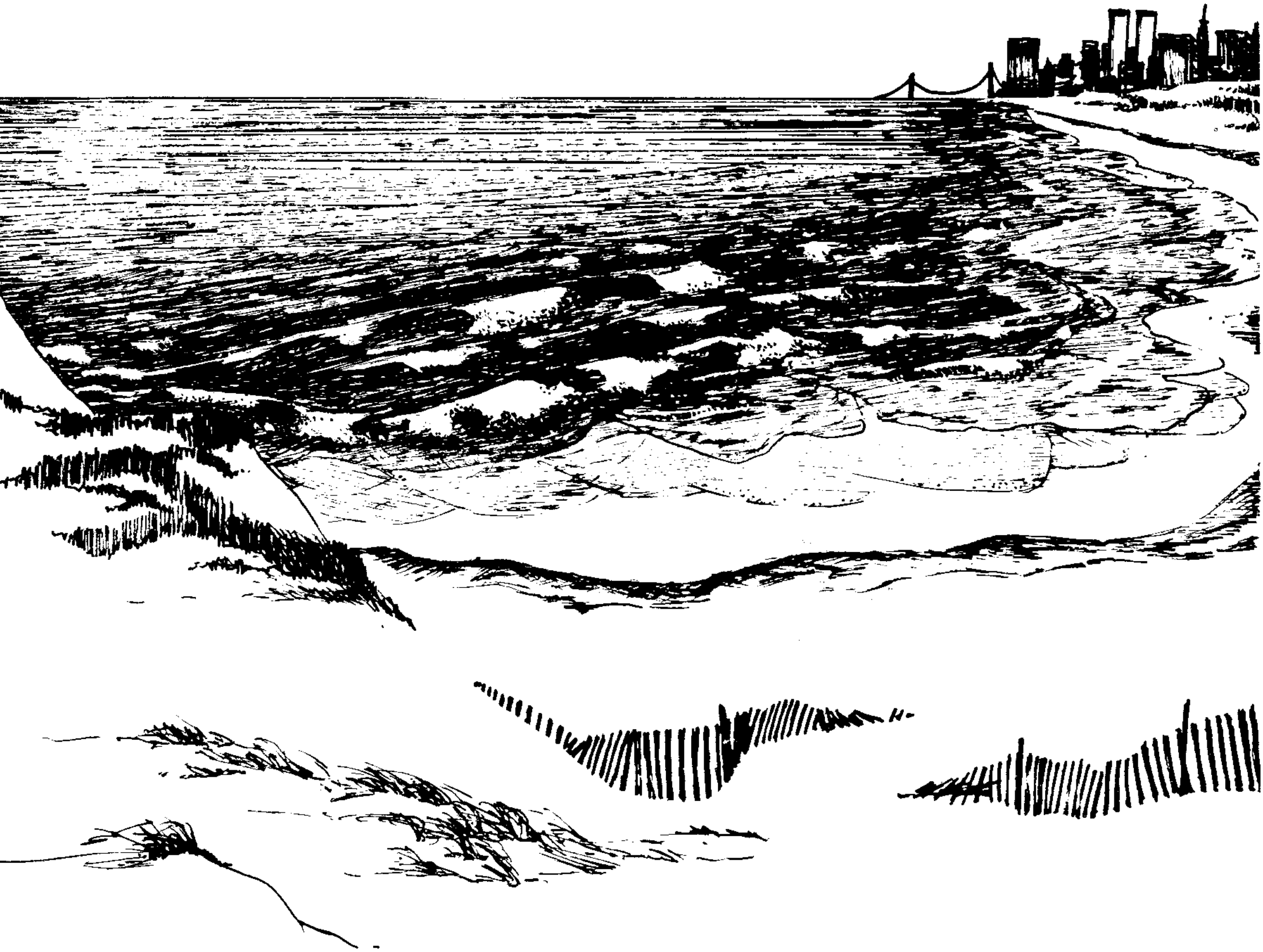
Storm Surge

N. Arthur Pore and Celso S. Barrientos



MESA NEW YORK BIGHT ATLAS MONOGRAPH 6

The offshore water in the bend of the Atlantic coastline from Long Island on one side to New Jersey on the other is known as New York Bight. This 15,000 square miles of the Atlantic coastal ocean reaches seaward to the edge of the continental shelf, 80 to 120 miles offshore. It's the front doorstep of New York City, one of the world's most intensively used coastal areas – for recreation, shipping, fishing and shellfishing, and for dumping sewage sludge, construction rubble, and industrial wastes. Its potential is being closely eyed for resources like sand and gravel – and oil and gas.

This is one of a series of technical monographs on the Bight, summarizing what is known and identifying what is unknown. Those making critical management decisions affecting the Bight region are acutely aware that they need more data than are now available on the complex interplay among processes in the Bight, and about the human impact on those processes. The monographs provide a jumping-off place for further research.

The series is a cooperative effort between the National Oceanic and Atmospheric Administration (NOAA) and the New York Sea Grant Institute. NOAA's Marine EcoSystems Analysis (MESA) program is responsible for identifying and measuring the impact of man on the marine environment and its resources. The Sea Grant Institute (of State University of New York and Cornell University, and an affiliate of NOAA's Sea Grant program) conducts a variety of research and educational activities on the sea and Great Lakes. Together, Sea Grant and MESA are preparing an atlas of New York Bight that will supply urgently needed environmental information to policy-makers, industries, educational institutions, and to interested people. The monographs, listed inside the back cover, are being integrated into this *Environmental Atlas of New York Bight.*

ATLAS MONOGRAPH 6 describes how destructive storm surges are born out of hurricanes and storms, flooding low-lying coastal areas. Damaging storms blow through the Bight area about once a year but no one place is particularly liable to storm surge effects; even with improving prediction methods storms have a way of surprising us with their paths and intensities. Of tropical storms like hurricanes, one in 2 years comes along the coast and one in 4.7 years actually crosses the coast. Knowing frequencies and heights of storm surges makes forecasting possible, to lessen property damage and personal injury and to inform builders of prospective coastal and offshore structures.

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Acknowledgments

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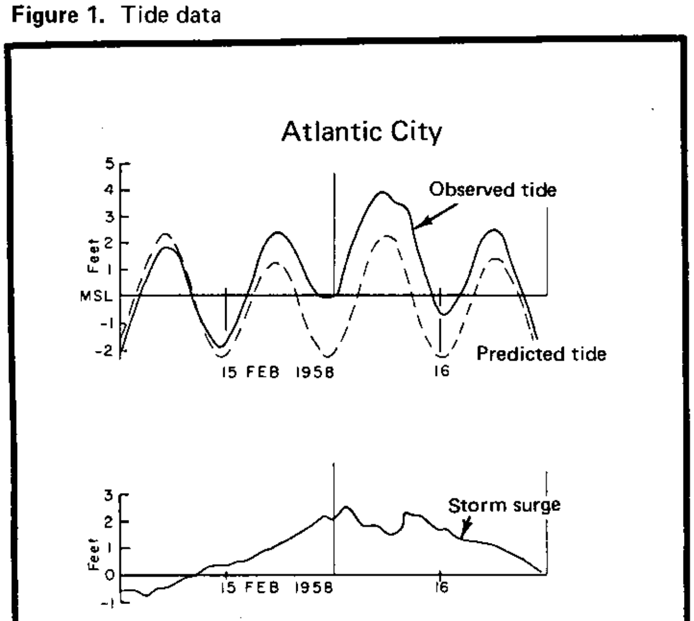
Abstract

Storm surges, which are departures of sea level from normal, are of great concern in the New York Bight area whenever hurricanes or extratropical storms approach or cross the coastline. During such storms, sea level can increase to more than 10 ft (3.1 m) above normal. Especially damaging to the Bight region were the hurricanes of September 1938 and September 1960 and the extratropical storms of November 1950 and March 1962. Factors significant in storm surge generation are direct wind, atmospheric pressure, water transport by waves, the earth's rotation, rainfall, and coastal configuration. Knowledge of the frequency and intensity of coastal storms likely to occur is important for protecting human life and property. The National Weather Service has developed a numerical model for forecasting hurricane storm surges and a statistical model for forecasting extratropical storm surges.

Introduction

Whenever a hurricane or intense extratropical storm approaches or crosses the New York Bight coastline, sea level rises, anywhere from a couple of feet to over 10 ft (3.1 m) above the normal tide. The departure of tide level from normal in such storms is called the *storm surge,* defined as the difference between the observed, actual sea level and the sea level that would have occurred in the absence of the storm. Storm surge is usually estimated by subtracting the normal or astronomic tide from the observed tide. This is illustrated in Figure 1, a two-day record for Atlantic City.

Figure 1. Tide data



Source: Pore 1974

Storm surge is one of the elements that earn hurricanes and extratropical storms their destructive reputation. *Hurricanes,* tropical cyclones with winds of 74 mph (64 knots) or greater, usually occur in late summer or early autumn. They form only over ocean areas where warm, moist air is available. This air flows into a counterclockwise circulation, ascends, and cools to the saturation point. The heat released in subsequent condensation is added to the storm as energy.

Extratropical storms occur mainly during winter months, developing along frontal zones separating major air masses of different origin. Most important are storms that form as waves along a polar front. Some become intense low-pressure systems causing severe coastal weather and storm surge conditions. The frontal system in such storms generally consists of a cold front in the rear of the storm, separating the polar air from the tropical air, and a warm front extending from the storm center through the forward part of the storm.

Major storms affecting the Bight region were the hurricanes of September 1938 and Setpember 1960 and the extratropical storms of November 1950 and March 1962.

Factors in Storm Surge Generation

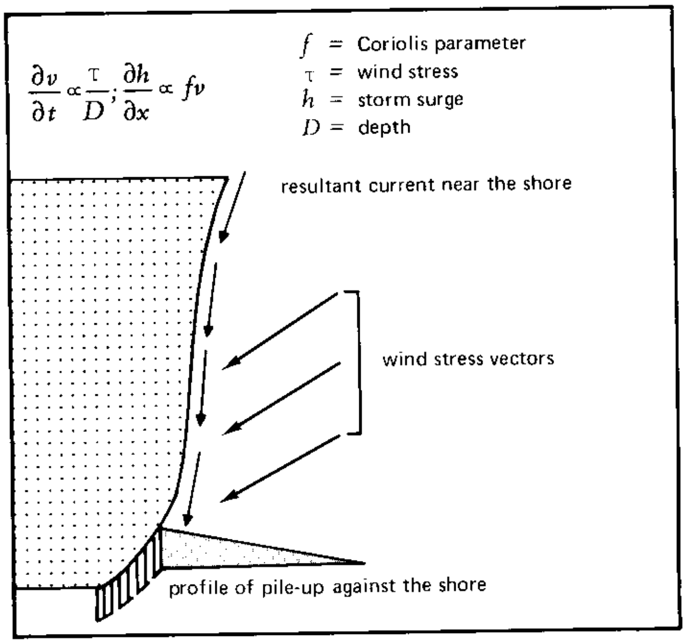
Storm surges result from a combination of processes or effects: direct wind, atmospheric pressure, water transport by waves and swell, the earth's rotation, rainfall, and coastline configuration and bathymetric conditions.

Direct Wind. Wind action that raises water levels consists of two components—onshore wind and the wind oblique to the shore. Figure 2 illustrates that the effect of the onshore wind is directly proportional to the wind stress and inversely proportional to the water depth. Figure 3 shows that the effect of wind oblique to the shore comes from the wind-generated current parallel to the shore.

Atmospheric Pressure. The rise of the surface of the ocean in an area of low atmospheric pressure has been called the *inverted barometer effect.* Sea level rises about one foot for an atmospheric pressure drop of one inch of mercury.

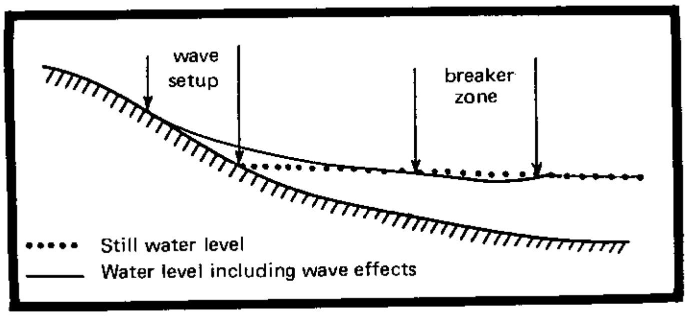
Water Transport by Waves and Swell. Theory and laboratory experiments indicate that waves breaking near the shore contribute to the storm surge. According to Harris (1963*a*), several investigators agree that the slope of the water surface near shore is directly proportional to the square of the wave height and inversely proportional to the water depth. Wave setup (Figure 4) is also affected by wave refraction—that is, wave setup is less than the theoretical value in areas of wave divergence and greater than the theoretical value in areas of wave convergence.

Figure 3. Effect of oblique wind on water level



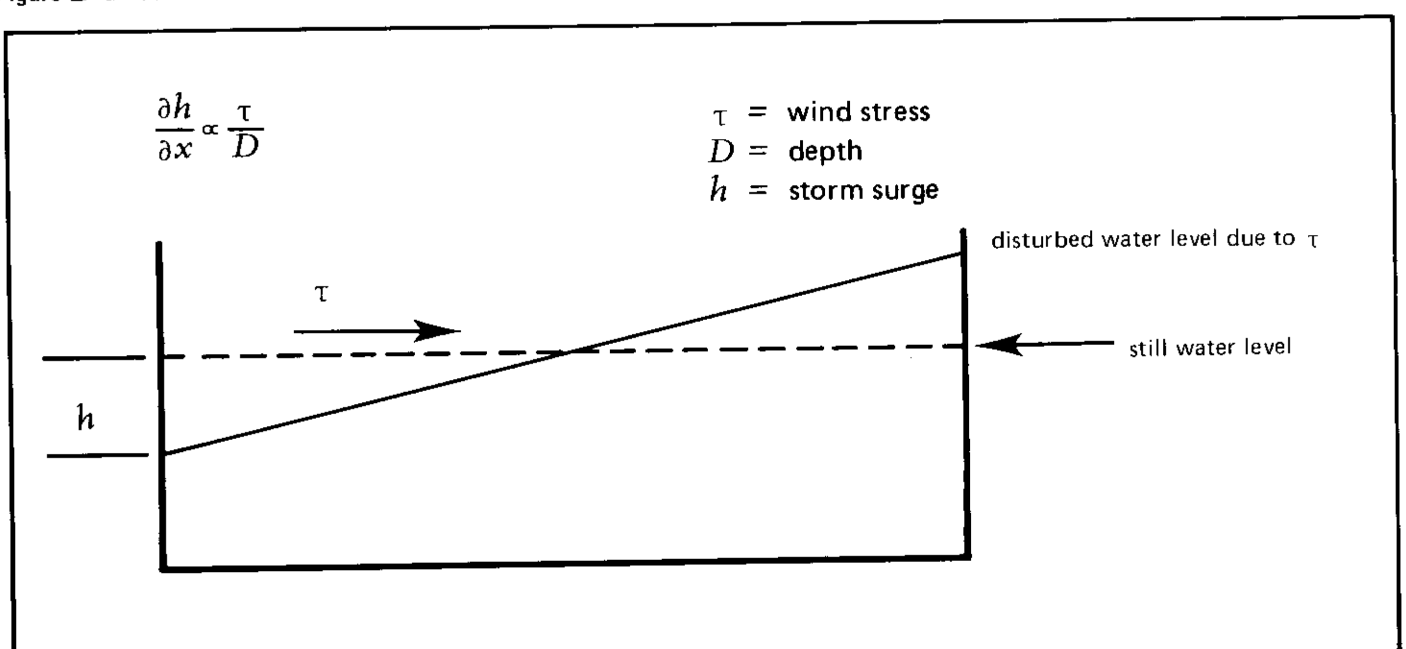
Source: Harris 1963*a*

Figure 4. Wave setup in vertical plane



Source: Harris 1963*a*

Figure 2. Effect of onshore wind on water level



Source: Harris 1963*a*

Table 1. Highest water levels recorded at several NOS tide gages

	Observation Period	Mean Tide Range		Highest Tide Level Above Mean High Water		Date of Record
		ft	m	ft	m	
Montauk, NY	1948-1970	2.1	0.6	6.6	2.0	31 August 1954
The Battery, NY	1920-1970	4.5	1.4	5.7	1.7	12 September 1960
Sandy Hook, NJ	1933-1970	4.6	1.4	5.7	1.7	12 September 1960
Atlantic City, NJ	1912-1920 and 1923-1970	4.1	1.3	5.2	1.6	14 September 1944
Breakwater Harbor, DE	1936-1970	4.1	1.3	5.4	1.6	6 March 1962

Source: US Army Corps of Engineers 1973

The Earth's Rotation. The earth's rotation produces an acceleration to the right in any current in the northern hemisphere. This deflection force (*Coriolis force*) depends on the speed of the current and the latitude. Wind parallel to a coast will generate a current in the same direction. The subsequent acceleration to the right results in water motion that can lead to an increase in water level. Northeast winds off the mid-Atlantic coast of the United States, for example, generate alongshore currents so that the deflection to the right contributes to increased sea level along the Bight shores. (It may be useful to know that winds are named by the direction they blow from, whereas water currents are called by the direction they flow toward.)

Rainfall. Hurricanes and extratropical storms may produce a great deal of rain over extensive areas, bringing floods that can increase sea level near the mouths of tidal estuaries.

Coastline Configuration and Bathymetric Conditions. The bottom topography near the shore has an extremely important effect on the height of the storm surge. Gently sloping bottom topography on the continental shelf—as in New York Bight—supports the generation of higher storm surges than does a steep continental shelf.

The configuration of the shore also affects the storm surge. For example, storm surge height increases in a bay with converging shorelines but decreases in a wide bay with only a narrow connection to the sea.

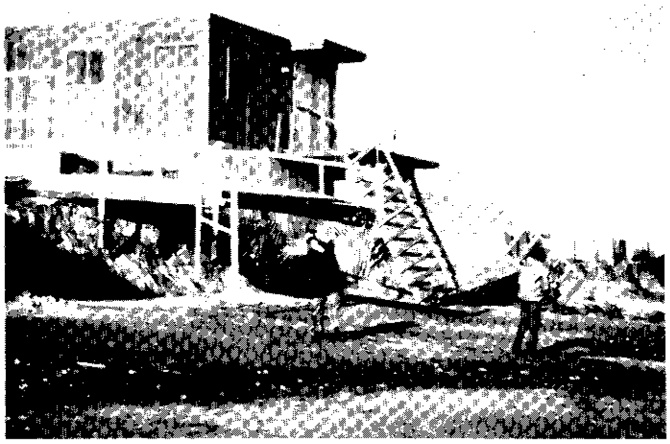
Extreme Water Levels

Table 1, based on National Ocean Survey (NOS) tide records, shows the extreme water levels recorded by several tide gages in the Bight area. The highest water level caused by a major storm is probably not recorded by a tide gage. Because the highest water level can occur almost anywhere along the coast, it will most likely occur someplace between the relatively widely spaced tide gages rather than exactly at a gage location. Also, tide gages often become inoperative during extremely high water conditions, especially when there are high wave conditions. Surveys made following major storms show much variability in high water elevations in a small area.

