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STORM TIDE FREQUENCY ANALYSIS FOR THE OPEN COAST OF VIRGINIA, MARYLAND, AND DELAWARE

Silver Spring, Md.
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STORM TIDE FREQUENCY ANALYSIS FOR THE OPEN COAST OF VIRGINIA, MARYLAND, AND DELAWARE

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Office of Hydrology
Silver Spring, Md.
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STORM TIDE FREQUENCY ANALYSIS FOR THE OPEN COAST OF VIRGINIA, MARYLAND, AND DELAWARE

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A report on work for the Federal Insurance Administration, Department of Housing and Urban Development by the National Oceanic and Atmospheric Administration, Department of Commerce.

ABSTRACT. Storm tide height frequency distributions are developed on the coast of Virginia, Maryland and Delaware for the National Flood Insurance Program. Storm tides are computed from a full set of climatologically representative hurricanes using the National Weather Service numerical-dynamic storm surge model. Winter storm effects are estimated from tide gage records. Storm tide levels from all storms are shown in coastal profile between annual frequencies of 0.10 and .002. This report is intended for use in estimating actuarial risk to buildings from coastal floods and in flood plain management.

1. INTRODUCTION

1.1 Objective and Scope

The Federal Insurance Administration (FIA), Department of Housing and Urban Development (HUD), requested the National Oceanic and Atmospheric Administration (NOAA) to study flood levels from storm tides on the open coast of Virginia, Maryland and Delaware (fig. 1). This includes the Atlantic Ocean coast of Sussex County, Del., Worcester County, Md., and Accomack County, Northhampton County, and Virginia Beach, Va. The assignment is limited to determining storm tide frequencies along the Atlantic Ocean coast on a common regional basis. Modifications of the storm tide levels within Chesapeake Bay and Delaware Bay are not included. These modifications have to be assessed by separate investigations, using the present study as part of the relevant information.

The tide frequencies are of still water levels that would be measured in a stilling well or tide gage house designed to exclude wave action. The destructive effects of waves on the beach front must be taken into account separately.

Storm tides in the study area are caused both by hurricanes -- which are storms of tropical origin occurring in the summer and fall months -- and by a winter type of coastal storm, commonly called northeasters. Both types of storms are included in the study. The hurricane tide frequency analysis was carried out primarily by the first two authors and the winter storm tide frequency by the last two.

1.2 Authorization

The National Flood Insurance Act of 1968, Title XIII, Public Law 90-448, enacted August 1, 1968, authorizes and directs the Secretary of Housing and Urban Development to establish and carry out a National Flood Insurance Program. The Secretary is authorized to secure the assistance of other Federal Departments on a reimbursement basis in assessing flood frequencies. Authorization for this particular study is Project Order No. 2, dated November 13, 1974, under agreement No. IAA-H-1975 between the Federal Insurance Administration and NOAA, as amended.

1.3 Study Method

The technique used in this tide frequency analysis for the oceanic coast of Virginia, Maryland, and Delaware (hereafter referred to as the Delmarva coast) is basically the same as that applied earlier to the North Carolina coast (Ho and Tracey 1975a, 1975b) and in other studies (e.g., Ho 1974).

Hurricanes and northeasters are studied separately, and the annual frequencies from each at a given tide level summed to obtain the overall annual frequency of that level. The northeasters are the most frequent, and in the aggregate over the years have caused the largest dollar value of damage in the study area, but hurricanes are potentially the most severe. This is clarified in the analysis. The hurricane tides are assessed from the climatology of hurricanes, by a joint probability method to be described. Winter storm tides are assessed directly by statistical analysis of tide records.

The first step is to assess the behavior of hurricanes along the coast from past records. Factors analyzed included depression of the atmospheric pressure at the storm center below the surrounding value, forward speed and direction of motion of the storm, and distance from the storm center to the band of maximum winds. All these factors relate to a storm's potential to produce high tides.

The second step in the tide frequency analysis is to calculate the coastal tide levels that each of a number of hypothetical but representative hurricanes from various combinations of the hurricane parameters would produce. For this a dynamic calculation method is used that has been demonstrated to reproduce storm tides of past hurricanes within acceptable tolerances. Each hypothetical hurricane is defined by a particular combination of the hurricane parameters determined in the first step.

Third, the computed hurricane surges are combined at several selected points on the coast with the astronomical tide variation by using a joint probability method to obtain a tide frequency distribution.

These three steps are amplified in sections 3, 4 and 5 of the report, respectively.

Fourth, winter storm tide frequencies are estimated at tide gage sites by a statistical analysis described in section 6.

Fifth, the tide frequencies are interpolated along the coast, separately for hurricanes and winter storms, described in sections 5 and 6, respectively. Finally, the hurricane and northeaster tide frequencies are summed. This is described in section 7.

2. SUMMARY OF HISTORICAL STORMS

This section summarizes the major hurricanes that have affected the study area since 1800 and selected recent severe winter-type coastal storms. Lesser storms are omitted.

2.1 Hurricane Tracks

Selected tracks of damaging hurricanes affecting the study area since 1871 are shown in figures 2a and 2b. The information on hurricane tracks is taken from the charts of North Atlantic tropical cyclones compiled by Cry (1965). For 1964 through 1974, similar tracks are published in the Monthly Weather Review.

2.2 Historical Notes on Hurricanes

Brief notes on the history of hurricanes and damages caused by them are abstracted from published papers. Reported wind speeds are included to indicate qualitatively the intensities of storms. Wind speeds from Weather Bureau stations from storms before the 1920s have been adjusted by the anemometer instrumental corrections developed by Harrison (1963). Since the 1920s, official wind reports include the corrections. Prior to 1940, the highest wind given for a storm was usually the "maximum velocity," an average wind speed for a 5-min period. In recent years, the highest sustained wind is an average over a 1-min period. The magnitude of storm surge is related to the wind integrated over a longer period of time.

Maximum storm tide levels are quoted from the original reports. For the 1933 and later hurricanes, these are heights above the reference level now known as the National Geodetic Vertical Datum, except for one or two instances where another reference level is explicitly stated. Datums for heights are discussed in section 8 of the report.

August 22-23, 1806

This large destructive hurricane crossed eastern North Carolina and moved out to sea again near Norfolk, Va. Shipping suffered severely as the storm picked up speed and moved up the Delmarva-New Jersey coast. The coastal ship Rose in Bloom upset in a stiff northeast gale off Barnegat Inlet, on the central Jersey coast, with the loss of 21 of 49 persons aboard (Ludlum 1963).

September 3, 1821

Shipping first reported the existence of this hurricane near Turks Island in the southeastern Bahamas on September 1st. It moved rapidly to the north and the center entered the North Carolina coast at daybreak on the 3rd. The storm continued moving to the north toward Norfolk, Va., where it inflicted great damage on shipping and installations, and high tides inundated the wharves by 3 to 5 ft. It then moved northward over the Delmarva Peninsula where the low-lying communities on Chesapeake Bay and the peninsula suffered greatly. "The crops are laid low, and the country exhibits one scene of widespread desolation and ruin," observed the American Commercial Beacon. At Pungoteague the water rose 10 ft. The storm moved over Cape Henlopen which experienced the eye and continued to the north-north-east over New York City (Graham and Hudson 1960; Ludlum 1963; Corps of Engineers, New York, N.Y. 1964).

October 13, 1846

Ludlum calls this "The Great Hurricane of 1846." The storm center passed west of all the principal ports of the South Atlantic States, then moved through east-central North Carolina and into the tidewater areas of Chesapeake Bay. The lowlands along the Delaware River near New Castle were overflowed in the greatest storm surge in 70 years. The waters rose high enough to put out the fire in a locomotive which had been stalled by the rising waters (Ludlum 1963).

August 18, 1879

A severe hurricane moved inland near Wilmington, N.C., on the 18th and back out to sea near Norfolk with highest winds at Cape Lookout. The anemometer cups at Cape Lookout were blown away indicating 138 mph. Anemometers were also destroyed at Hatteras, Fort Macon, Kitty Hawk, Portsmouth, N.C., and Cape Henry, Va., with speeds estimated at 100 mph or more. The schooner A. J. Bently, about 90 mi off the coast of the lower Delmarva Peninsula reported waves 40 ft from trough to crest. At Cape Henry the wind had reached a velocity of 76 mph when the anemometer cups were carried away. Lowest pressure observed at Cape Henry was 983.8 mb (29.05 in). The damage to maritime property was enormous. Over 100 large vessels were shipwrecked or suffered serious injury while the number of yachts and smaller vessels which were destroyed or seriously damaged exceeded 200 (U. S. Weather Bureau 1879).

August 23, 1933

This hurricane caused extensive damage in northeastern North Carolina, eastern Virginia, the Delmarva Peninusla, and New Jersey. Most of the damage was caused by high tides and waves. The storm passed over Norfolk, Va., during the morning of August 23 and moved northward along Chesapeake Bay. Norfolk had a low pressure of 971.2 mb (28.68 in.) and a maximum wind velocity of 56 mph, while high tides flooded the business district with 4 to 6 ft of water (Graham and Hudson 1960). Cape Henry had a maximum wind velocity of 68 mph. As the storm moved north of Norfolk, it caused great destruction to resorts on the Delmarva Peninsula and New Jersey coasts. The greatest damage occurred on the Delaware coast and at the tip of Cape May, N.J. The wind at Cape Henlopen, Del., was estimated to have reached 75 mph. Damage from the storm was estimated at $17,500,000 in Maryland and Delaware, $10,000,000 in Virginia and $3,000,000 in New Jersey. The storm moved northward through central Pennsylvania with decreasing intensity and then northeastward towards the St. Lawrence River Valley. In his chronicle of Maryland's coastal hurricanes, Truitt gives the following description:

> "The August 1933 storm did the greatest damage to the seaside recorded up to that time, and statewide, perhaps the greatest damage of all time. The state's loss was estimated as high as $30 to $40 million and, in Worcester County, the damage was placed at approximately $800,000 at a time when money values were much higher than they are today. Of the 41 oyster houses readied for seasonal operations, only 8 were left usable though damaged. Farm crops were laid waste and boardwalk, cottages, and many other buildings, together with a new marina and machine shop at Ocean City, were carried away. While this destruction was vast, the accompanying winds were barely, if at all, of hurricane strength. Rather over a long haul, or fetch, they built up waves and tides that were highly devastating. No lives were lost. The Ocean City inlet was gained by the out-flow of pent-up high water in Assawoman and Isle of Wight Bays, and later made permanent" (Truitt 1976).

This storm caused the highest tide of record, 7.7 ft at Baltimore (Harris and Lindsay, 1957). In the Portsmouth area of Virginia, high tide was 8 ft, while at Old Point Comfort, Va., the high tide reached 8.6 ft (Corps of Engineers, Norfolk, Va., 1963). At Breakwater, Del., the tide reached 6.1 ft (Corps of Engineers, Philadelphia, Pa., 1963), while at Atlantic City the maximum wind reached 76 mph and the highest tide was 5.0 ft. At St. George Ferry Terminal in New York City, the highest tide reached 4.9 ft (Corps of Engineers, New York, N.Y., 1964). As stated in the introduction to this section, tide hights here are above NGVD. Winds in this storm over coastal waters and Chesapeake Bay have been reconstructed by Graham and Hudson (1960), along with a detailed track.

<u>September 18, 1936</u>

This storm approached Cape Hatteras from the southeast, began recurving to the north, and passed east of the Virginia Capes on September 18th. At Cape Henry the full force of the hurricane was not recorded since the anemometer cups were blown away but the wind was estimated at 75 mph (Tannehill 1936). Tides in the Norfolk-Portsmouth area reached 6.0 to 7.5 ft (Corps of Engineers, Norfolk, Va., 1963). This was a severe storm for the Delmarva Peninsula. Late crops in Maryland were destroyed by wind and water to the extent of 60% of their normal yield. This storm is known as the <u>Morro Castle</u> Storm because of difficulties it placed in the way of aid to the stricken liner (Truitt 1967). The storm passed 100 miles southeast of New York City where much of Ocean Avenue was flooded (Corps of Engineers, New York, N.Y., 1964).

September 14, 1944

This rapidly moving hurricane passed over Hatteras moving to the northnortheast. Of this storm Tannehill states: "There is no definite proof of a more violent hurricane in the records." The storm has become known as the Great Atlantic Hurricane and wrecked and sank 5 U.S. Navy vessels off North Carolina. As the hurricane moved northeastward, it damaged coastal resorts along the Delmarva Peninsula. The center passed about 30 mi east of Atlantic City, N.J., where it destroyed the steel pier and most of the boardwalk. The storm passed the New Jersey coast near time of high astronomical tide. This resulted in high storm tides with extensive flooding and great damage. The greatest damage was done on Long Beach Island and Absecon Island. The hurricane approached New York City, but passed well out at sea about 60 mi to the southeast and moved across the eastern tip of Long Island and into New England where it diminished in intensity. The total property damage has been estimated at $100 million (1944 prices). Three hundred and ninety people lost their lives in this storm, the majority on the sunken vessels. The lowest reported pressure of 947.2 mb (27.97 in) occurred at 8:20 a.m. on September 14 at Hatteras, N.C., and the highest recorded wind speed of 134 mph at Cape Henry, Va., on the same date. Maximum winds equalled or exceeded all previous records at Hatteras, Cape Henry, Atlantic City, and Block Island. Some of the noteworthy extreme winds (fastest mile) were: Hatteras, N.C., estimated 110 mph, Norfolk, Va., 73 with gusts estimated to 90 mph, Cape Henry, Va., 134 mph with gusts estimated to 150 mph, Cape May, N.J., gusts to 92 mph, Atlantic City, 91 mph, and New York City, 99 mph. Some of the high tides were: 8.0 ft at Naval Air Station, Cape May, N.J., 7.6 ft at Atlantic City, N.J., and 7.4 ft at Perth Amboy, N.J., (Corps of Engineers, New York, N.Y. 1964; Ludlum 1963; Sumner 1944; Tannehill 1956).

October 15, 1954 (Hazel)

Hurricane Hazel moved inland near the South Carolina-North Carolina border on October 15th. It moved northward very rapidly, passing near Washington, D.C., through central Pennsylvania and western New York, then across Lake Ontario into Canada, maintaining its intensity most of the way. Peak wind speeds of 90 mph or more were reached near and east of the center from the Carolinas through New York. Along the Maryland coast considerable damage was done to floating equipment, houses, and the boardwalk and cottages at Ocean City. In "High Winds. . . . High Tides," Truitt states; "The Chesapeake Bay and its tributaries bore the brunt of Hazel's fury in gale and wind and tidal action with corresponding losses, though five-foot tides were reported at Public Landing in Chincoteague Bay." At Breakwater, Del., the tide reached 4.6 ft and at Philadelphia, Pa., winds gusted to 94 mph and the tide reached 7.5 ft. (Corps of Engineers, Philadelphia, Pa. 1963) At Atlantic City, N.J., winds gusted to 80 mph and the tide rose to 4.6 ft

(Corps of Engineers 1965). Although the path of the storm was about 200 mi west of New York City, gusts to 100 mph were reported in the metropolitan area (Corps of Engineers, New York, N.Y. 1964). Graham and Hudson (1960) reconstruct the coastal and Chesapeake Bay wind fields in this storm also.

August 12-13, 1955, (Connie)

Hurricane Connie entered the North Carolina coast near Morehead City about 8:30 a.m. on August 12th. It continued moving northward across eastern North Carolina, then over Norfolk, Va., along Chesapeake Bay, through central Pennsylvania and western New York State into Canada. As the storm moved north, it brought torrential rains all the way into Pennsylvania. Along the Maryland coast, Connie brought high seas and tides that caused great damage, although winds did not reach hurricane strength of 75 mph (Truitt 1967). At Breakwater, Del., the highest tide was 4.4 ft. Although the hurricane passed 125 mi to the west, Atlantic City, N.J. had a maximum wind of 65 mph and a high tide of 4.0 ft (Corps of Engineers 1965).

September 12, 1960 (Donna)

Hurricane Donna passed inland over the North Carolina coast between Wilmington and Morehead City on September 11th. The storm moved northeastward across North Carolina, then parallel to the Delaware-New Jersey coast, across eastern Long Island and into New England. As the storm passed east of the mouth of Chesapeake Bay, severe wind damage was sustained throughout the area. A maximum wind velocity of 138 mph was recorded at the mouth of Chesapeake Bay. At Norfolk Harbor the maximum tide reached 6.3 ft. Other measured tides in the area were: 5.5 ft at Sewells Point, 4.8 ft at Old Point Comfort, and 5.8 ft at Gloucester Point. Along the Maryland coast, winds were estimated at 75 mph at Chincoteague and higher at Ocean City. Only light damage was suffered on the Delmarva coast. Donna was located about 80 to 100 mi east of Atlantic City, N.J., at noon on the 12th, moving to the northeast at 40 mph. Along the Delaware coast, low tide occurred during the peak of the storm and there was no appreciable damage from flooding. But there was considerable damage from medium to heavy wave action and flooding of low areas along the New Jersey coast. Atlantic City reported a wind of 1-min duration of 60 mph, gusts up to 83 mph, and a maximum tide of 6.1 ft. (Hardy and Carney 1962; Corps of Engineers, Norfolk, Va. 1963; Truitt 1967; Corps of Engineers 1965).

September 16, 1967 (Doria)

Doria was one of the most erratic hurricanes ever observed. The storm, centered 250 mi east of Jacksonville, Fla., on September 7th, moved slowly and passed about 100 mi southeast of the North Carolina Capes on the 10th. It continued moving to the east-northeast for several hundred miles, then on September 13th, reversed its course and moved westward. In its westward movement it passed over colder water and encountered colder and drier air which weakened the storm. The weakened center reached land near the Virginia-North Carolina border and continued southward across the North Carolina Capes and back to sea on September 17th. Doria attained her lowest central pressure, 973 mb (28.73 in.), well at sea, midway between Nantucket and Bermuda, on September 14. The highest wind reported by a land station near the center was 50 mph with gusts to 83 mph at Indian River Inlet, Del. The highest tide, 6.5 ft above normal, also occurred there (Sugg and Tanner 1968).

2.3 Winter Coastal Storm Characteristics

The study area is exposed to winter coastal storms, characterized by strong winds from a northeast quadrant over long reaches of coast, hence, the familiar name "northeaster." These winds are part of a counterclockwise cyclonic atmospheric circulation about a center of atmospheric low pressure at sea. The proximity of warm gulf stream water to the colder continent during winter and spring favors the development of such storms. Most of these storms move rapidly to the north and northeast past the coastal reach of the study area, but under favorable conditions of the general atmospheric circulation they can stall and intensify with little forward motion for a couple of days.

