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STORM TIDE FREQUENCY ANALYSIS FOR THE COAST OF NORTH CAROLINA, SOUTH OF CAPE LOOKOUT

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STORM TIDE FREQUENCY ANALYSIS FOR THE COAST OF NORTH CAROLINA, SOUTH OF CAPE LOOKOUT

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 North Carolina, south of Cape Lookout, for the National Flood Insurance Program by computing storm tides from a full set of climatologically representative hurricanes, using the National Weather Service hydrodynamic storm surge model. Tide levels 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 land use 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 North Carolina, south of Cape Lookout. This includes the coast of Brunswick, New Hanover, Pender, Onslow and the southern portion of Carteret Counties. The assignment is limited to determining storm tide frequencies at the open coast on a common regional basis. Modifications of storm tide levels in bays and estuaries and over land are not included. These modifications have to be assessed by separate investigations, using the present study as a baseline.

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

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 frequencies. Authorization for this particular study is Project Order No. 2, dated November 13, 1974, under Agreement No. IAA-H-19-75 between the Federal Insurance Adminstration and NOAA.

1.3 Study Method

The technique used in the tide-frequency analysis for the open coast of North Carolina in the study is basically the same as that applied to other coastal areas (e.g., Department of Commerce 1970; Myers 1970; Ho 1974; Ho and Tracey 1975). The procedure is explained in detail in a report in preparation (Myers 1975).

First, the behavior of hurricanes along the coast is assessed 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 observed storm tides of past hurricanes within acceptable tolerances.

Finally, the computed storm surges were combined with the astronomical tide variation by using a joint probability method to obtain a frequency distribution of the resulting total tide at several selected points on the open coast of the study area. Frequency profiles along the coast were then constructed by interpolation, taking into account water-depth variations ("shoaling factor," defined in par. 4.2) and trend along the coast in the hurricane climatology parameters.

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

2. SUMMARY OF HISTORICAL HURRICANES

2.1 Hurricane Tracks

This section summarizes the major hurricanes that have affected the study area since 1800. A few of the lesser storms are omitted. The tracks of major hurricanes of the late 19th century are shown in figure 1, and dates are given along the respective tracks. Similar tracks for damaging 20th century hurricanes are shown in figure 2. 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

Brief notes on the history of hurricanes and damages caused by them are abstracted from published papers. Wind speeds are quoted as given in the original sources as indicators of the general intensity of storms. The U.S. Weather Bureau developed instrumental corrections to anemometers in the 1920's (Harrison 1963) and official wind reports since that time include the corrections.

For a complete chronology of tropical cyclones since 1586, the reader is referred to the publication on "North Carolina Hurricanes" (Hardy and Carney 1962).

August 21-23, 1806

This storm approached the coast from the Bahamas. The main force of the hurricane struck the Cape Fear area; Wilmington and Smithville (Southport) were especially hard hit. The editor of the Wilmington Gazette thought that it was the "most violent and destructive storm of wind and rain ever known here." The tide rose to a height hitherto unknown and "when the wind shifted to the southeast, it seemed to threaten universal destruction." At Smithville, the tide rose higher than that of 1762 or 1763 when a new inlet was broken through in a hurricane (Ludlum 1963).

September 4, 1815

A major hurricane cut across extreme eastern North Carolina in early September 1815. This hurricane moved inland on the morning of September 4, passing close to New Bern on the Neuse River and recurved northeastward. At Beaufort, N.C., the tide flowed four feet higher than ever known. Every vessel at Ocracoke Inlet, some twenty in number, was driven ashore by the shifting gale. In New Bern, the tide, which was one foot higher than in any storm since 1795, reached an elevation of nearly 12 feet above common high-water mark (Ludlum 1963).

August 25, 1827

This hurricane was traced to its origin in the Windward Islands on August 17. It struck the coast between Cape Fear and Cape Hatteras on August 25. Ludlum (1963) gives some descriptive accounts of the storm tides along this stretch of the coast: "At Wilmington, waves rolled over the tops of garden fences as far as 600 feet from the beach; at its peak the water was estimated at ten feet above normal high water mark. The towns of New Bern and Washington, both heads of navigation for tidal river emptying into Pamlico Sound, suffered severely from high tides, and such high waters here, too, are always caused by wind with an easterly component. At Washington the tide was 12 to 15 feet above ordinary tides and houses on Water Street found the river five or six feet deep in their first floors during the height of the storm tide. At New Bern all communication for a while was by canoe."

September 4-5, 1856

"A 'perfect tempest' accompanied this hurricane in the Wilmington area, where the wind blew hard from the north or northeast for about two days and then veered to south or southwest. There was considerable damage to crops, especially rice. At that time, Wrightsville Beach was said to have been one-half mile wide and covered with live oak trees. Water swept across Wrightsville, washing away most of the oaks (the remainder died within a few days) and swept debris across the Sound onto the mainland. Breakers it is told, beat on areas one-half mile inland from the Sound at an elevation of 30 feet" (Hardy and Carney 1962).

October 18-25, 1878

This hurricane moved northward across Cuba, skirted the east coast of Florida and moved inland between Wilmington and Morehead City. It struck the Outer Banks with full hurricane force; with maximum winds of 100 mph recorded at Cape Lookout and 82 mph at Portsmouth. The steamer City of Houston was lost at Frying Pan Shoals; a great many ships were damaged or lost in the storm all along the Atlantic coast (Hardy and Carney 1962).

August 13-19, 1879

A severe hurricane moved inland near Wilmington 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 when indicating 138 mph and the wind was afterward estimated to have reached 168 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. A ship report indicated waves forty feet from trough to crest. This storm was most destructive in the Morehead City - Beaufort, N.C., area where two hotels were destroyed and 1,000 feet of railroad track torn up. All the wharves were washed away and the chimneys of most houses were blown away. On the Outer Banks, the storm caused great damage at Diamond City, which was near Cape Lookout (Hardy and Carney 1962).

September 9, 1881

This severe hurricane moved northwestward across the Wilmington-Wrightsville Beach area and curved northeastward to near Norfolk and then out to sea. At Smithville, it was reported as the most violent storm in 50 years with the town "covered with fallen trees, scattered fences and the debris of demolished buildings." Many ships were sunk and driven ashore. At Wrightsville, the tide "marked a height never before witnessed," water washed over the turnpike carrying large quantities of earth out to sea and making the road impassable. At Wilmington, the wind recorder had been indicating a speed of 90 mph for four minutes when the anemometer wires broke.

Excerpts from the Wilmington Morning Star give eyewitness accounts of this hurricane which was considered the most severe storm there since 1822 or 1838.

"Terrific storm at Wrightsville, (N.C.) -- Turnpike washed away -- bath houses gone -- trees uprooted and twisted off -- landmarks gone. Soon after 7 o'clock (September 9) the wind rose and by 8 the boats were drifting away and the marsh hens flying in. The wind continued to increase in velocity, and the whole sound was full of white-capped waves, equal to an ordinary ocean surf, not a vestige of marsh grass being visible. The tide marked a height never before witnessed by this generation; it swept over the turnpike, washing away that part of the curve, rendering it impassable.

"Before 2 o'clock the wind which was blowing from the east, increased in velocity to such an extent that it was difficult to move against it. Several trees were blown down. The old cedar at Lippitt's Point, being undermined by the water, was blown over. All the boats dragged anchor and no boat could live in such a sea. The grandstand at the banks is a thing of the past, being completely swept away. One or two planks only marked the spot.

"After 12 the wind shifted in a directly opposite direction with redoubled fury, and then the great damage was done to property.

"At Fort Fisher, where there is a small fishing village, all houses but one were swept away. One house, located near the water, was washed entirely away, not a vestige of it being left.

"At Wilmington, N.C., the oldest inhabitants say that it has been many years since this immediate section has been visited by such storms as those of yesterday. One old gentleman says Wilmington experienced such another gale in the year 1822, and another remembers one that occurred in 1838, at which time the water in the river was up to Front Street, which he thinks will compare with the hurricanes of yesterday. The Signal Officer here reported the velocity of the wind at one time during the last gale at 90 mph.

"It was related as a fact that three large trees were uprooted at Masonboro Sound by the first of the storms on the eventful Friday of last week, which was from the northeast, and that the second and more severe one, which was from the southwest, blew them back into position again, where they are standing at the present, looking as if nothing ever happened to them."

September 4-13, 1883

This major hurricane moved steadily from near Martinique on the 4th, on a curved path to the north and passed inland near Smithville on the 11th. Maximum winds at Smithville were from the southeast at 93 mph at 8:20 a.m. Newspaper accounts stated that the wind blew at a speed of 81 mph for seven hours resulting in considerable damage to buildings and telegraph and telephone lines. Many vessels broke from their moorings and were driven ashore in the Smithville area. The storm was reported very disastrous to vessels between Hatteras and Wilmington, with much wreckage drifting onto shore near Wilmington. Considerable crop damage due to violent wind and rain was reported as far inland as Harnett County (Hardy and Carney 1962). Excerpts from the Wilmington Morning Star follow:

"The long continued gale drove an immense volume of water up the river, and as a consequence everything on the west side of the river was flooded."

At Federal Point--

"The gale commenced Sunday morning, and the wind continued to blow pretty hard until about half past 12 o'clock Monday night, at which time it shifted to the southeast, from which quarter it continued to blow very heavily until Tuesday at 12:30 p.m., attaining at times a velocity of eighty mph, the storm being, on account of its length, even more severe than the great storm of 1881. As soon as the wind shifted to the southeast, the tide commenced making encroachments upon the beach."

Myrtle Grove--

"At this Sound we hear the storm was intensely severe. The spray from the ocean was blown over the banks, across the intervening mile of sound, and well up among the crops on the mainland."

Masonboro--

"The beach was strewn with boards and posts which were supposed to be some of the remains of the Wrightsville bathing houses. The marsh was completely submerged by the water, and while the storm raged, the beach was imperceptible from the mainland."

Wrightsville Sound--

"The damage at Wrightsville was pretty severe."

August 21-26, 1885

This severe hurricane moved through the Bahamas on the 23rd, skirted the eastern coast of Florida, then moved inland near Savannah, Ga., and passed across North Carolina just west of Wilmington and Hatteras. Maximum 5-minute winds of 98 mph were recorded at Smithville, 92 mph at Fort Macon and 52 mph at Wilmington and Hatteras, all from the southwest or south. At Smithville, the anemometer was blown away at 5:15 p.m. with the 98 mph wind and winds were estimated to have reached 125 mph during the next half hour. The damage at Smithville was estimated at over $100,000. The storm did great damage further south at Charleston, S.C., where damage was estimated at $1.7 million. The storm was severe in Wilmington and there was considerable damage to property at Morehead City. As a result of this destructive storm it was proposed that a weather reporting network be set up in the West Indies and Mexico (Hardy and Carney 1962).

August 15 - September 2, 1893

This severe hurricane skirted the east coast of Florida then penetrated the Georgia and South Carolina coast line on August 27-28. An estimated 2,000 people lost their lives on the coastal islands and in the low lands between Tybee Island, Ga., and Charleston, S.C. After crossing the coast, the storm moved northward passing over Charlotte, N.C., on the 28th and then turned to the northeast. There was great destruction in the South Atlantic states. A number of ships were lost at sea off the North Carolina coast in the Cape Fear area. Maximum winds of 72 mph from the south were reported at Southport and Wilmington, N.C., on the 28th. At Wilmington, "the river tide was the highest ever known here" (Hardy and Carney 1962). An old newspaper report stated that the sea washed across Wrightsville Beach Island and Carolina Beach, N.C. (Corps of Engineers 1961). Maximum high tide was 6.7 ft MSL at South Island, Winyah Bay, S.C., and prevailed along the middle and South Atlantic coasts (U.S. Weather Bureau 1893).