Extratropical Storm Surges

Descriptions of a few extratropical storms that have blown through the New York Bight region, and their storm surges, are presented in this section. Reports containing the available meteorological and oceanographic data are often published following major storms. Most of the extratropical storm surge data here are from a study by Pore, Richardson, and Perrotti (1974) on forecasting extratropical storm surges. The most intense storms affecting the Bight area in recent years, as well as several typical storms,

Figure 5. Damage to house at Westhampton Beach, NY, by 18-20 February 1972 storm. (Courtesy of US Army Crops of Engineers Coastal Engineering Research Center)



are described. The storms are presented in chronological order except for the 18-20 February 1972 storm, which is discussed first because graphs of its observed tide data and storm surge data help in visualizing how storm surge values are determined.

The 18-20 February 1972 coastal storm caused extremely high tides, plus extensive damage and beach erosion along the northern US Atlantic coast (Figures 5 and 6). The front of a low-pressure system centered over the Great Lakes at 0700 EST on 18 February extended southward over eastern Tennessee, Georgia, Alabama, and into the Gulf of Mexico. Subsequent developments, as depicted on surface weather charts, are shown in Figure 7. By 1300 EST on 18 February a closed low had formed over Georgia. Further deepening occurred and the storm moved rapidly toward the north-northeast to just north of Cape Cod on 0100 EST on 20 February.

Figure 6. Undermined concrete slab parking lot at Jones Beach, NY, from 18-20 February 1972 storm. (Courtesy of US Army Crops of Engineers Coastal Engineering Research Center)

Hourly values of the observed tide, obtained from NOS, were used to prepare the upper graph in Figure 8 for five locations from Montauk Point, NY, to Breakwater Harbor near Cape Henlopen, DE. The semidiurnal nature of the tide—two highs and two lows daily—is evident.

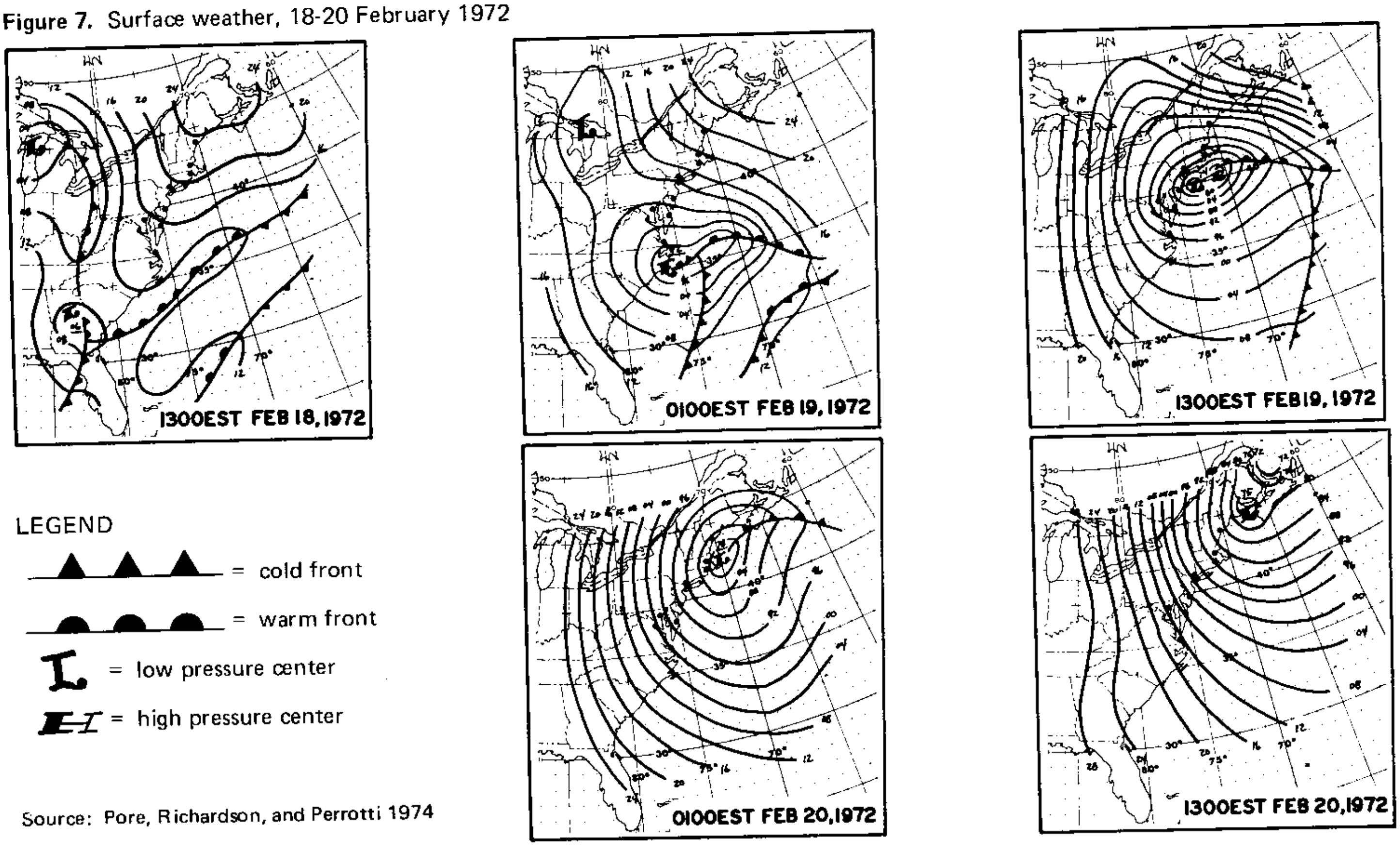
On 17 February tides at the five stations were running about normal. The effect of the storm is most noticeable in the tide curves for 19 February, when the tides were higher and more irregular. On the twentieth, when strong offshore winds began, the tides were lower than normal. The storm surge curves in the lower graph of Figure 8 were obtained by subtracting hourly values of normal tide from the observed tide. Storm surge curves show the effect of storms on sea level better than tide curves do. Only curves of storm surge will be presented for storms discussed later.

Timing of storm surge with respect to normal tide phases is extremely important. In the Bight area, the maximum storm surge occurred near noon on the nineteenth, which happened to be near the time of normal high tide. If the maximum surge had occurred at normal low tide, the actual water level would have been much lower. The situation could have been worse, however, if the surge had occurred on either the previous or the following high tide. Usually the two daily high tides are not of equal height, and in this storm the surge occurred on the lower of the high tides for that day. Actual water level would have been from 0.5 to 1.0 ft (0.2 to 0.3 m) higher if the surge had coincided with the higher high tide.

The 25-26 November 1950 storm, considered by some meteorologists to be the worst on record for the eastern United States (Smith 1950; Bristor 1951), caused severe cold, heavy rain, deep snow, destructive ice accretion, high winds, and extremely high storm surges along the northeast coast. The storm occurred near the time of spring tide—the highest of the monthly cycle; full moon was on 24 November.

Figure 9 shows six surface weather patterns from 0130 EST 24 November to 1330 EST 26 November. The storm first appeared on the chart for 0730 EST 24 November as a low on a cold front over North Carolina and Virginia. The low deepened considerably before a new low formation became evident near Erie, PA, at 1030 EST 25 November (Smith 1950). This new center became the main storm and at 1930 EST 25 November was near Cleveland, OH, with a central pressure of 983 millibars (mb). The lowest pressure, 978 mb, was

Figure 7. Surface weather, 18-20 February 1972



Source: Pore, Richardson, and Perrotti 1974

Figure 8. Track, observed tide curves, and storm surge curves for 17-21 February 1972. Zero on vertical scale of observed tide curve is mean sea level.

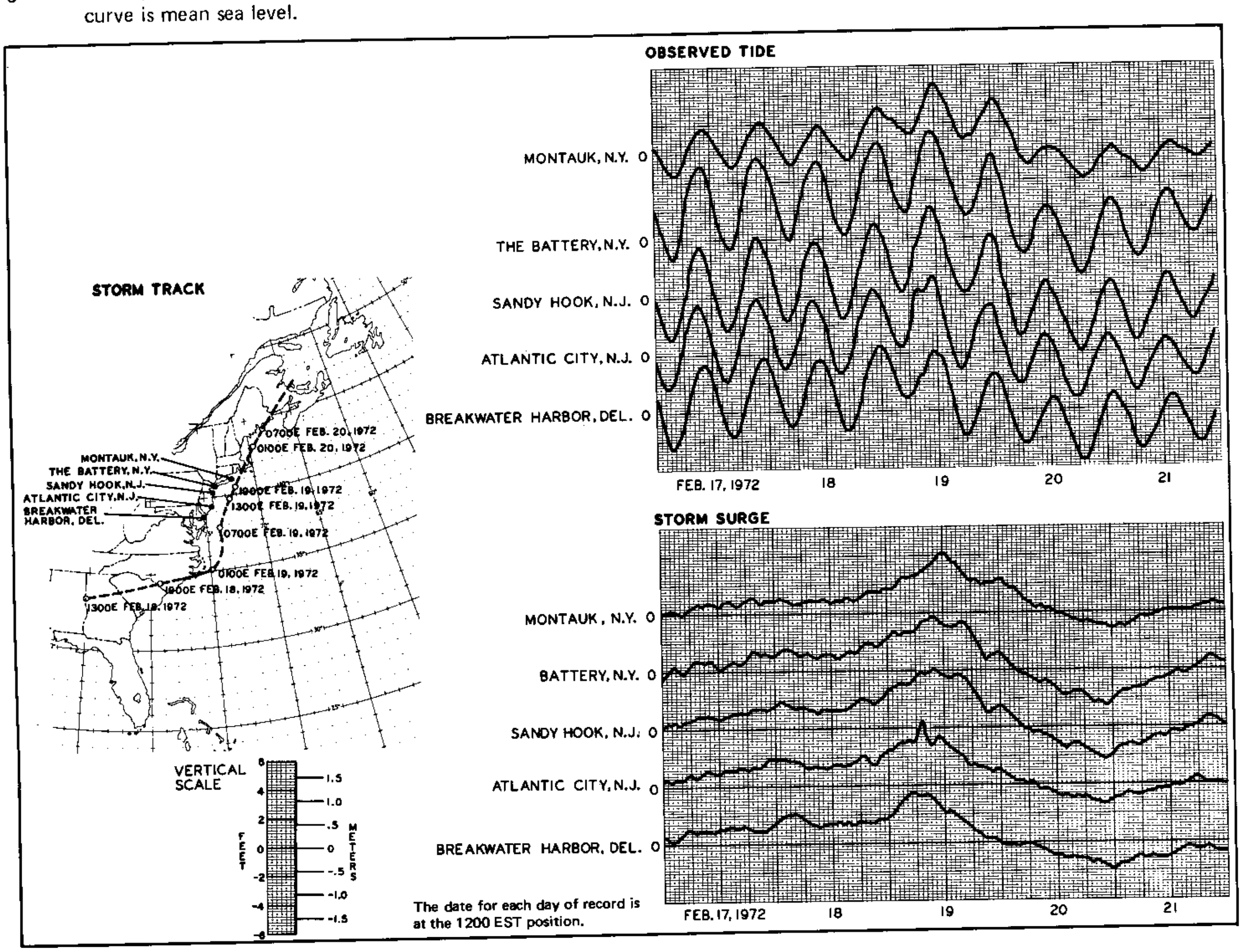
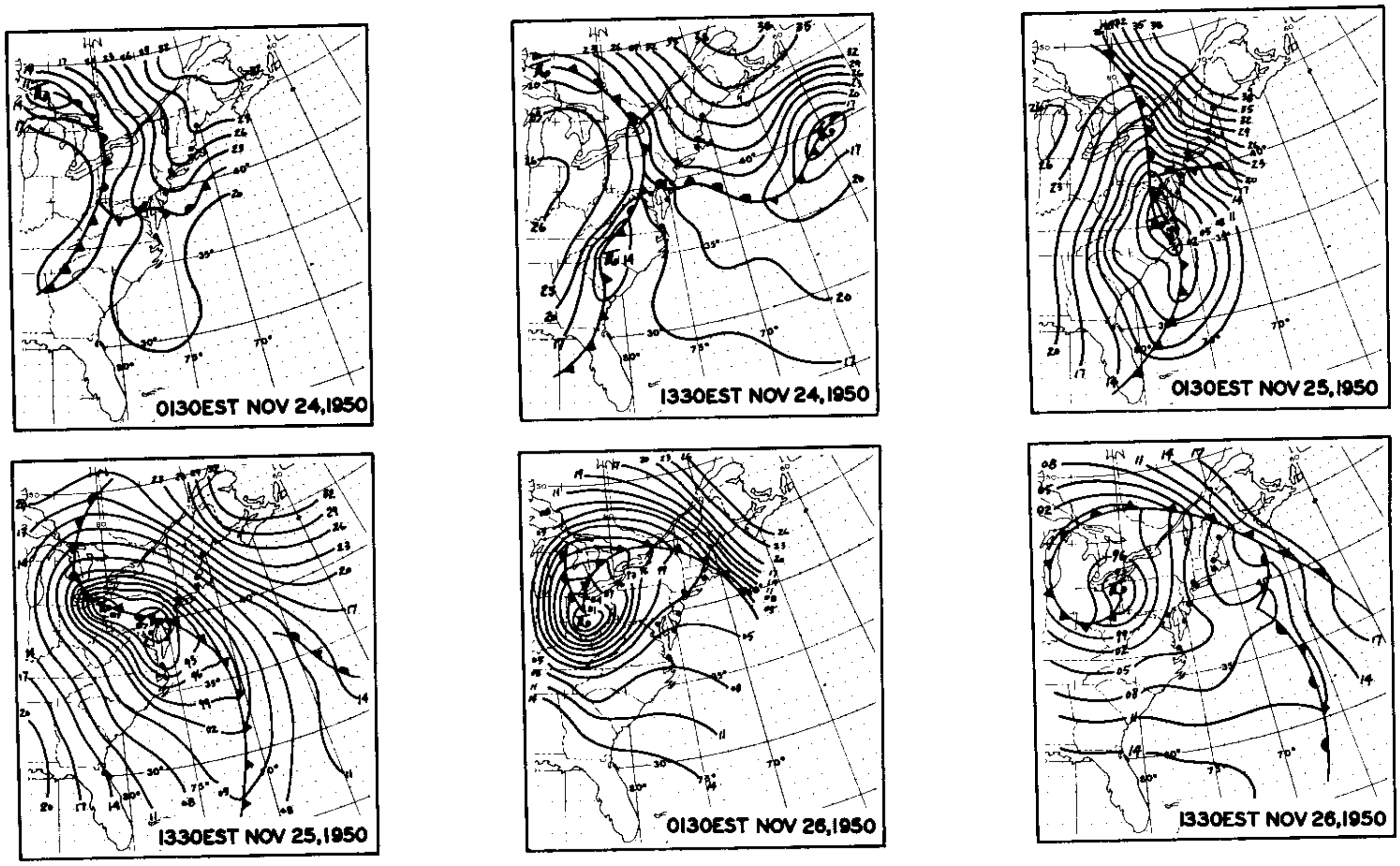
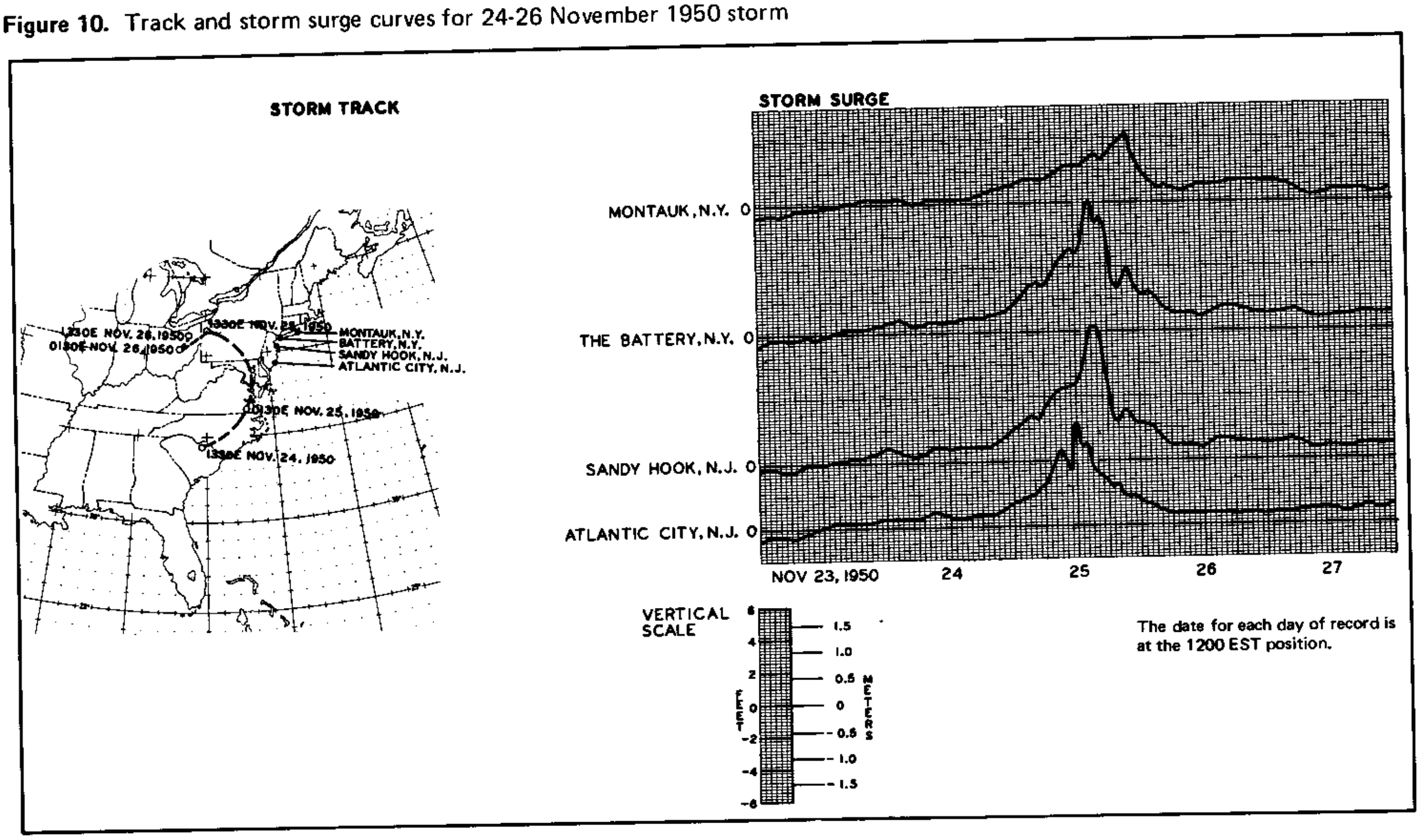


Figure 9. Surface weather, 24-26 November 1950



Source: Pore, Richardson, and Perrotti 1974

Figure 10. Track and storm surge curves for 24-26 November 1950 storm



reached at 0130 EST 26 November. The storm subsequently moved northward.

This was an unusual storm because the strong winds were easterly and southeasterly, whereas extratropical storms (commonly called *northeasters*) ordinarily cause northeast winds in the area. The surface weather charts indicate the long fetch (note the storm's elongated shape in Figure 9) important in storm surge generation. The situation was complicated by a moving frontal system over the coastal area. For example, the wind at La Guardia Airport shifted from east-southeast to south-southwest with the frontal passage around 1800 EST on 25 November.