Another characteristic of those winter storms generating the highest coastal surges is an unusually long fetch of strong winds directed toward the coast. Surge-generating characteristics of winter storms are summarized in a recent monograph by Pore and Barrientos (1976). The Earth's rotation causes a rise in water level to the right of any current. The most critical direction for the wind fetch is, therefore, an angle of less than 90° to the coast, enabling this rotational effect and the direct wind and water transport effect to combine in producing the coastal surge.

The critical surge-generating fetch is illustrated by sea level weather charts for three winter storms significant to the study area. The isobars on these charts may be construed as approximate wind streamlines, counterclockwise about the low pressure center. Contributing to the long fetch in each case is either an unusual elongation of the low center or a double center.

Figure 3 is for the storm of November 1950. This storm was most severe in New York Harbor but also produced the third highest tide of record in the northern part of the present study area (second highest northeaster tide). The weather map may be compared with the storm marigrams at Atlantic City, N.J., in figure 6 (marigrams not available at Lewes, Del., within the study area). The datum reference in this figure is 1941-59 local MSL (left-hand column of table 7).

Figure 4 is for the April 1956 storm that produced the second highest northeaster tide of the last 40 years in the Norfolk-Hampton Roads area. This was a more local storm, in terms of length of coast affected, than the other two cited here. The wind fetch aimed at the mouth of Chesapeake Bay is evident in the figure. The marigrams appear in figure 6.

The March 1962 northeaster produced the second highest tide of record in most of the study area, being exceeded only by the 1944 hurricane in the northern part and the 1933 hurricane in the Hampton Roads-Norfolk area. The storm lasted through five high-tide cycles. The fetch directed at a critical angle to the coast north of an elongated intense low center is illustrated in figure 5. Marigrams are depicted in figure 6. It has not been determined whether the 12.4-hr periodicity in the surge is a real dynamic effect from storm surge-astronomical tide interaction or a spurious effect from a timing discrepancy.

Further discussion is given below of local effects in the November 1950 and March 1962 storms. Wind velocities over the continental shelf in these two storms have been reconstructed by Graham and Hudson (1960) and by Goodyear (1963), respectively. Tide heights quoted from Corps of Engineers reports are above National Geodetic Vertical Datum.

2.4 Historical Notes on Winter Storms

November 25-26, 1950

The November 25-26, 1950, storm was considered the worst winter storm on record for the eastern United States up to that time (Bristor 1951). Destruction resulted primarily from high tides on the coast and flood-producing rains inland, but local wind damage was also extensive. The unusual SE fetch of winds directed toward the coast is indicated by figure 3. The storm struck the day following full moon, thus coincided with spring tides. The highest tide reported at Lewes, Del., was 7.2 ft (Corps of Engineers, Philadelphia, Pa. 1963). Effects were felt inland from the southeast gales, Philadelphia (Pier 8) on the Delaware River and Cambridge, Md., on Chesapeake Bay, observing the highest tide of record up to that time (Pore et al. 1974).

March 6-8, 1962

The storm of March 6-8, 1962 was the worst northeaster of the present generation in aggregate coastal damage. To the south the storm opened a new inlet near Buxton, N.C., while to the north it breached Long Beach Island, N.J. Two inlets were cut through Assateague Island 3 miles south of Ocean City, Md. Tidal flooding was widespread in communities along the entire coast of the study area. Five successive high tides over a period of 48 hours carried the water inland to reach buildings and structures which would ordinarily be beyond the reach of such tides. Houses and other structures were destroyed on sites where they had been safe for 60 to 80 years. Some ocean front buildings were undermined and tilted, while others were washed away. Boardwalks at Rehoboth Beach, Bethany Beach, Del., and Ocean City, Md., were seriously damaged.

The tide gage at Lewes, Del., recorded a maximum of 7.4 ft, at Ocean City, Md., 7.5 ft. This last tide was 1.5 ft higher than the previous record high in the hurricane of August 1933. The gage at Fort Norfolk, Norfolk, Va., recorded a highest tide of 7.4 ft, 0.6 ft below the record

8.0 ft reached during the same hurricane (Corps of Engineers, North Atlantic 1963). Along the south shore of Long Island, N.Y. the tides reached elevations approaching record highs (Cooperman and Rosendal 1962).

3. CLIMATOLOGY OF HURRICANE CHARACTERISTICS

This section describes important characteristics of hurricane parameters that are needed for calculating tide levels on the coast. Basic parameters of hurricanes affecting the U.S. coast, including central pressure, radius of maximum winds, speed of forward motion, and direction of forward motion, all factors affecting storm tide producing capability, were published in 1959 (Graham and Nunn 1959). This compendium of hurricane characteristics has been updated through 1973 and adapted to the needs of the Flood Insurance Program, including specification of probability distributions of the individual parameters. These data are published in a separate report (Ho, Schwerdt, and Goodyear 1975), hereafter referred to as the Climatology Report, and are the primary data source on hurricanes for the present study. These data are used directly for the portion of the study area north of Cape Charles, with certain refinements in alongshore hurricane track count described later. The methods of the Climatology Report were extended by certain additional analyses in the North Carolina study (Ho and Tracey 1975b). These same methods, adopted in the present study for the Virginia coast south of Cape Henry, are discussed in par. 3.2.

For the purpose of determining parameter probabilities in the Climatology Report, hurricanes and tropical storms are grouped into three classes, those that landfall on the coast, those that bypass alongshore with the center remaining at sea, and those that exit the coast following an earlier entry.

3.1 North of Cape Charles

3.1.1 Probability distribution of hurricane intensity

Storm surge magnitude varies approximately with the strength of the wind, other factors being constant. An index of the wind stress in hurricanes is the intensity of the storm as measured by the depression of the storm's central pressure below representative peripheral pressure (D). The assessment of probability distributions of this parameter for landfalling and alongshore storms is described in the Climatology Report.

3.1.2 Probability distribution of radius of maximum winds

Winds in all hurricanes increase from low values within the eye to their most intense velocity just beyond the edge of the eye, then decrease gradually. The average distance from the storm center to the circle of the maximum wind speed is called the radius of maximum winds (R) and is adopted as a convenient single number to be used as an index to the size, or lateral extent, of the hurricane, a factor which affects the surge profile along the coast. R values are taken from the Climatology Report.

3.1.3 Probability distributions of speed and direction of forward motion

The speed (T) and direction (θ) of forward motion of hurricanes also affect surge height. The height of the surge on the coast increases with increasing storm speed. Thus, the fastest moving storms, especially if they are large and moving directly toward the coast, pose the greatest hazard. Probability distributions of forward speed for the landfalling and alongshore storms are given in the Climatology Report previously cited. The probability distribution of direction of forward motion for landfalling hurricanes and tropical storms is also discussed in the Climatology Report.

3.1.4 Frequency of hurricane tracks

The overall frequency of hurricane occurrences is basic to calculating the resulting tide frequencies. The frequency with which hurricanes and tropical storms have entered or exited the coast and have moved approximately parallel to the coast at sea ("alongshore") based on 103 years of data smoothed along the coast is given in the Climatology Report. These counts are used in this study. Additional counts of alongshore storms immediately opposite Ocean City, Md., and Parramore Island, Va., were made from Cry's (1965) annual track charts to secure more detail. Hurricanes and tropical storms that bypassed within 100 n.mi. off the coast or 30 n.mi. inland were assessed by separate counts of storm tracks crossing lines normal to the coast at these points. The cumulative track counts along each line were plotted and a smooth curve fitted by eye to the data on each of these frequency plots. The resultant track frequencies, as well as other hurricane parameters, are listed in the parameter tables in section 5. Parameters for exiting storms are not included in the tables. They are not significant here and are not included in the tide frequency analysis for coastal stations north of Cape Charles.

3.2 South of Cape Henry

Landfalling hurricanes and tropical storms in the study area south of Cape Henry are further classified, as in the North Carolina report previously cited (Ho and Tracey 1975b), to deal with the joint probability questions referred to in chapter 6 of the Climatology Report, and to take account of the effects on the coast of storms passing inland from the coast. These are covered in detail in the North Carolina Report and briefly discussed in the following paragraphs. Parameters not specifically mentioned are treated in the same way as north of Cape Charles.

3.2.1 Conditional probability question

It will be explained in section 5 that assessing the probability of a certain combination of hurricane parameters involves multiplying together the probabilities of each of the parameters, on a scale of 0 to 1.0, provided the distributions of the several parameters are independent in the statistical sense (chapter 6 of the Climatology Report). If the distributions for any two parameters are not essentially independent, this must be recognized by either using conditional probabilities or by segregating the possible hurricane events into subsamples. An example in the Climatology Report is the division of hurricanes into "landfalling" and "alongshore". Separate forward speed distributions are then determined for each subsample.

3.2.2 Separation of NE and SE landfalling hurricane parameters

South of Cape Henry we must deal with the correlation between hurricane intensity and the direction of storm motion relative to the coast. This is alluded to in par. 6.3 of the Climatology Report as an example of conditional probability questions that may be expected in various regions, but specific data are not developed. Hurricanes landfalling from the southeast quadrant cover the full range of intensities from very severe to weak. From time to time in this region a hurricane meanders and strikes the coast from the northeast quadrant. These storms are either of a weaker category initially or, if originally intense, have been weakened by transit over cold water and other effects. The speed distribution for these storms is also different from those moving from the southeast quadrant. These storms all move at less than 15 kt. A separation for all parameters, including track frequency, was made between landfalling storms from the SE and NE quadrants south of Cape Henry.

3.2.3 Exiting hurricanes

Because of coastal configurations and the propensity of hurricanes to recurve south of the study area and move northward, many hurricanes landfall on the coast south of Cape Hatteras and then pass through Virginia on a course approximately parallel to the coast. The central pressure for such inland storms was estimated by applying an average filling rate after the storm center landfalls. This filling rate was derived from an empirical study of central pressure vs. time overland by Malkin (1959). The application is described in detail in the North Carolina Report (Ho and Tracey 1975b).

The frequency with which hurricanes and tropical storms exited the coast is given in the Climatology Report. Other parameters are adapted from those for the landfalling and inland categories. Approximating the parameters and grouping into fewer class intervals suffices for these computations as exiting storms produce lower storm tides, and, as it turns out, make an almost negligible contribution to the overall storm tide frequencies.

4. HURRICANE SURGE

4.1 Surge Model

The National Weather Service has developed a two-dimensional numerical-dynamic surge model for calculating the water levels induced by hurricanes on the continental shelf (Jelesnianski 1967, 1972, and 1974). The objective of this work was to develop a tool to forecast open coast surges when hurricanes were approaching. The model has become the backbone of NOAA's tide-frequency studies for the flood insurance program. The development of the model is described by Jelesnianski in the 1967 paper and operational applications (designated as SPLASH I and II) in the others. Both limitations and verification of the model are described in the references. Replications of surge profiles produced by past hurricanes agree well with observed storm tides and high water marks adjusted to include astronomical tide. The model computes the surge, the difference between the local storm-induced level and the normal water levels for the area. Thus, the computed storm surge must be added to the predicted astronomical tide.

Inputs to a computer surge calculation are hurricane central pressure deficit, radius of maximum winds, storm direction of motion and forward speed, and ocean depths at a series of grid points. The hurricane climatology just described is oriented toward providing these parameters. The computer program generates the needed moving sea level pressure field and moving wind field from the basic parameters by predetermined relations which are part of the model.

The SPLASH I version is limited to storms moving forward at constant velocity and intensity toward a specified landfall point while the earlier version of SPLASH II has been expanded to accommodate storms with generalized motions of not too great complexity. Also, storm strength and size are allowed to vary in a continuous monotonic manner with time. These models were used for the Virginia coast south of Cape Henry. The later version of SPLASH II further incorporates the dynamic effects of the curvature of the coast and was used to compute surges generated by both classes of hurricanes, landfalling and alongshore, in tide frequency analysis north of Cape Charles.

4.2 Shoaling Factor

The capacity of a hurricane of given characteristics to produce a coastal surge depends on the profile of water depth. The shallower the coastal water the higher the surge. This variation along the East coast is depicted in a report by Barrientos and Chen (1975, fig. 3b) as the ratio of the surge that would be produced locally at each coastal point by a standardized hurricane to the surge from the same hurricane moving over a continental shelf of average or standard slope. This ratio is called the shoaling factor and is generated by computing surges by the model that has been described at the various coastal points and over the "standard basin" and taking ratios of the peak surges. The Delmarva portion of this diagram is reproduced in figure 7. The shoaling factor is implicit in calculations of hurricane surge by the model at selected coastal points, since sloping depths of the continental shelf are introduced to the calculation as input data. The shoaling factor is a primary guide to interpolating between coastal computation points. The shoaling factor curve of figure 7 reveals that a minimum factor is reached near Ocean City, Md. Comparatively higher factors appear to the north and south of the study area.

5. HURRICANE TIDE FREQUENCIES

5.1 The Joint Probability Method

The joint probability method has been described in detail in a separate report (Myers 1975, especially pp. 12-13). The first step is to define the probability distributions of the several hurricane parameters, as described in section 3. Each distribution is divided into class intervals, and the mid-point values are read out for each class interval. The parameters derived in this way and used in the subsequent computations are listed in tables 1 to 5 for the coast at Rehoboth Beach, Del., Ocean City, Md., Parramore Island, Va., Virginia Beach, Va., and at the Virginia-North Carolina border, respectively.

As the second step, calculations are made with the SPLASH computer program of the coastal profile for representative hurricanes. The adjustment of surge envelopes obtained by SPLASH computations to give other surge envelopes is described in the next section. There are two kinds of adjustments, to different hurricane parameters and to a shifted landfall point.

As the third step, all surge profiles including the ones obtained by adjustment are added to the astronomical tide with random time phasing. Handling this phasing in a probabilistic manner is described in the report previously cited (Myers 1975). The requisite analysis of a 19-yr cycle of the astronomical tide to obtain these ranges is further discussed in the next section. Since each surge profile has a prescribed frequency, as have the astronomical tides, the tides resulting from a combination have prescribed frequencies.

As a fourth step, summing all hurricane possibilities yields the total tide frequency from these storms.

5.2 Maximum Hurricane Surge Computations

Different variations of the second step of the above procedure were used north of Cape Charles and south of Cape Henry. These are described in the following paragraphs.

5.2.1 Coastal surge envelopes from landfalling hurricanes - north of Cape Charles

Hurricanes landfalling on this stretch of the coast are described by the parameters listed in tables 1A to 3A. The possible combinations of these parameters in each table give 160 hurricanes representing climatologically possible storms landfalling near the indicated coastal station or in its vicinity. Potential surges that would be produced by the hurricanes were obtained from SPLASH computations and from adjustments. Surge computations were made by using the later version of SPLASH II surge prediction model with the possible combinations of assigned values of

R, T, and θ (2Rs x 5Ts x 2θs = 20 hurricanes), all at D = 62 mb. Each surge profile generated in this way was adjusted by a predetermined surge-pressure relation to each of the 8 Ds listed in the tables, yielding 160 potential surge profiles.

Another parameter required for a SPLASH computation is the landfall point of the storm. Landfall points were spaced at approximately 48-mi intervals for the SPLASH computations indicated above. Landfall points at 8-mi intervals in between were simulated by shoaling factor adjustment of surge envelopes pertaining to the nearest primary computation track, as in previous studies (e.g., Myers 1975).

5.2.2 Maximum surges for alongshore hurricanes - north of Cape Charles

Maximum surge heights produced by alongshore storms bypassing stations north of Cape Charles were obtained by direct computations using the later version of SPLASH II surge prediction program. Six storm tracks assigned to hurricanes in the computations of alongshore surges (fig. 9), were spaced at distances of 5, 15, 25, 40, 60 and 80 n.mi. from the coast off Cape May, N.J. Surge computations were made for the 6 combinations of R and T values in tables 1B, 2B, and 3B, on each of the six tracks, all at D = 62 mb. Each of the 36 coastal surge profiles was adjusted to the eight D classes by the same relation used for the landfalling storms, providing 288 surge values at each coastal point.

The direct computation of alongshore storm surges is a refinement of the previous procedure in which surge values generated by alongshore storms were read from prepared nomograms as cited in an earlier report (Myers 1975). The surge model incorporates dynamic effects on storm surges from the curvature of the coast, and computed surge heights indicate more distinct variations along the coast than values obtained by using the cited nomograms.

The bathymetric effects on alongshore hurricane surges vary somewhat from those of landfalling storms. To illustrate these points, peak surge values at coastal points computed from one of the initial 6 representative hurricanes (D = 62 mb, R = 48 n.mi., T = 23.1 kt), moving along the several tracks, were plotted against the distance of the storm center from the coast. This distance was measured from the coastal location as the storm center passed abeam. These surge values were analyzed and contours joining equal surge heights drawn. The resultant analysis, shown in figure 8, indicates a minimum area near the coast in the vicinity of Ocean City, Md., and maximum near the southern end of the Delmarva peninsula and near the entrance of Delaware Bay area. These variations are partially caused by the curvature of the coast and the gradient of the sloping continental shelf offshore, as indicated in the landfalling storm shoaling factor curve in figure 7. Similar analyses (not shown) made of the peak surges produced by the other five initial hurricanes indicate the same features.

Legend for Tables 1 to 5

θ_c = Orientation of coast, measured clockwise from north.

P_o = Central pressure (mb).

D = Central pressure deficit (mb).

P_i = Proportion of total storms with indicated D value.

R = Distance from center of storm to principal belt of maximum winds (n.mi.).

P_r = Proportion of storms with indicated R value.

T = Forward speed of storm (kt).

P_t = Proportion of storms with indicated T value.

F_n = Frequency of storm tracks crossing coast (storm tracks per n.mi. of coast per year).

θ_L = Direction of entry or exit, measured clockwise from the coast (deg.).

P_θ = Proportion of storms with indicated θ_L value.

L = Distance of storm track from coast inland or seaward (n.mi.).

F_a = Frequency of storm tracks crossing line normal to coast (storm tracks per n.mi. per year).

D_L = Distance interval from coast (n.mi.).

LL = Effective distance of storm over land (n.mi.).

Table 1.--Hurricane and tropical storm parameters - Rehoboth Beach, Del.