September 25 - October 15, 1893

"The hurricane which passed northward across North Carolina on October 13, 1893 was similar to Hurricane Hazel of 1954, except that its path was a little more to the west and the damage not quite as severe. Crossing the South Carolina coast somewhat north of Charleston, the storm center moved directly northward, its eye passing nearly over Raleigh. The highest reported wind in North Carolina was 94 mph at Southport. In the Wilmington area, the tide and overflow water were reported as the highest known to date, being 16 inches above the high water mark of 1853. Damage to the Wilmington water front was estimated at $150,000. Great destruction was reported to forests, crops, property" (Hardy and Carney 1962). At South Island, Winyah Bay, S.C., the maximum recorded wind was 90 mph from the northeast and a high tide of 9.3 ft MSL was reported (U.S. Weather Bureau 1893).

August 3-24, 1899

One of the most severe hurricanes on record for the Hatteras area moved slowly northward across the Outer Banks during August 16-18. By early morning of the 17th, the wind was blowing from the northeast at 70 mph at Hatteras. By early afternoon it had reached 84 mph, with extreme velocities of 120 to 140 mph. The anemometer then blew away; stronger winds probably occurred. The Weather Bureau observer at Hatteras reported that "the entire island" was covered with water to a depth of 4 to 10 ft. There were not more than four houses in which the tide did not rise to a depth of 1 to 4 ft. All fishing piers and equipment were destroyed; all bridges were swept away; a great proportion of the homes on the island were damaged. There was much destruction at Diamond City, which was located in the vicinity of Cape Lookout. Flooding of much of the coastal areas and strong winds and heavy rains inland as far as Raleigh did great damage to crops (Hardy and Carney 1962). See next paragraph for statement concerning water level at Wrightsville Beach.

October 23 - November 4, 1899

This major hurricane followed closely the path taken by Hurricane Hazel 55 years later. It struck the North Carolina coast on the morning of October 31 and caused great destruction. The exact point where the center crossed the coast is unknown, but from the behavior of the winds at coastal and inland points and from the fact that tides were very high at Wrightsville Beach and northward, the center probably hit the coast somewhere below Wrightsville, then moved across the state, very likely passing east of Raleigh. Highest wind reported was 72 mph (sustained 5-minute velocity) at Kitty Hawk. At Wrightsville Beach, water was reported as 8 ft above normal high tide and 2 feet higher than in the August hurricane "or ever before." Water came over the wharves in Wilmington and flooded some streets. There was much flooding and damage in New Bern, Morehead City, and Beaufort. At Southport, it was "the worst ever" (Hardy and Carney 1962). The Wilmington Morning Star stated that 27 cottages at Carolina Beach were wrecked and swept away; excerpts from the same source follow:

"The storm at Wrightsville Beach was awful, and havoc was wrought by wind and waves. The damage to the cottages and club houses on the beach and the track and trestles of the Wilmington Seacoast Railway is estimated at $75,000.

"The Caribbean storm which reached Wilmington at full force Monday night at 10 o'clock, increased in velocity till 5:30 o'clock yesterday morning and it will go down in history as one of the worst wards of elements ever experienced on the coast. The tide at the seaside and in the river were enormous. At Wrightsville Beach the tide was eight feet above the high water mark, and in the city the river came over the wharves and flooded Water and Nutt Streets.

"At 5 o'clock yesterday morning the barometer (at Wilmington Weather Bureau) began to rise from 28.98 inches (981.4 mb), the lowest registered. The strong southwest wind which kept up its blow during the night ran the tide up to nearly the highest point it has reached in the river during the history of the port, and much damage was done to submerged wharves and warehouse floors. Only at one time, during the fearful storm of September, 1893, has it been higher."

September 3-18, 1906

This hurricane approached the coast from the east-southeast and moved inland a little south of Myrtle Beach, S.C. The estimated wind velocity of 100 mph was reported by the steamship NAVAHO located at about 13 mi southeast of the mouth of the Cape Fear River (Corps of Engineers, Wilmington, N.C. 1961). There was considerable damage to shipping along the coast from Charleston, S.C., to Wilmington, N.C. Maximum winds of 50 mph were reported at Wilmington. Cottages, a hotel and other property was damaged at Wrightsville as breakers swept across the island and sound and rolled "high up on the mainland" (Hardy and Carney 1962).

July 25 - August 3, 1908

This storm had its inception as a tropical storm off the east coast of Florida. It then moved to the east-northeast, did a complete "loop" and became a hurricane as it moved northeastward off the coasts of Georgia and the Carolinas. It moved inland near Cape Lookout on July 31 then across Pamlico Sound, continuing its northeastward movement. At Wilmington, the maximum wind was 48 mph from the northeast while the barometer reached a low of 987 mb. Highest reported wind was 58 mph at Hatteras, but the storm piled up considerable water on the North Carolina coast south of Hatteras. This combined with torrential downpours (10.73 in. in 72 hr at New Bern and 9 in. at Kinston) caused much flooding in the eastern counties. Wind-driven water covered Wrightsville Beach (which had been evacuated) and destroyed considerable property. Damage was "immense," but no injuries or fatalities were recorded. At New Bern, this was "the worst storm in history" (Hardy and Carney 1962; Corps of Engineers, Wilmington, N.C. 1961; and Sugg, et al. 1971).

September 8-21, 1933

This hurricane formed east of the Leeward Islands, moved northwest and then northward, increasing in intensity and striking the coast a little west of Hatteras about 8 a.m. on the 16th. Maximum wind speed at Hatteras was estimated at 76 mph because a portion of the anemometer was blown away. Winds were estimated up to 125 mph in New Bern and Beaufort. Minimum barometric pressure at Hatteras was 957 mb. Damage was heavy from a short distance south of New Bern to the Virginia line. Wind and water did great damage at New Bern where water reached a height of 3 to 4 ft in some streets. Old residents at Beaufort said the storm was the worst they had ever experienced. High winds, waves, and the piling up of water in Pamlico and Albermarle Sounds caused 21 deaths. It was reported that hardly a building was left standing in several coastal towns. Damage was estimated at $3 million (Hardy and Carney 1962).

October 5-18, 1954 - HAZEL

Hurricane Hazel was the most destructive storm in the history of North Carolina. The storm entered the coast just north of Myrtle Beach, S.C., as hurricane winds hit the Atlantic coast between Georgetown, S.C., and Cape Lookout. Storm tides devastated the immediate ocean front of this stretch of coast. Every fishing pier from Myrtle Beach, S.C., to Cedar Island, N.C., a distance of 170 mi, was destroyed. There was complete devastation on that portion of the immediate waterfront between the S.C.-N.C. state line and Cape Fear. Grass-covered dunes, some 10 to 20 ft high, along and behind which beach homes had been built in a continuous line 5 mi long, simply disappeared, dunes, houses and all. From Cape Fear to Cape Lookout the degree of devastation was not as great, but ocean front property was damaged an average of fifty percent along the entire stretch. North of Cape Lookout damage was relatively light. High tides of 16.6 ft MSL were observed at Holden Beach Bridge and Calabash, N.C. The lowest recorded barometric pressure of 938 mb was reported at Little River Inlet on the N.C.-S.C. border. Maximum wind speeds were 82 mph with gusts to 98 mph at Wilmington, 106-mph gusts at Myrtle Beach, S.C., and an estimated 150 mph at Cape Fear. The storm continued inland through North Carolina bringing widespread damage due to high winds and record rainfall. There were 19 known dead and an estimated 200 persons injured during this storm. It was estimated that $36 million damage was done on the North Carolina beach area but when the total inland crops and property damage are included, the total was close to $100 million (Hardy and Carney 1962; Sugg et al. 1971; and Corps of Engineers, Charleston, S.C., 1957). The collection of tide heights published by the U.S. Weather Bureau (Rhodes 1955) includes a level of 14.6 ft MLW (12.7 ft MSL) at the Wrightsville Beach drawbridge. Harris (1963) also publishes this value.

August 3-14, 1955 - CONNIE

Hurricane Connie entered the North Carolina coast close to Cape Lookout about 8:30 a.m. on August 12. The prolonged pounding of high waves against the coast caused tremendous beach erosion estimated to have been worse than that caused by Hazel in 1954. Tides on the coast from Southport to Nags Head were reported at about 7 ft above normal (6.9 ft MSL at Wrightsville Beach and 7.5 ft MSL at Kure Beach), while water in the sounds and near the mouths of rivers were 5 to 8 ft above normal. At Wilmington, highest reported winds were 72 mph gusting to 83 mph. At Fort Macon, winds of 75 mph with peak gusts of 100 mph and lowest pressure of 962 mb were reported. The storm also brought torrential rains with the maximum, ranging around 12 in. within 48 hr falling near Morehead City. Total damage, throughout the state was estimated at $50 million (Hardy and Carney 1962, and Corps of Engineers, Wilmington, N.C. 1961).

August 7-21, 1955 - DIANE

Before the damage from Hurricane Connie could be estimated, Hurricane Diane five days later, struck the coast near Carolina Beach about 6 a.m. on August 17. The highest wind reported was 74 mph at Wilmington Airport. Tides ranged from 5 to 9 ft above mean low water on the beaches (6.8 ft MSL at Wrightsville Beach) and estimated 5 to 9 ft above normal in parts of sounds and rivers emptying into sounds. Water was 3 ft above floor level in the business district of Belhaven and "waist deep" in parts of Washington and New Bern. Beach erosion caused by Diane was severe. The total damage caused in North Carolina by both Connie and Diane was estimated in excess of $90 million. There were no deaths or injuries directly attributable to either of the storms in North Carolina (Hardy and Carney 1962, and Corps of Engineers, Wilmington, N.C. 1961).

September 10-23, 1955 - IONE

Hurricane Ione, moving from the south, crossed the North Carolina coast near Salter Path, about 10 mi west of Morehead City, about 5 a.m. on September 19. It then slowly curved to the northeast passing out to sea near the Virginia state line early on September 20. When Ione entered North Carolina, highest winds were a little over 100 mph in gusts. The highest recorded wind speed was 75 mph gusting to 107 mph at Cherry Point. Minimum barometric pressure over North Carolina was 960 mb. Heavy rains accompanied Ione. At the same time, prolonged easterly winds drove tide water onto the beaches and into the sounds and their estuaries to a height of 3 to 10 ft above normal. The result was inundation of the greatest area of eastern North Carolina ever known to have been flooded. At New Bern, the depth of water was the greatest of record, being about 10-1/2 ft above mean low water, with 40 city blocks flooded. Several hundred homes were washed away and thousands were flooded by water with depths ranging up to 4 ft (Hardy and Carney 1962). A high tide of 6.9 ft MSL was reported at Atlantic Beach, N.C. (Harris 1963) and 5.3 ft MSL was estimated at Wrightsville Beach by the Corps of Engineers (1961).

September 21 - October 3, 1958 - HELENE

Hurricane Helene was one of the most powerful storms of recent history and fortunately for North Carolina, the storm center moved up the coast staying well out at sea on September 26-27. Even so, the highest winds of record were recorded at Wilmington, with peak gust at 135 mph and fastest mi 85 mph. The lowest reported central pressure of 932 mb occurred at a point south-southeast of Cape Fear early on the morning of the 27th. There was some beach erosion due to seas and tides but this was minimized by the passage of the storm at time of low astronomical tide. Highest tides on ocean beaches were estimated at 3 to 5 ft above normal (Hardy and Carney 1962). A high tide of 5.1 ft MSL was reported at Wrightsville Beach (Corps of Engineers 1961). Tides were higher on the southern edge of Pamlico Sound, where a sudden rise following the wind shift as the center passed, brought the tides to 7 or 8 ft above normal (Hardy and Carney 1962, and Corps of Engineers, Wilmington, N.C. 1961). The Corps of Engineers (1961) cite an estimated stage at Wrightsville Beach of 7.0 ft MLW (5.1 ft MSL).