The storm surge curves in Figure 10 show considerable oscillation near the time of maximum surge. This is probably an interaction effect: the speed of the astronomic tide varies with changing water depth caused by the storm surge. The maximum storm surge was 8.1 ft (2.5 m) at The Battery in New York City. The highest actual water levels at The Battery occurred about six hours before the highest surge, near the time of high astronomic tide. According to an index of tide gage records by Harris and Lindsay (1957), during this storm new high tide records were established at many locations along the Bight's coast.

The 6-7 November 1953 storm caused strong onshore coastal winds with speeds approaching those of the famous 1950 storm. A low had formed in the northeastern Gulf of Mexico. It moved to just off the Georgia–Florida coast by 0130 EST on the sixth, to the Cape Hatteras area by 1330 EST on the sixth, and to the Delaware area by 0130 EST on the seventh (Figure 11). The storm crossed Long Island and was over New York State at 1330 EST on the seventh. A pressure gradient between the storm's low pressure and a strong high over the Great Lakes brought on extremely high winds north of the storm center. These winds caused high storm surges with considerable flooding and flood damage along the mid-Atlantic and New England coasts. Atlantic city had a fastest mile* wind of 69 mph (60 knots). The storm surge curves are shown in Figure 12; the peak surge at The Battery was 5.4 ft (1.6 m).

The 8-9 March 1957 storm closely followed the coast north of Cape Hatteras (Figure 13) and caused moderate storm surges. Peak storm surge values of 2.2 ft (0.7 m) were computed for The Battery and Atlantic City (Figure 14).

The waves and storm tides generated by **the 5-8 March 1962** storm caused an unprecedented $200 million damage to coastal areas from southern New England to Florida. Two contributing factors were that winds blew over an extremely long fetch and that the storm occurred at a time of very high astronomic tide. Articles by Stewart (1962) and Cooperman and Rosendal (1962) give details of the storm.

At 7 am EST on 5 March there was an ill-defined low-pressure area with a frontal wave northeast of the Bahamas. Low pressure also extended northwestward through the Carolinas and Virginia (Figure 15). By 7 am EST on the sixth the entire low-pressure area had deepened, resulting in a long easterly fetch over the western Atlantic north of Cape Hatteras. The storm continued to intensify into an elongated low with a strong northeast wind over a very long fetch.

That a storm of such magnitude with a long northeasterly fetch would coincide with spring tide was a rare and disastrous circumstance. Not only did the storm occur at spring tide but at the time of the moon's perigee—when the moon is nearest to the earth. Perigee spring tide is close to maximum astronomic tide.

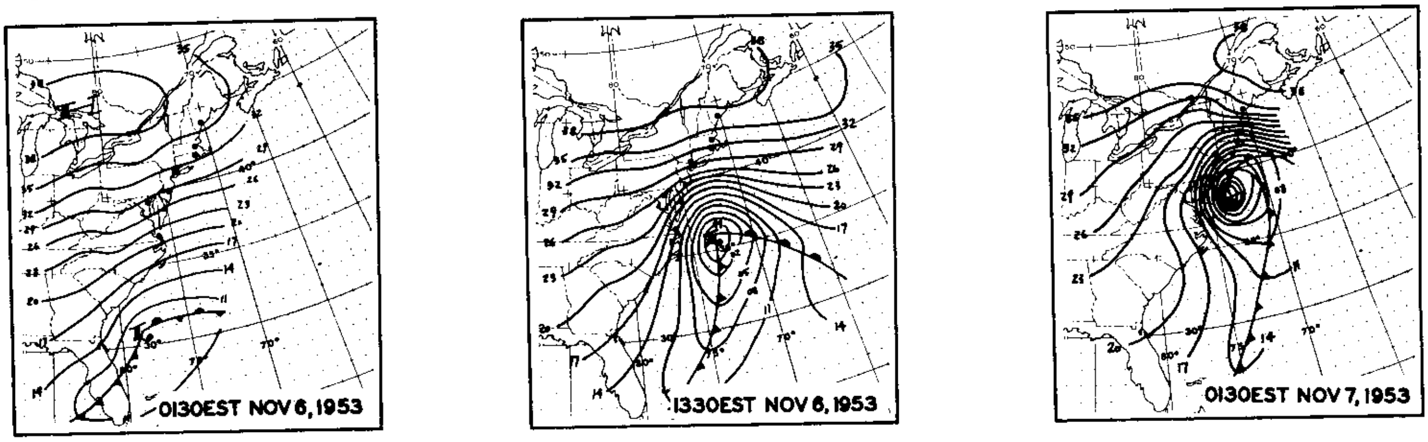
Several agencies—the US Geological Survey, the Corps of Engineers, and the Coast and Geodetic Survey (now NOS)—collected observations of high water marks after this storm. Many are shown in Map 1. Variations in maximum water levels of 2 to 4 ft (0.6 to 1.2 m) were found within a distance of half a mile (Harris 1963*a*). This was the first extratropical storm in which high water marks were observed sufficiently close together to show this variation.

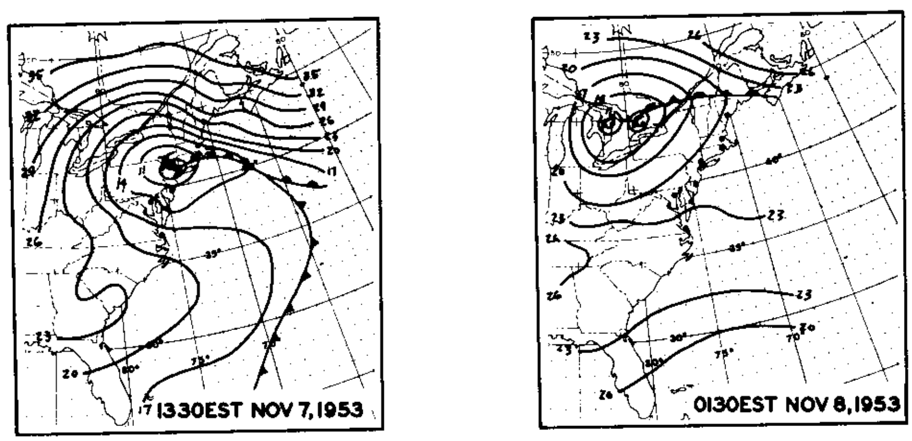
Storm surge curves are shown in Figure 16. Maximum storm surge values were high; 6.3 ft (1.9 m) was observed at Breakwater Harbor, DE. Since the surge stayed high through about five tide cycles, the timing of high or low tide phases made very little difference in this storm.

The 23-24 January 1966 storm resulted in high tides that caused considerable damage along the northeast coast. The low developed in the eastern Gulf of Mexico, moved northeast, and was near Cape Hatteras at 0100 EST 23 January (Figure 17). It subsequently moved northeast away from the coast. Storm surge graphs for Bight stations are shown in Figure 18.

*Fastest mile of wind is the fastest speed in miles per hour of any "mile" of wind over a specified period, usually the 24-hr observational day.

Figure 11. Surface weather, 6-8 November 1953





Source: Pore, Richardson, and Perrotti 1974

Figure 12. Track and storm surge curves for 6-7 November 1953 storm

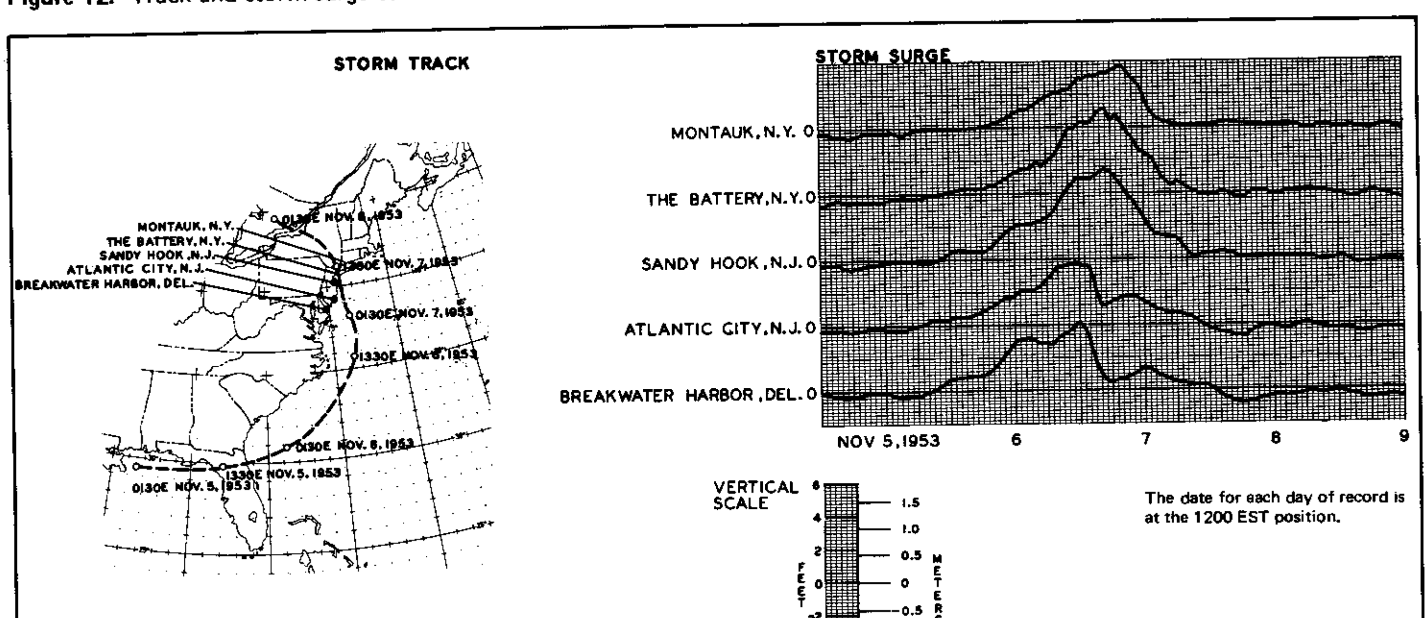
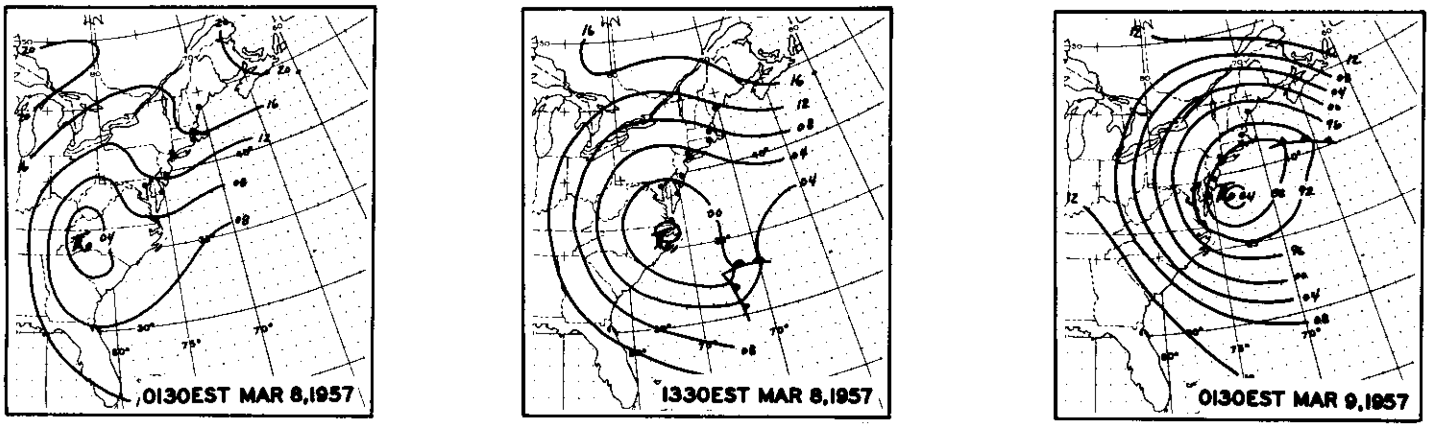
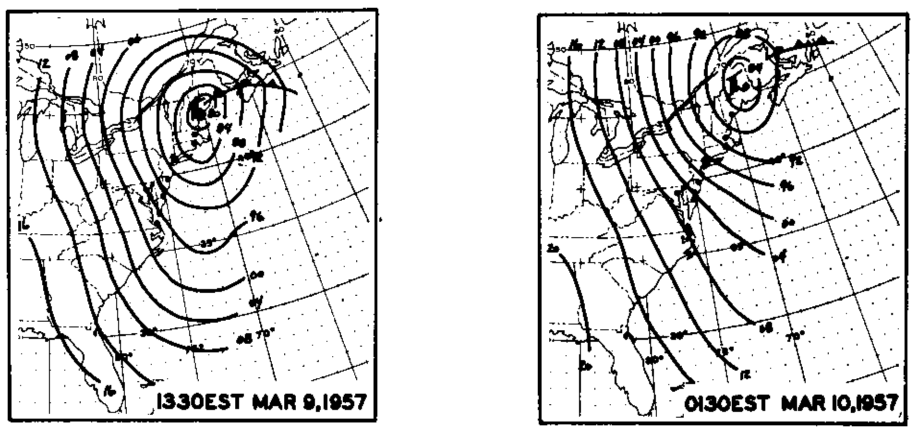


Figure 13. Surface weather, 8-10 March 1957





Source: Pore, Richardson, and Perrotti 1974

Figure 14. Track and storm surge curves for 8-9 March 1957 storm

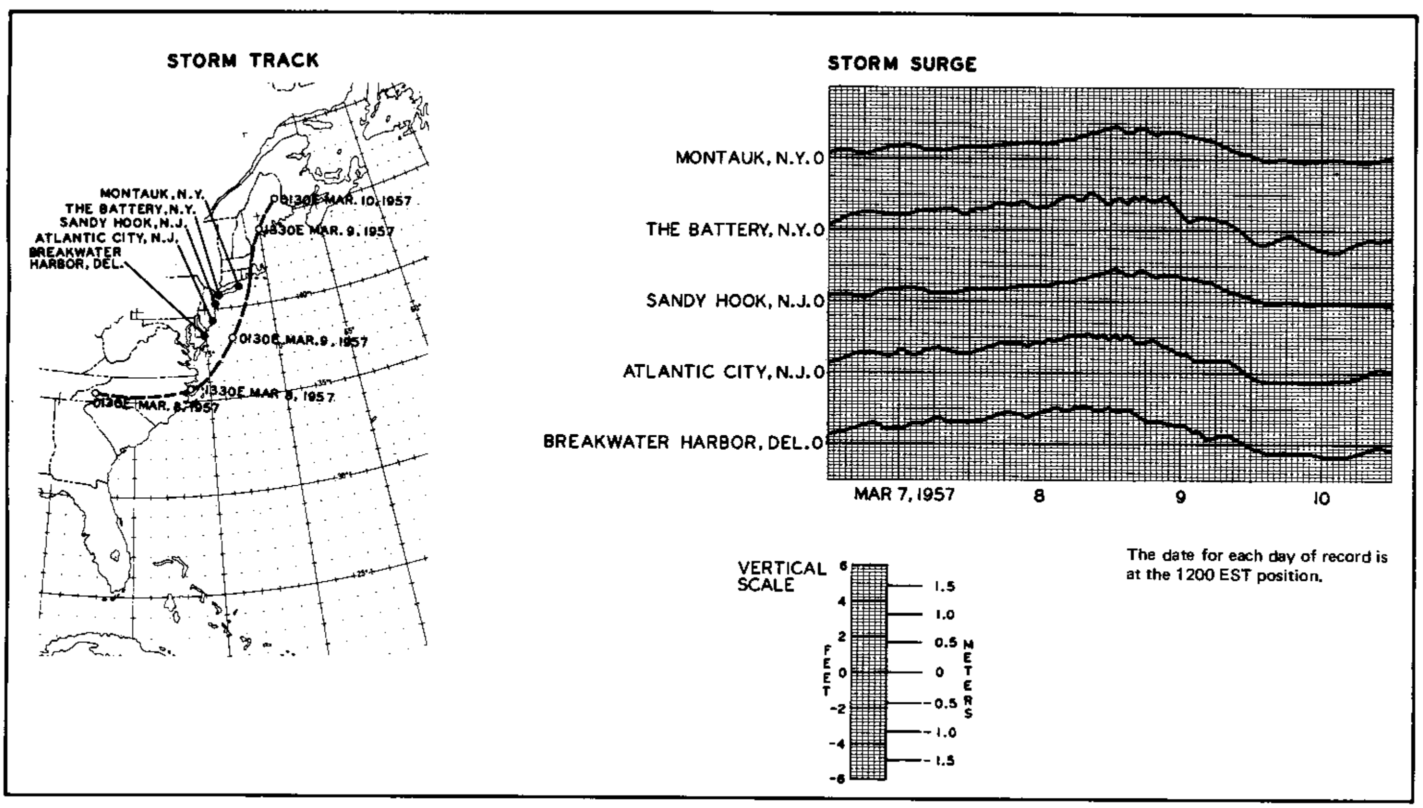
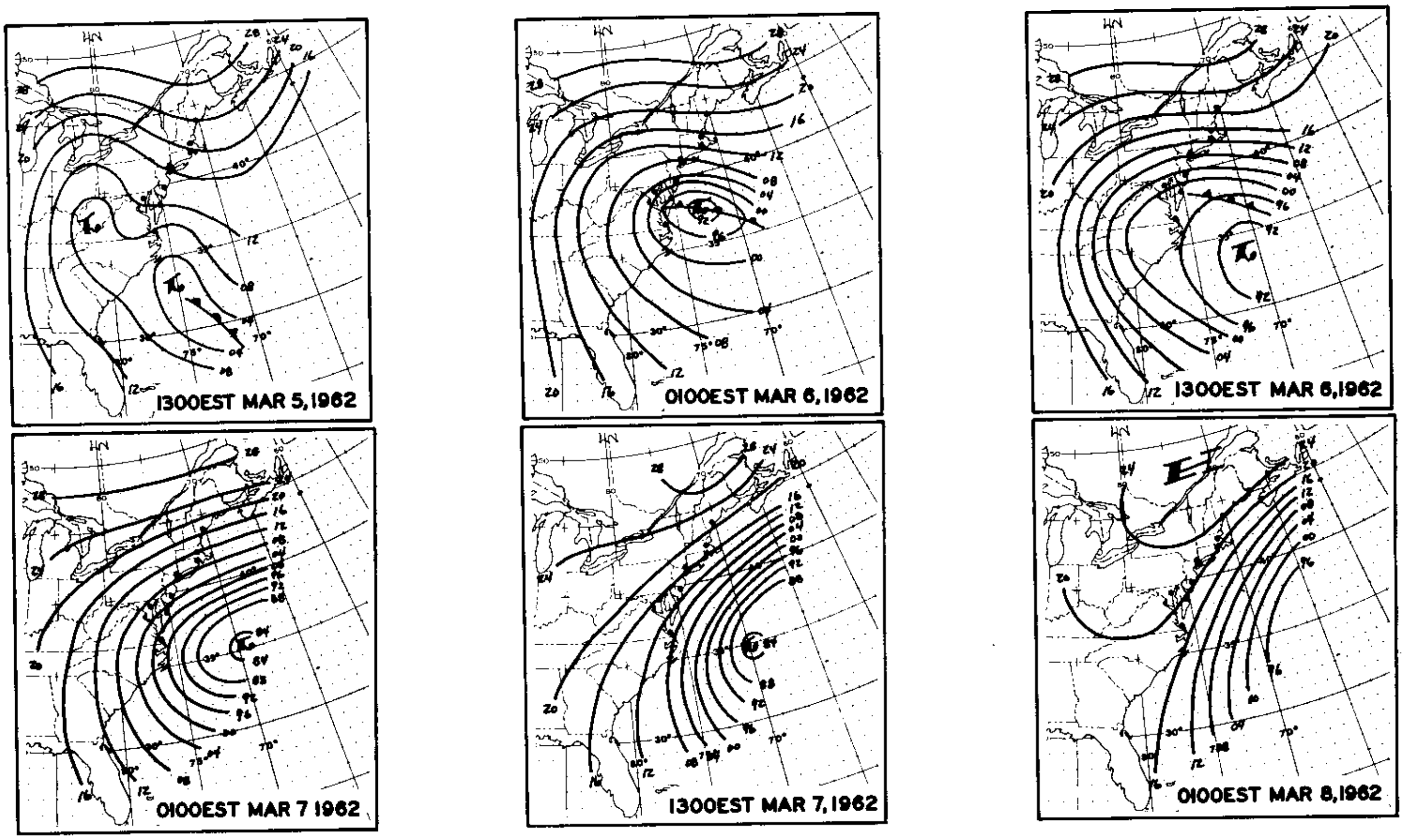
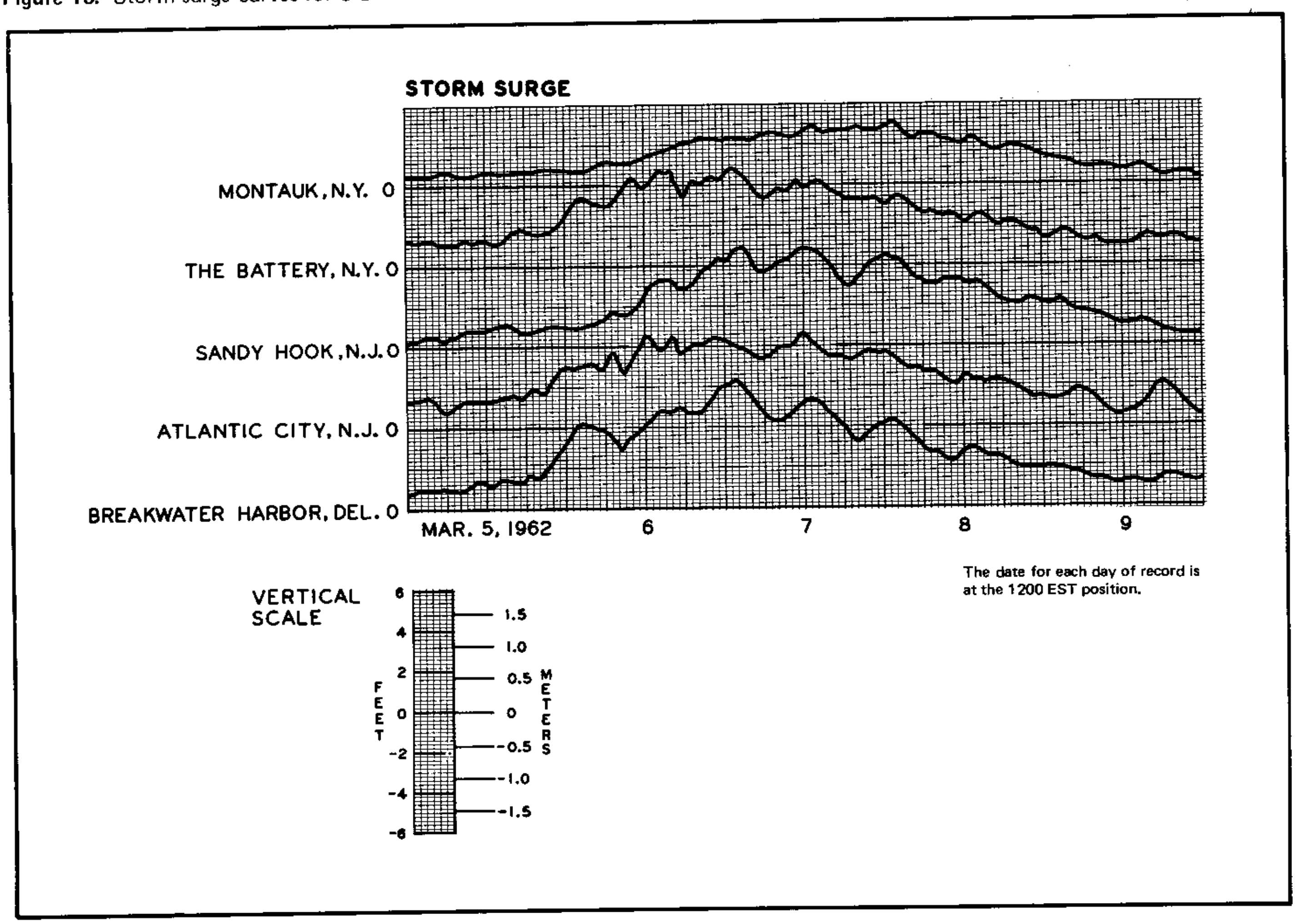