A. Landfalling storms

				F_n = .00016			θ_c = 030°	
P_o	D	P_i	R	P_r	T	P_t	θ_L	P_θ
936.9	76.3	.02	30.5		10.0	.1	120	.5
944.8	68.4	.03	41.7	.5	13.5	.2	145	.5
950.4	62.8	.05		.5	18.0	.3		
956.7	56.5	.10			24.1	.2		
967.0	46.2	.20			31.9	.2		
977.1	36.1	.20						
985.6	27.6	.20						
996.0	17.2	.20						

B. Alongshore storms*

D_L	L	F_a	R	P_r	T	P_t
0 to 10	5	.00160	30.5	.5	16.5	.20
10 to 20	15	.00190	41.7	.5	23.1	.42
20 to 30	25	.00250			34.3	.38
30 to 50	40	.00280				
50 to 70	60	.00350				
70 to 90	80	.00320				

*P_o, D, and P_i are the same as those for landfalling storms.

Table 2.--Hurricane and tropical storm parameters - Ocean City, Md.

A. Landfalling storms

F_n = .00019 θ_c = 030°

P_o	D	P_i	R	P_r	T	P_t	θ_L	P_θ
936.8	76.4	.02	30.5	.5	9.4	.1	120	.5
944.8	68.4	.03	41.7	.5	12.8	.2	145	.5
950.4	62.8	.05			17.2	.3		
956.8	56.4	.10			23.4	.2		
966.7	46.5	.20			31.1	.2		
977.6	35.6	.20						
986.2	27.0	.20						
996.3	16.9	.20						

B. Alongshore storms*

D_L	L	F_a	R	P_r	T	P_t
-10 to 0	-5	.00200	30.5	.5	16.5	.32
0 to 10	5	.00240	41.7	.5	23.1	.40
10 to 20	15	.00260			34.3	.28
20 to 40	30	.00295				
40 to 60	50	.00305				
60 to 80	70	.00270				

*P_o, D, and P_i are the same as those for landfalling storms.

Table 3.--Hurricane and tropical storm parameters - Parramore Island, Va.

A. Landfalling storms

F_n = .00029 θ_c = 030°

P_o	D	P_i	R	P_r	T	P_t	θ_L	P_θ
936.4	76.8	.02	30.5	.5	8.1	.1	120	.5
944.7	68.5	.03	41.7	.5	11.2	.2	145	.5
950.2	63.0	.05			15.6	.3		
956.7	56.5	.10			21.8	.2		
966.2	47.0	.20			29.5	.2		
977.8	35.4	.20						
986.8	26.4	.20						
996.6	16.6	.20						

B. Alongshore storms*

D_L	L	F_a	R	P_r	T	P_t
-15 to -5	-10	.00250	30.5	.5	16.5	.36
- 5 to 5	0	.00160	41.7	.5	23.1	.40
5 to 15	10	.00150			34.3	.24
15 to 35	25	.00265				
35 to 55	45	.00320				
55 to 75	65	.00265				

*P_o, D, and P_i are the same as those for landfalling storms.

Table 4.--Hurricane and tropical storm parameters - Virginia Beach, Va.

$\theta_c = 345°$

	P_o	D	P_i	R	P_r	T	P_t	F_n	θ_L	P_θ
SE Landfalling	935.4	77.8	.02	*	*	7.9	.2	.00031	137	1.0
	943.2	69.3	.03	*	*	11.5	.2			
	949.8	63.4	.05	24.1	.33	11.5	.2			
	956.2	57.0	.10	37.0	.33	20.6	.2			
	965.6	47.6	.20	42.8	.33	25.9	.1			
	977.8	35.4	.20							
	987.2	26.0	.20							
	996.7	16.5	.20							
NE Landfalling	962.0	51.2	.02	24.1	.33	6.1	.2	.00012	90	1.0
	964.8	48.4	.03	37.0	.33	6.8	.2			
	968.8	44.4	.05	42.8	.33	7.5	.2			
	975.2	38.0	.10			8.7	.2			
	984.3	28.9	.20			10.4	.1			
	991.7	21.5	.20			12.9	.1			
	996.0	17.2	.20							
	999.6	13.6	.20							
Exiting	963.6	49.6	.1	24.1	.33	9.7	.3	.00212	230	.5
	971.0	42.2	.1	37.0	.33	15.5	.4		263	.5
	978.0	35.2	.2	42.8	.33	25.9	.3			
	987.0	26.2	.2							
	994.0	19.2	.2							
	1001.0	12.2	.2							

	L	F_a	LL	R	P_r	T	P_t	Remarks
Alongshore	5	.0004		*	*	12.8	.2	P_o, D, and P_i, are the same as those for SE landfalling storms.
	15	.0008		24.1	.33	17.4	.2	
	25	.0009		37.0	.33	20.5	.2	
	35	.0011		42.8	.33	24.9	.2	
	50	.0012				30.6	.1	
	70	.0012				36.5	.1	
Inland	5	.0015	70	24.1	.33	11.2	.3	D's are adjusted from landfalling storms by eq (1) using LL and T values.
	15	.0016	80	37.0	.33	25.1	.3	
	25	.0017						
	35	.0017	100					
	50	.0013	120					

*SE landfalling and alongshore storms with P_o<945 mb:
R = 24.1 and 37.0 n.mi. are each assigned a probability of 0.5.

Table 5.--Hurricane and tropical storm parameters
N.C.-Va. border. $\theta_c = 342°$

	P_o	D	P_i	R	P_r	T	P_t	F_n	θ_L	P_θ
SE Landfalling	934.8	78.4	.02	*	*	7.5	.2	.00033	140	1.0
	942.9	70.3	.03	*	*	11.3	.2			
	949.2	64.0	.05	23.8	.33	15.2	.2			
	955.8	57.4	.10	36.9	.33	20.0	.2			
	964.7	48.5	.20	42.8	.33	25.2	.1			
	975.2	38.0	.20			31.0	.1			
	985.0	28.2	.20							
	996.7	16.5	.20							
NE Landfalling	962.0	51.2	.02	23.8	.33	6.1	.2	.00021	93	1.0
	964.8	48.4	.03	36.9	.33	6.8	.2			
	968.8	44.4	.05	42.8	.33	7.5	.2			
	975.2	38.0	.10			8.7	.2			
	984.3	28.9	.20			10.4	.1			
	991.7	21.5	.20			12.9	.1			
	996.0	17.2	.20							
	999.6	13.6	.20							
Exiting	959.7	53.5	.1	23.8	.33	9.4	.3	.00240	233	.5
	967.9	45.3	.1	36.9	.33	15.2	.4		266	.5
	975.4	37.8	.2	42.8	.33	25.2	.3			
	985.1	28.1	.2							
	992.8	20.4	.2							
	1000.2	13.0	.2							

	L	F_a	LL	R	P_r	T	P_t	Remarks
Alongshore	5	.0008		*	*	12.5	.2	P_o, D, and P_i are the same as those for SE landfalling storms.
	15	.0008		23.8	.33	17.2	.2	
	25	.0009		36.9	.33	19.9	.2	
	35	.0011		42.8	.33	24.4	.2	
	50	.0012				29.9	.1	
	70	.0012				35.6	.1	
Inland	5	.0015	50	23.8	.33	11.2	.3	D's are adjusted from landfalling storms by eq (3) using LL and T values.
	15	.0016	60	36.9	.33	17.7	.4	
	25	.0017	65	42.8	.33	25.1	.3	
	35	.0017	70					
	50	.0013	90					

* SE landfalling and alongshore storms with P_o<945 mb:

R = 23.8 and 36.9 n.mi. are each assigned a probability of 0.5.

5.2.3 South of Cape Henry

Older procedures were used here that differed from the foregoing in a few details, and are identical with the procedure used in the North Carolina report. The earlier versions of the computer programs, SPLASH I and II, a single primary landfall point, and more 8-mi step adjustments, were employed.

Surge computation SPLASH runs were made for all possible combinations of R and θ indicated in tables 4 and 5, with a standardized D and T value. Separate computations were made to determine the relation of surge height to T, this time at standard R and θ. Surge profiles that would be produced by all possible combinations (D, T, R, and θ) were then obtained by adjustments, including the usual adjustment for D from Jelesnianski (1972). Potential surges that would be produced by alongshore and inland storms were obtained from pre-prepared nomograms from the combinations of hurricane parameters in the tables. The procedures are described in detail in an earlier report (Myers 1975).

5.3 Astronomical 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 a maximum in September-October. The months July, August, September, and the first half of October are taken to represent the hurricane season. Astronomical high and low tides at Cape May, N.J., Lewes, Del., Wallops Island, and Virginia Beach, Va., for these representative months were recomputed for a 19-yr period by running the standard tide computation program written by Pore and Cummings (1967). The accumulated frequencies of the high and low tides were calculated separately by months, then weighted in proportion to hurricane occurrences in each month (July 13%, August 27%, September 39%, October 21%). The weighted mean distributions are shown in figure 10. The resulting probability distributions for Wallops Island are almost the same as those for Virginia Beach, Va. The range of high and low tides near the Delaware Bay entrance is slightly greater than those of the southern stations. Interpolating from the probability curves of the stations leads to distributions used in tide frequency analyses for locations along the northern portion of the study area. As in previous studies, each distribution is divided into four class intervals. The representative astronomical tide marigrams needed to combine with each hurricane surge marigram were then approximated as cosine waves with a period of 12.42 hours oscillating between corresponding high and low tide class intervals. This assumes that the highest high tides occur with the lowest low tides, etc.

5.4 Hurricane Tide Frequencies at Selected Points

The hurricane tide frequencies are combined for all classes of storms: landfalling and alongshore hurricanes for stations north of Cape Charles; landfalling, alongshore, exiting, and inland hurricanes for stations south of Cape Henry. The complete detailed computation procedures were applied to five selected stations mentioned in par. 5.1, and also at the Virginia-Maryland State line, and Bethany Beach, Del. Hurricane tide frequencies for other intermediate points were obtained by interpolations, described in section 7.

6. WINTER COASTAL STORM TIDES

6.1 Evaluation of Northeaster Tide Levels in Study Area

Most of the 10-yr return period magnitude (10% probability of being equalled or exceeded per year) storm tides in this study area are caused by northeasters, as will be shown in section 7. The 1962 northeaster produced the second highest tide of record and the largest damage in dollar value in the study area. At the 100-yr return period magnitude (1% chance of being equalled or exceeded in any year), the activating storms are hurricanes and the additional contribution by northeasters is small by comparison.

For purposes of this study, the northeaster contribution to storm tide frequency may be evaluated with sufficient precision by direct analysis of long-period tide gage records and interpolation along the coast. For an overall view, the northeaster tide frequency analysis was extended beyond the study area to Sandy Hook, N.J., on the north. Northeaster tide frequencies for contiguous coastal reaches to the south are contained in the previously cited report (Ho and Tracey 1975b).

6.2 Analysis of Tide Gage Records

6.2.1 Selection of data

The National Ocean Survey (NOS) primary gages that are maintained over many years in and adjacent to the study area are listed in table 6 with their periods of record. A selection of stations for analysis, indicated in the table, was made considering spacing between stations, length of record, and representing open coast as contrasted with estuarine conditions insofar as possible. The locations of the selected stations are shown in figure 11.

To focus on northeasters and excluded hurricanes, at each station the maximum tide was abstracted for each October-through-May season, with an additional check of weather maps to exclude any hurricanes that might occur in early October. These northeaster annual maxima are listed in table 7.

Table 6.—Primary tide gages of the National Ocean Survey in and adjacent to study area.

Station	Years of record
Willets Point, N.Y.	1931-
The battery, N.Y.	1920-
*Sandy Hook, N.Y.	1932-
*Atlantic City, N.J.	1922-
Cape May, N.J.	1956-
Reedy Point, Del.	1956-66
*Lewes, Del.	1948-
*Kiptopeke Beach, Va.	1951-
*Hampton Roads, Va.	1927-
Norfolk, Va.	1935-

*Station selected for analysis.

6.2.2 Adjustment for sea level trend

Sea level with respect to the adjacent land has been rising more or less steadily during the period of tide gage measurements in the study area. For example, at New York City, where the longest record is available, sea level has increased about 0.7 ft since 1890. In order to interpret the past experience in terms of present conditions, the annual tide maxima were adjusted to 1970 conditions before performing a statistical frequency analysis. Hicks and Crosby (1974) have analyzed secular variations in sea level at NOS primary gages. They also publish average trends in millimeters per year, based on a linear regression fit to the period 1940-72 and to the entire series of record at the particular station. Each maximum annual tide in table 7 during or since 1940 was adjusted to 1970 by the latter trend. This is a statistical estimate of the maximum annual tide that would have been observed from a combination of the weather and solar and lunar gravitational forces during the particular year but under 1970 mean sea level conditions. For years prior to 1940, the annual trend was calculated for each station that, averaged with the "since 1940" trend weighted by years, gives Hicks and Crosby's "entire series" trend. The earlier records were then adjusted to 1940 by this trend and again to 1970 by the later trend. An example of these statistical trends is shown graphically in figure 12. This procedure was used in preference to Hicks and Crosby's "entire series" trend at each station so as to not introduce artificial distinctions between adjacent stations related to respective length of record rather than geophysical factors. The maximum annual tides thus adjusted are listed in table 7, marked "adj."

6.2.3 Statistical analysis of maximum annual tides

The tides adjusted to 1970 conditions in table 7 were treated as an annual series and frequency curves fitted by the Gumbel method for Fisher-Tippett type I. It was judged subjectively that this distribution fits the data points as closely as several other standard distributions, including log normal. The resulting curves for Lewes, Del., Kiptopeke Beach, Va., and Hampton Roads, Va., are shown in figures 13a, 13b, and 13c, respectively. Similar plots for Atlantic City and Sandy Hook, N.J. were used in the analysis but are not shown.

The return period to assign to the most severe known storm events is always a difficult question. It is known from historical accounts that the two highest winter tides of record at Lewes, in the 1962 and 1950 storms, have not been equalled previously since 1900. Assuming a period of record of 76 years (1900-75) leads to the supplementary plotting positions for these two storms, shown in figure 13a as additional guidance in drawing conclusions on frequencies. The frequency for equalling or exceeding these events implied by the statistically fitted curve is 0.02 and 0.03 per year, respectively. These seem reasonable, and the fitted curve is adopted. Similar considerations apply to the 1962 storm at Kiptopeke Beach (fig. 13b) and Hampton Roads (fig. 13c).

6.2.4 Coastal profile of tide frequencies

Coastal profiles of northeaster tide frequencies are shown in figure 14. Elevations scaled from figures 13a, 13b, and 13c, and from similar curves for Atlantic City and Sandy Hook are controlling points.

In constructing the curves an adjustment is made from Hampton Roads and Keptopeke Beach gage locations to "open coast."

A limited amount of information was derived from each of several guides in making the interpolation between stations shown on the figure. Hurricane shoaling factor (fig. 7) is only suggestive. Northeasters, because of their larger lateral extent, are less dominated by medium-scale bathymetric factors than hurricanes. Specific "shoaling factor" curves have not been worked out for northeasters. Historical storms should give a clue to prevailing storm tide variations along the shore. This information is limited, however, by the scarcity of tide reports, only a few more than the primary tide gages between which interpolation is required. Coastal profiles of the maximum tide in the November 1950 and March 1962 storms are depicted in figure 15. Finally, the local mean range of the astronomical tide profiled in figure 16 from the large number of determinations in National Ocean Survey (1975) _Tide Tables_ is also suggestive. The astronomical tide range is more responsive to very local bathymetric and coastal configuration effects than northeaster tides, in which direct wind setup is a major factor.

7. TOTAL STORM TIDE FREQUENCY

7.1 Combination of Hurricane and Northeaster Tide Frequencies

The tide frequency curves for landfalling and alongshore hurricanes and tropical storms, and winter coastal storms, are plotted together on figure 17 and combined to give an all-storm frequency curve for Rehoboth Beach, Del. Similar tide frequency curves are shown in figure 18 for Ocean City, Md., and figure 19 for Parramore Island, Va. The all-storm curve is obtained by add-