August 29 - September 13, 1960 - DONNA

Hurricane Donna passed inland over the North Carolina coast between Wilmington and Morehead City on September 11. The "eye" of the storm passed a few miles east of Wrightsville Beach, although Wilmington and Wrightsville beach were in the "eye" for about an hour. Lowest barometric pressure at Wilmington was 962 mb. Tides of 6 to 8 ft above normal, combined with high winds caused severe damage at many points. Maximum winds were of hurricane force with Wilmington reporting a peak gust of 97 mph. The storm center moved northward along a path slightly east of a line from Wilmington to Norfolk during the night of the 11th. Wind gusts were in excess of 100 mph and tides 4 to 8 ft above normal. High tides of 10.3 and 8.3 ft MSL were reported at Atlantic Beach and Wrightsville Beach, respectively (Harris 1963). Coastal communities suffered heavy structural damage from Wilmington to Nags Head, with considerable beach erosion. Eight deaths and an estimated 100 injured were attributed to the storm. Estimated damages were well up in the millions (Hardy and Carney 1962, and Corps of Engineers, Wilmington, N.C. 1961).

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 pressures, radius of maximum winds, speed of forward motion, and other factors affecting storm tide-producing capability, were published in 1959 (Graham and Nunn). This compendium of hurricane characteristics has been updated through 1973 by the National Weather Service and adapted to the needs of the Flood Insurance Program, including specification of probability distributions of the individual parameters. These data used in this and other flood insurance studies by NOAA are being prepared for publication in a separate report (Ho, Schwerdt and Goodyear 1975). The specific values adopted for tide frequency computations in the present study are presented in par. 5.1.

3.1 Frequency of Hurricane Tracks

The overall frequency of hurricane occurrences is basic to calculating the resulting tide frequencies. The tide frequency analysis in this study treats landfalling and storms moving alongshore separately then adds the results together. The frequency with which hurricanes and tropical storms have entered the coast and have moved approximately parallel to the coast ("alongshore") was assessed by counting tracks and smoothing the count along the coast in the previously cited reference (Ho, et al. 1975). These counts were used in this study, except that a special count of alongshore storms was made from the track charts opposite Cape Fear and Cape Lookout to secure more detail near these seaward extensions of the land.

Hurricanes also exit the coast of the study region after recurving inland, but these infrequent events contribute little to the frequency of high storm tides in the area under study. Because of hydrodynamic factors a hurricane of given intensity exiting gives half or less the surge height from the same storm landfalling. They are not considered further in this report.

3.2 Probability Distribution of Hurricane Intensity

Storm surges vary directly with the strength of the wind that is putting stress on the water surface, other factors being constant. A measure of this 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. The probability distribution of hurricane central pressures near Wrightsville Beach, N.C., based on storms from 1900 to 1973 and smoothed along the coast, is shown in figure 3. It will be noted that the diagram shows only the fraction of all hurricanes with intensities below certain levels and makes no reference to frequency in terms of events per year. For storm tide computation this continuous distribution is divided into eight class intervals each represented by the central pressure at the mid-point of the class interval. This computational probability distribution is indicated by the dashed line.

3.3 Probability Distribution of Radius of Maximum Winds

In all hurricanes, proceeding from the storm center outward, winds increase from low values at the center of 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 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 of the size or lateral extent of the hurricane, a factor which affects the surge profile along the coast. The probability distribution of this parameter is divided into three class intervals for computation.

3.4 Probability Distributions of Speed and Direction of Forward Motion

The speed and direction of forward motion of hurricanes also affect surge height. In the study area the height of the surge on the coast increases with increasing storm speed. Thus, the occasional fast-moving storms, especially if they are large and moving directly toward the coast, pose the greatest hazard (Jelesnianski 1967). Six class intervals of the probability distribution of the speed of motion were adopted, separately for landfalling and alongshore computations. A test comparison grouping storm direction into five classes vs. only three showed no difference in resulting tide frequencies in the 10- to 500-yr return period range, and three class intervals were used thereafter.

4. HURRICANE SURGE

4.1 Surge Model

The National Weather Service has developed a two-dimensional hydrodynamic 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 coastal inundations 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. Replication of surge profiles produced by past hurricanes along this stretch of the coast agree quite well with observed tides and high water marks. 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.

Running this model requires a large computer. The model program is at present in residence at NOAA's computer complex at Suitland, Md. Meteorological inputs to a computer surge calculation are hurricane central pressure, radius of maximum winds, storm direction of motion. and forward speed. The hurricane climatology just described is oriented toward providing these parameters. The computer program generates the needed moving sea-level pressure and surface wind fields from the basic parameters by predetermined relations. The input also includes basin data. A basin is described by coastal boundaries, their orientation, local and geographic references, and the distribution of ocean depths over the basin.

The SPLASH I version is limited to storms moving forward at constant velocity and intensity toward a specified landfall point while 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. In the present study, SPLASH II was used to compute surges generated by alongshore hurricanes. Since SPLASH I and II give the same result for landfalling hurricanes with a constant velocity and intensity, landfalling hurricane surges were computed in this study by the SPLASH I program, which is slightly simpler to use.

4.2 Shoaling Factor

The capacity of a hurricane of given characteristics to produce a coastal surge depends on the slope and depth of the continental shelf. The shallower the coastal water the higher the surge. This variation along the East coast is depicted in figure 3b of a separate report (Barrientos and Chen 1975) showing the ratio of the surge that would be produced at each coastal point by a prescribed hurricane compared to that over a continental shelf of average slope ("standard basin"). 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 North Carolina portion of this diagram is reproduced in figure 4. The shoaling factor is implicit in calculations of hurricane surge by the model at selected coastal points, since the depths of the continental shelf are introduced by input data to the calculation. The shoaling factor is specified at 4-mi intervals in the SPLASH program (relative to value at the center of the "basin") and is a primary guide to interpolating between coastal computation points. The shoaling factor curve of figure 4 reveals that a maximum factor is reached near Cape Fear and a gradual sloping curve extended northward to a minimum near Cape Hatteras (outside the right hand margin of the diagram). The top curve (for R = 26 n.mi.) is applicable to hurricanes with R >19.5 n.mi. in this study and the lower curve to smaller hurricanes.

The water depths as depicted on National Ocean Survey Nautical Charts, are shown in figure 5. Techniques for smoothing this for input to the computer are described by Barrientos and Chen (1975).

5. TIDE FREQUENCY ANALYSIS BY JOINT PROBABILITY METHOD

5.1 The Joint Probability Method

The first step in the joint probability method is to divide the hurricane parameters into class intervals for the landfalling storms and read out the mid-point value of each class interval, as indicated in figure 3. These parameters used in the computations are listed in the left part of tables 1 to 5 for the coast at Cape Fear, Wrightsville Beach, New River Inlet, Atlantic Beach, and Cape Lookout, N.C., respectively. The parameters adopted in the tables are eight pressure depression categories, three R categories, six forward speed categories and three direction-of-approach categories. These factors were considered independent in the statistical sense except that the three R's were not the same for all pressure depression categories, smaller values being used with the more intense pressure depressions in line with the discussion in the hurricane climatology study (Ho, et al. 1975). Each combination of D, R, f, and θ_L represents a climatologically possible landfalling hurricane or tropical storm. Thus, each of the five tables defines 432 different landfalling hurricanes and tropical storms (8X3X6X3 = 432) which in the aggregate represent the climatological possibilities in the vicinity. The probability (fraction of all hurricanes) of each of these is obtained by multiplying the respective parameter probabilities in the table. The sum of the probabilities of the 432 hurricanes, of course, equals 1.0. The frequency of all landfalling storms is .00147 to .00158 per nautical mile of coast per year (par. 3.1).

As the second step, calculations are made with a pre-prepared computer program of the coastal surge profile for each landfalling hurricane. Most of the surge profiles are obtained by adjustment of other profiles rather than by complete surge calculations. Each storm is allowed to strike the coast not only at the most critical point but at 8-mi intervals (being a multiple of SPLASH grid) on both sides of a location under study, and the storm surge profiles shifted along the coast accordingly. As the third step, all 432 profiles in all shifted positions were added to low astronomical tide, high tide, and two intermediate tide levels. Further discussion on astronomical tides is included in the next section. Since each surge profile has a prescribed frequency, as have the astronomical tides, all the profiles may be combined into a single tide frequency curve for a fixed coastal point.

Table 1.-- Hurricane and tropical storm parameters - Cape Fear, N.C.

LANDFALL STORMS $F_n = .00147$										ALONGSHORE STORMS			
			P_{rd}					$\theta_c = 075$					
			R										
P_o	D	P_i	18.8	30.1	40.2	f	P_f	θ_L	P_θ	L	F_b	f	P_f
926.0	87.2	.02	.5	.5	.0	5.3	.1	045	.33	4	.034	7.9	.1
933.6	79.6	.03	.5	.5	.0	7.7	.2	089	.33	13	.038	10.5	.2
941.6	71.6	.05	.33	.33	.33	9.9	.2	119	.33	22	.040	12.9	.2
951.9	61.3	.10	.33	.33	.33	13.2	.2			30	.040	15.8	.2
963.7	49.5	.20	.33	.33	.33	17.1	.2			43	.090	20.5	.2
976.6	36.6	.20	.33	.33	.33	22.8	.1			61	.092	27.0	.1
988.2	25.0	.20	.33	.33	.33								
996.5	16.7	.20	.33	.33	.33								

Table 2.-- Hurricane and tropical storm parameters - Wrightsville Beach, N.C.

LANDFALL STORMS F_n = .00150										ALONGSHORE STORMS			
			P_{rd}					θ_c = 080					
P_o	D	P_i	R 19.3	R 30.5	R 40.5	f	P_f	θ_L	P_θ	L	F_b	f	P_f
926.1	87.1	.02	.5	.5	.0	5.3	.1	043	.33	4	.018	8.0	.1
933.7	79.5	.03	.5	.5	.0	7.8	.2	090	.33	13	.029	10.7	.2
941.5	71.7	.05	.33	.33	.33	10.0	.2	117	.33	22	.032	13.2	.2
951.8	61.4	.10	.33	.33	.33	13.4	.2			30	.036	16.2	.2
963.5	49.7	.20	.33	.33	.33	17.3	.2			43	.081	20.7	.2
976.4	36.8	.20	.33	.33	.33	23.2	.1			61	.085	27.5	.1
988.1	25.1	.20	.33	.33	.33								
996.4	16.8	.20	.33	.33	.33								

Table 3.-- Hurricane and tropical storm parameters - New River Inlet, N.C.

			LANDFALL STORMS $F_n = .00156$										
P_o	D	P_i	P_{rd} R = 19.8	P_{rd} R = 32.5	P_{rd} R = 41.4	f	P_f	$\theta_c = 031$ θ_L	$\theta_c = 031$ P_θ	L	F_b	f	P_f
927.0	86.2	.02	.5	.5	.0	5.2	.1	086	.33	4	.005	8.4	.1
934.4	78.8	.03	.5	.5	.0	7.8	.2	136	.33	13	.020	11.3	.2
942.0	71.1	.05	.33	.33	.33	10.2	.2	155	.33	22	.025	13.9	.2
952.0	61.2	.10	.33	.33	.33	13.9	.2			30	.030	16.7	.2
963.2	50.0	.20	.33	.33	.33	18.0	.2			43	.071	21.7	.2
976.0	37.2	.20	.33	.33	.33	24.3	.1			61	.078	28.5	.1
987.6	25.6	.20	.33	.33	.33								
996.3	16.9	.20	.33	.33	.33								

Table 4.-- Hurricane and tropical storm parameters - Atlantic Beach, N.C.

LANDFALL STORMS $F_n = .00158$										ALONGSHORE STORMS			
			P_{rd}					$\theta_c = 055$					
			R										
P_o	D	P_i	20.3	33.4	44.8	f	P_f	θ_L	P_θ	L	F_b	f	P_f
928.2	85.0	.02	.5	.5	.0	5.2	.1	062	.33	4	.005	8.7	.1
934.8	78.4	.03	.5	.5	.0	7.8	.2	112	.33	13	.020	11.9	.2
942.7	70.5	.05	.33	.33	.33	10.5	.2	131	.33	22	.025	14.5	.2
952.4	60.8	.10	.33	.33	.33	14.4	.2			30	.030	17.3	.2
963.2	50.0	.20	.33	.33	.33	18.6	.2			43	.071	22.4	.2
975.9	37.3	.20	.33	.33	.33	25.1	.1			61	.078	29.3	.1
987.6	25.6	.20	.33	.33	.33								
996.2	17.0	.20	.33	.33	.33								

Table 5.-- Hurricane and tropical storm parameters - Cape Lookout, N.C.