Figure 15. Surface weather, 5-8 March 1962

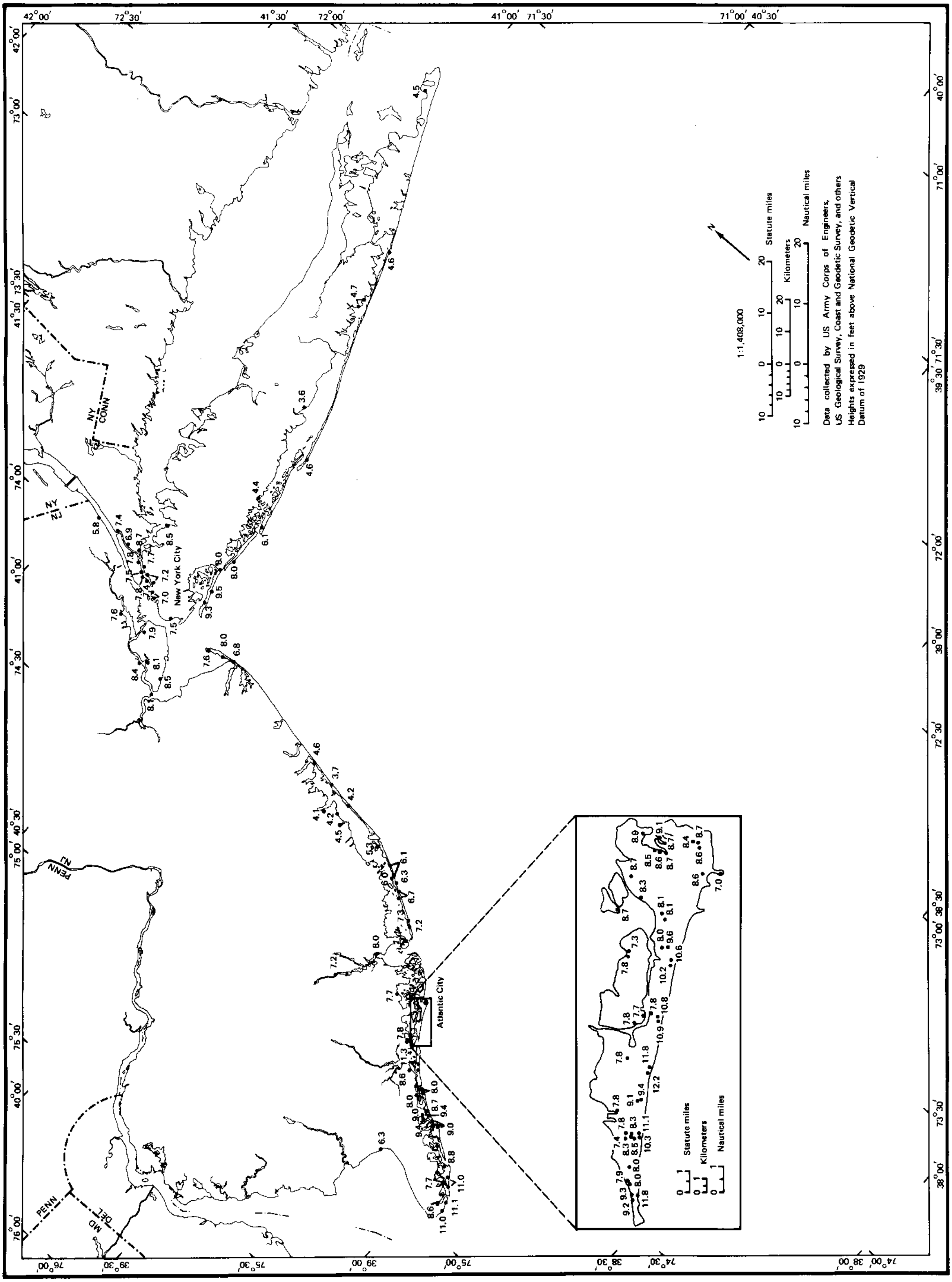


Source: Pore, Richardson, and Perrotti 1974

Figure 16. Storm surge curves for 5-8 March 1962 storm

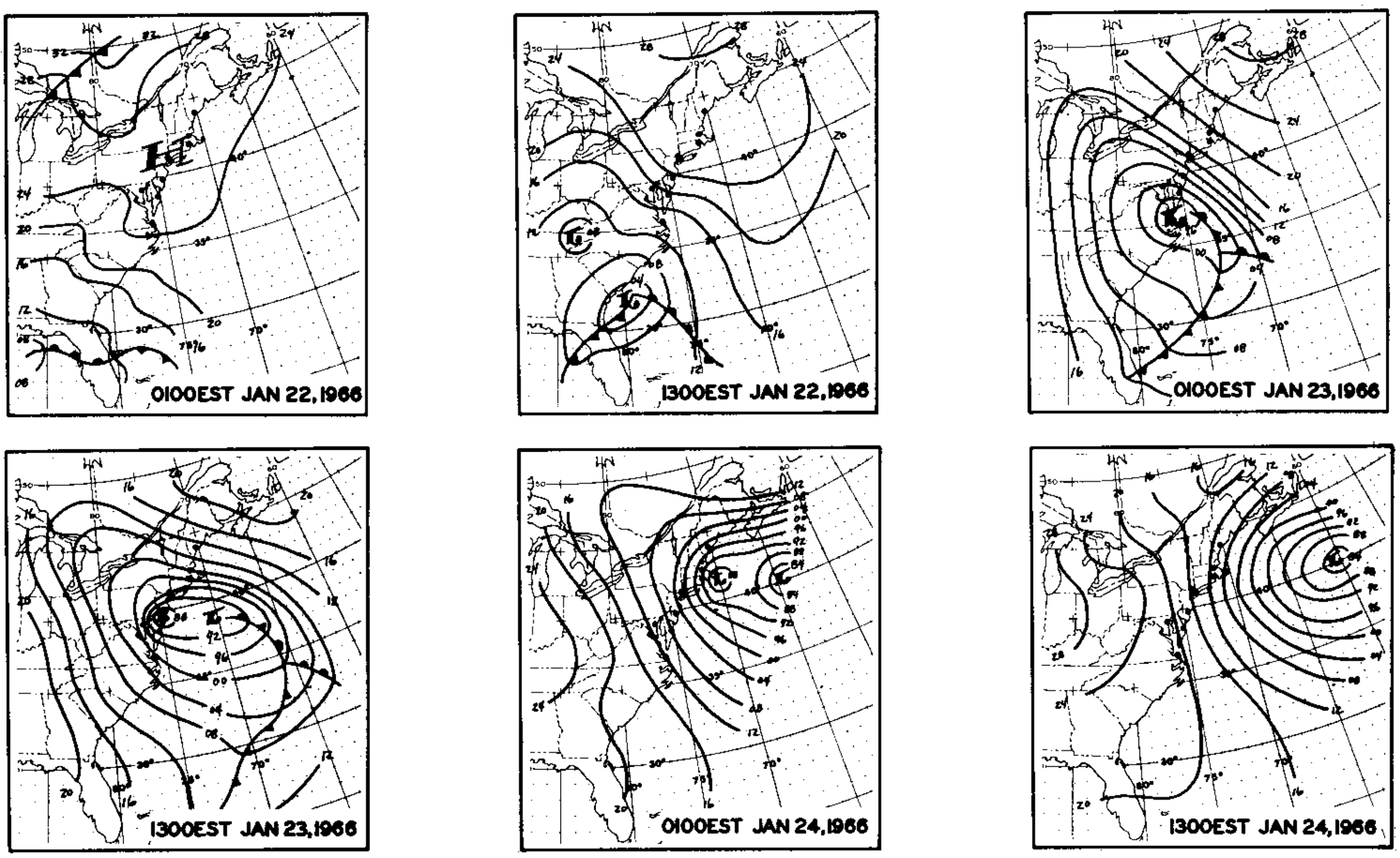


Map 1. High water marks, March 1962 storm



Source: Harris 1963a

Figure 17. Surface weather, 23-24 January 1966



Source: Pore, Richardson, and Perrotti 1974

Figure 18. Track and storm surge curves for 23-24 January 1966 storm

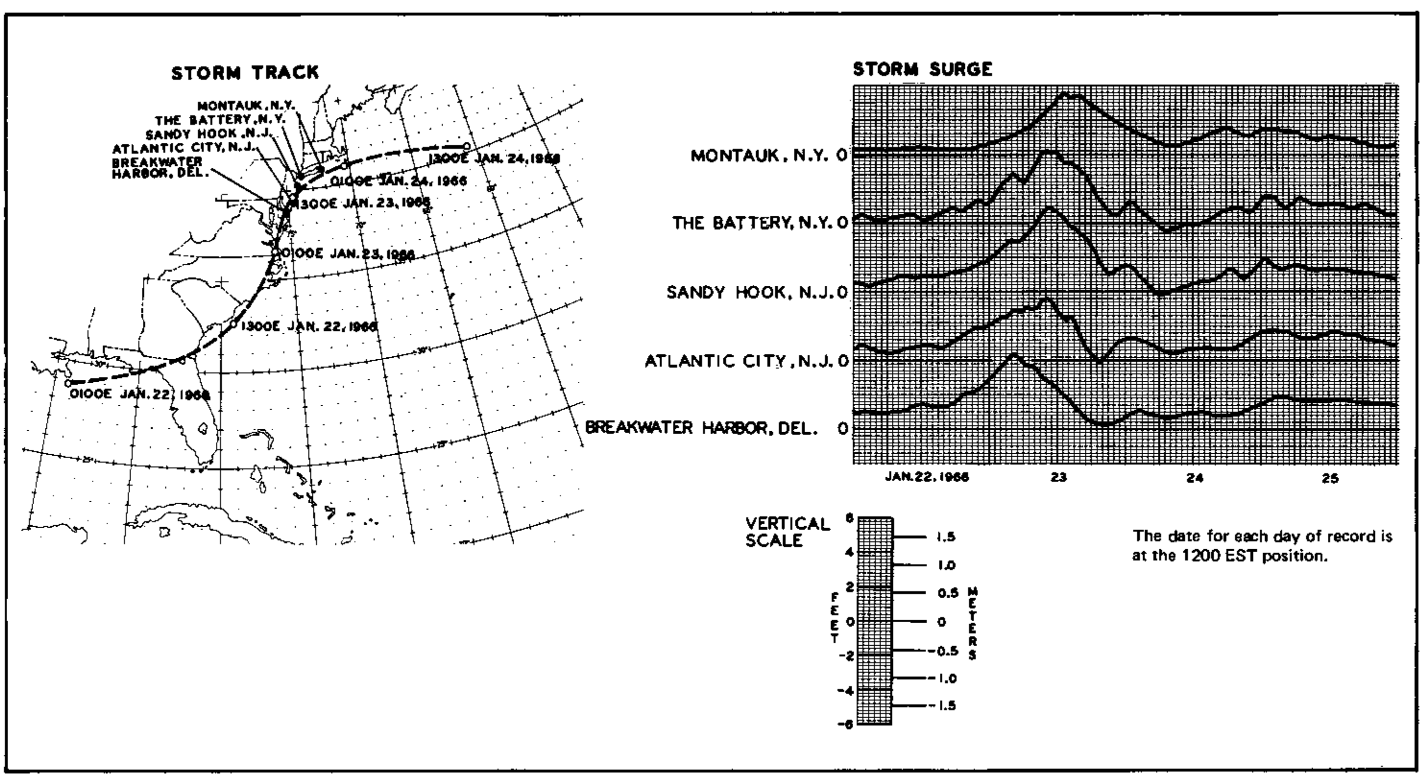
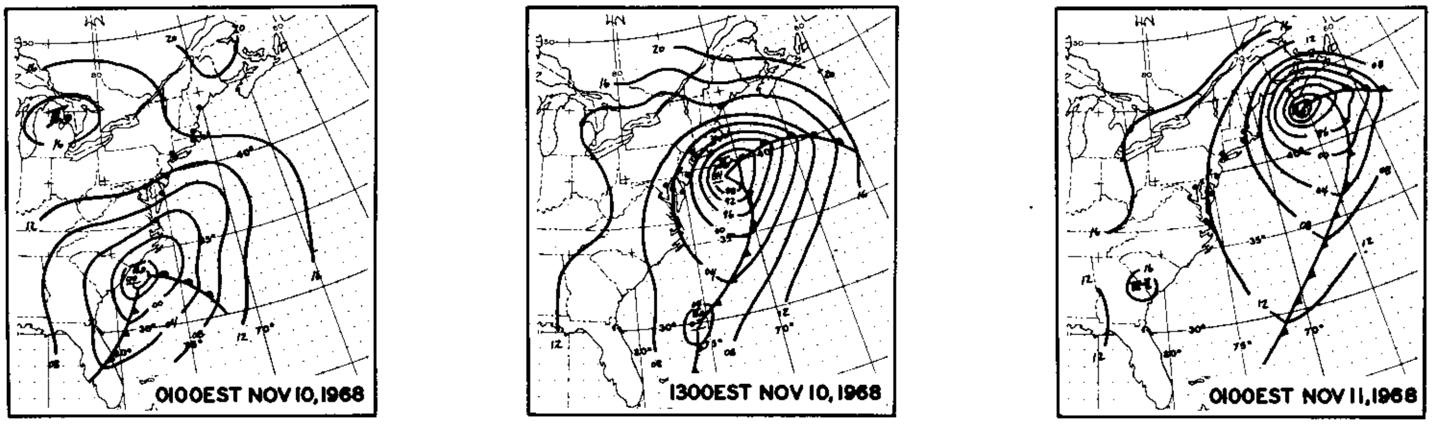
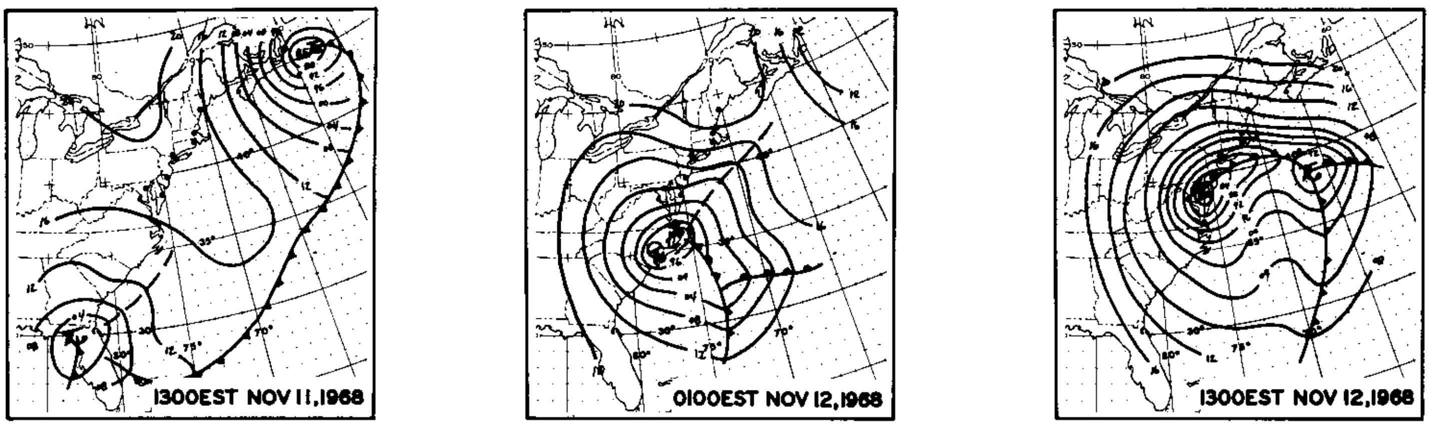