Table 7.--Maximum October - May tides from northeasters

Season	Hampton Roads Va.			Kiptopeke Beach Va.			Lewes Del.			Atlantic City N.J.			Sandy Hook N.J.			Montouk N.Y.			New London Conn.			Newport R.I.		
	Max	Date	Adj	Max	Date	Adj	Max	Date	Adj	Max	Date	Adj	Max	Date	Adj	Max	Date	Adj	Max	Date	Adj	Max	Date	Adj
1922-23										4.0	3-06	4.6												
24										4.5	3-21*	5.1												
25										4.0	10-30	4.6												
26										3.9	2-10	4.5												
27										4.6	2-20	5.1												
28	2.7	5-08	3.4							4.1	12-05	4.6												
29	3.0	4-16	3.7							4.0	4-16	4.5												
1929-30	3.4	10-01	4.0							4.3	10-02	4.8												
31	4.1	11-04	4.7							4.9	3-04	5.4										3.2	10-11	3.6
32	3.6	3-06	4.2							4.3	3-06	4.8										3.8	4-21*	4.2
33	3.8	1-26	4.4							5.2	11-10*	5.7	5.4	11-10	6.0							4.4	1-27	4.8
34	2.9	10-06	3.4							3.8	10-05	4.2	3.8	4-11	4.4							3.4	1-16	3.8
35	2.8	1-24	3.3							4.1	10-24	4.5	4.1	10-24	4.7							3.3	10-22	3.6
36	3.3	11-17	3.8							4.9	11-17	5.3	5.4	11-17	6.0							3.3	11-25*	3.6
37	3.6	1-29	4.1							4.5	4-26	4.9	4.6	10-01*	5.1							4.1	10-01	4.4
38	3.4	5-30	3.9							4.4	10-23	4.8	4.9	10-23	5.4							3.8	10-23*	4.1
39	3.1	4-29	3.5							5.0	5-03	5.4	4.7	5-03	5.2				3.0	4-02*	3.3	3.7	4-02	4.0
1939-40	4.1	1-24	4.5							4.7	1-24	5.0	4.5	4-20	5.0				3.0	4-21	3.3	3.9	4-21	4.2
41	3.6	10-01	4.0							4.8	10-01	5.1	4.7	10-01	5.2				3.4	11-27	3.6	3.9	11-02	4.1
42	3.0	3-28	3.4							4.8	3-03	5.1	4.7	3-03	5.2				4.3	3-03	4.5	4.6	3-03	4.8
43	-	-	-							4.2	12-19	4.5	4.9	3-06	5.3				4.0	12-02	4.2	-	-	-
44	2.7	12-29	3.1							5.1	10-26	5.4	5.4	10-26	5.8				3.3	10-27	3.5	3.9	2-23	4.1
45	3.0	11-18	3.3							5.4	11-30	5.7	5.3	11-30	5.7				4.2	11-30	4.4	5.3	11-30	5.5
46	3.9	12-05*	4.2							4.8	12-02	5.1	4.9	11-29	5.3				3.8	11-22	4.0	3.8	12-20	4.0
47	3.0	4-21	3.3							4.2	4-21	4.5	4.3	11-10*	4.7				3.2	3-03	3.4	4.8	3-03	5.0
48	3.7	11-02	4.0				5.2	11-01	5.4	5.5	11-01	5.8	5.0	10-31	5.4	4.7	11-12	4.9	4.5	11-12	4.7	4.6	11-12	4.8
49	4.6	10-05	4.9				4.9	10-05	5.1	4.9	10-06	5.1	4.8	10-06	5.2	3.2	13-31	3.4	3.4	12-31	3.6	3.9	12-30	4.1
1949-50	3.3	10-17*	3.6				4.4	10-18	4.6	4.4	10-18	4.6	4.5	10-22	4.8	2.9	10-21	3.0	2.9	10-21*	3.1	4.2	10-22	4.4
51	3.5	5-18	3.8				#7.2	11-25	-	6.6	11-25	6.8	6.9	11-25	7.2	5.4	11-25	5.5	6.3	11-25	6.5	4.5	2-07	4.7
52	3.5	2-27	3.7	3.4	2-27	3.6	-	-	-	4.8	11-01	5.0	5.0	11-01	5.3	3.5	11-03	3.6	3.9	11-03	4.1	4.4	11-03	4.6
53	3.3	11-21	3.5	3.7	11-21	3.9	4.5	12-22	4.7	4.4	12-22	4.6	4.6	12-23	4.9	3.3	12-23	3.4	3.2	2-15	3.3	4.3	2-15	4.4
54	3.9	10-23	4.1	3.9	10-23	4.1	5.5	10-23	5.7	5.7	10-23	5.9	7.6	11-07	7.9	5.1	11-07	5.2	5.5	11-07	5.6	5.0	11-07	5.1
55	3.5	12-06	3.7	3.1	4-25	3.3	4.4	4-24	4.6	4.5	4-24	4.7	5.0	4-24	5.3	3.0	3-22	3.1	3.4	3-22	3.5	-	-	-
56	5.5	4-11	5.7	3.7	1-11	3.9	5.2	1-10	5.4	4.8	1-10	5.0	5.9	10-14	6.1	4.5	3-16	4.6	4.1	3-16	4.2	4.2	10-16	4.3
57	3.5	10-28	3.7	3.2	10-25*	3.4	4.6	11-03	4.7	4.3	2-15	4.5	4.4	2-15*	4.6	3.0	11-26	3.1	3.1	11-26	3.2	3.5	1-16	3.6
58	4.8	10-06	5.0	4.7	10-06	4.9	4.6	4-03	4.7	4.7	4-03	4.8	5.6	3-20	5.8	4.6	2-16	4.7	4.2	2-16	4.3	4.5	4-03*	4.6
59	4.5	10-21	4.7	3.8	10-21	4.0	4.3	12-12*	4.4	4.2	12-12	4.3	5.2	3-27	5.4	3.5	10-26	3.6	3.6	10-26*	3.7	4.3	11-10	4.4
1959-60	3.4	2-01	3.5	3.1	12-29*	3.2	4.3	12-30*	4.4	4.9	12-29	5.0	5.3	12-29	5.5	4.3	2-19	4.4	4.6	2-19	4.7	4.6	2-19	4.7
61	3.1	1-16	3.2	3.3	1-16	3.4	5.1	1-16*	5.2	5.0	1-16	5.1	6.4	4-13	6.6	3.9	3-09	4.0	4.1	3-09	4.2	4.4	1-16	4.5
62	6.4	3-07	6.5	6.1	3-07	6.2	7.4	3-06	7.5	6.8	3-06*	6.9	7.3	3-06	7.4	4.3	3-07	4.4	4.1	3-07	4.2	4.9	3-07	5.0
63	4.0	11-27	4.1	3.8	11-27	3.9	5.6	11-03	5.7	4.6	11-03*	4.7	5.6	11-10	5.7	3.6	12-06	3.7	4.1	12-06	4.2	4.2	12-06	4.3
64	3.0	1-01	3.1	3.2	1-01*	3.3	5.4	1-13	5.5	4.5	11-07	4.6	4.6	1-13	4.7	3.6	11-30	3.6	4.2	11-30	4.3	5.7	11-30	5.8
65	4.0	1-16	4.1	3.7	1-17	3.8	4.8	1-17	4.9	4.5	1-17	4.6	5.0	1-17	5.1	2.9	1-17	2.9	3.1	1-17*	3.2	4.2	11-20	4.3
66	3.5	1-27	3.6	3.1	1-26	3.2	4.8	1-23	4.9	5.5	1-23	5.6	6.7	1-23	6.8	2.8	1-08	2.8	4.0	1-23	4.0	4.0	1-08	4.0
67	3.9	5-24	4.0	3.7	5-24	3.8	5.1	5-24	5.1	4.7	5-24*	4.7	5.0	4-27*	5.1	4.0	12-29	4.0	4.7	12-29	4.7	4.7	12-29	4.7
68	4.1	5-27	4.1	3.6	5-27	3.6	4.2	1-14	4.2	4.5	12-29	4.5	4.7	11-03*	4.7	3.0	10-31*	3.0	2.7	10-31	2.7	4.0	11-03	4.0
69	4.1	3-02*	4.1	3.7	3-02	3.7	4.8	11-12*	4.8	5.3	11-12	5.3	6.7	11-12	6.7	5.0	11-12	5.0	5.1	11-12	5.1	4.3	11-12*	4.3
1969-70	3.3	11-10	3.3	3.6	11-10	3.6	5.3	11-10	5.3	-	-	-	5.8	12-26	5.8	3.4	12-26	3.4	3.7	12-26	3.7	4.0	11-11	4.0
71	4.2	3-26	4.2	3.6	3-26	3.6	4.7	3-27*	4.7	-	-	-	5.2	3-27	5.2	3.3	4-07	3.3	3.9	12-17	3.9	4.4	12-17	4.4
72	3.7	10-19	3.7	3.6	10-19	3.6	4.6	2-18	4.6	5.4	2-19	5.4	6.2	2-19	6.2	4.9	2-19	4.9	4.8	2-19	4.8	5.3	2-19	5.3
73	4.3	2-11	4.3				5.6	12-22	5.6				5.8	12-22	5.8				4.5	4-04	4.5			

Legend:

Max = maximum observed at gage during October-May season, feet above local MSL based on 1941-59 epoch. Hurricanes excluded by inspection of weather maps.

Adj = maximum adjusted to 1970 sea-level conditions, using trends from Hicks and Crosby. (See text.)

* = same elevation attained on one or more additional dates. Date listed is simultaneous with seasonal maximum at another station as first choice, earliest in season as second choice.

= High-water mark. Gage not in operation.

ing horizontally the frequencies (reciprocal of return period) for each tide level. The overall frequency is reinverted to return period for plotting on the diagram. The all-storm frequency curves for Virginia Beach, Va., and at the Virginia-North Carolina border obtained in a similar manner are shown in figure 20.

Tide frequencies for locations other than the above primary computation points along this stretch of the coast were obtained in the same manner, after interpolation of each storm type separately along the coast. The interpolation of hurricane tide frequencies was based on consideration of the frequency of storms, the variation in the shoaling factor (fig. 7), and the trend in the hurricane climatology parameters along the coast. Analyzed peak surge heights generated by alongshore storms, as shown in figure 8 for example, were also used as an additional guide in the interpolation of alongshore hurricane tide frequencies. Interpolation of winter coastal storm tide frequencies is discussed in section 6. Figure 21 shows the resulting variation of the total tide heights along the coast for the 10-, 50-, 100-, and 500-yr return period.

The tide levels are stated as heights above local mean sea level, adjusted to the 1941-59 epoch. Datum levels and differences between datums in use are covered in section 8. The "open coast" tide frequencies apply to ocean beaches at or near the locations indicated. It should be emphasized that these frequency values 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 destructive effects of waves on the beach front must be taken into account separately. In insurance rating this is taken into account by the ocean front "velocity zone."

Local effects can modify the elevation of the storm tide. Local features diminishing "open coast" elevations in the landward direction include narrow passes and inlets and obstructions to inundation such as dunes and swamp vegetation. Converging shores of bays and strong winds over long fetches of shallow water (wind setup) have the opposite effect. The net results of these effects can result in either higher or lower storm-tide levels of a given mean return period at estuarine, bay, and inland locations compared to the open coast. These differences have to be determined by localized studies.

7.2 Comparison of Frequency Curves

The derived frequency curves are compared with tide records, statistically analyzed, at the two primary gages in the study area with the longest record and with historical storm tide levels in the vicinity.

Figure 22 shows the frequency curve at Rehoboth Beach, Del., in comparison to the 28-yr series of maximum annual tides at Lewes, Del., (inside the breakwater) and also the four highest known tide levels at Lewes. The maximum annual series, unlike figure 13a, includes all storms and is not restricted to hurricanes. The four historical values are known to be the highest since 1900 and are construed as a 76-yr record (1900-75) for computing plotting positions. The 1944 value is from Cape May.

Figure 23 shows a similar comparison of the computed frequency curve at Virginia Beach, Va., to the 47-yr series of maximum annual tides at the Hampton Roads gage. (Tides of less than 2-yr return period omitted from diagram.) Virginia Beach storm tide levels are expected to be higher than Hampton Roads. The six highest tides in Norfolk Harbor (Corps of Engineers 1959) since 1908, construed as a 68-yr record, are also shown.

The annual maxima in figures 22 and 23 are adjusted for sea level trend by the procedures of par. 6.2.2.

8. REFERENCE DATUM

The National Ocean Survey, NOAA, and its component, the National Geodetic Survey, have developed the following standards for elevation control. Abbreviated definitions are given here for convenience in consistent application of the results of this study. Further details are given in the Tide and Current Glossary (Shureman 1975) and Variability of Tidal Datums and Accuracy in Determining Datums from Short Series of Observations (Swanson 1974).

Mean sea level (MSL). A tidal datum for a specific location, also referred to as local MSL. It is the arithmetic mean of sea-level heights over a specific 19-yr series of observations, or Metonic[1] cycle. Boundaries and elevations of land adjacent to the sea are generally expressed with reference to a tidal datum in legal definitions. The storm tide levels in this report, by the manner in which they are derived, are heights above local MSL.

The National Geodetic Vertical Datum (NGVD). (Formerly known as "Sea Level Datum of 1929.") A fixed reference adopted as a standard geodetic datum for heights. NGVD coincides with the average height of the sea at 26 selected tide gage sites in the United States and Canada, based on records available in 1929. It does not reflect the changing stands in sea level since that time nor non linear variations of mean sea level with respect to an equipotential surface along line segments between these stations. Elevation contours on topographic maps are generally related to this datum.

The standard 19-yr epoch for tidal datum is currently 1941-59. Short-period or recent tide gage records are adjusted to this standard epoch by comparison to primary stations having at least 19 years of record. The National Ocean Survey has an active program of establishing tidal bench marks, based on such adjustments.

Differences between local MSL for the 1941-59 Metonic epoch and NGVD have been established at primary gages and certain subordinate stations by differential leveling. Established differences on the outer coast applicable to the study area are:

Atlantic City, N. J. . . . 1941-59 local MSL 0.4 ft above NGVD

Virginia Beach, Va . . . 1941-59 local MSL 0.0 ft above NGVD

[1]Devised by Meton, an ancient Greek astronomer (Shureman 1975).

To adjust the coastal storm tide frequency levels of this report to heights above NGVD from Cape Charles northward, add a difference obtained from the above table by interpolation. From Cape Henry southward the difference between the two datums is negligible. Datum differences are under constant review and differ somewhat in bays and estuaries from coastal values. Local planners and engineers requiring datum differences in bays and estuaries should obtain the latest information from the National Ocean Survey, Rockville, Md., 20852.

MSL relative to land is increasing slowly on the east coast, at the rate of about a foot a century. Data on trends in sea level relative to land are given by Hicks and Crosby (1974). This trend is thought to be due to subsidence of the land and change in volume of water in the sea from melting ice. Adjustments of tide data for sea-level trend are described in par. 5.22. If the base epoch for MSL is changed (Swanson 1974) the data of this study should be used as elevations above the new MSL datum level, as an implicit adjustment for sea-level trend.

9. RELATION OF THIS REPORT TO DISASTER PLANNING

The most disastrous display of hurricane force on the U.S. Coast in recent years was by Camille, which struck the Bay St. Louis - Pass Christian - Gulfport - Biloxi, Miss., areas in 1969. According to high-water marks, the storm tide reached a level of almost 25 ft MSL (Corps of Engineers 1969). This is the most intense hurricane so far to strike the United States mainland during the period of record keeping. Other diasasters could also be recounted, including Hazel at the North Carolina-South Carolina border in 1954 and the New England Hurricane of 1938. The high-water mark data for the New England storm collected by the Corps of Engineers, Woods Hole Oceanographic Institution, and others, were compiled by Harris (1963, fig. 8.3). The highest storm tides were about 12 ft MSL at the open coast and 14-16 ft MSL in Narraganset Bay and Buzzards Bay. If a hurricane equal to the 1938 storm were to strike the coast of the study area at a climatologically probable speed and direction, a maximum surge of about 17 ft would be produced. Disaster planning objectives should take into account such a possibility.

The central purpose of this report is to develop actuarial frequencies for insurance rating and related uses; therefore, all frequencies, including the coastal profiles of figure 21, are stated in terms of probabilities or mean recurrence intervals at <u>points</u>. The likelihood of a severe storm tide of any given level somewhere within the study area in any given year is much greater than the point recurrence interval for the same storm, a difference that needs to be taken into account in regional planning against disasters. Regional disaster planning should be based on studies for that particular purpose.

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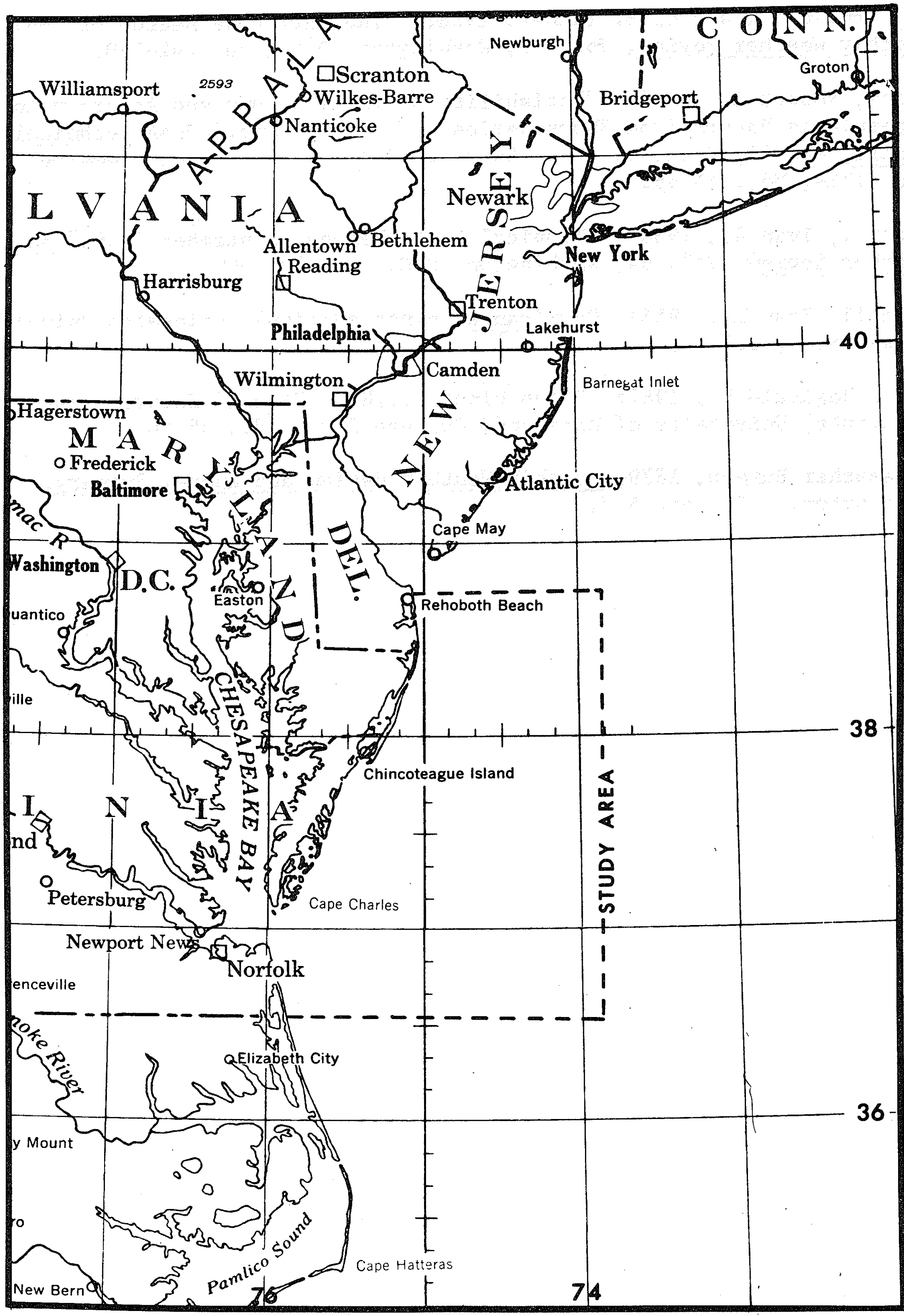

Figure 1.--Location map.