			LANDFALL STORMS F_n = .00155								ALONGSHORE STORMS		
			P_{rd}					θ_c = 090					
			R										
P_o	D	P_i	20.4	33.6	41.9	f	P_f	θ_L	P_θ	L	F_b	f	P_f
928.5	84.7	.02	.5	.5	.0	5.3	.1	044	.33	4	.038	9.0	.1
935.6	77.6	.03	.5	.5	.0	8.0	.2	086	.33	13	.059	12.3	.2
943.3	69.9	.05	.33	.33	.33	10.7	.2	112	.33	22	.065	15.0	.2
952.9	60.3	.10	.33	.33	.33	14.8	.2			30	.066	17.9	.2
963.5	49.7	.20	.33	.33	.33	19.1	.2			43	.124	23.1	.2
976.1	37.1	.20	.33	.33	.33	25.8	.1			61	.115	29.4	.1
987.5	25.7	.20	.33	.33	.33								
996.2	17.0	.20	.33	.33	.33								

Legend for Tables 1 to 5

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 principal belt of maximum winds (n.mi.).
P_r	=	Proportion of storms with indicated R value.
f	=	Forward speed of storm (kt).
P_f	=	Proportion of storms with indicated f value.
P_{rd}	=	Proportion of storms in D class with indicated value.
θ_c	=	Orientation of coast, measured clockwise from north (deg).
θ_L	=	Direction of entry, measured clockwise from the coast (deg).
P_θ	=	Proportion of storms with indicated θ_L value.
L	=	Effective distance perpendicularly outward from coast to storm track (n.mi.).
F_b	=	Average number of storms per year that pass at distance L.
F_n	=	Frequency of landfalling storm tracks crossing coast (storm tracks per n.mi. of coast per year).

Note: Alongshore storms have the same value of D, R, P_i, and P_{rd} as those for landfalling.

As the fourth step, storm tides were similarly computed for the alongshore storms from the data in the right-hand part of tables 1-5. Summing all the possibilities yields the total tide frequency. The tide frequency is adjusted to datum as explained below.

5.2 Astronomical Tide

Most of the combinations of forces producing the astronomical tide 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 local monthly variation in average tide level at Southport, N.C., is depicted in figure 6.

This is calculated from the semi-annual (SSA) and annual (SA) tide prediction harmonics (Shureman 1958). Similar annual trends are experienced along the rest of the coast. The month of September is taken to represent the hurricane season. Astronomical high and low tides at Southport for this representative month were recomputed for a 19-yr period. This was obtained by rerunning the standard tide computation program written by Pore and Cummings (1967). The accumulated frequencies of high and low tides were tabulated and analyzed separately. The resulting probability distributions are shown in figure 7. Similar to previous studies, these distributions are 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 hr oscillating between corresponding high tide and low tide class interval values. This assumes that the highest high tides occur with the lowest low tides, etc.

5.3 Tide Frequencies at Selected Points

Figure 8 shows the resultant total tide frequency curves on the open coast near Cape Fear, New River Inlet, and Cape Lookout, N.C. Similar curves for Wrightsville Beach, Atlantic Beach, and at the N.C.-S.C. border are shown in figure 9. 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 par. 5.5. 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 "set-up") have the opposite effect.

The net result 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 than at the open coast. These differences have to be determined by localized studies.

5.4 Adjustment Along Coast

The estimated tide frequencies for locations other than those selected for computation along this stretch of the coast were obtained by interpolation. The interpolation was based on consideration of the frequency of storms, the variation in the shoaling factor (fig. 4) and trend in the hurricane climatology parameters along the coast. Figure 10 shows the variation of the total tide heights along the coast for the 10-, 50-, 100-, and 500-yr return periods, scaled from these diagrams and interpolated as indicated.

Results of this study are derived from the SPLASH continental shelf model which makes computation on a 4 mi x 4 mi grid. Storm tide levels within 0.5 ft of the heights of figure 10 would be expected over appreciably larger areas than previously defined in most instances, but the extend of such areas has not been determined.

5.5 Reference Datum

The National Ocean Survey, NOAA, and its component, the National Geodetic Survey, have developed the following standards for elevation control. Both standards are defined here for convenience in consistent application of the results of this study. The difference between the two is not large.

> The National Geodetic Vertical Datum (NGVD) of 1929. This is a level surface, perpendicular everywhere to the earth's gravity field. Its position is defined by precise leveling between geodetic benchmarks throughout the United States. Elevation contours on current topographic maps are generally related to this datum. The NGVD is approximately, but not exactly, at the mean level of the sea on the coasts. It cannot coincide exactly because of the fact that the sea is not a geopotential surface, and sea level has risen since the 1929 adjustment.
>
> Local mean sea level (local MSL). This is the average height of the surface of the sea, during a specified 19-yr period, or tidal epoch, as observed during that period or adjusted to that period. Nineteen years is required to complete one lunar nodal cycle which governs the main tidal forces. The current reference tidal epoch is 1941-59.

The next tidal epoch scheduled to be adopted is 1966-84. Two reasons for using local MSL in coastal work are: First, this datum is defined in terms of actual sea conditions, and therefore meets legal requirements for establishing "mean low water" and the like which are determined from tide observations. Second, it is much more economical in many coastal communities to establish a benchmark by observation of the height of the sea over a period of time by a gage installed for the purpose, than by leveling from the geodetic net. The National Ocean Survey has an active program of establishing tidal benchmarks in this way. Short-period or recent records from these gages are adjusted to the 1941-59 epoch based on comparison with simultaneous tide observations at long-record primary stations.

Differences between NVGD and local MSL have been established at primary tide gages by leveling, and at certain subordinate tide stations. These differences are interpolated between points at which they have been established. Differences determined in this way in the study area are given below:

To adjust from height above local MSL, 1941-59 tidal epoch, to height above NVGD:

N.C.-S.C. line to Cape Fear, add 0.3 ft.
Cape Fear to Cape Lookout, add 0.2 ft.

The methods of developing storm tide frequencies in this study inherently yield heights above local MSL. The heights on the frequency graphs are in terms of this datum referred to the 1941-59 epoch. These values can be related directly to tidal benchmarks. Where adjustment to NVGD is required, for example for use in connection with topographic maps, apply the corrections given above. If a local difference has been established between NVGD and local MSL, this should take precedence.

Additional information on tidal and geodetic datums can be obtained from the National Ocean Survey, Rockville, Md. 20852. The tidal datum program is described in the NOAA publication "Variability of Tidal Datums and Accuracy in Determining Datums from Short Series of Observations" (Swanson 1974).

Local 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 in the above cited publication and by Hicks and Crosby (1974). This trend is thought to be due mostly to slow subsidence of the land, but may also reflect change in volume of water in the sea from melting of ice. No adjustment has been made for this secular trend in this study.

5.6 Comparison of Frequency Curves with Observed Tides and High-Water Marks

Figure 11 shows representative highwater marks of observed storm tides along the coast in comparison to the 100-yr return period values of this study. As expected, during the period of observed data, some coastal points experienced hurricane tides higher than the "100-yr" level, while others either did not reach this level or it was not observed. The 100-yr level is to be construed as the tide level having a probability of occurrence each year of 0.01.

Wrightsville Beach was a popular resort before 1881 and more information about hurricane damages is available there than at any other point in the study area. There are no long term records from permanent tide gages on the open coast in the study area. Numerical values for storm tide levels at Wrightsville Beach are available in nine hurricanes since 1881, based on highwater marks or visual references to normal tide levels (e.g., "8 ft above normal high tides" on October 31, 1899). These water levels range from 5.1 ft MSL in hurricane Helene in 1958 to 12.7 ft MSL in Hazel. From the descriptions of flooding of the island (Section 2) it is clear that in seven other hurricanes since 1881 the water level was higher than Helene's 5.1 ft. These must be included in a 95-yr 1880-1974 data series. These hurricanes are listed in an estimated order of tide level at Wrightsville Beach in table 6. The seven hurricanes without specific levels are assigned a position in the data series but not a specific water level, based on the damage description, the proximity of the track, the high winds, and the reported pressures. Hurricanes that likely did not attain 5.1 ft are omitted. Hazel has been listed no. 1 in the series though it is quite possible that the 1881 hurricane or one of the other early storms attained this level.

The data from table 6 are compared with the adopted tide frequency curve for Wrightsville Beach in figure 12, using the plotting position formula proposed by Beard (1962). No attempt is made to fit a frequency curve to the plotted points. The purpose here is to verify the correspondence of the computed frequency curve in figure 9 to the local historical record.

6. RELATION OF THIS REPORT TO DISASTER PLANNING

The most recent disastrous display of hurricane forces on the U.S. coast was by Camille, which struck the Bay St. Louis - Pass Christian - Gulfport - Biloxi, Miss., area in 1969. According to high-water marks, the storm tide reached a level of 24.6 ft above mean sea level (Corps of Engineers 1969). The central pressure at landfall was about 908 mb. This is the most intense hurricane so far to strike the United States mainland during the period of record-keeping. Other disasters could also be recounted, including Hazel at the N.C.-S.C. border in 1954 and the Ga./S.C. hurricane of 1893. All of the eastern seaboard south of Cape Hatteras is exposed to these. For the area of this study, the National Weather Service recommends a repeat of Camille, the worst hurricane to strike the mainland, as a disaster planning objective without regard to the statistical frequency of such a storm at an individual point. Such a storm on a critical path for the south end of the study area of this report would produce a maximum tide of about 18 to 20 ft MSL.

As the shoaling factor decreases gradually northward along the coast of the study area, a Camille-type hurricane would produce high tides of approximately 13 to 15 ft MSL near Cape Lookout.

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 10, are stated in terms of probabilities or mean recurrence intervals at <u>points</u>. The likelihood of Camille or any other given intensity of storm 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.

7. COORDINATION AND COMPARISON WITH OTHER REPORTS

This report has been coordinated with the Corps of Engineers, Department of the Army, which has made and is making various Flood Insurance studies in the area.

Comparison with frequency levels in earlier studies, made during the first part of the Flood Insurance Program, are given in table 7. The tide frequencies on the open coast at the N.C.-S.C. state border are the same as in a report for Horry County, S.C., prepared by NOAA for the Federal Insurance Administration (Department of Commerce 1974).

Table 6.-- Frequency Analysis of Hurricane Tidal Elevations (higher than 5.0 ft) affecting Wrightsville Beach, N.C., 1880-1974.

Rank	Storm date	Height (ft MSL)	Plotting position* (yr^{-1})
1	1954	12.7	.00733
2	1881	-	.01781
3	1899 (Oct.)	10.5	.02830
4	1893 (Oct.)	9.5	.03878
5	1906	-	.04926
6	1899 (Aug.)	8.5	.05974
7	1960 (DONNA)	8.3	.07023
8	1883	-	.07861
9	1955 (CONNIE)	6.9	.09119
10	1955 (DIANE)	6.8	.10167
11	1944	6.7	.11215
12	1908	-	.12264
13	1893 (Aug.)	-	.13312
14	1885	-	.14360
15	1955 (IONE)	5.3	.15408
16	1958 (HELENE)	5.1	.16457

*Plotting position formula (Beard 1962):

P = (M-0.3)/(N+0.4) where P = probability, M = serial number of event,

N = length of record (assume 95 yrs).