Figure 19. Surface weather, 10-11 November 1968



Source: Pore, Richardson, and Perrotti 1974

Figure 20. Surface weather, 11-12 November 1968



Source: Pore, Richardson, and Perrotti 1974

Figure 21. Tracks and storm surge curves for 10 and 12 November 1968 storms

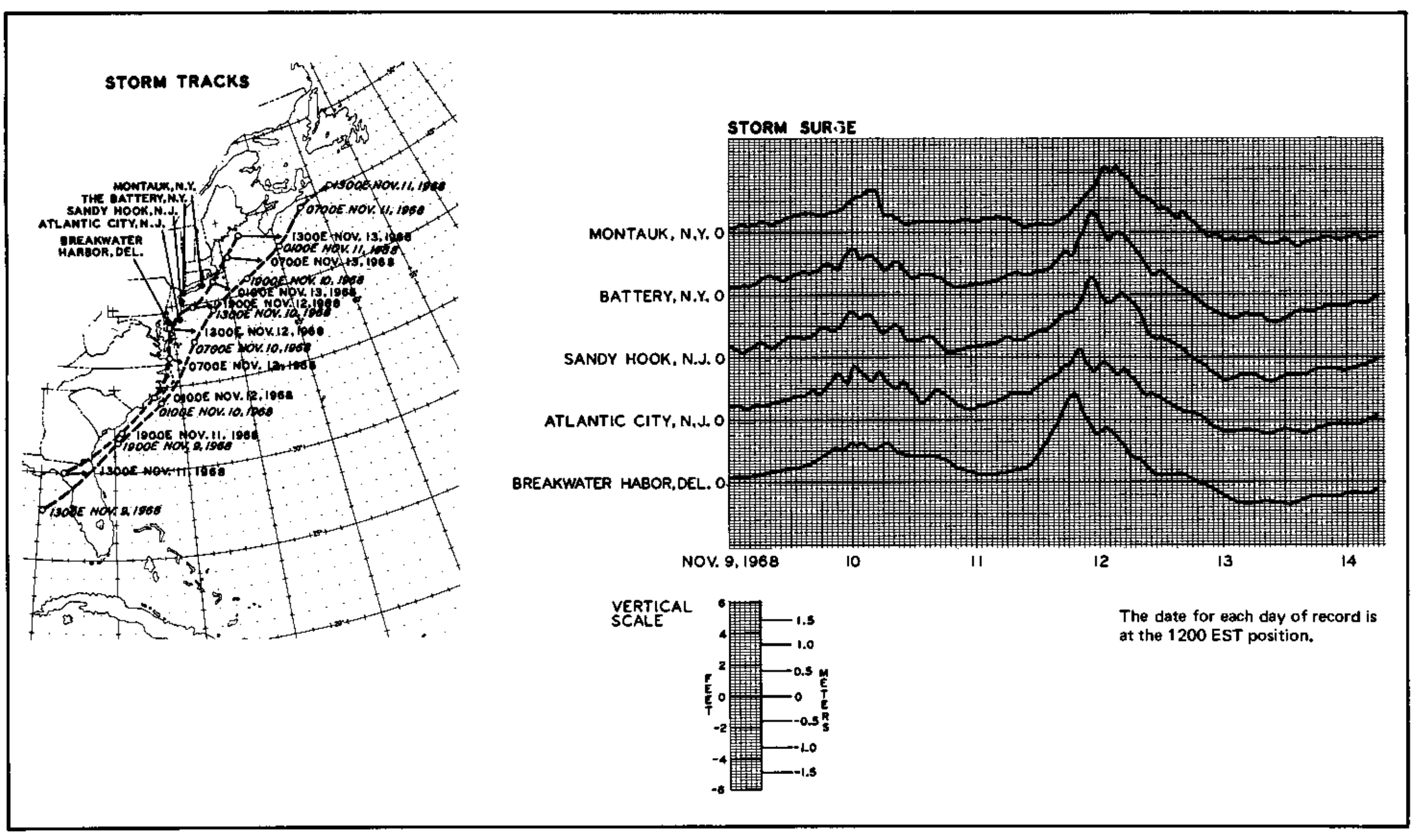
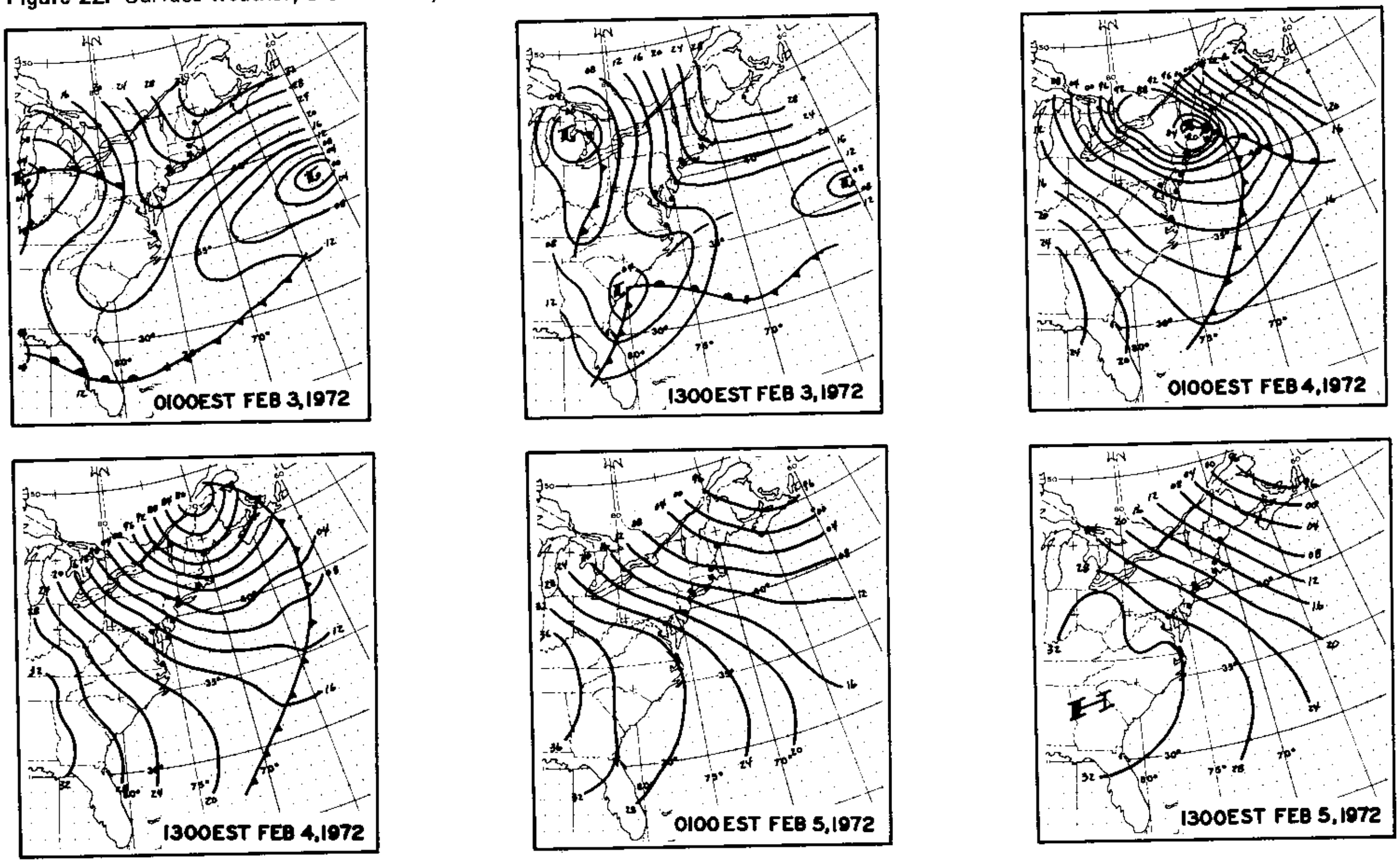
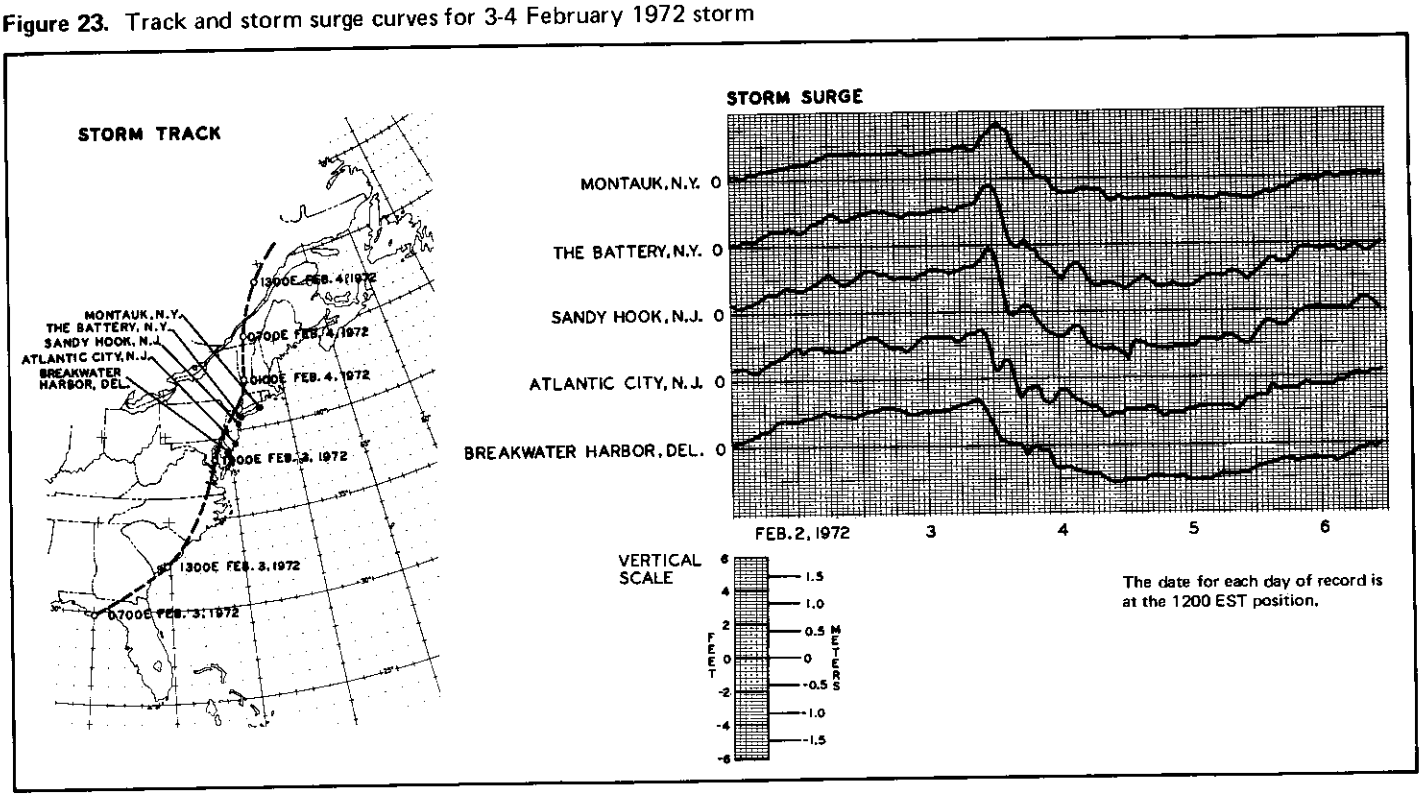


Figure 22. Surface weather, 3-5 February 1972



Source: Pore, Richardson, and Perrotti 1974

Figure 23. Track and storm surge curves for 3-4 February 1972 storm



Two storms affected the tide during 9-13 **November 1968**. The first developed in the Gulf of Mexico and moved northeast along the coast in a typical manner (Figure 19). On 11 November the next storm developed and followed a similar path (Figure 20). It was the largest and most damaging storm to affect the area in several years (Weather Bureau 1968). Peak wind gusts registered 60 mph (52 knots) at New York. Storm surge curves for both storms are shown in Figure 21.

The 3-4 February 1972 storm developed near the South Carolina coast, moved rapidly northeastward, and caused moderate surges in the Bight area (Figures 22 and 23).

Hurricane Storm Surges

Most of the storm surge data presented in this section are from a study by Harris (1963*b*) on the characteristics of the hurricane storm surge. Harris gives storm surge data of hurricanes that affected the Gulf of Mexico coast and the US east coast from 1926 to 1961, but here we discuss only five major hurricanes pertinent to the Bight area.

The 21-22 September 1938 storm is well documented by Tannehill (1938), Pierce (1939), and Cry (1965). It originated near the Cape Verde Islands on 10 September and reached hurricane strength on the fourteenth. The storm moved toward the west-northwest and recurved to the north on the nineteenth and twentieth. On the morning of the twenty-first the center was about 75 mi (121 km) off Cape Hatteras where the wind was 50 mph (43 knots) from the northwest. The center passed east of Atlantic City about 1 pm. The lowest pressure reading at Sandy Hook was shortly after 2 pm. The calm storm center moved over Brentwood, Long Island, between 1:50 pm and 2:50 pm and reached the Connecticut coast, between New Haven and Bridgeport, shortly before 4 pm. Synoptic charts for this storm are shown in Figure 24.

Water levels caused by this storm exceeded the previous records at some locations. In Figure 25, the storm surge curves for Sandy Hook and The Battery show the main storm surge near the time of storm passage, a rapid drop of surge following the main surge, and then a second rise. Such resurgences are referred to as *edge waves* by Munk, Snodgrass, and Carrier (1956). The authors point out that the period of the resurgence depends on the speed of the hurricane and the slope of the ocean bottom over which the storm passes. Resurgences are common in the tide records of this area when hurricanes travel alongshore close to the coast.

High water mark data, collected by the Corps of Engineers, Woods Hole Oceanographic Institution (WHOI), and others are shown in Map 2. Considerable variations in water levels within short distances are indicated.

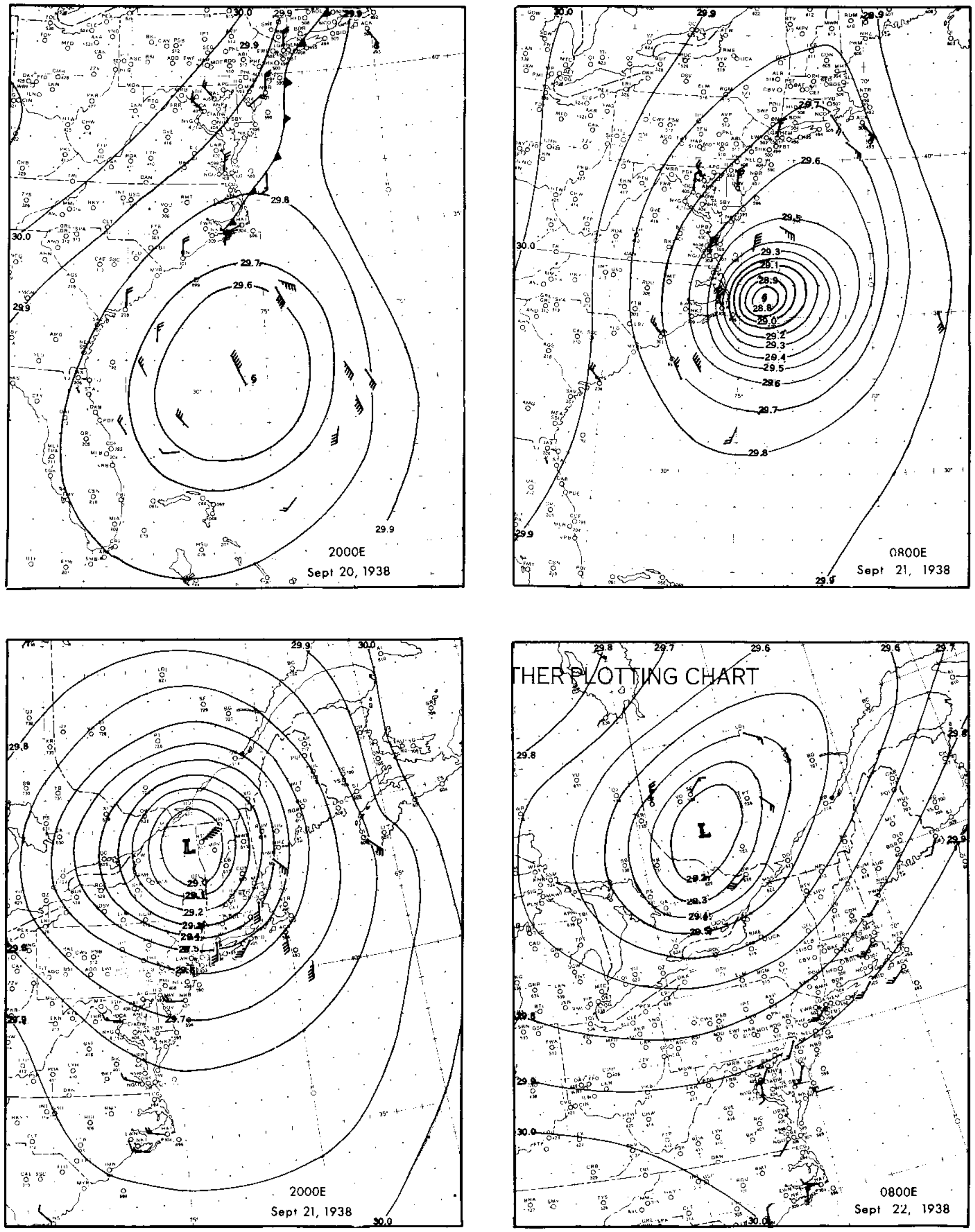
The storm surge caused by **the 13-15 September 1944 storm** was similar to that of the September 1938 storm. However, the peak surge with the 1944 storm occurred near the time of normal low tide. Therefore the observed tides were lower and caused less damage.