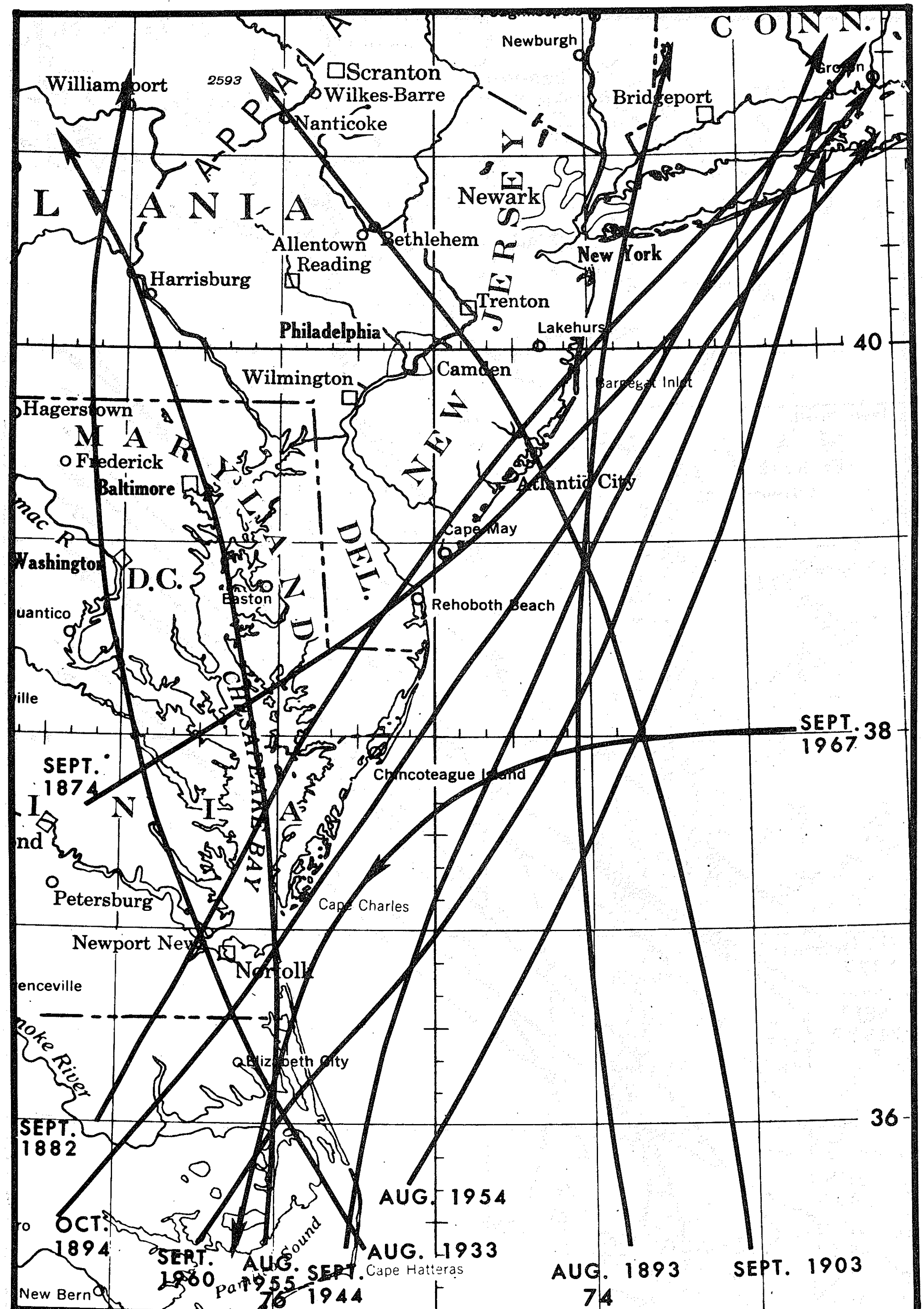

Figure 2a.--Tracks of selected hurricanes affecting the study area.

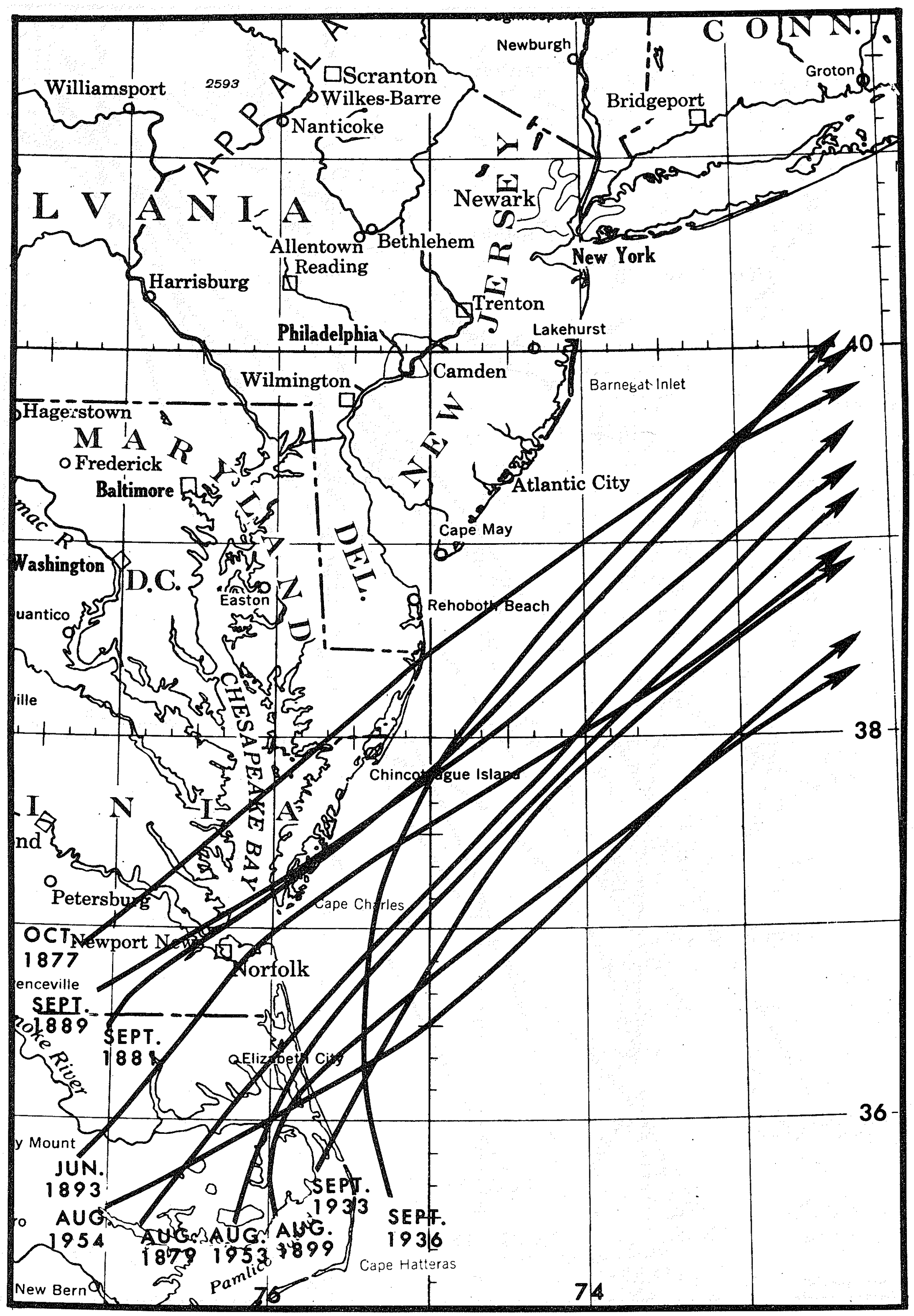

Figure 2b.--Tracks of selected hurricanes affecting the study area, continued.

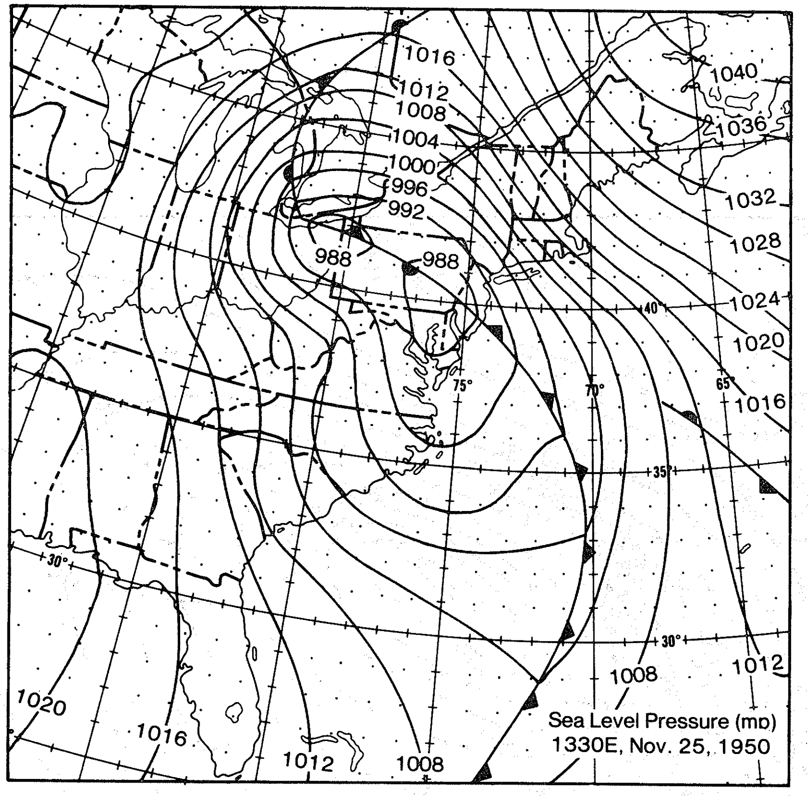

Figure 3.--Weather map for 1330E, November 25, 1950.

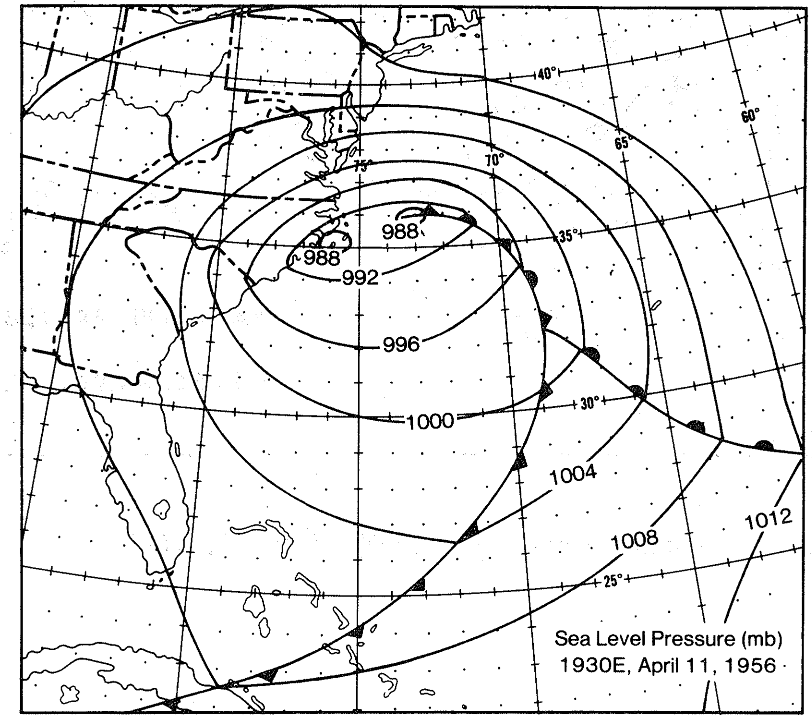

Figure 4.--Weather map for 1930E, April 11, 1956.

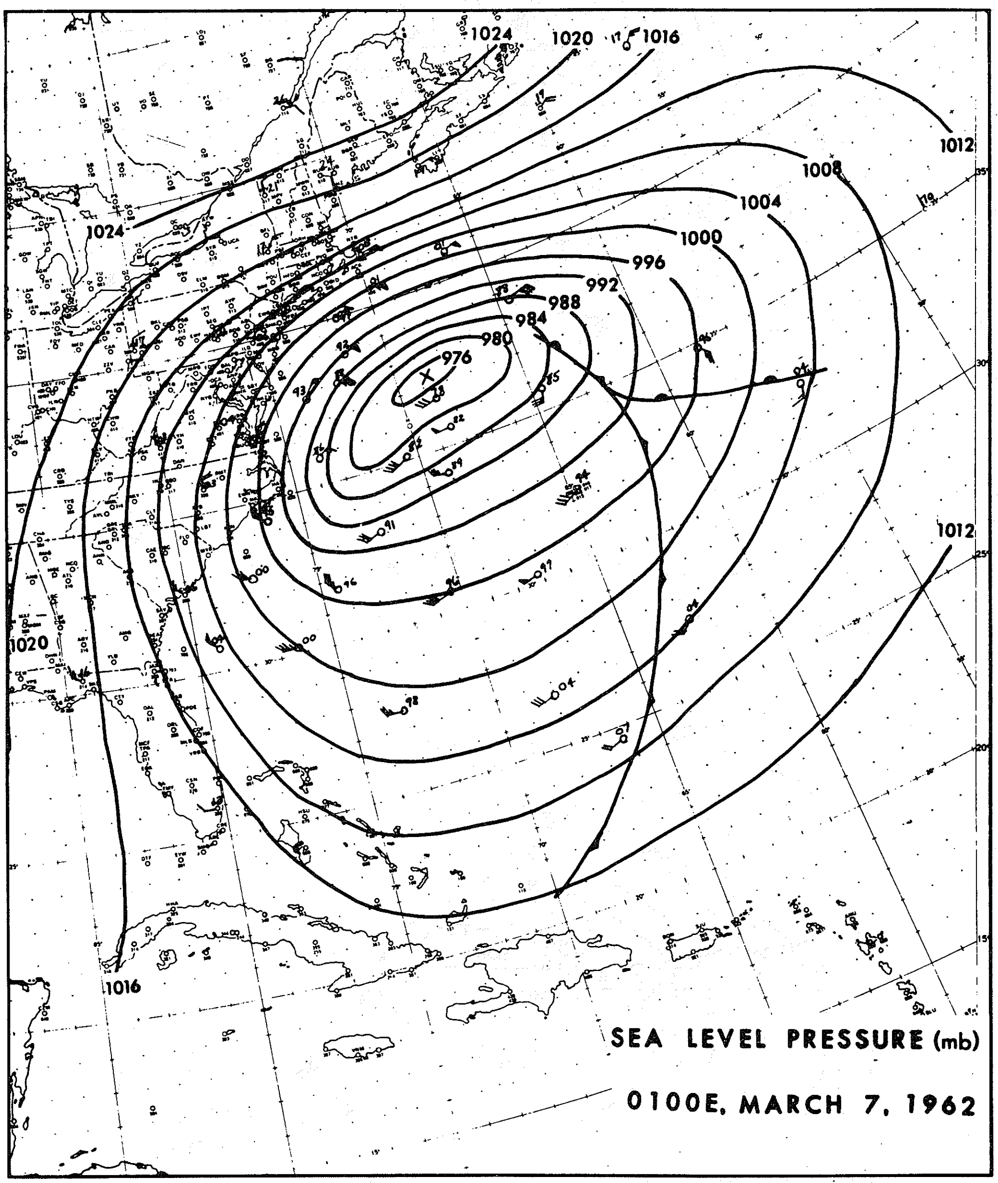

Figure 5.--Weather map for 0130E, March 7, 1962.

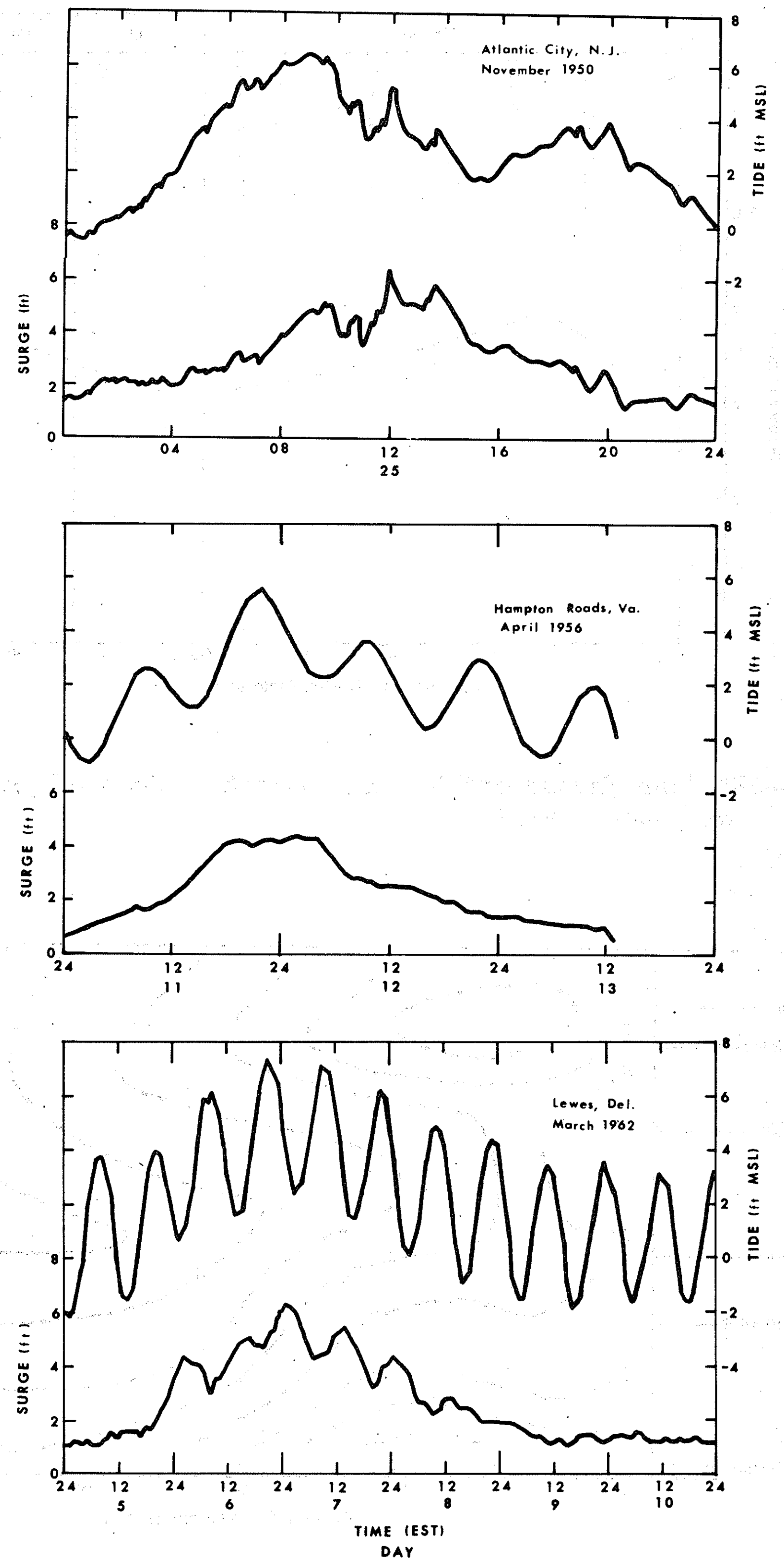

Figure 6.--Marigrams for winter coastal storms of November 1950, April 1956, and March 1962.