Table 7.--Comparison of tide frequencies

Location and agency studies*	Tide Level for return periods 10-yr	100-yr (ft MSL)#	500-yr
Sunset Beach, N.C.			
FIS study, May 1972	8.5	14.0	16.1
Present study	6.8	13.2	17.0
Ocean Isle Beach, N.C.			
FIS study, May 1972	8.5	14.0	16.1
Present study	7.0	13.3	16.9
Holden Beach, N.C.			
FIS study, December 1971	8.5	14.0	16.1
Present study	7.2	13.4	16.8
Carolina Beach, N.C.			
FIS study, February 1972	6.5	12.0	15.0
Present study	7.3	13.3	16.7
Wrightsville Beach, N.C.			
FIS study, May 1970	6.5	12.1	15.0
Present study	7.0	13.0	16.6
Topsail Beach, N.C.			
FIS study, December 1973	7.6	10.1	13.3
Present study	6.8	12.6	16.0
Carteret County (unincorporated areas), N.C.			
FIS study August 1973	6.1	11.0	14.2
Present study (from Emerald Isle to Atlantic Beach)	6.0-5.6	11.0-10.2	14.2-13.1
NOAA Bogue's Bank Study for Corps of Engineers, July, 1972	6.1	11.0	14.2
Present study (from Bogue's Inlet to Atlantic Beach)	6.1-5.6	11.2-10.2	14.4-13.1

*FIS study - Flood Insurance Study prepared for FIA by Corps of Engineers, U. S. Army, Wilmington, N.C., District

#Tide levels in the present study are above local MSL, in the FIS studies above National Geodetic Vertical datum of 1929. For differences see Section 5.5.

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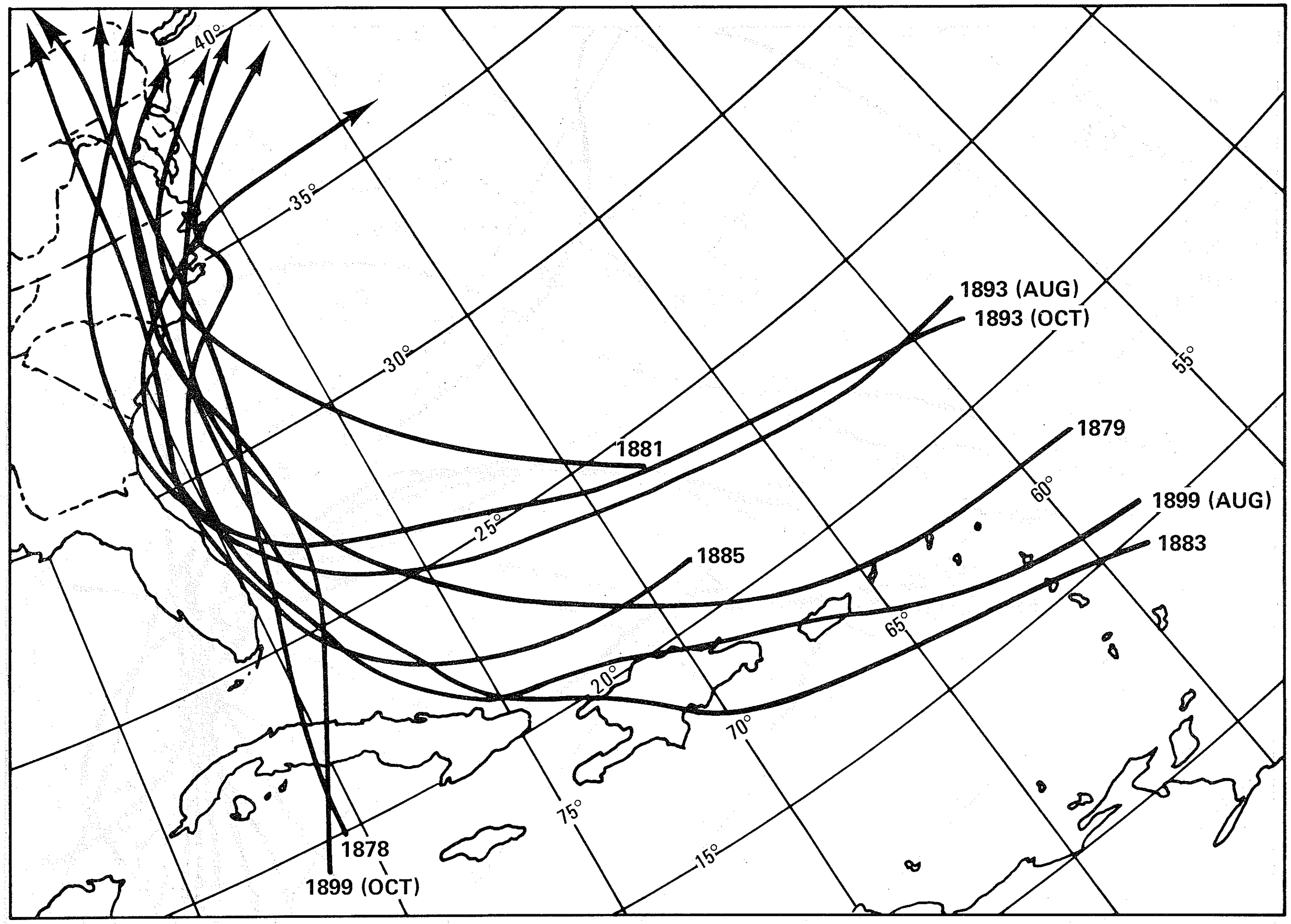

Figure 1.--Tracks of major, late 19th century hurricanes affecting North Carolina, south of Cape Lookout.

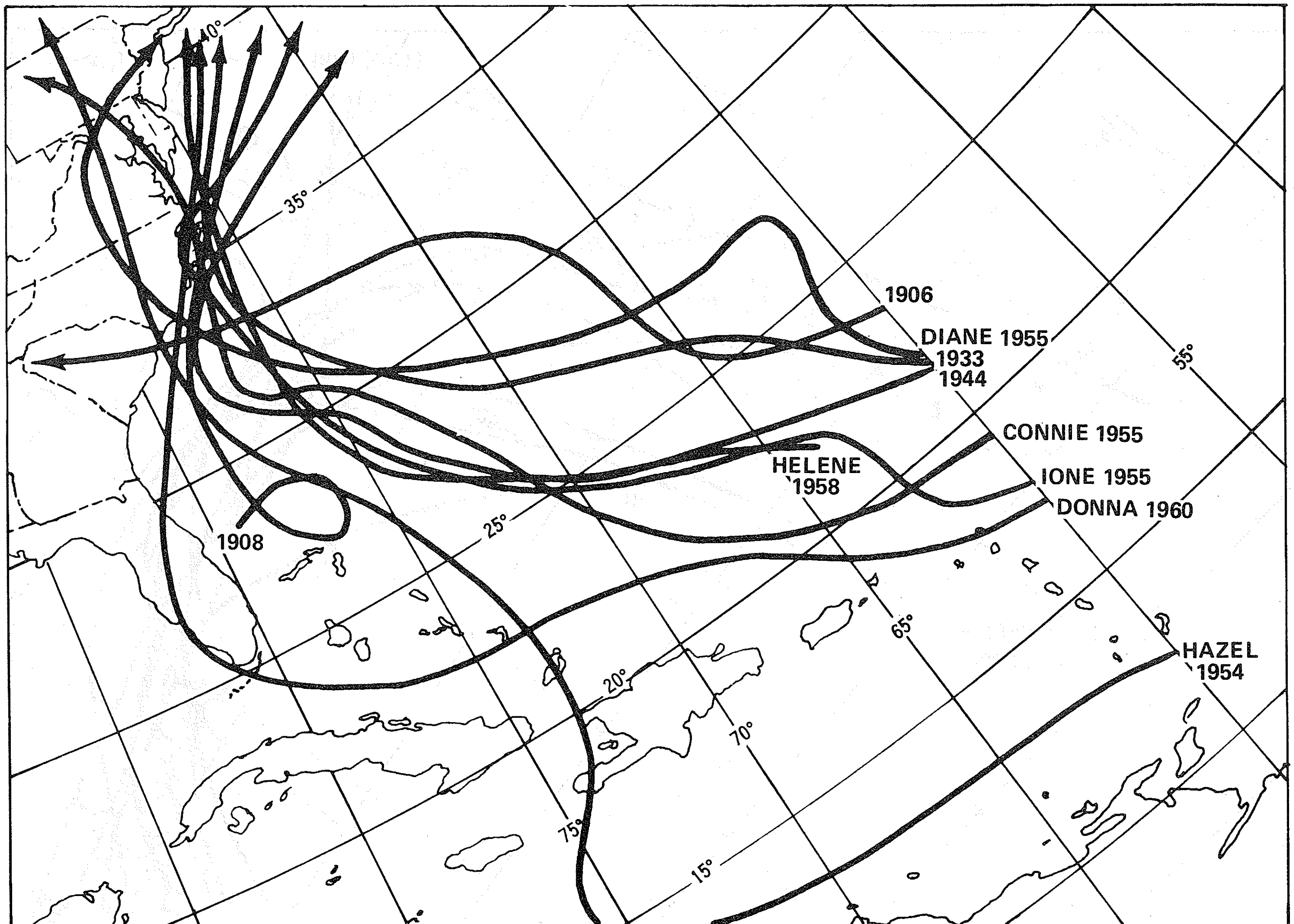

Figure 2.--Tracks of damaging hurricanes of the 20th century affecting North Carolina, south of Cape Lookout.

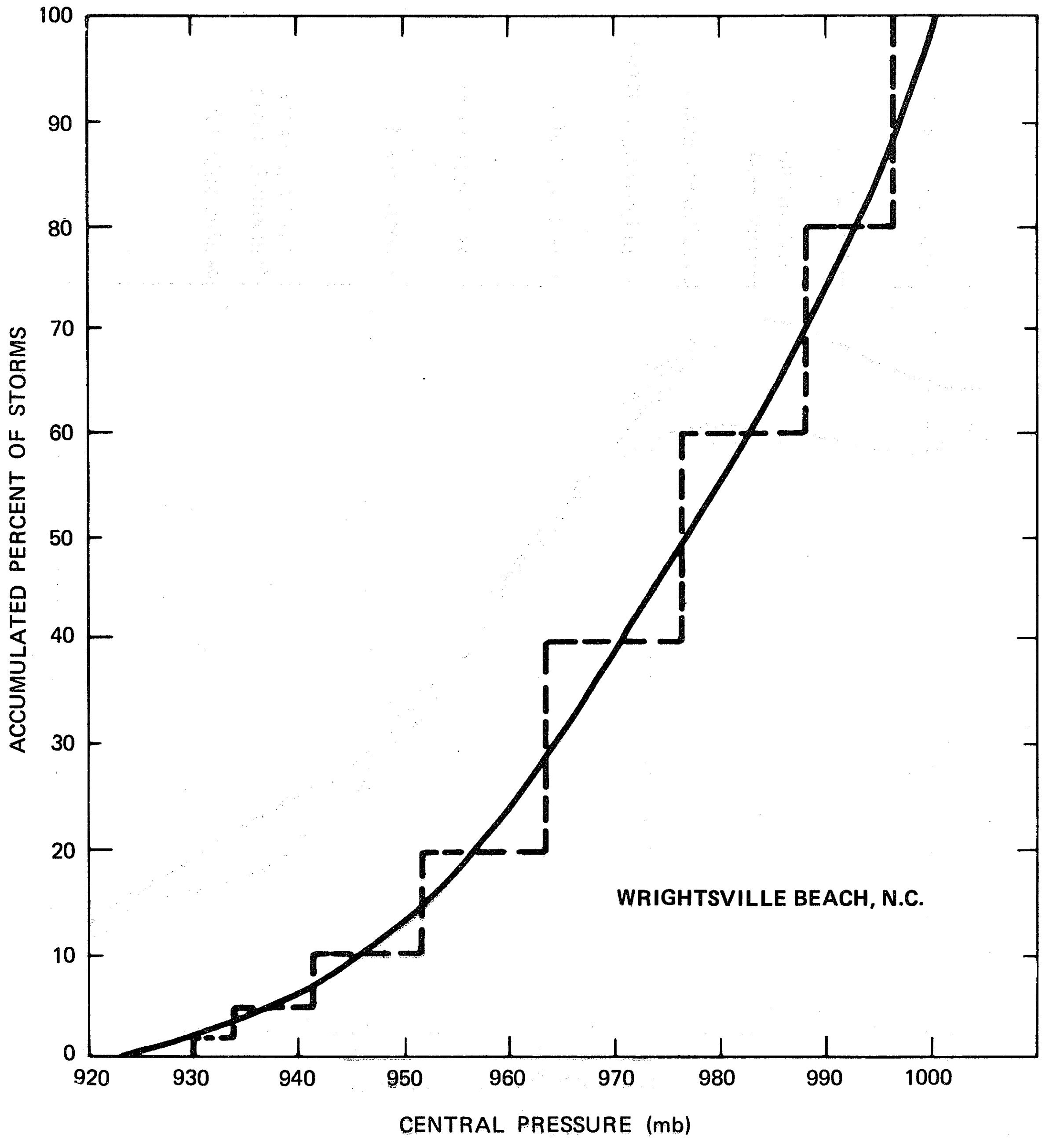

Figure 3.--Probability distribution of central pressure of hurricanes and tropical storms adopted for Wrightsville Beach, N.C.