Storm surge curves are shown in Figure 26 and synoptic charts in Figure 27. These storm surge curves are good examples of resurgences occurring after the main storm surge. High water marks are indicated in Map 3; note that the peak surge exceeds the high water mark at some locations. The recorded tide traced from the original gage record and the normal astronomic tide are presented in Figure 28, which shows the type of high-frequency oscillations evident in most records of well-exposed tide gages during hurricanes.

Hurricane Carol of 30-31 August 1954, which crossed the eastern tip of Long Island, was a devastating storm in the Bight region. Meteorological accounts of the storm are given by several writers, including Davis (1954) and Winston (1954). Surface weather is shown in Figure 29; storm surge curves for Carol are shown in Figure 30. Once again, there are resurgences in the storm surge curves following passage of the storm. Many high water marks were surveyed after the storm (Map 4).

Two weeks after Carol, **hurricane Edna (10-12 September 1954)** traced a similar path between Cape Hatteras and New England. The meteorological aspects of the storm have been discussed extensively by Malkin and Holzworth (1954). Storm surge curves for

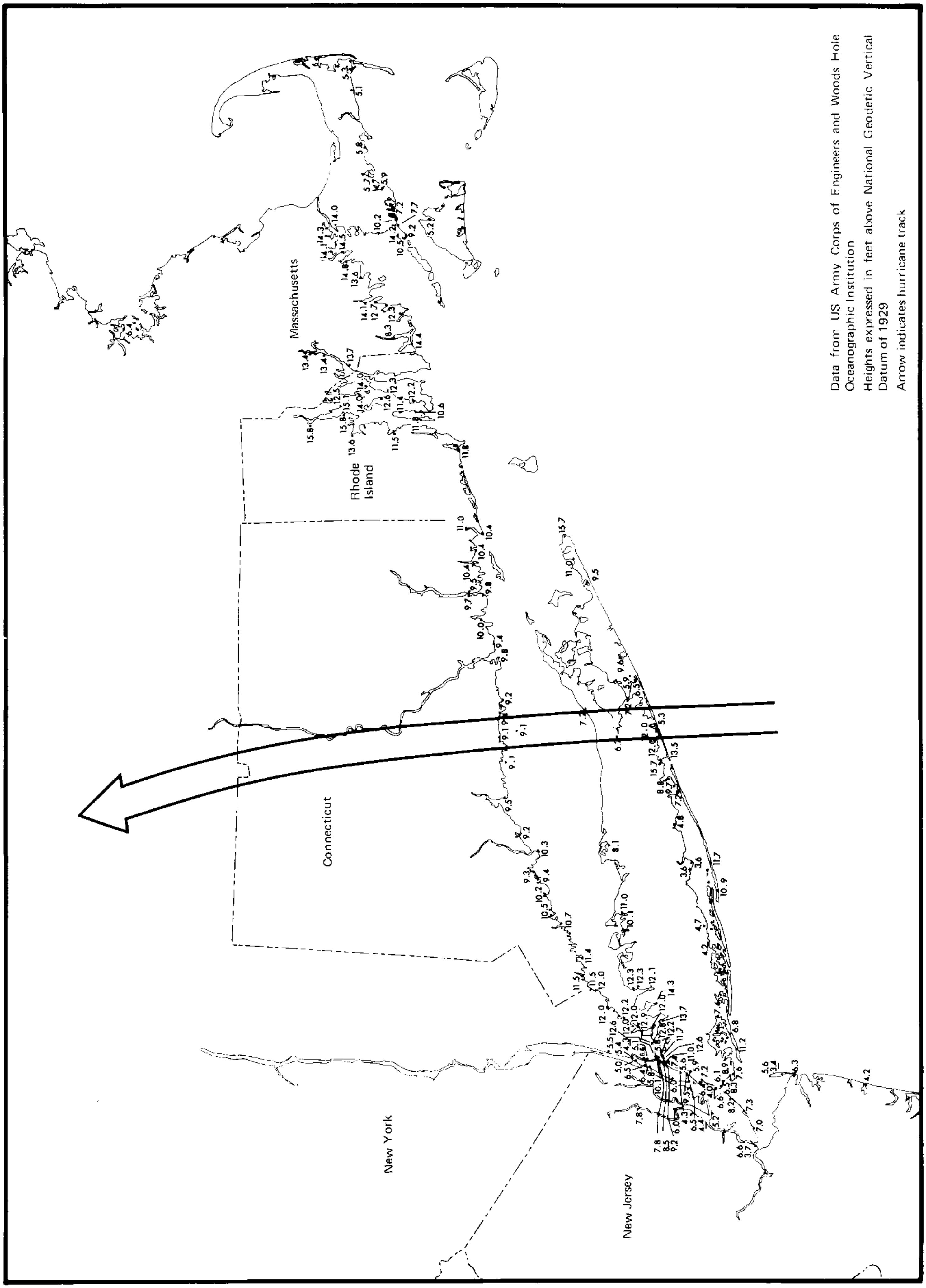
Figure 24. Synoptic charts for 21-22 September 1938 hurricane



Source: Harris 1963*b*

NOTE: The symbol points in the direction the wind is blowing. The wind barbs (the "feathers") indicate the speed: a full barb is 10 knots, a half barb is 5 knots, and a solid triangle is 50 knots.

Map 2. High water marks, September 1938 hurricane



Source: Harris 1963*b*

Figure 25. Track and storm surge curves for 21-22 September 1938 hurricane

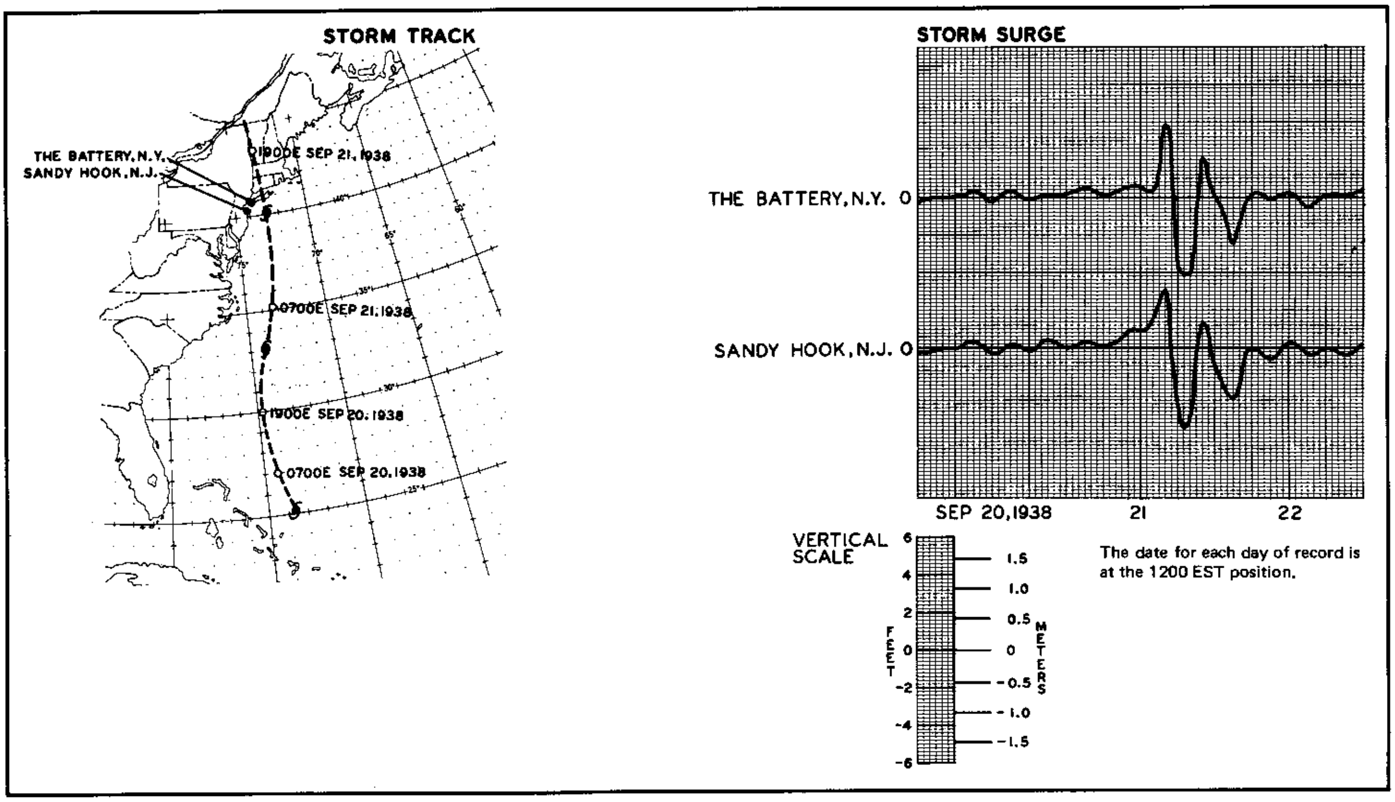


Figure 26. Track and storm surge curves for 13-15 September 1944 hurricane

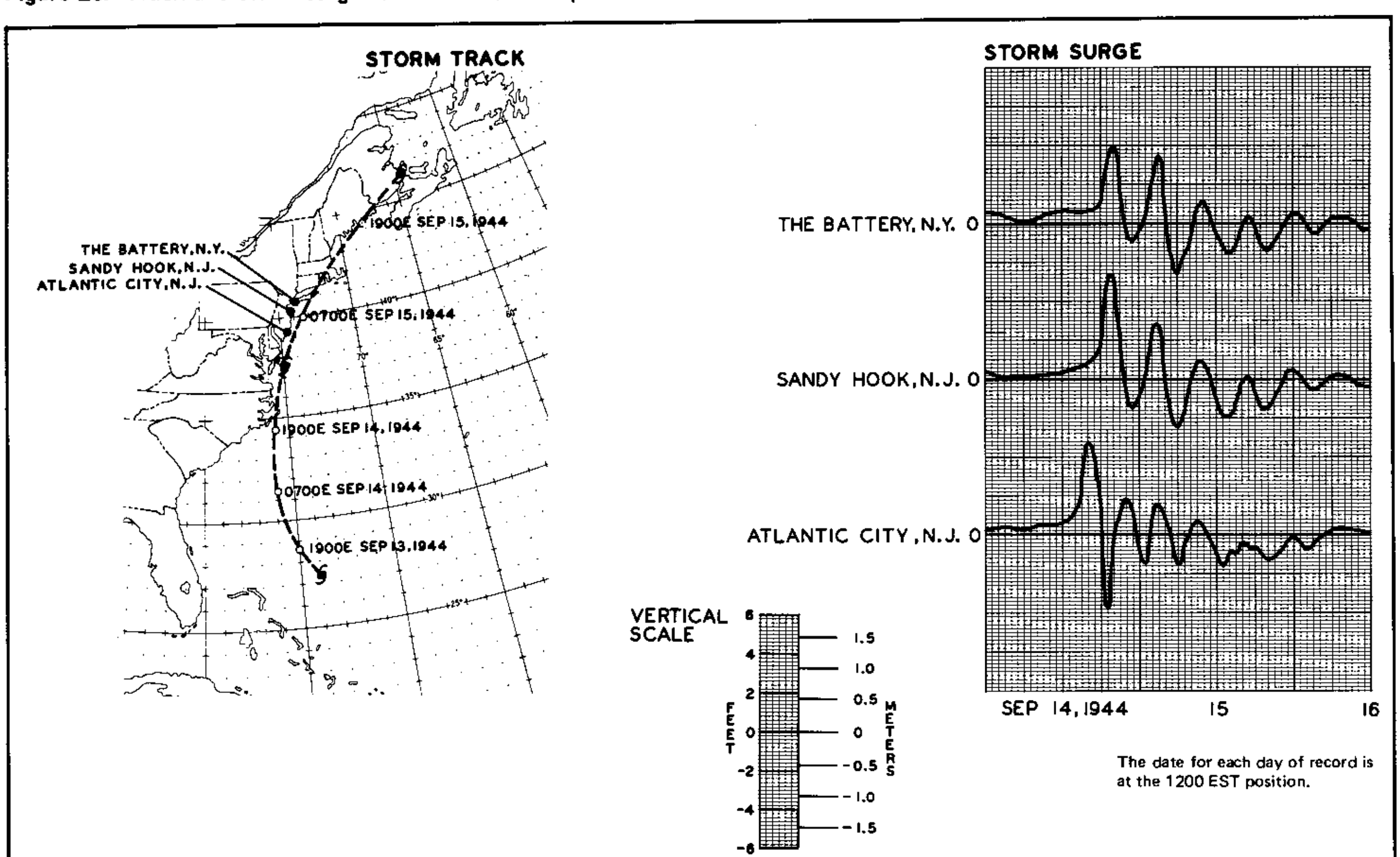


Figure 27. Synoptic charts for 13-15 September 1944 hurricane

Source: Harris 1963*b*

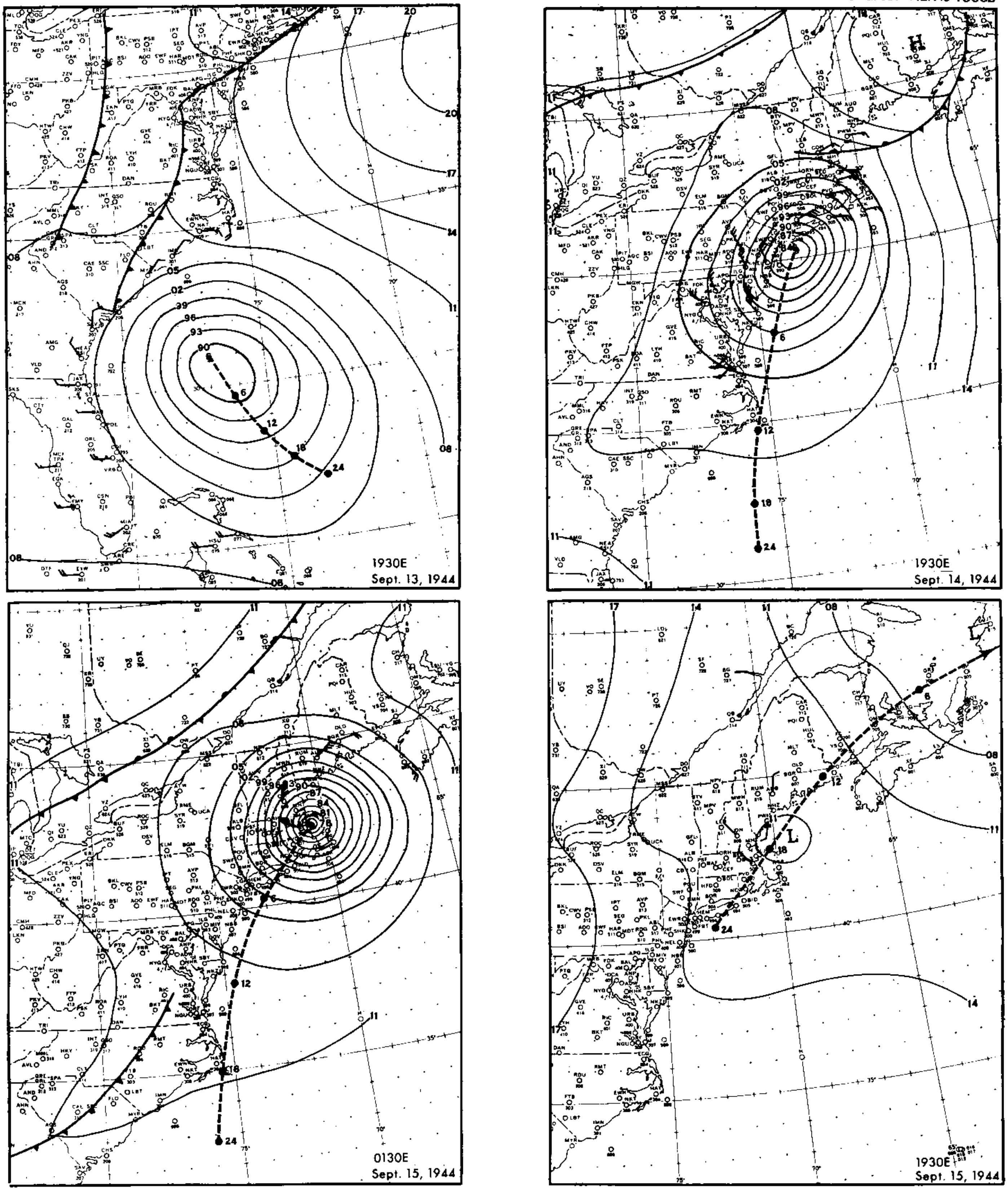
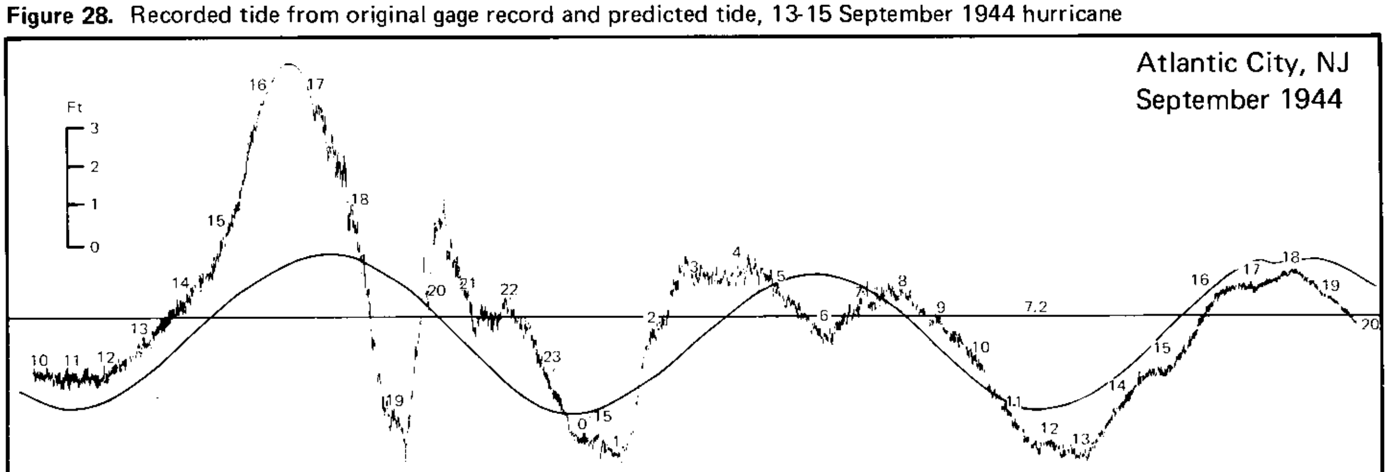
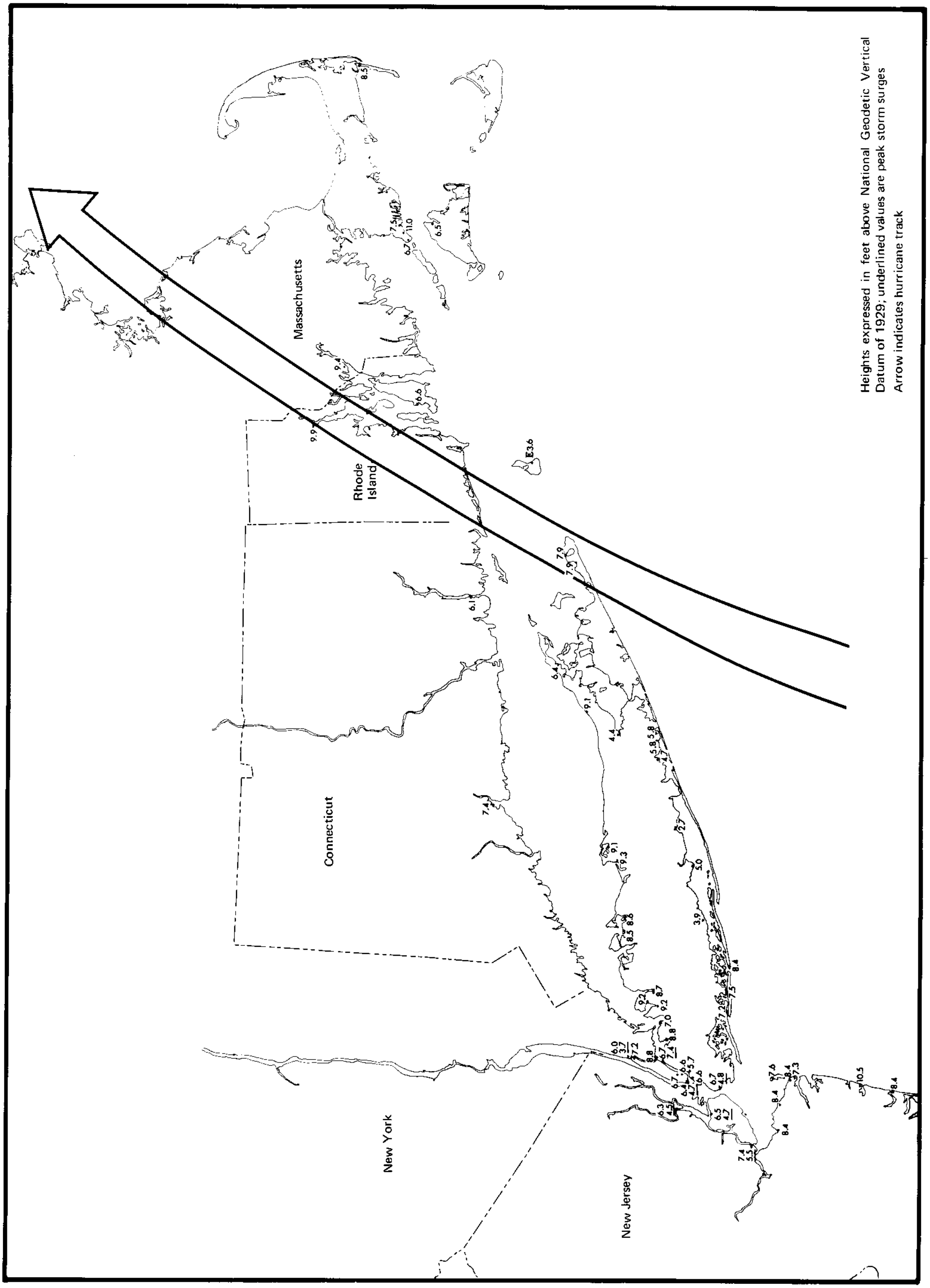