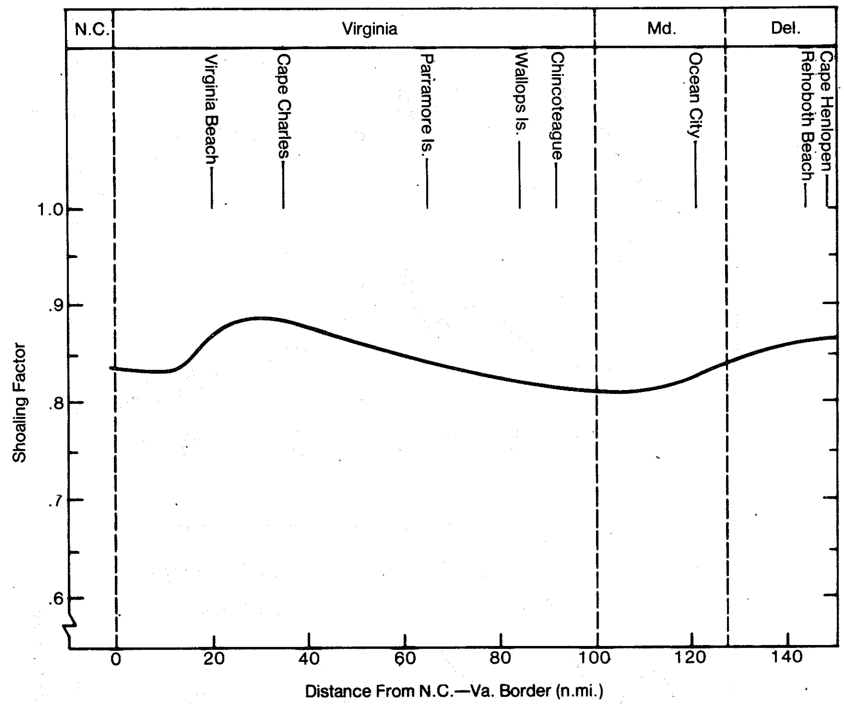

Figure 7.--Shoaling factor off Delmarva coasts. Adapted from Barrientos and Chen (1975).

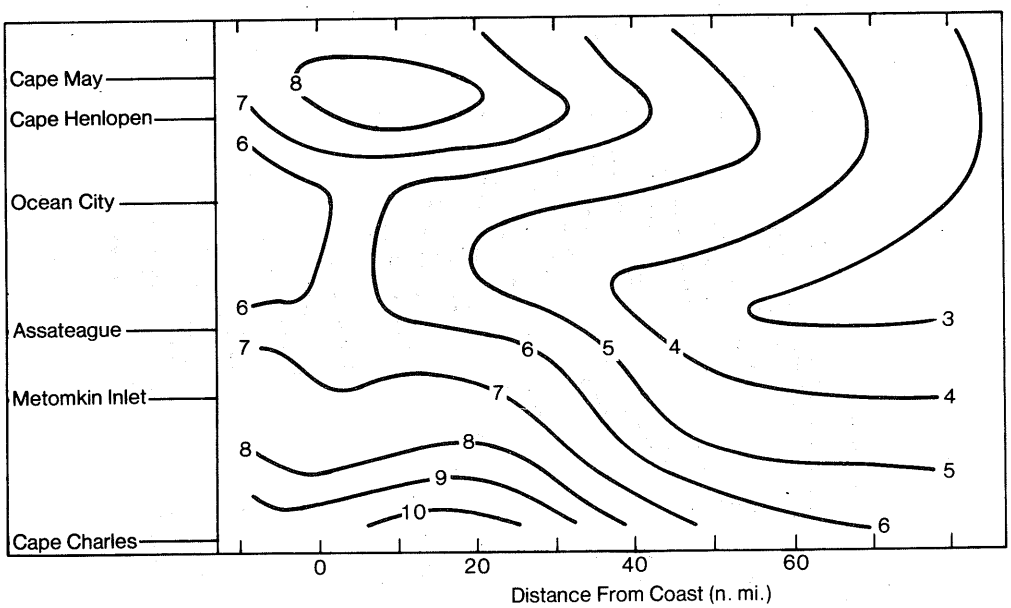

Figure 8.--Peak surge heights (ft) at the coast produced by alongshore hurricanes. The abscissa denotes distance of storm track from coast.

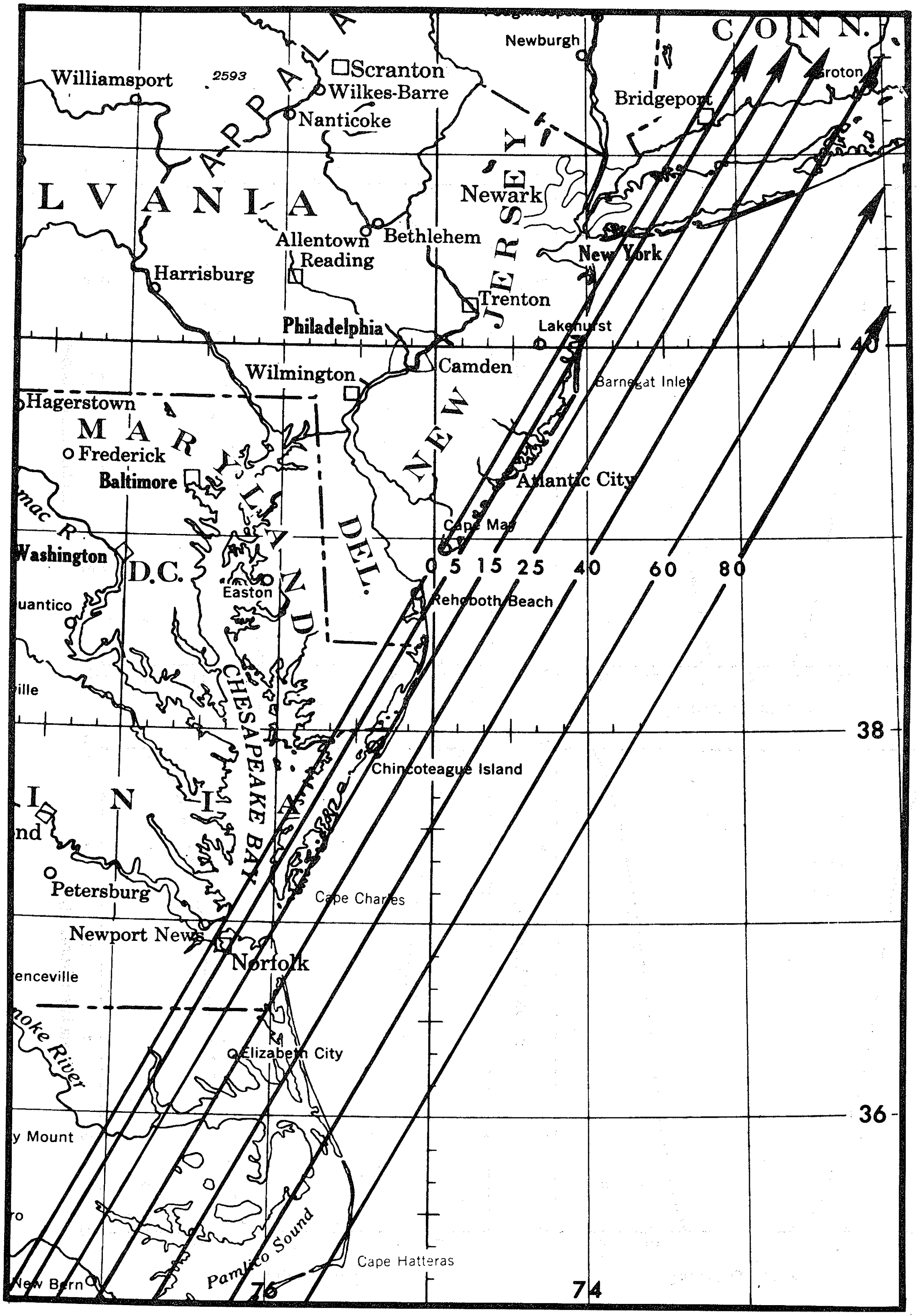

Figure 9.--Storm tracks for surge computations for alongshore storms.

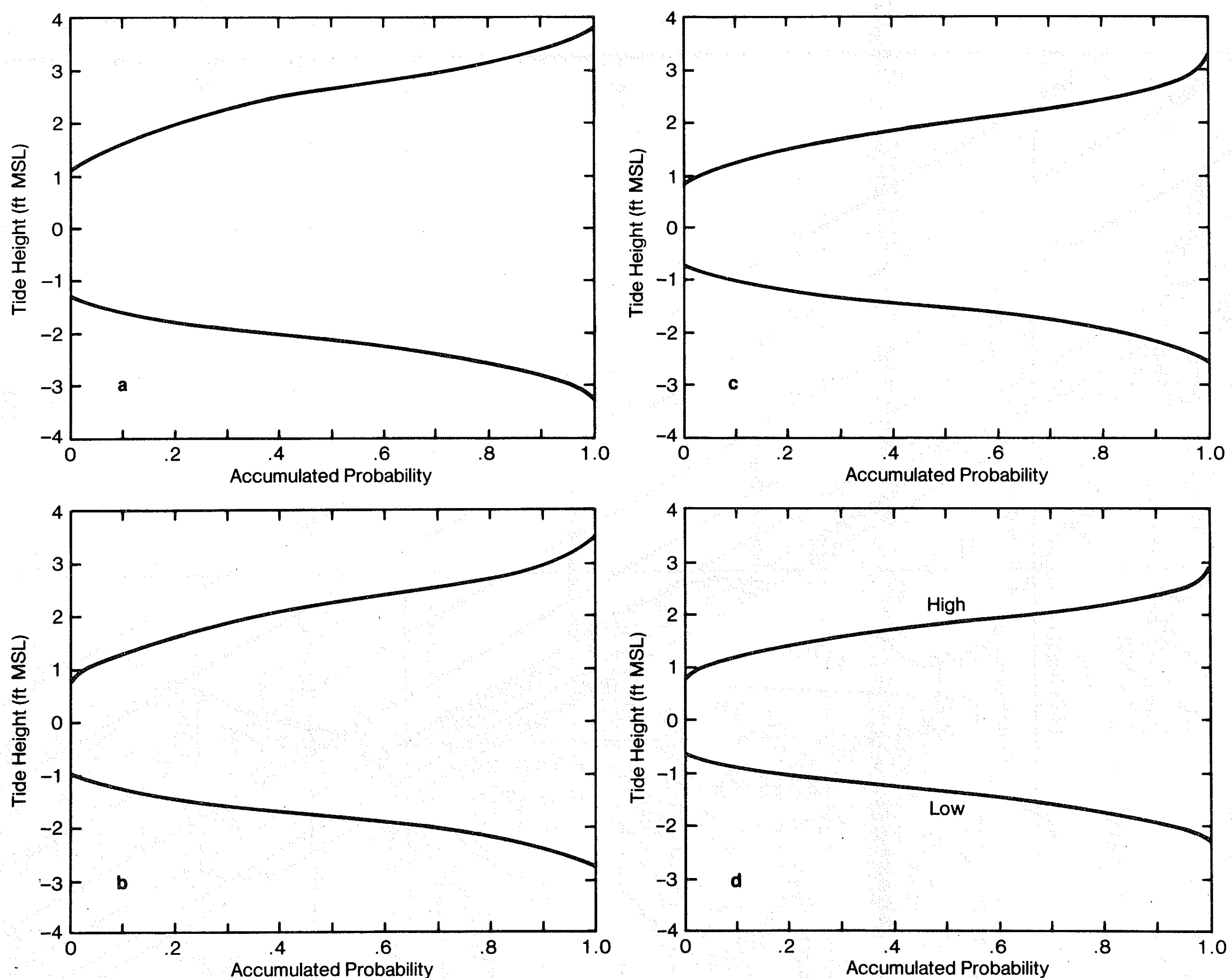

Figure 10.--Probability distribution of astronomical high and low tides for hurricane season, 1955-1973, for (a) Cape May, N.J., (b) Lewes, Del., (c) Wallops Island, Va., and (d) Virginia Beach, Va.

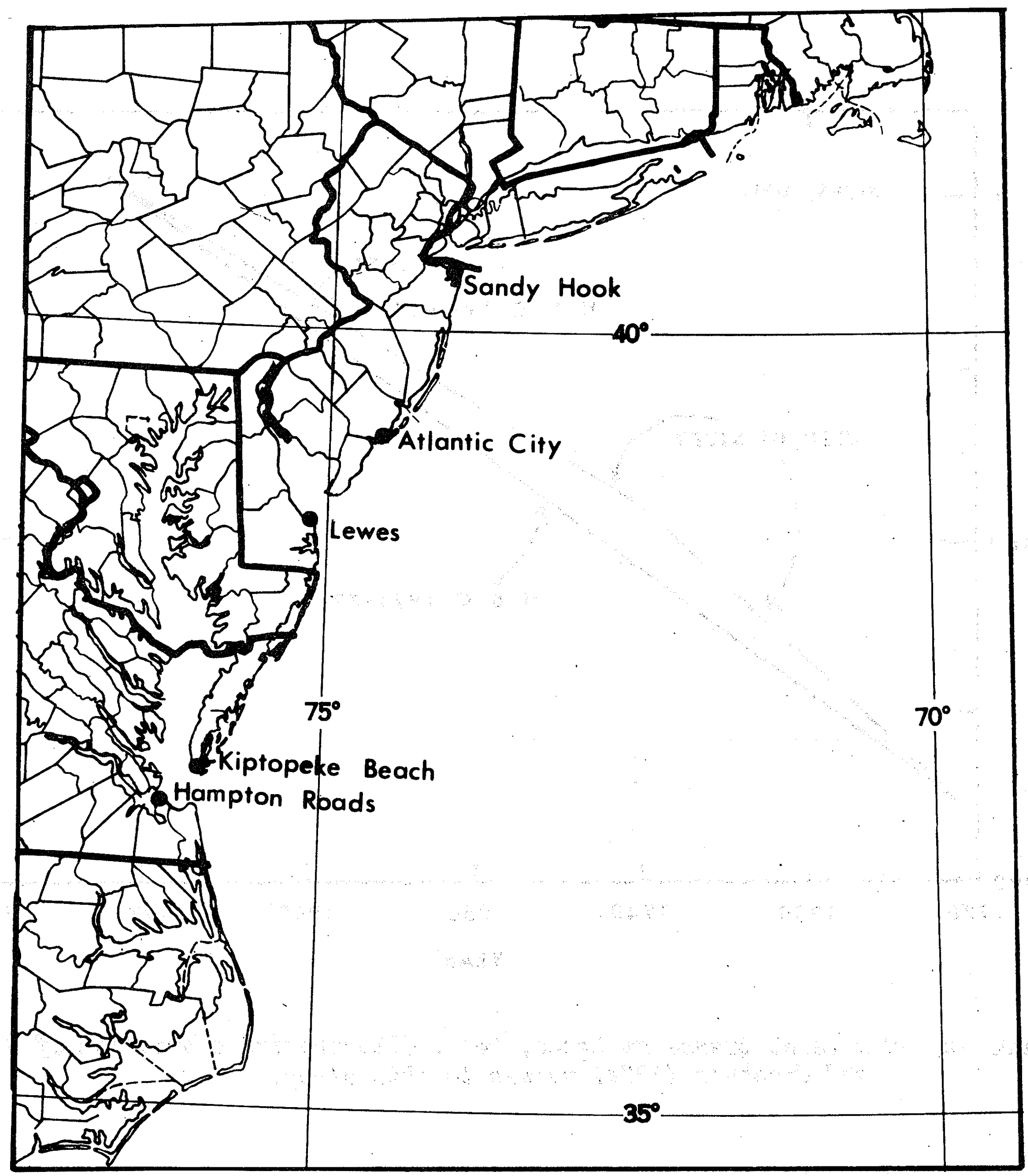

Figure 11.--Location of selected tide gage stations.

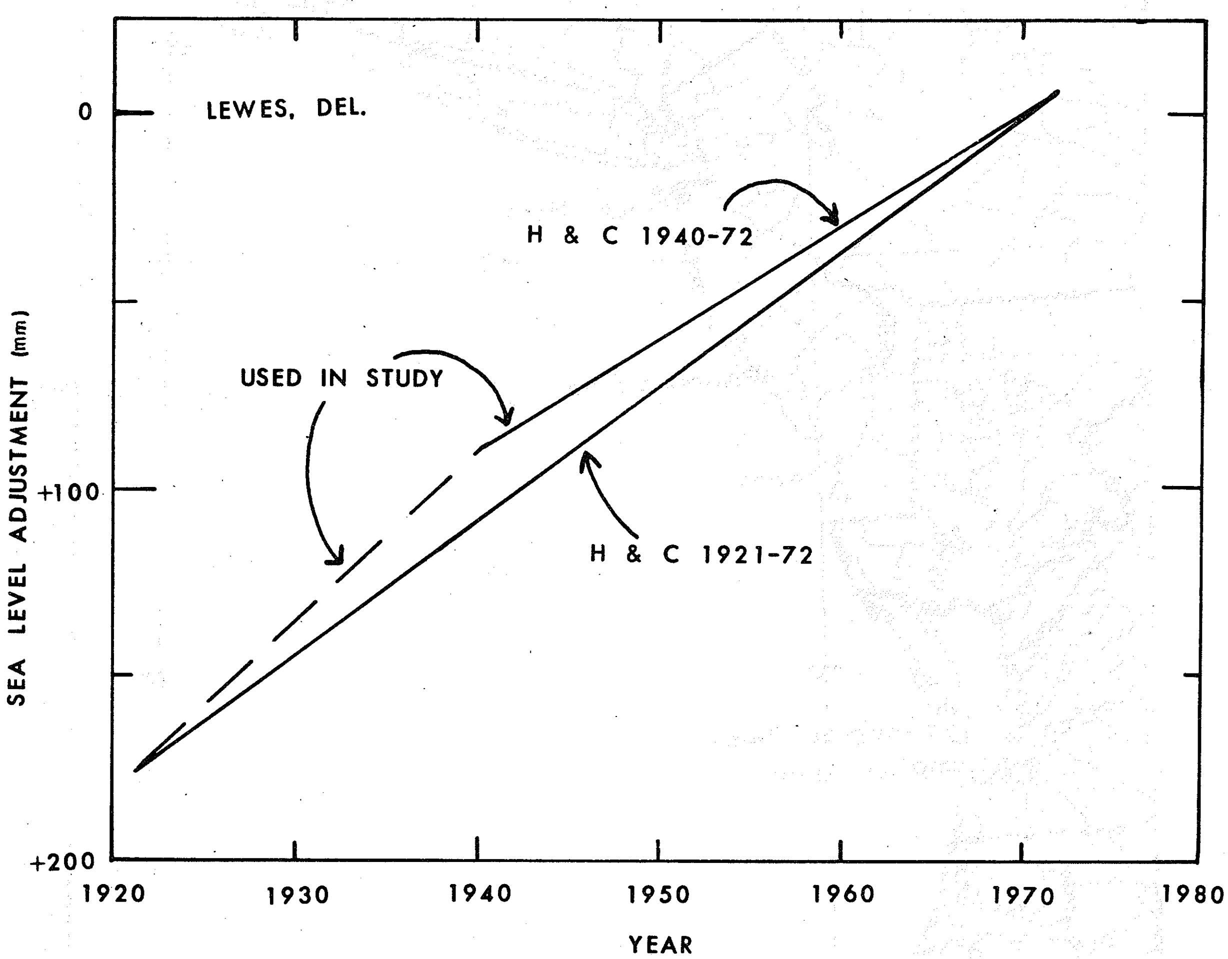

Figure 12.--Sea level trends at Lewes, Del., illustrating adaptation of Hicks and Crosby's (1974) values to this study.