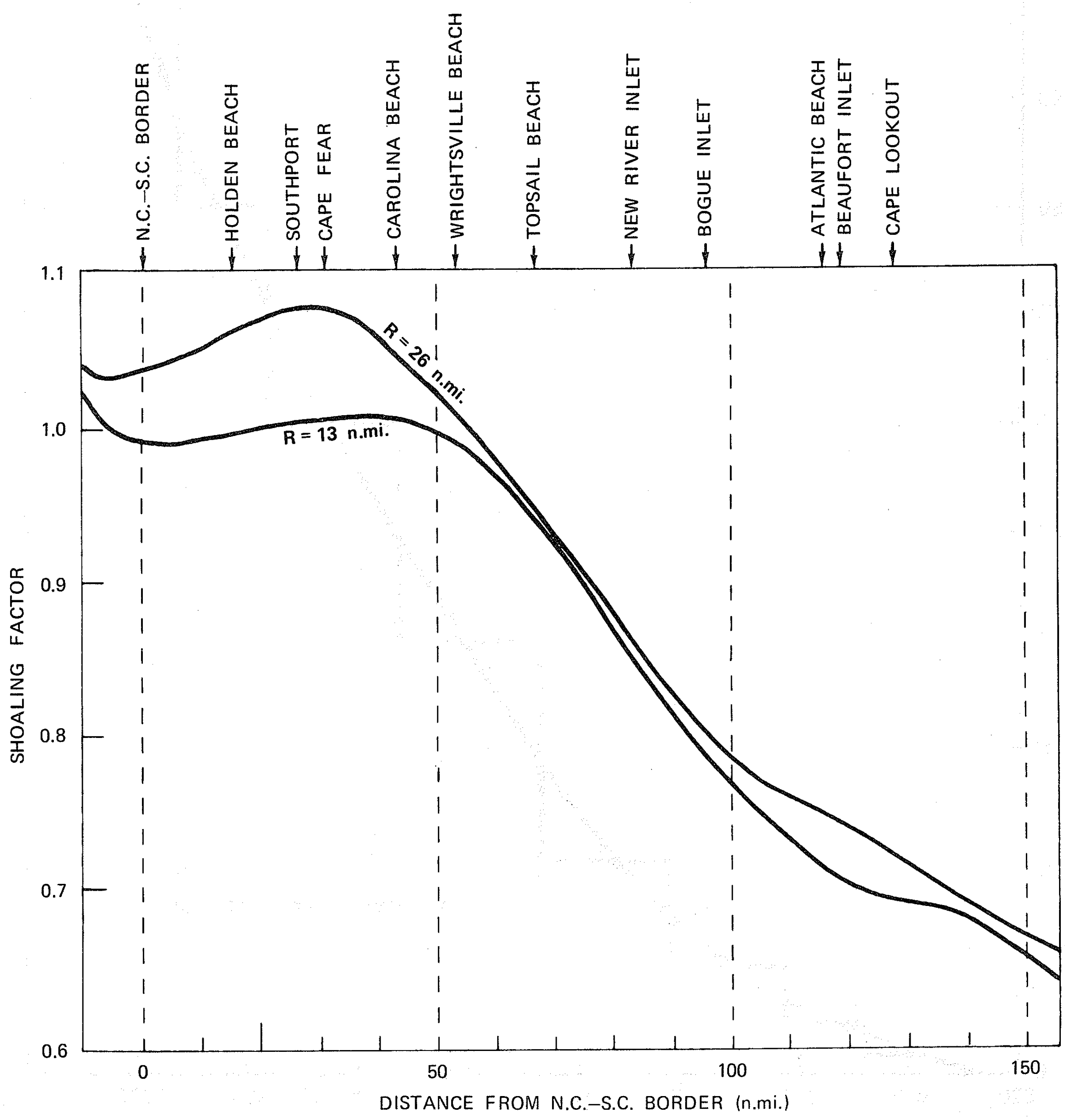

Figure 4.--Shoaling factor, North Carolina coast south of Cape Lookout. Adapted from Barrientos and Chen (1975).

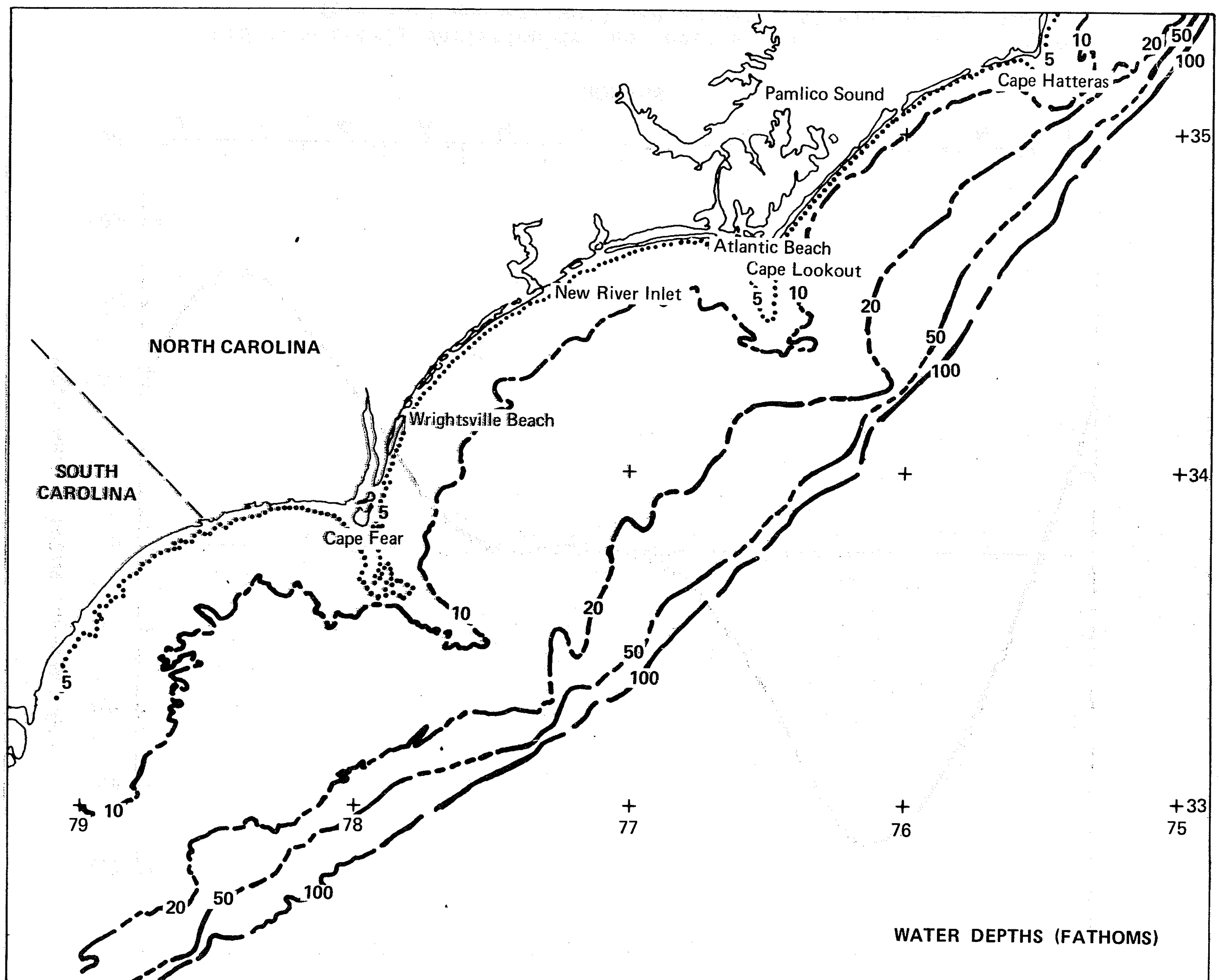

Figure 5.--Water depth off North Carolina coast, south of Cape Hatteras.

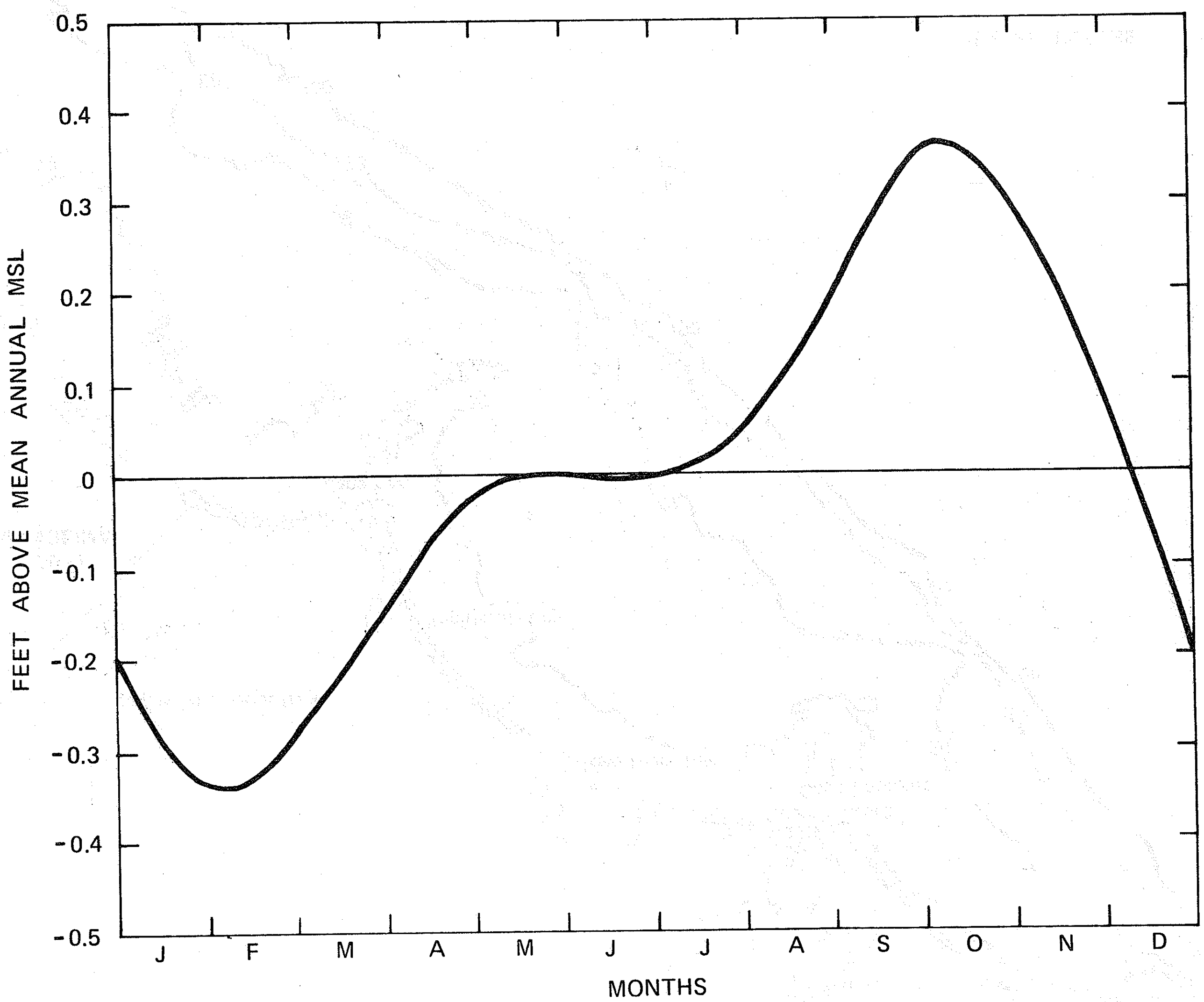

Figure 6.--Monthly variation in sea level at Southport, N.C. Derived from semi-annual (SSA) and annual (SA) tide prediction harmonics.