Figure 28. Recorded tide from original gage record and predicted tide, 13-15 September 1944 hurricane

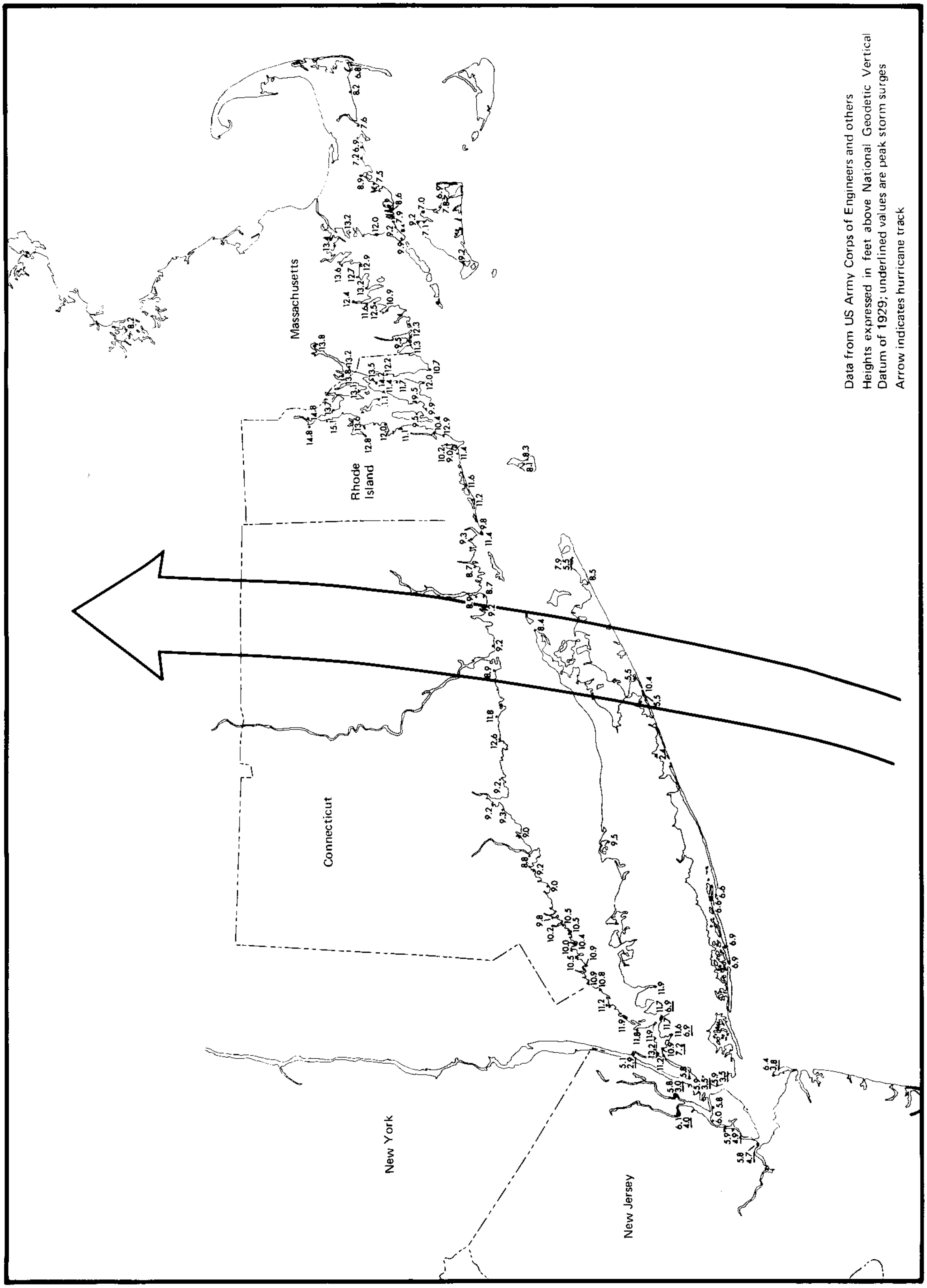


Map 3. High water marks, September 1944 hurricane



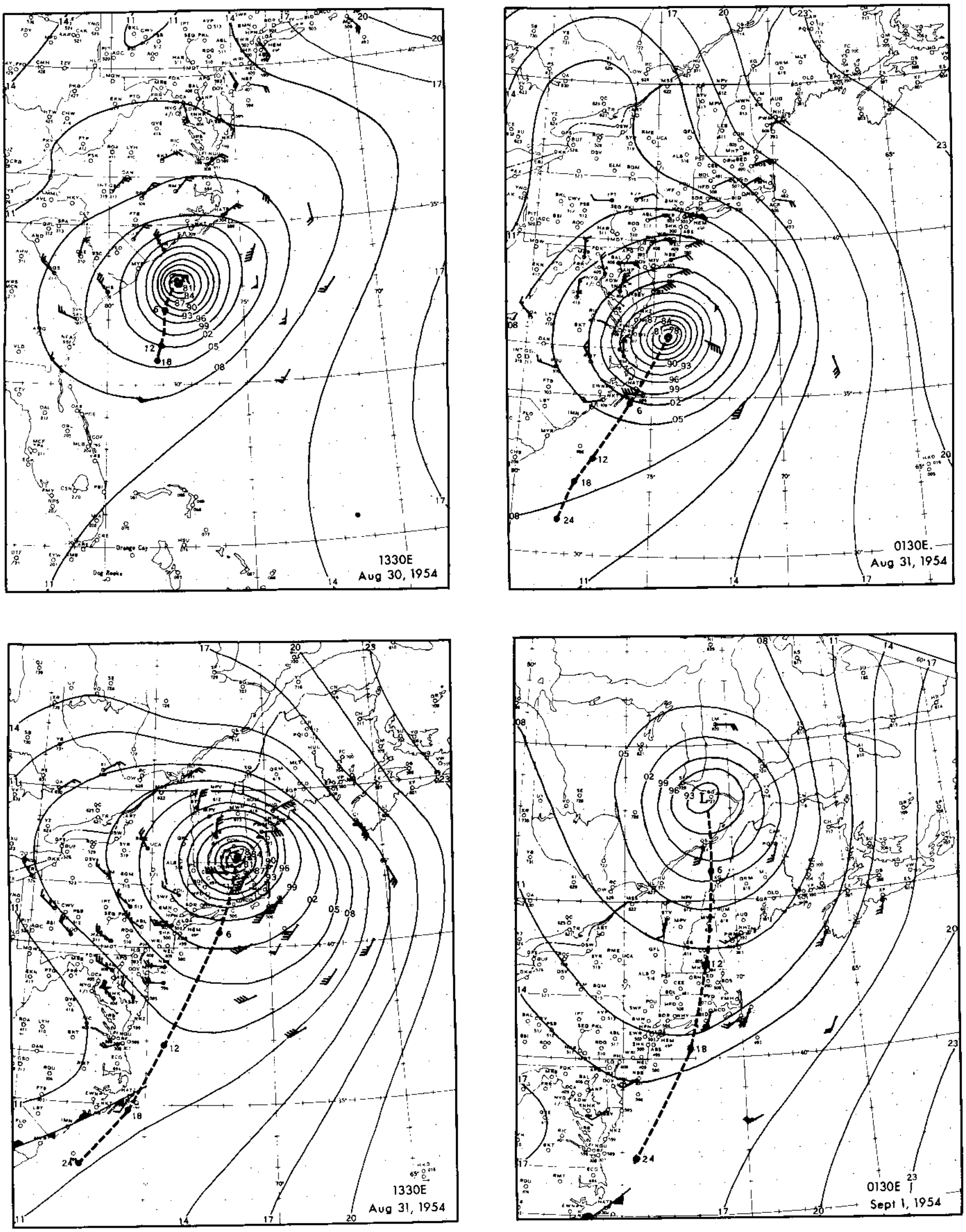
Source: Harris 1963b

Map 4. High water marks, hurricane Carol, August 1954



Source: Harris 1963*b*

Figure 29. Synoptic charts for hurricane Carol, 30-31 August 1954



Source: Harris 1963*b*

Figure 30. Track and storm surge curves for hurricane Carol, 30-31 August 1954

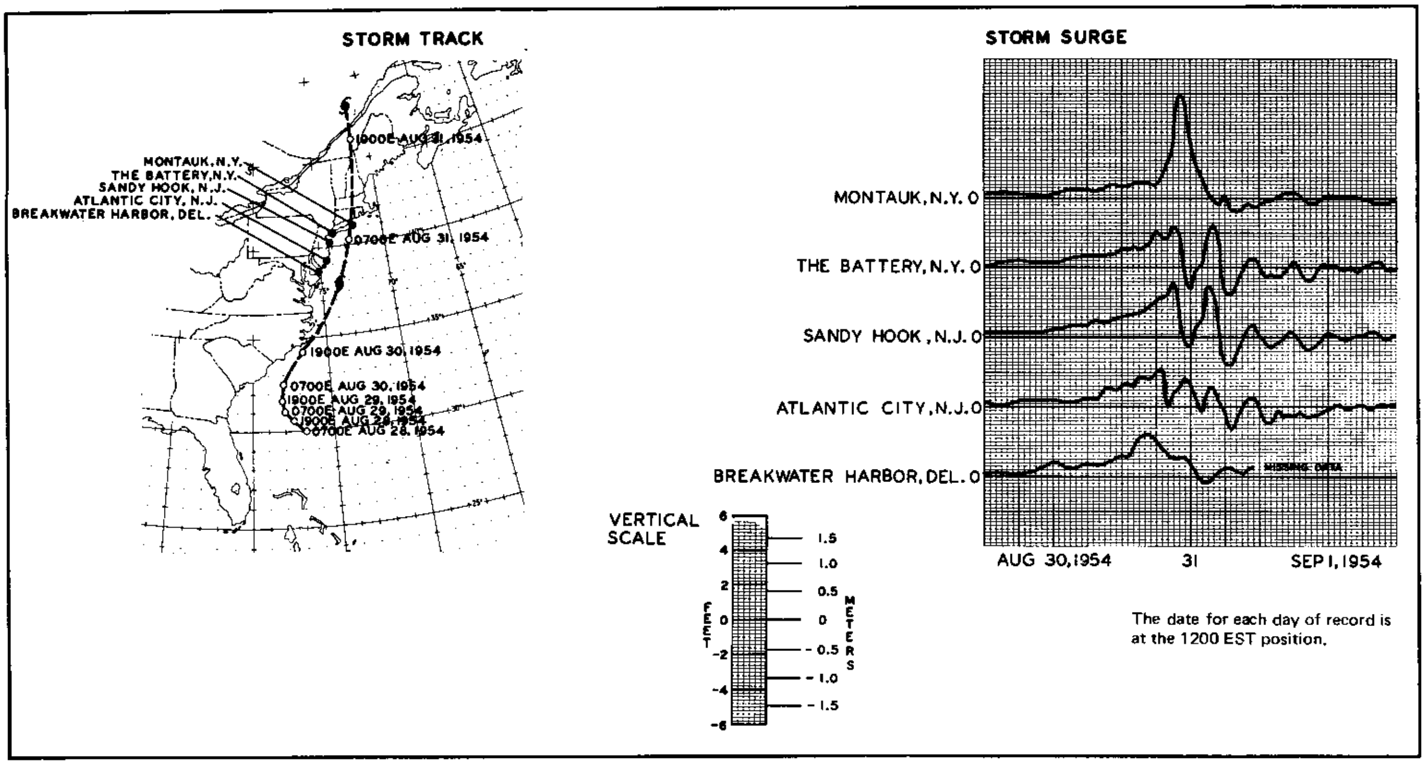


Figure 31. Track and storm surge curves for hurricane Edna, 10-12 September 1954

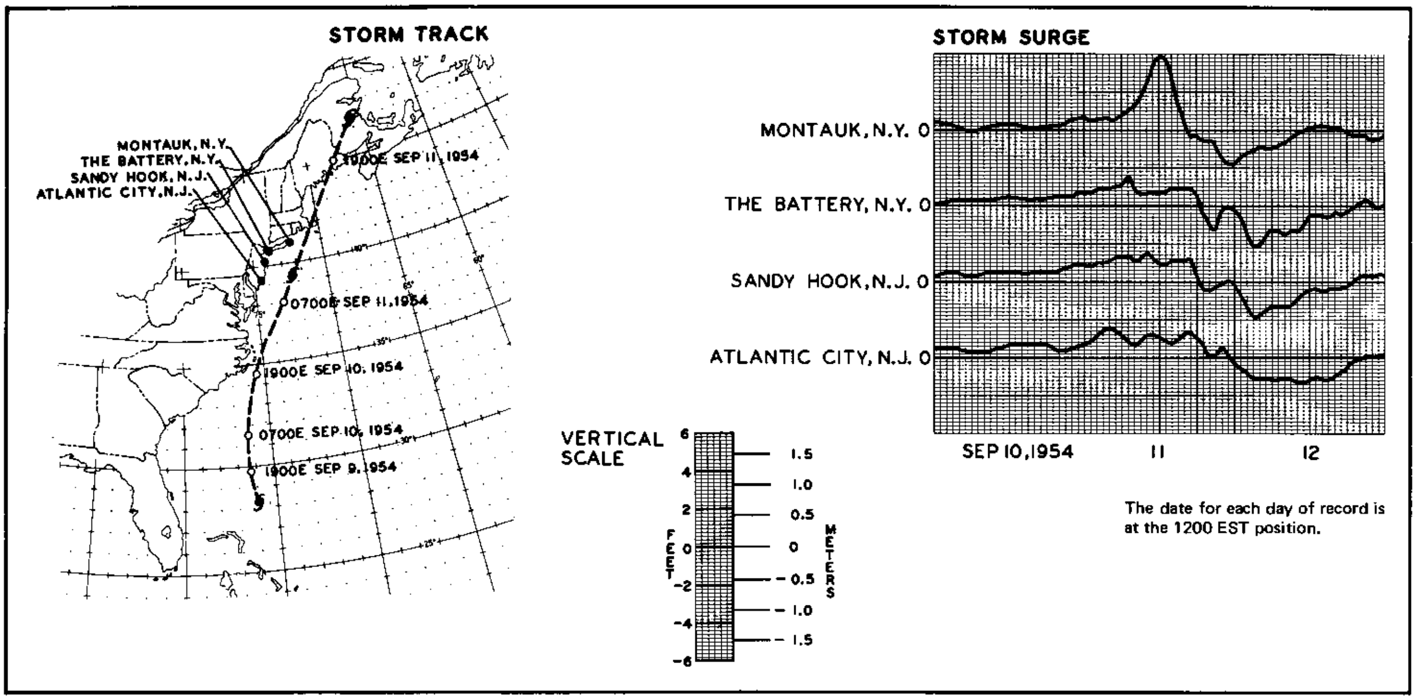
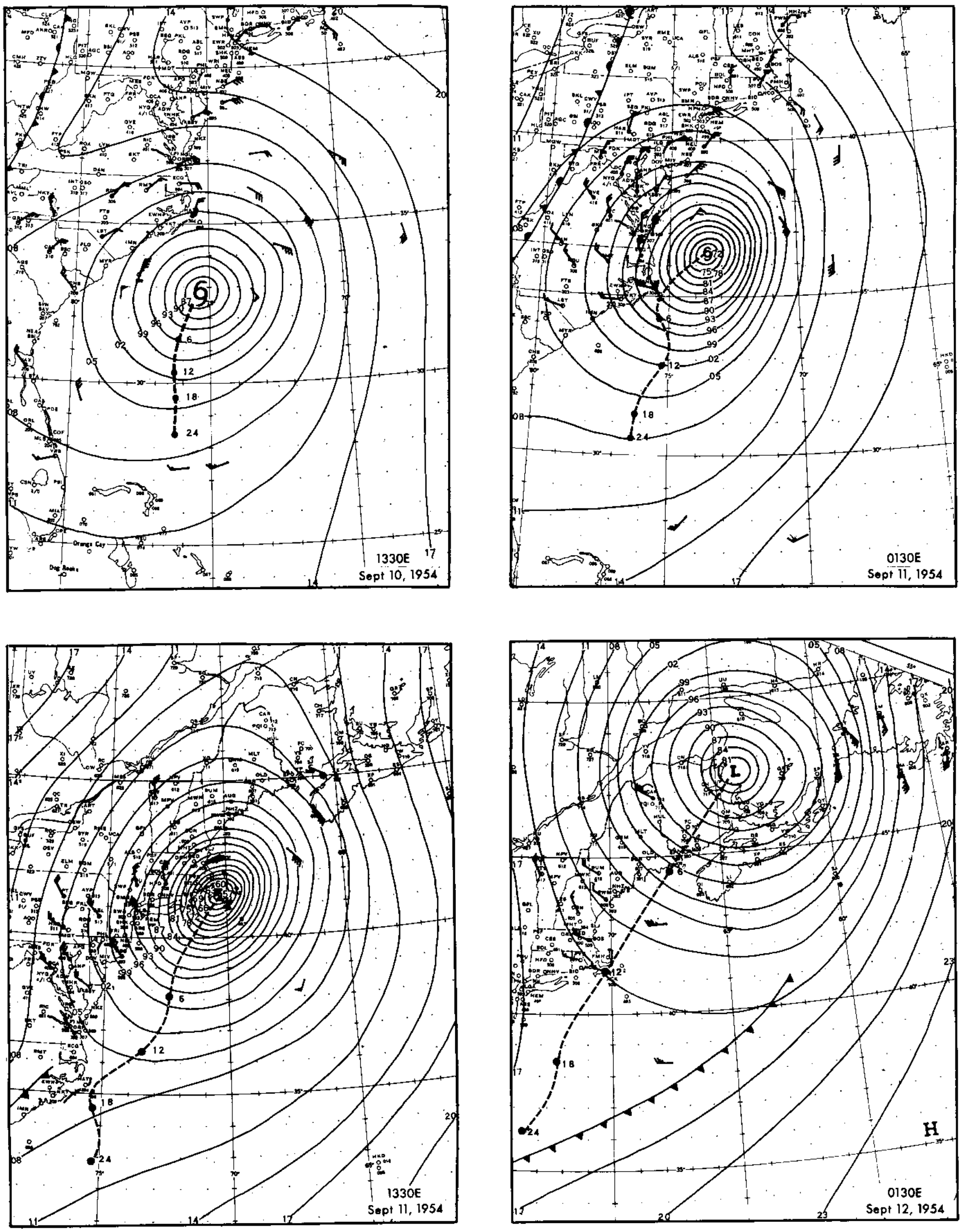
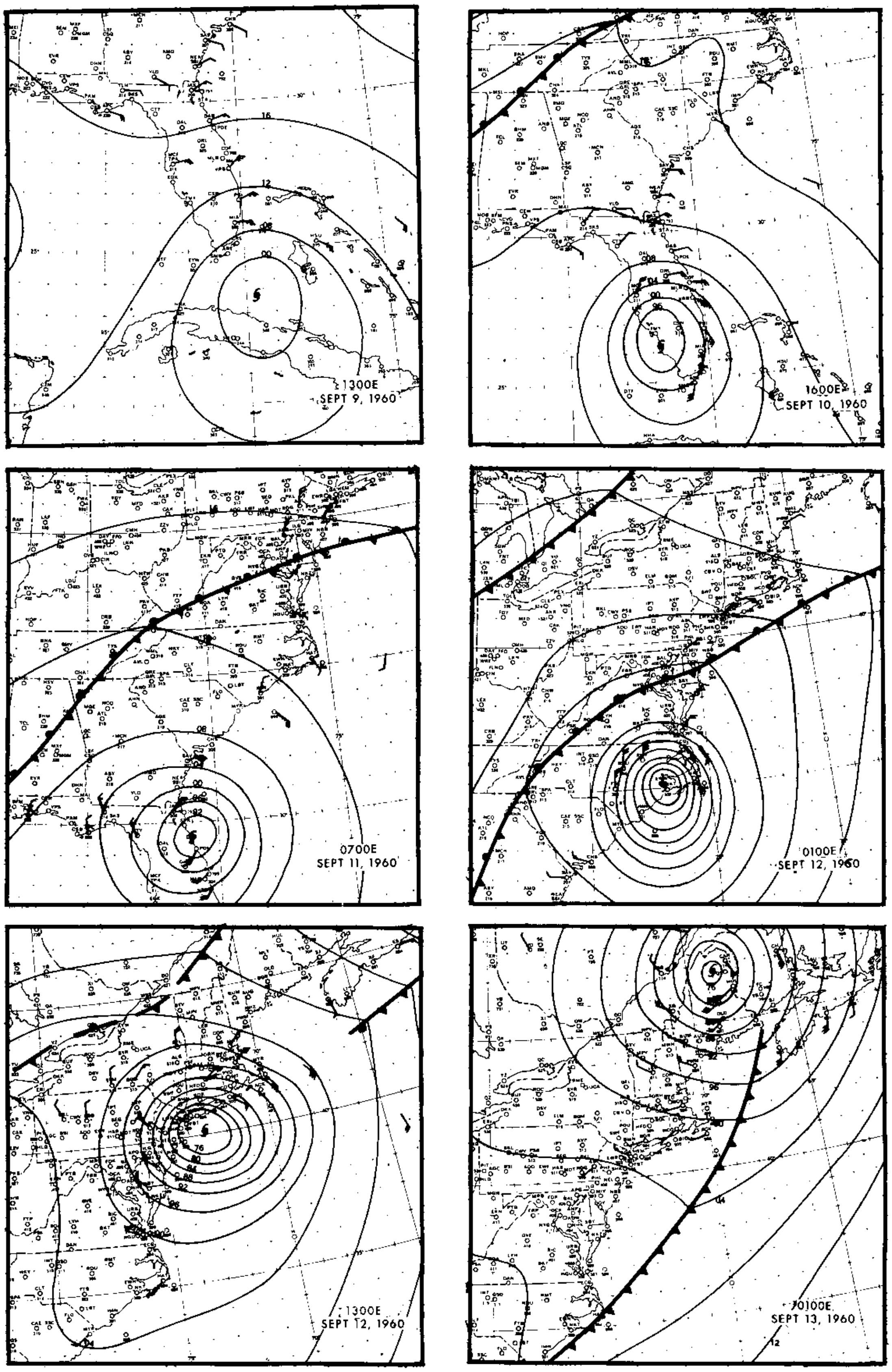


Figure 32. Synoptic charts for hurricane Edna, 10-12 September 1954



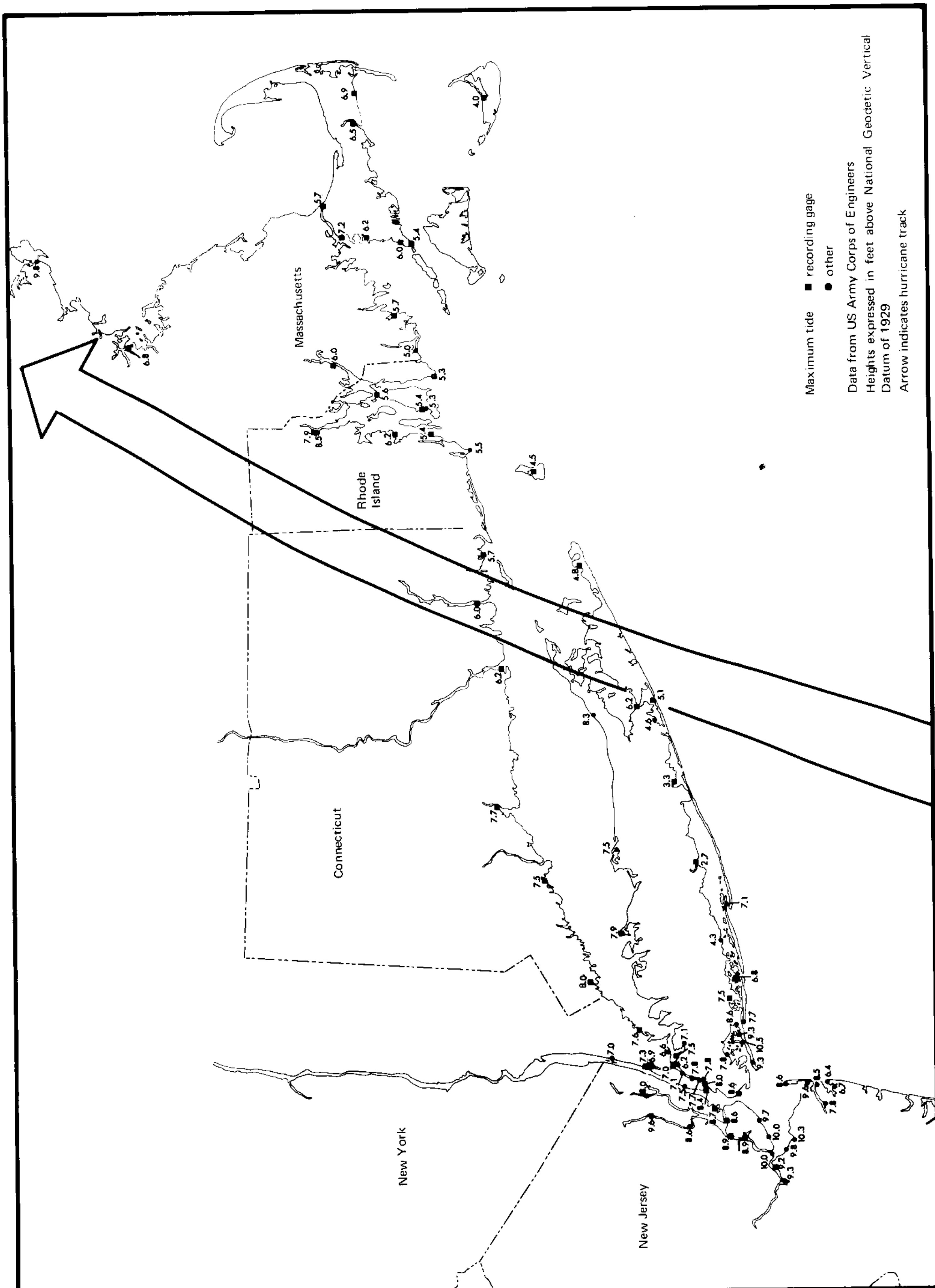
Source: Harris 1963*b*

Figure 33. Synoptic charts for hurricane Donna, 9-13 September 1960



Source: Harris 1963*b*

Map 5. High water marks, hurricane Donna, September 1960



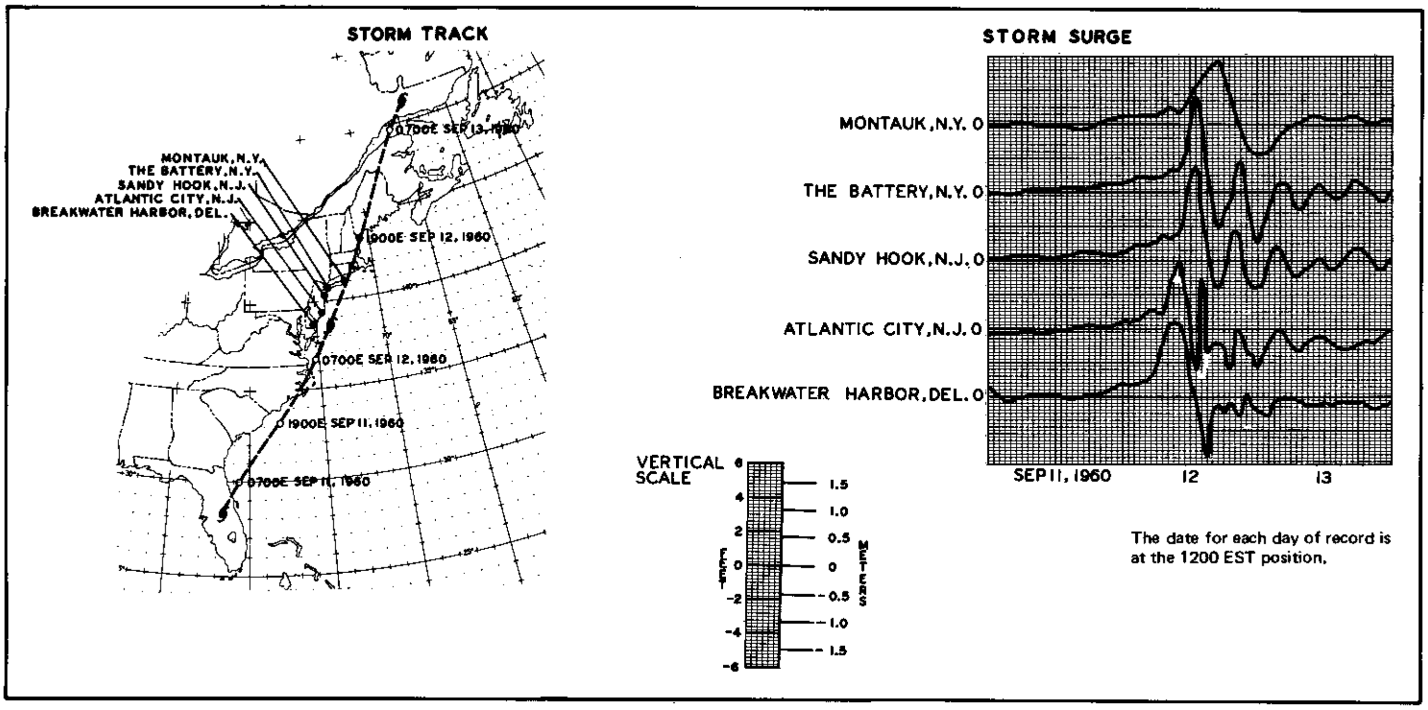
Source: Harris 1963*b*

Edna are presented in Figure 31 and synoptic charts in Figure 32.

Donna, 12 September 1960, was one of the most destructive hurricanes to affect the United States. The meteorological history of the storm has been documented by Dunn (1961). The storm stayed close to the entire east coast of the United States and was believed to have caused hurricane winds over a greater portion of the US coastline than any earlier hurricane.

Sustained winds of about 104 mph (90 knots) were recorded at several points on Long Island; 58 to 69 mph (50 to 60 knot) winds blew in New York City. Gusts of 115 mph (100 knots) or greater were reported at Montauk, Long Island (Dunn 1961). Synoptic charts are presented in Figure 33, storm surge curves in Figure 34, and high water marks in Map 5. The storm surges observed in the Bight area were similar to those of the other four hurricanes discussed in this section.

Figure 34. Track and storm surge curves for hurricane Donna, 9-13 September 1960



Climatology of Storms and Storm Surges

Knowing the frequency and intensity of coastal storms likely to occur in the future, along with the frequency and heights of the associated storm surges, is important for coastal zone planning. Such knowledge can be acquired by studying what happened in the past. The ideal way to determine the climatology of storm surges for the Bight area would be to take a long series of tide observations, say about 200 years for a dozen or more locations, subtract out the astronomic tide, and tabulate frequencies of the resulting storm surge heights. This has not been done because continuous tide records for such long periods have not been kept and because storm surges are not calculated regularly for climatological purposes. Therefore, we will present data from several excellent studies on the occurrence of storms, both tropical and extratropical, for the area. We will also present limited data on the frequency of extratropical storm surges during a relatively short period (14 years).

Burton and his associates (1965) studied coastal storms that caused at least some water damage along the east coast from 1921 to 1964. Their analyses of daily weather charts for the 195 storms in those years revealed that certain types of weather situations recurred many times. On the basis of storm origin, structure, and path, they were able to classify storms into eight types. The descriptions of the storm types, taken directly from their report, are:

1. Hurricanes and severe tropical storms.
