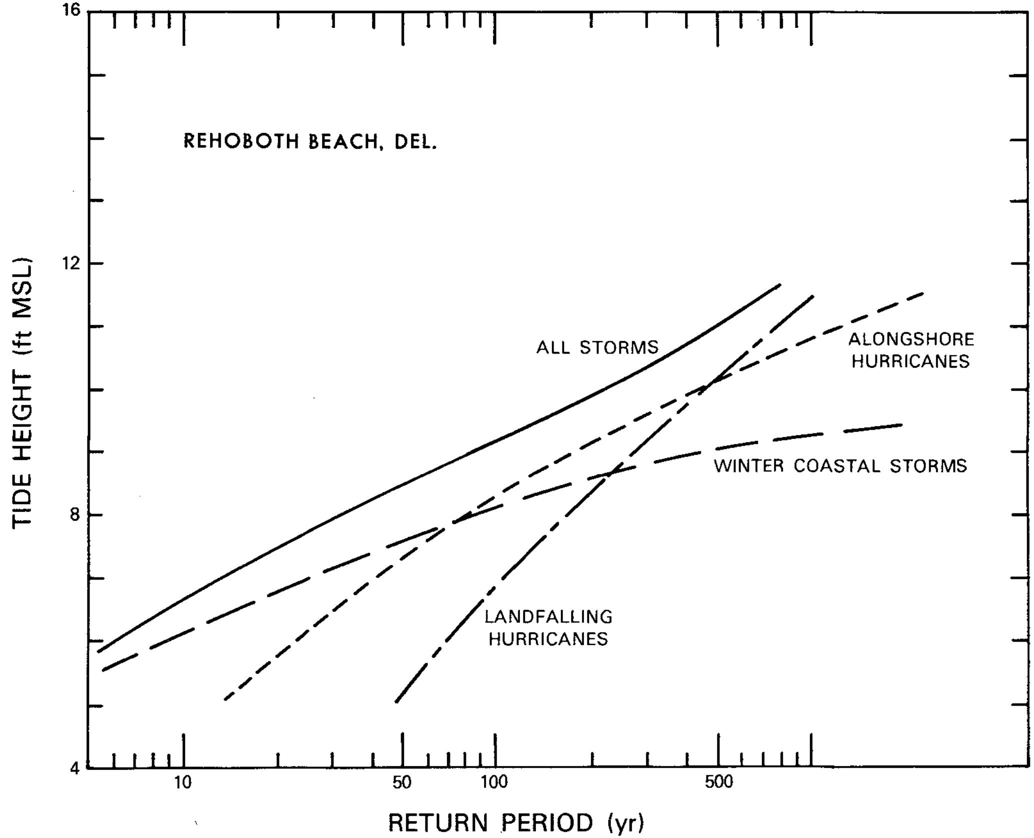

Figure 8.--Tide frequency curves to illustrate significant contribution of alongshore hurricanes, landfalling hurricanes and winter coastal storms.