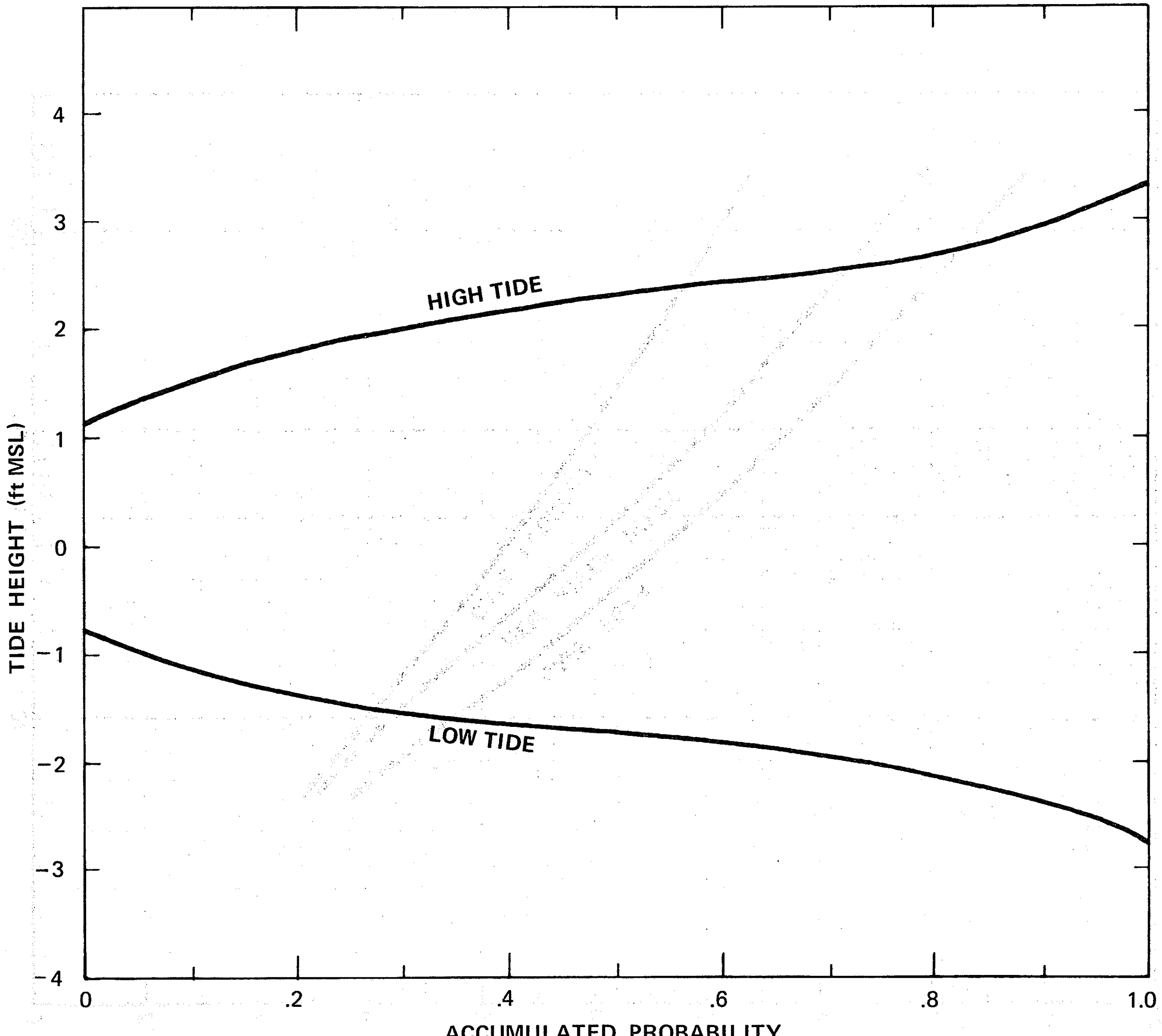

Figure 7.--Probability distributions of astronomical high and low tides, Southport, N.C., September 1953-71.

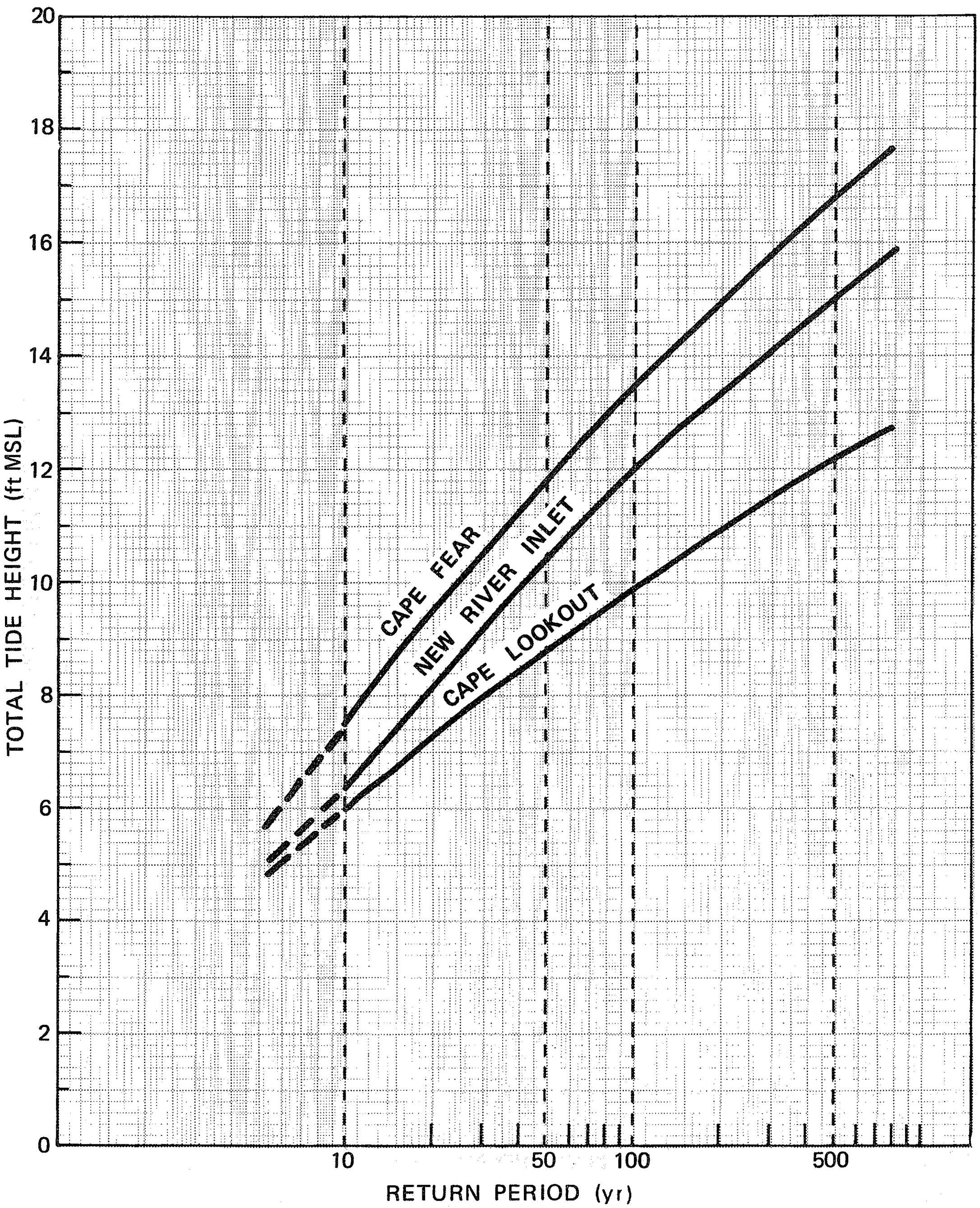

Figure 8.--Tide frequencies at selected points on the open coast. Cape Fear, New River Inlet, and Cape Lookout, N.C.

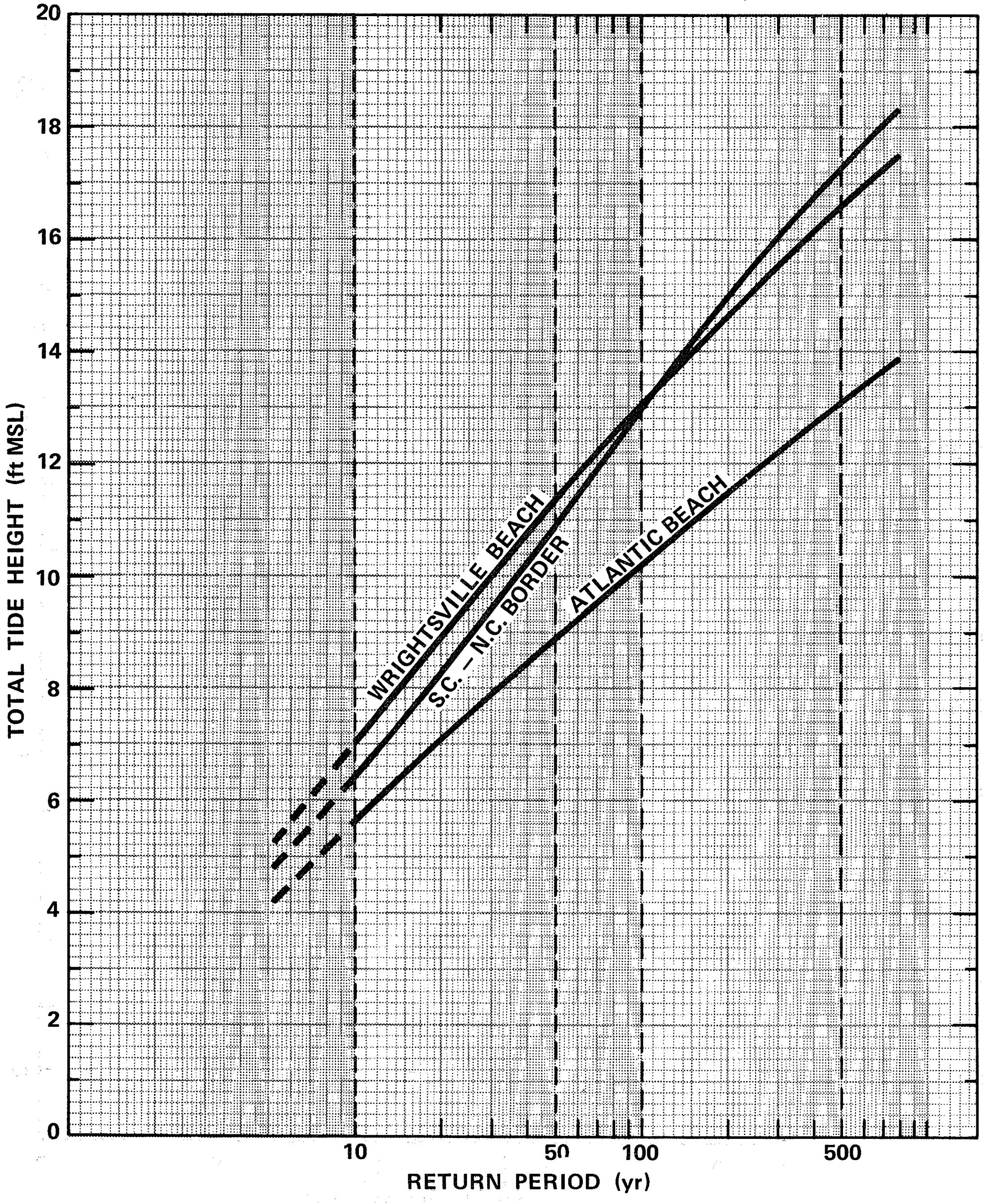

Figure 9.--Same as figure 8 for Wrightsville Beach and Atlantic Beach, N.C., and at N.C.-S.C. border.