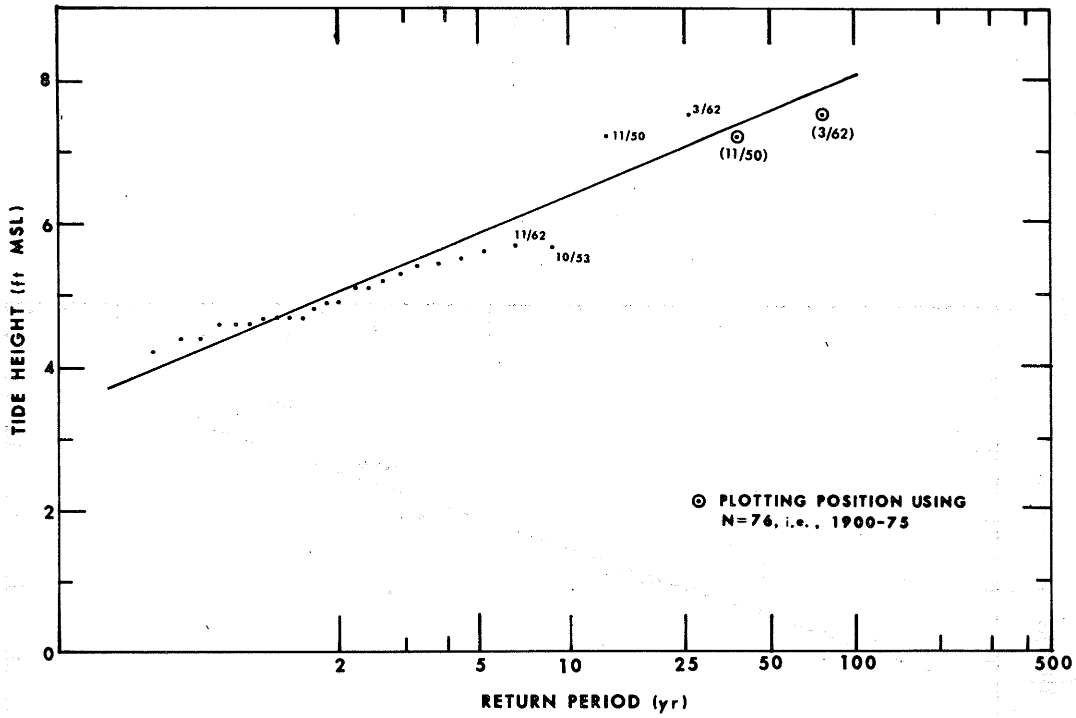

Figure 13a.--Tide frequencies at Lewes, Del., from winter coastal storms. Plotted points are seasonal (October-May) maxima.

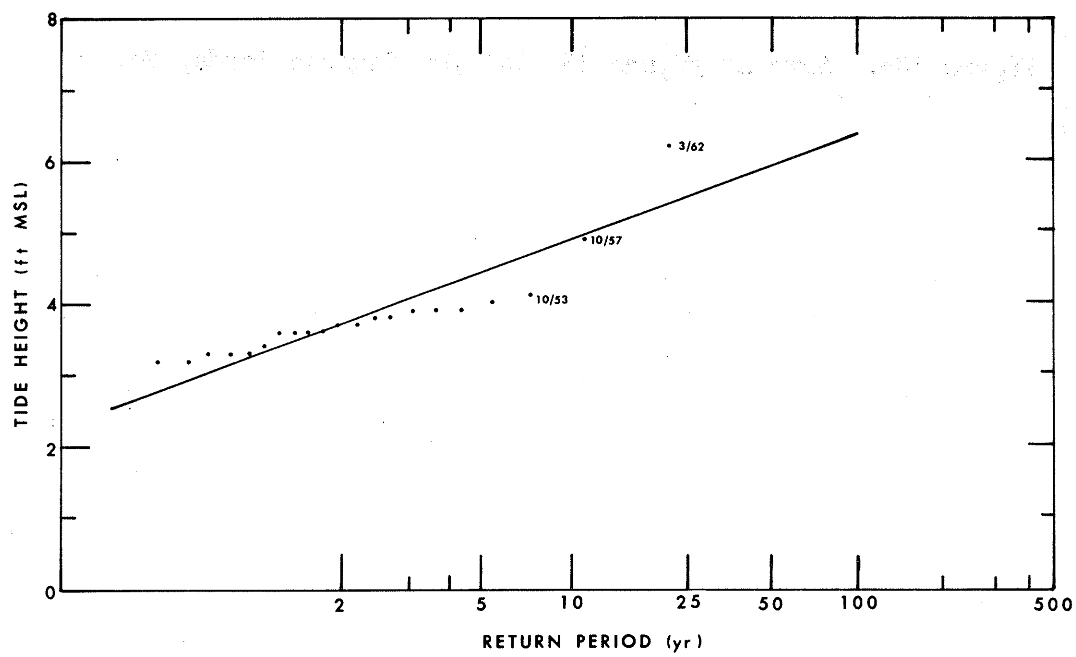

Figure 13b.--Same as figure 13a but for Kiptopeke Beach, Va.

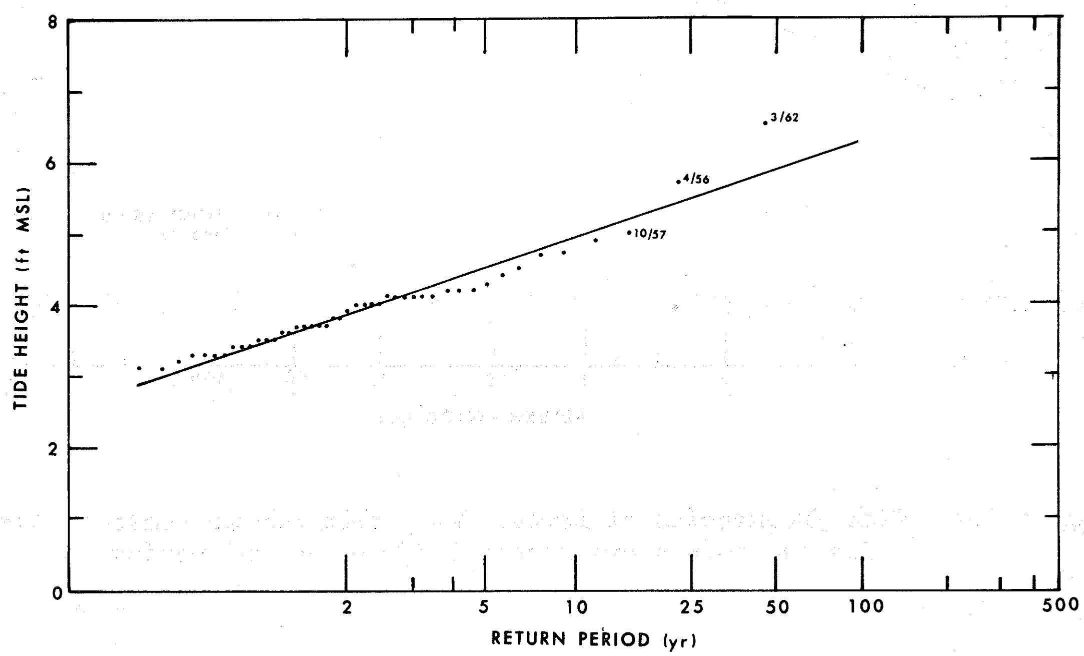

Figure 13c.--Same as figure 13a but for Hampton Roads, Va.

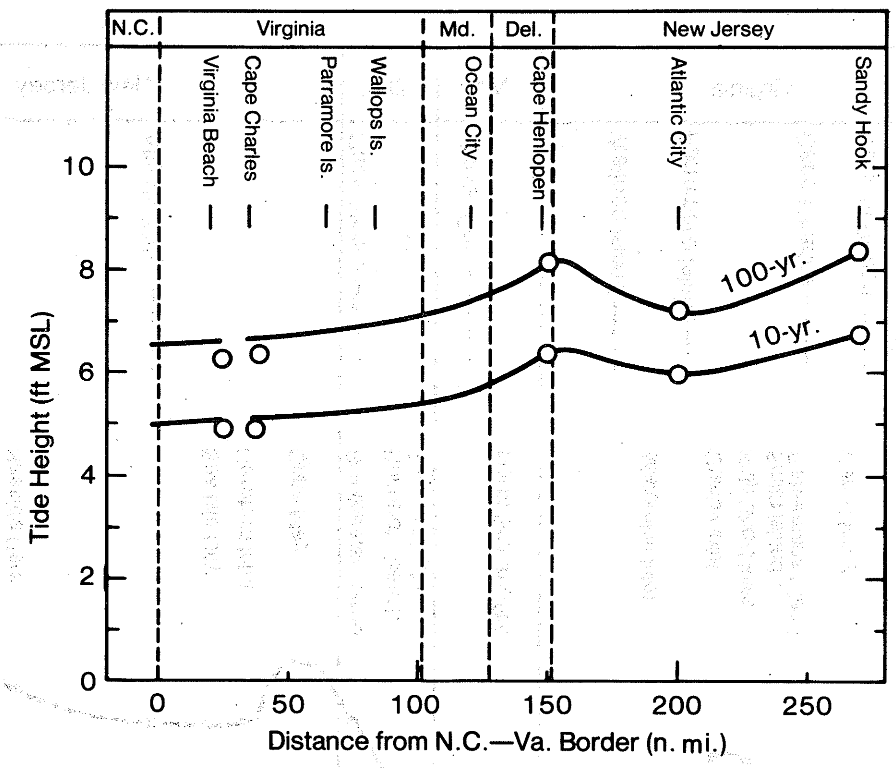

Figure 14.--Coastal tide frequencies from winter coastal storms.

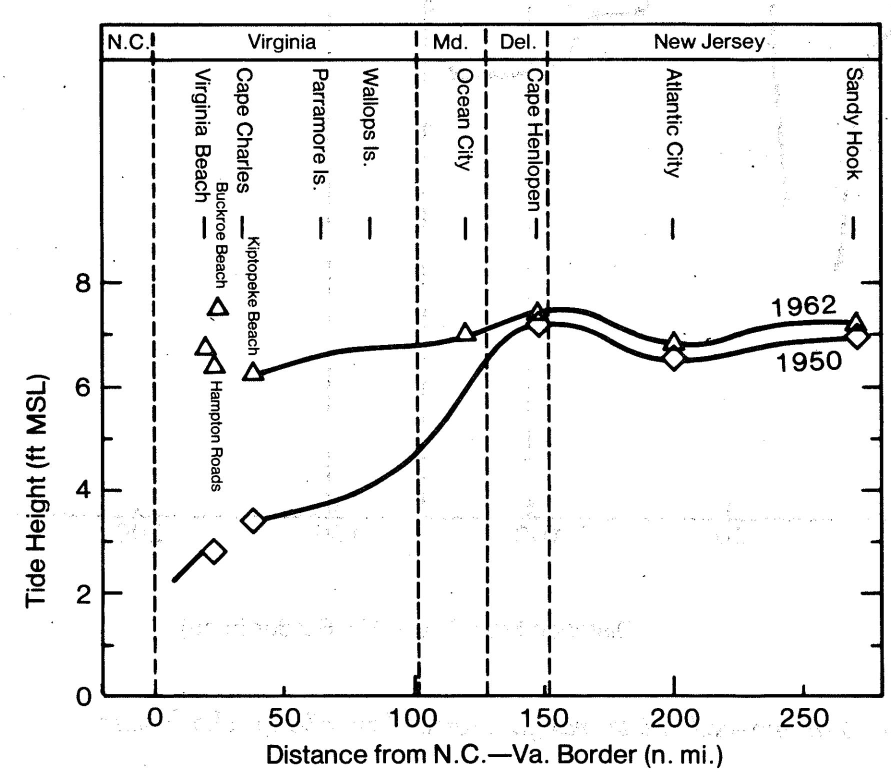

Figure 15.--Coastal tide heights observed in the storms of March 1962 and November 1950.

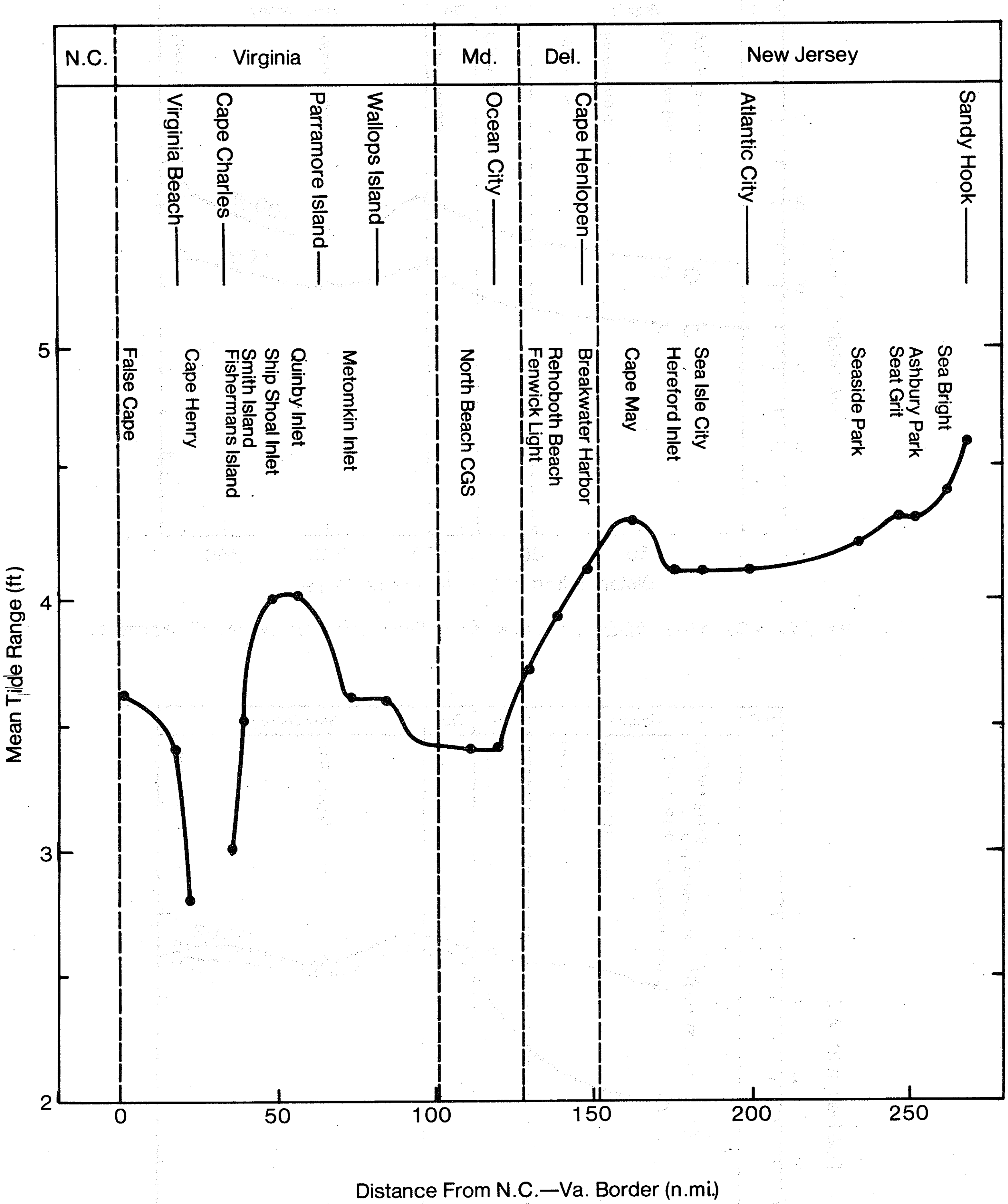

Figure 16.--Mean normal tide range variation along the coast.

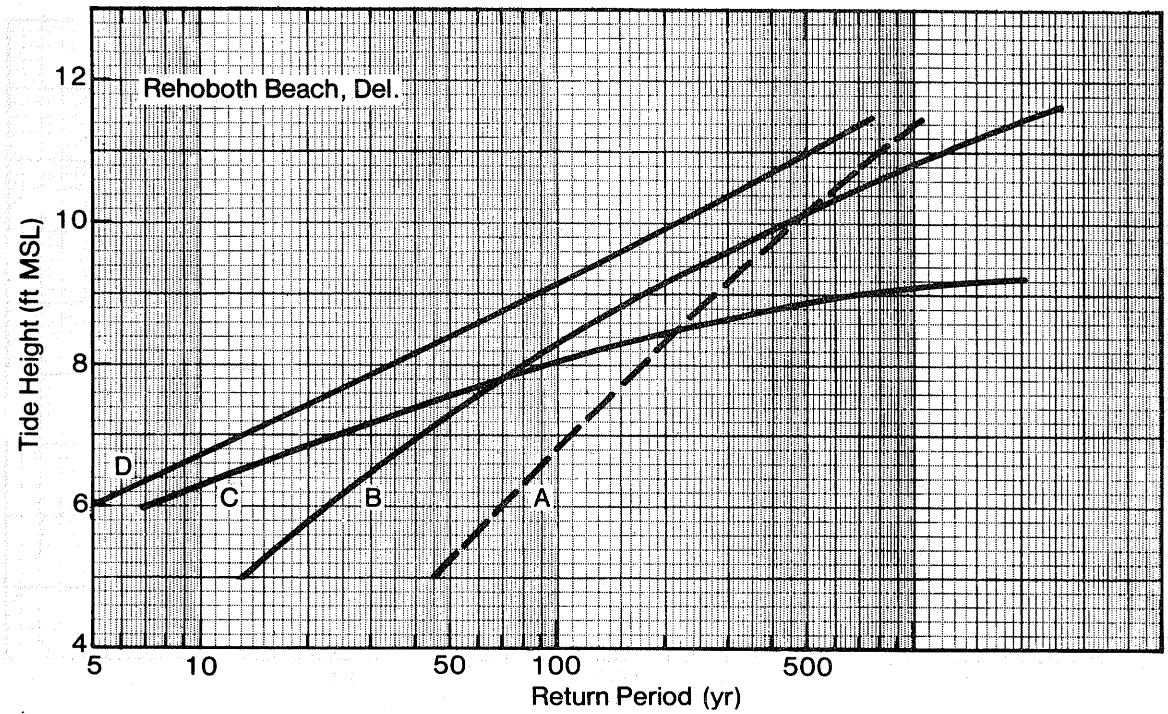

Figure 17.--Tide frequencies at Rehoboth Beach, Del., for several classes of storms: (A) landfalling hurricanes and tropical storms, (B) alongshore hurricanes and tropical storms, (C) winter storms, and (D) all storms. Datum reference is 1941-59 local MSL.