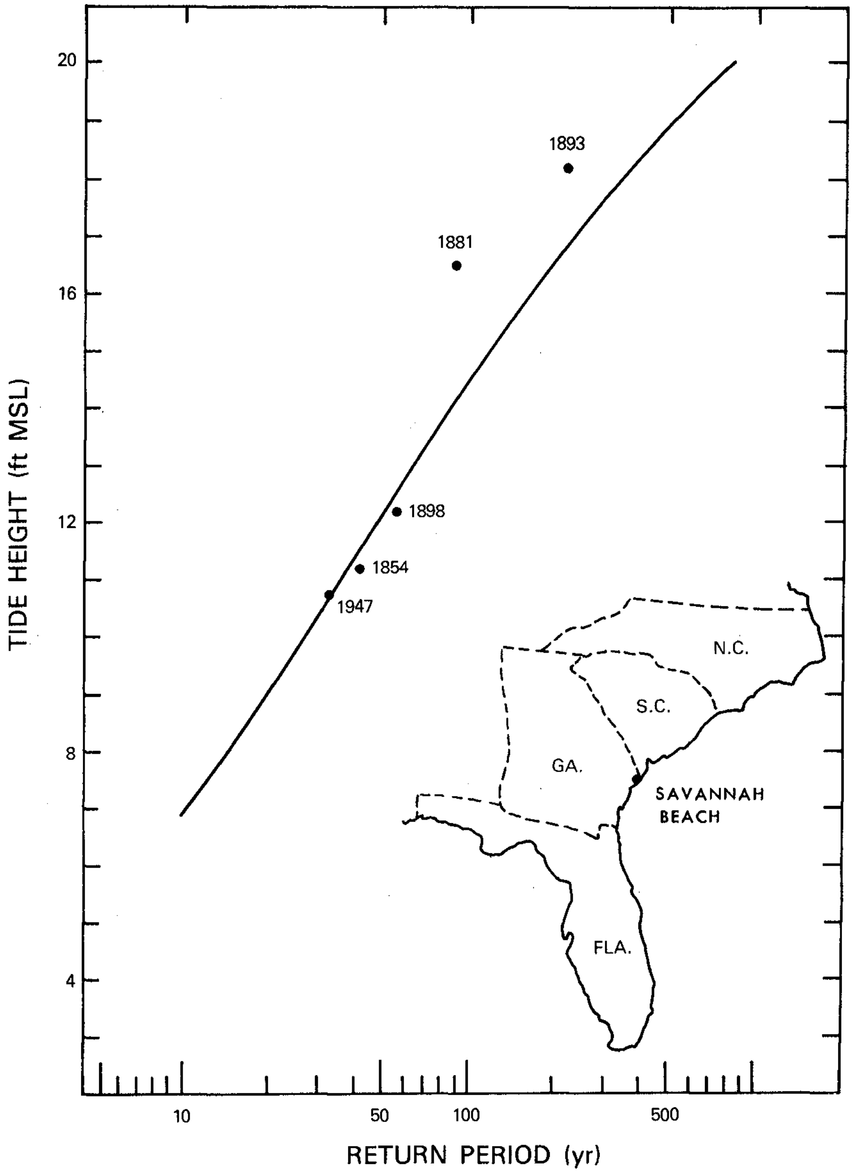

Figure 9.--Comparison of computed tide frequency curve at Savannah Beach, Ga., and high-water marks.

Coastal Profiles of Total Tide Frequency

Interpolating from results of tide frequency analyses at many points, we have coastal profiles of tide frequencies. Figure 10 shows such profiles for a portion of the Atlantic coast for the 10-yr, 100-yr, and 500-yr recurrence intervals. The 100-yr tide frequencies vary from about 16 ft MSL south of Savannah, Ga., and 14 ft near Miami, Fla., to a low of about 8 ft along the northern portion of the Florida peninsula.

In summary, these coastal variations are associated with the variations of hurricane parameters and the shoaling factor along the coast, illustrated schematically in figure 11. The 100-yr tide frequency profile in the figure is copied from figure 10 (heavy line). Effects of bathymetry are reflected in both the 100-yr tide profile and the shoaling factor curve. The rapid northward decrease of the 100-yr tide level on the Florida coast is related to both the decreasing frequency of hurricane occurrence northward, and weaker hurricane intensities as indicated by the decreasing ΔP curves, ΔP being the depression of the central pressure of a hurricane below its peripheral pressure.

North of Cape Hatteras both the ΔP and the hurricane frequency curve (which pertains to landfalling storms) decrease. The 100-yr flood level remains about the same because of increased frequency (not shown on the diagram) of by-passing hurricanes. Higher storm speeds and larger R's are also compensating factors which tend to increase the storm tide levels in this region.

IV. OTHER STUDIES

Hurricane tide frequency profiles along the Gulf coast of Florida have been obtained in the same manner as for the southern Atlantic coast (5). Other sections of the Gulf coast are not covered in this series of studies. Hurricane tide frequencies on the coast of Puerto Rico have also been developed from a set of climatologically representative hurricanes, using the NWS numerical dynamic surge model adapted to local conditions (2).

NOAA has also extended the joint probability method of tide frequencies in bays and estuaries as part of the Flood Insurance Program (3, 15). Apalachicola Bay in Florida and the Cape Fear River estuary in North Carolina were selected for pilot projects. Hydrodynamic models had to be developed for routing hurricane tides into the bay and the estuary respectively (16, 17). Again, without going into details, this development leads to hurricane tide frequency estimates in the selected bay and estuary by storm tide simulation.

V. Conclusion

The tide frequency analysis technique developed by NOAA has been extended along the Atlantic coast. The simulation method has the advantages of giving results that are consistent from one stretch of coast to another, and for giving a result where there is little local data available. Tide frequencies estimated in this way form the technical basis for flood hazard boundary maps prepared for the Flood Insurance Program for communities subject to inundation from the sea.