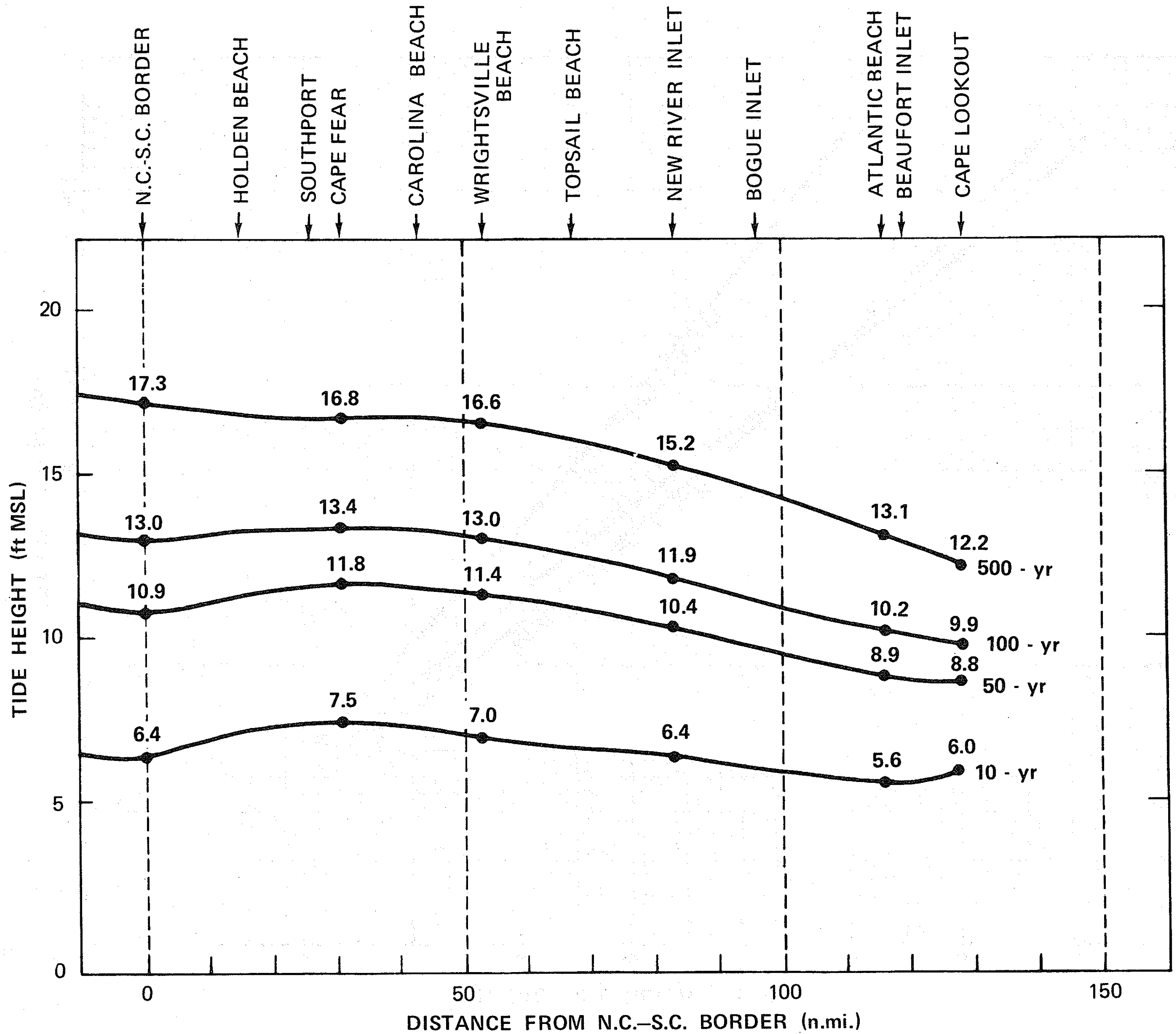

Figure 10.--Coastal tide frequencies. North Carolina, south of Cape Lookout.

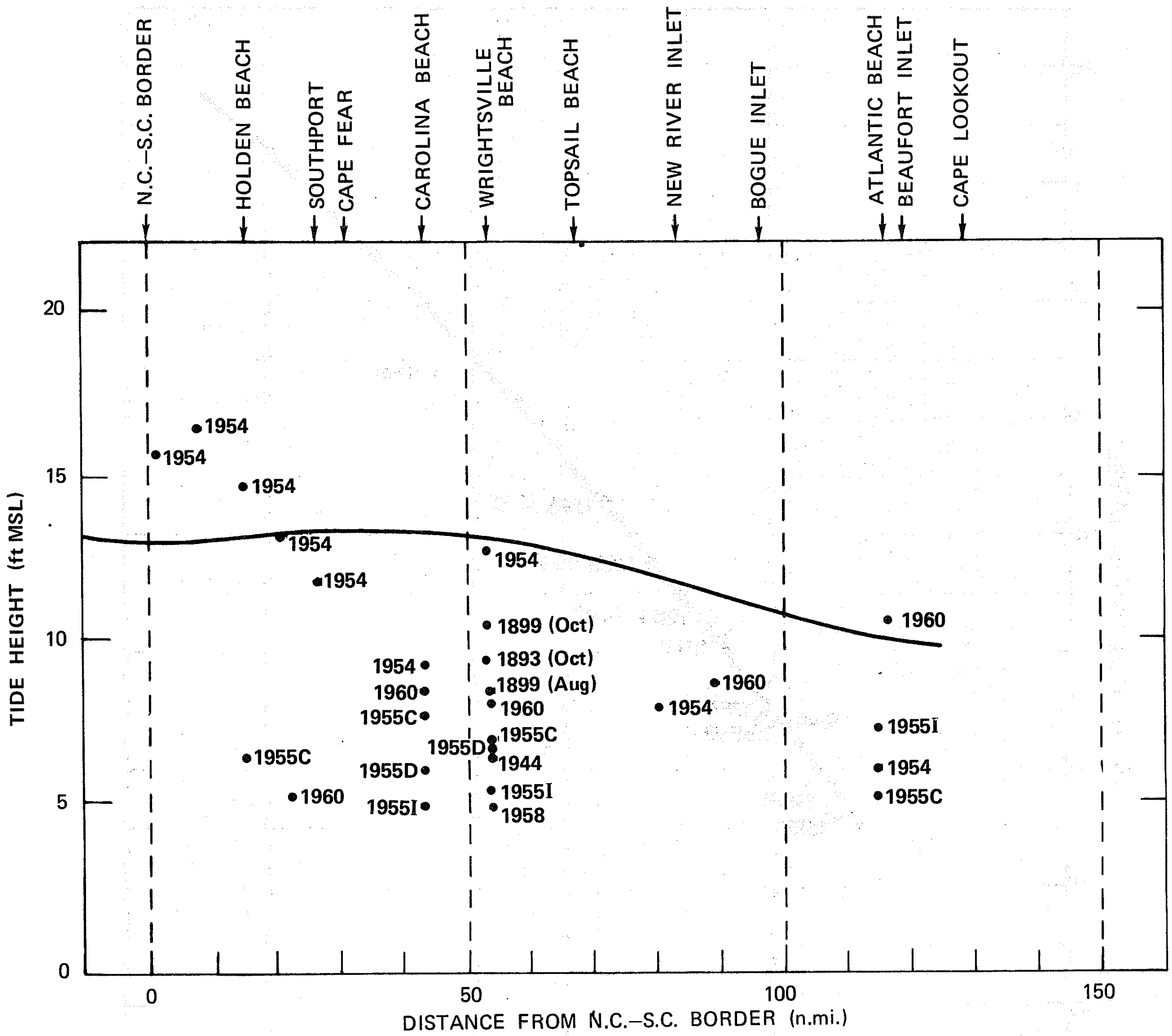

Figure 11.--Representative high-water marks compared with tide frequencies for the 100-yr return period.

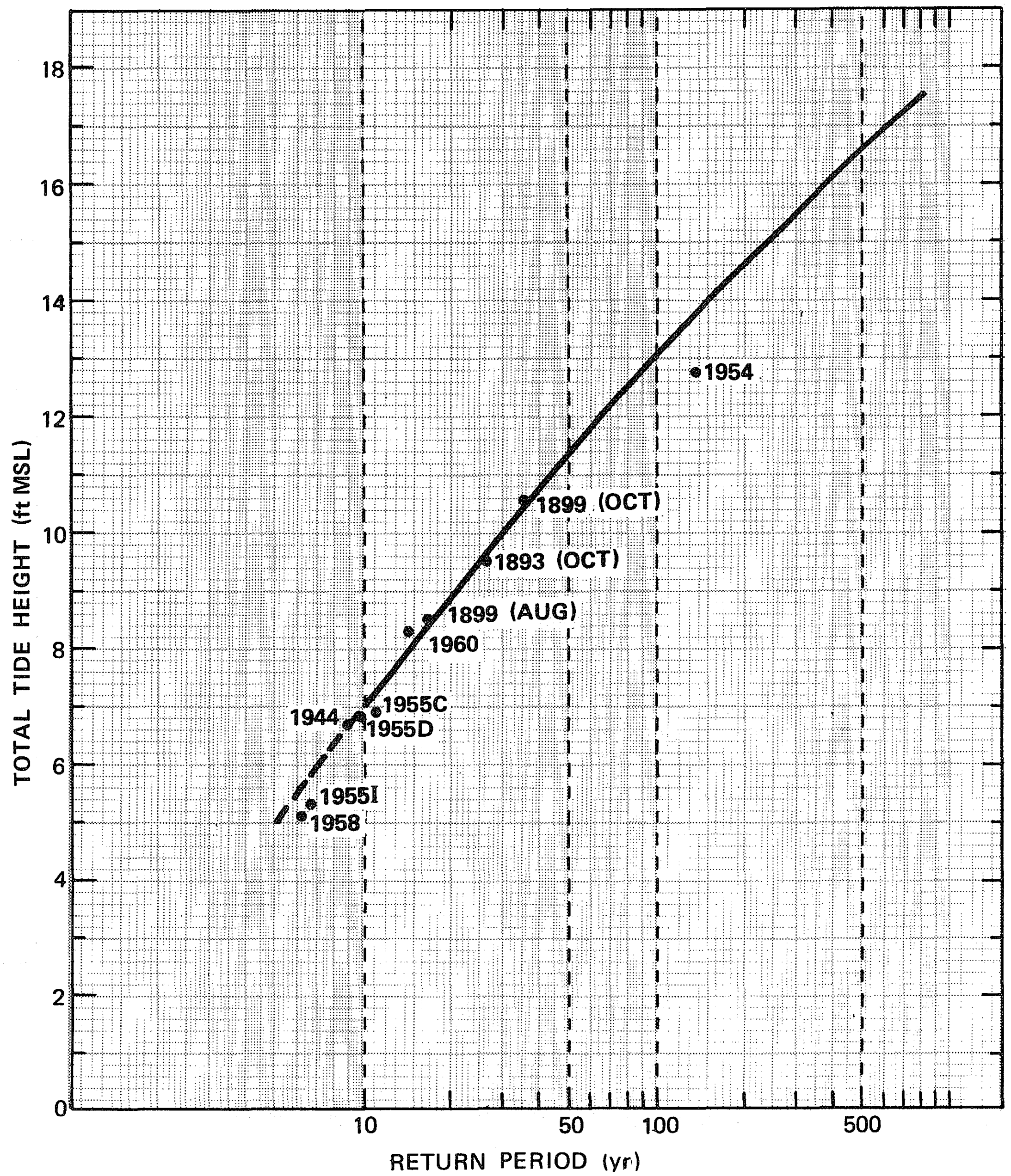

Figure 12.--Comparison of tide frequency curve and high-water marks at Wrightsville Beach, N.C.