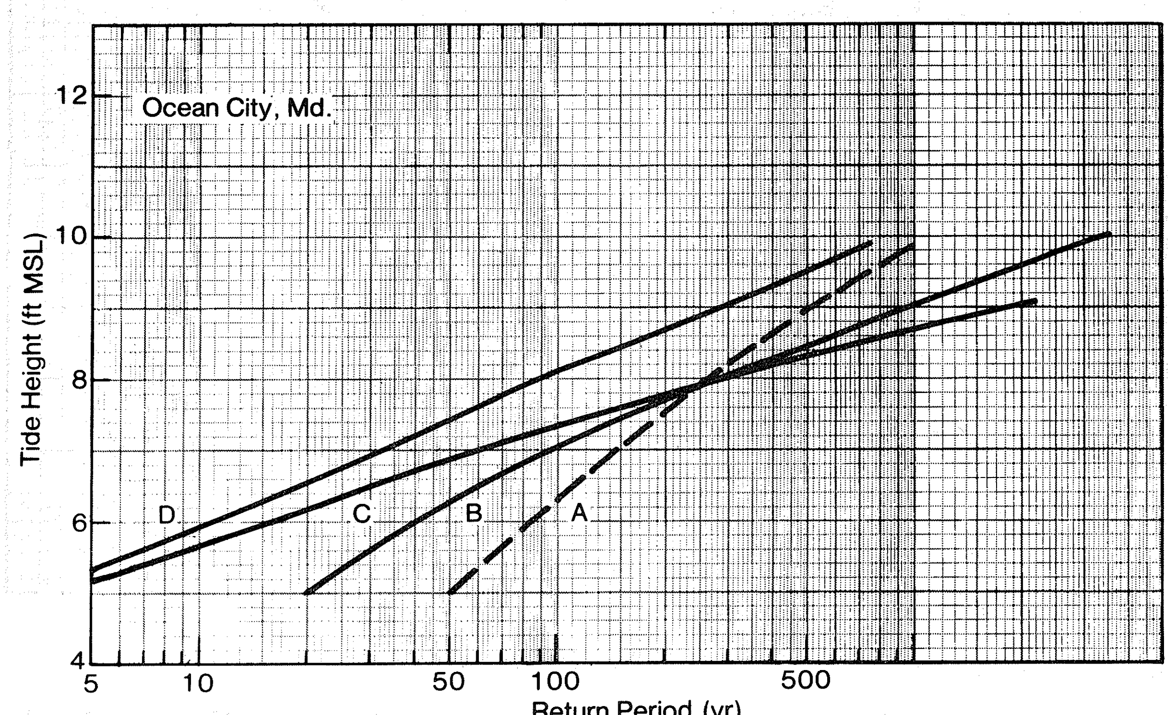

Figure 18.--Same as figure 17 but for Ocean City, Md.

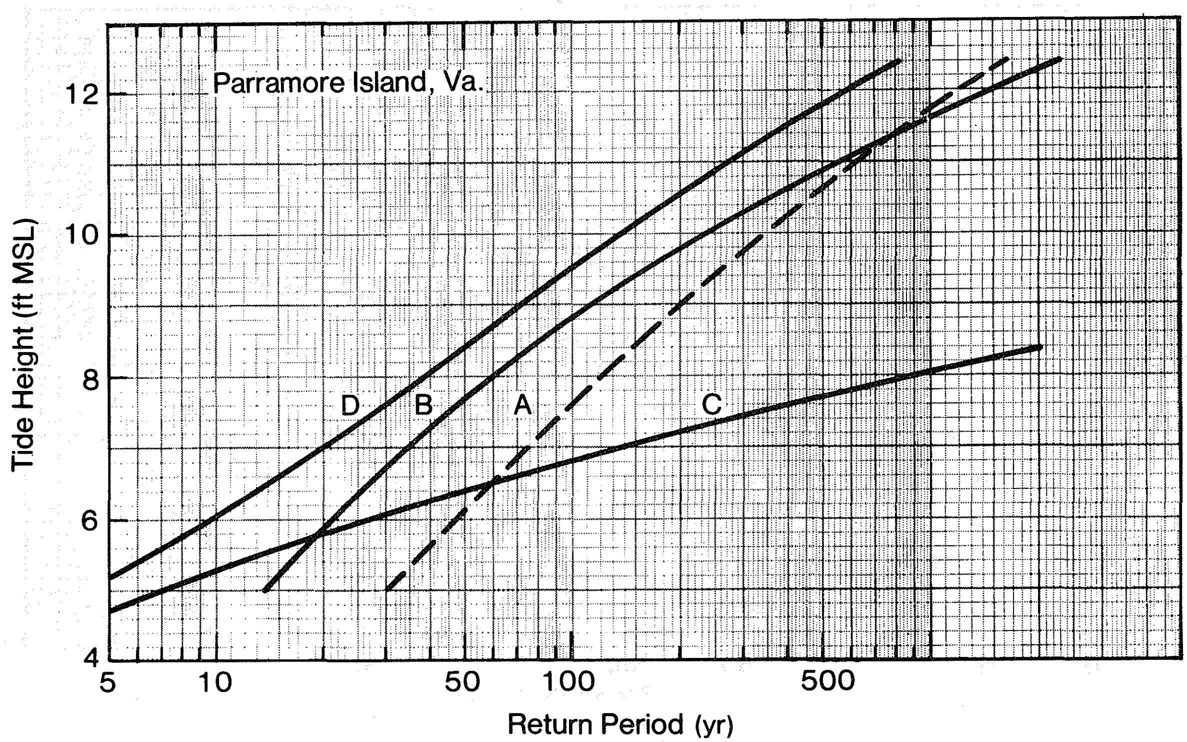

Figure 19.--Same as figure 17 but for Parramore Island, Va.

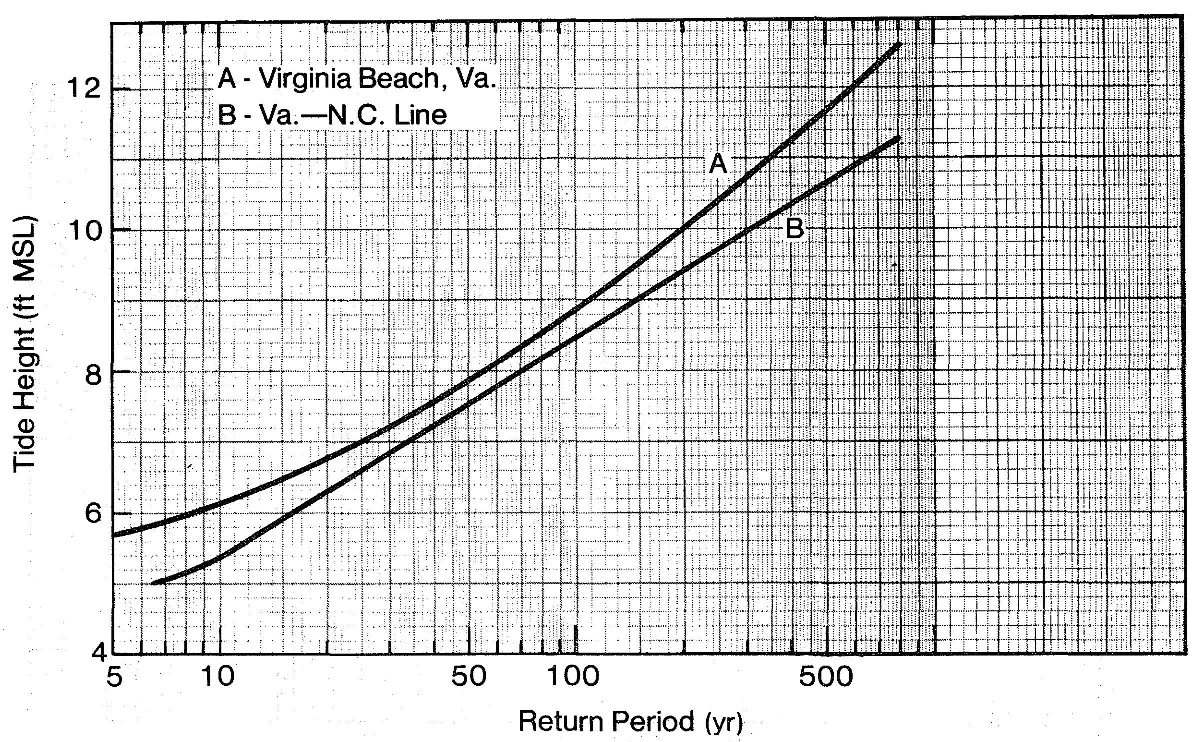

Figure 20.--Total tide frequencies on the open coast at (a) Virginia Beach, Va., and (b) Va.-N.C. border. Datum reference is 1941-59 local MSL.

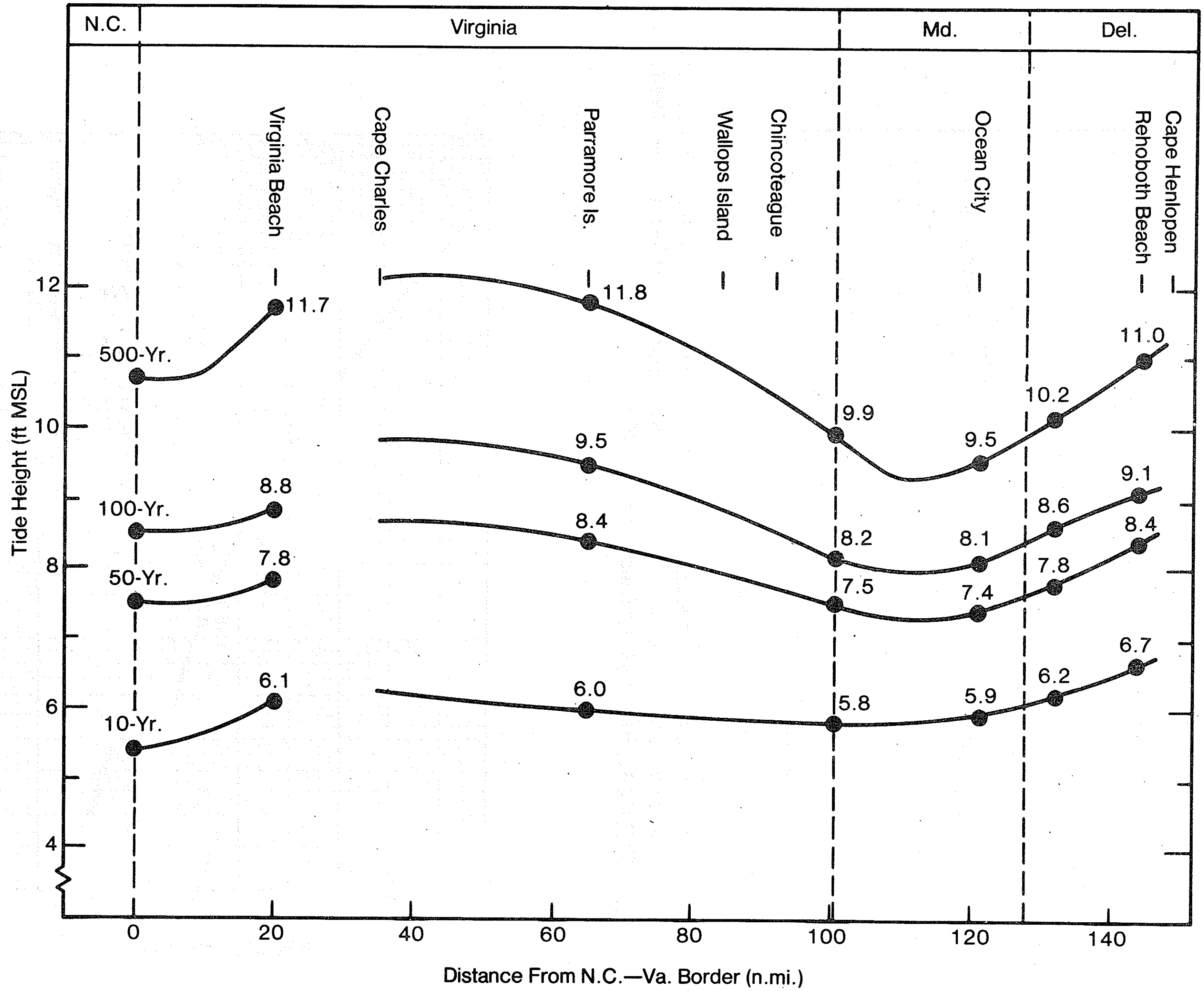

Figure 21.--Coastal tide frequencies. Delmarva coasts. Datum reference is 1941-59 local MSL.

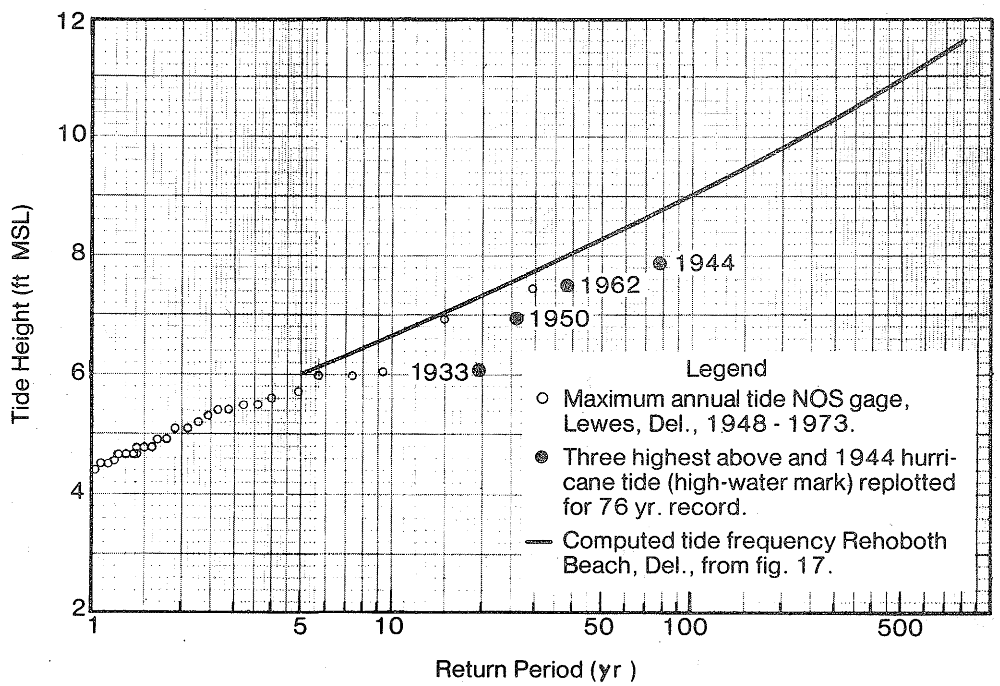

Figure 22.--Comparison of tide frequency curve at Rehoboth Beach, Del., with observations at Lewes, Del.

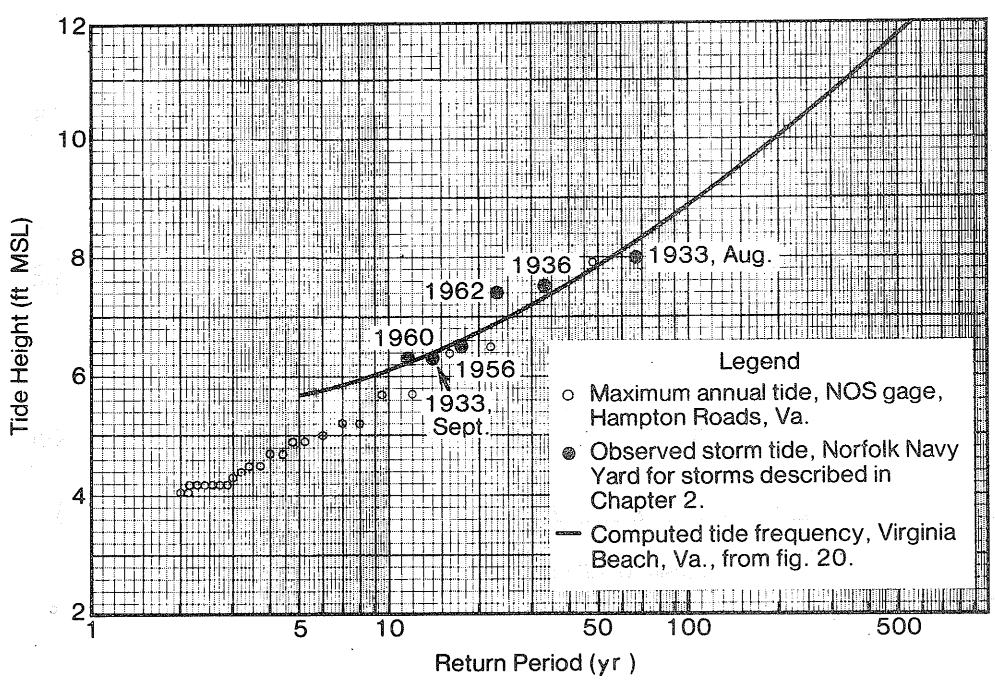

Figure 23.--Comparison of tide frequency curve at Virginia Beach, Va., with tide observations at Hampton Roads and Norfolk Navy Yard.

(Continued from inside front cover)

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NWS HYDRO 18 Numerical Properties of Implicit Four-Point Finite Difference Equations of Unsteady Flow. D. L. Fread, March 1974.

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NWS HYDRO 21 Storm Tide Frequency Analysis for the Coast of North Carolina, South of Cape Lookout. Francis P. Ho and Robert J. Tracey, May 1975. (COM-75-11000/AS)

NWS HYDRO 22 Annotated Bibliography of NOAA Publications of Hydrometeorological Interest. John F. Miller, May 1975.

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