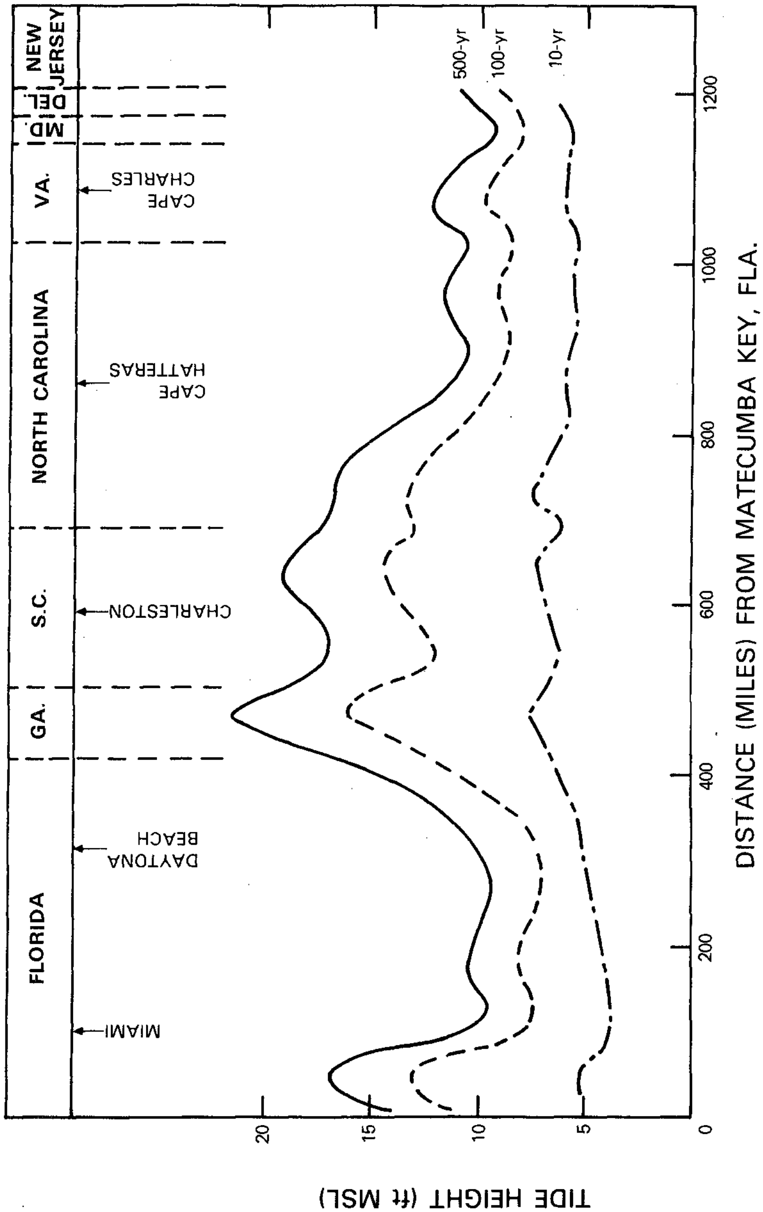

Figure 10.--End product -- tide frequency profiles along open coast.

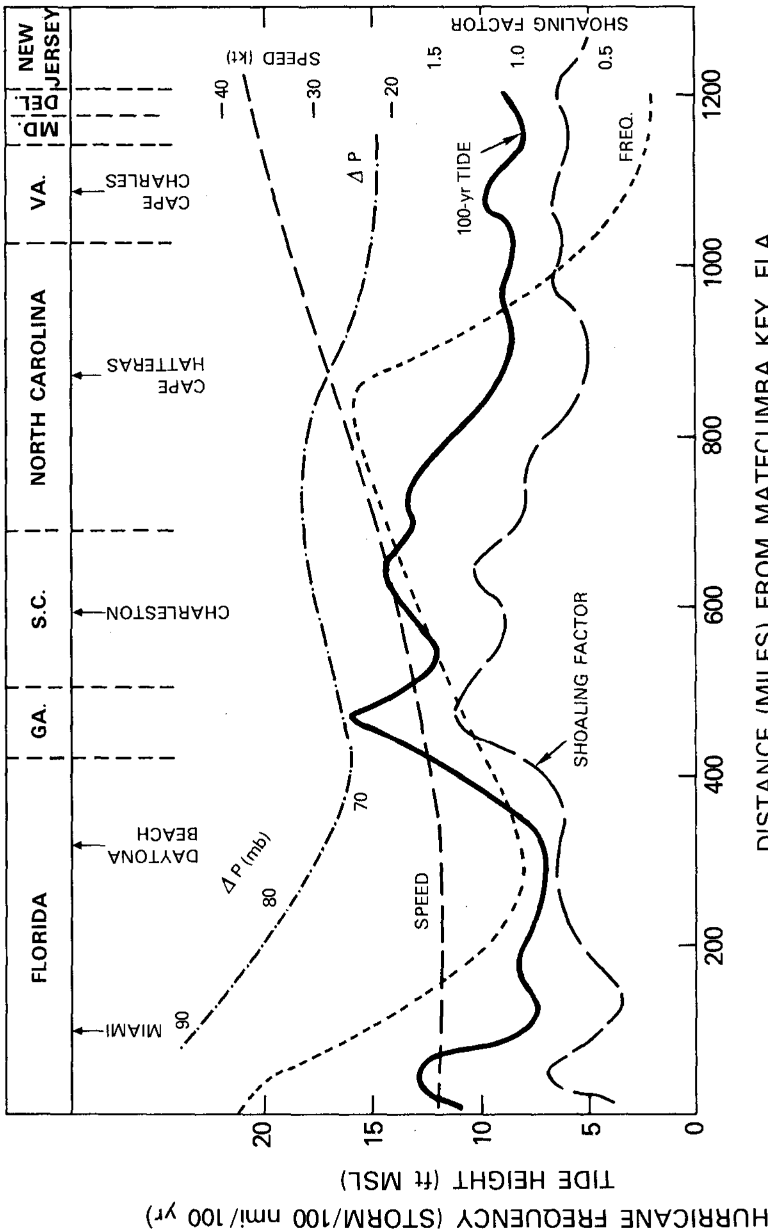

Figure 11.--Schematic illustration of regional relations along the Atlantic coast between storm tide frequency, shoaling factor, and hurricane climatology: landfalling hurricane frequency, pressure deficit (ΔP), and speed of forward motion.

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