2. Wave developments forming in the Atlantic Ocean well east of the United States mainland or in the vicinity of Cuba.
3. Wave developments along cold or stationary fronts over the southeast coastal states or in the Atlantic Ocean just off the southeast coast.
4. Wave developments along cold or stationary fronts in the Gulf of Mexico forming west of 85°W longitude.
5. Depressions moving across the southern half of the United States that intensify upon reaching the Atlantic coast; no secondary development ahead of the storm center.
6. Depressions which develop as strong secondary cyclonic disturbances along the coast (often in the Hatteras area) ahead of a trailing wave or occluded center.
7. Intense cyclonic storms whose origin and entire path of movement are over land surfaces so that the low center remains west of the coastal margin.
8. Strong cold fronts accompanied by squall lines and severe local weather.

A tabulation of the storms by class and state was made for New York and New Jersey from 1921 to 1964 and is shown in Table 2. New York had a total of 47 damaging storms, of which 11 were hurricanes; New Jersey had 56, 18 of them hurricanes. Both states had a frequency of damaging storms of slightly over one per year.

Table 2. Damage-producing storms, 1921-1964

	Class								Total	Storms per Year
	1	2	3	4	5	6	7	8		
New York	11	1	10	8	4	9	4	0	47	1.07
New Jersey	18	3	10	8	4	8	4	1	56	1.27

Source: Burton et al 1965

Burton further classified these storms by severity (Table 3). Three relative classes of damage were used: light, moderate, and severe.

Table 3. Coastal storms and recurrence interval, 1921-1964

	Number of Storms			Mean Recurrence Interval of Moderate and Severe Damage Storms
	Light Damage	Moderate Damage	Severe Damage	
New York	14	24	9	1.3 years
New Jersey	25	26	5	1.4 years

Source: Burton et al 1965

The records for several NOS (then Coast and Geodetic Survey) tide gages were examined by Burton for the 11-year period 1952-1962. The occurrences of tides at selected intervals above mean high water are shown in Table 4; also shown is the number of storms for which some damage was reported at each location. The inconsistency of more damaging storms being reported than the total number of tides over 2 ft (0.6 m) above mean high water (see Montauk on Table 4) indicates problems with using tide records directly to assess storm damage. One possible explanation for the inconsistency is that the same tide height may be damaging at one location but not at another.

The Table 4 storms causing some damage are further explored in Table 5. Here the storms are put into five classes according to the amount of damage caused. The average water level for each class of storm has been determined. As one would expect, this table shows a definite, though not very high, correlation between the average tide and the amount of damage.

Table 4. Occurrences of selected high tides, 1952-1962

	Tides Above Mean High Water				Number of Storms Causing Storm Damage
	2.0-2.9 ft	3.0-3.9 ft	4.0+ ft	Total	
Montauk, NY	29	7	2	38	68
Sandy Hook, NJ	44	8	4	56	51
Atlantic City, NJ	65	5	1	71	57
Breakwater Harbor, DE	46	8	1	55	56

Source: Burton et al 1965

Table 5. Average of maximum tides above mean high water, 1952-1962

Gaging Station	Very Light			Light			Moderate			Moderate-Heavy			Heavy		
	No. Storms	Avg. Tide ft	m	No. Storms	Avg. Tide ft	m	No. Storms	Avg. Tide ft	m	No. Storms	Avg. Tide ft	m	No. Storms	Avg. Tide ft	m
Montauk, NY	53	1.55	0.47	4	2.18	0.66	3	2.40	0.73	4	2.52	0.77	4	4.25	1.30
The Battery, NY	56	1.56	0.47	5	2.44	0.74	4	2.75	0.84	1	2.30	0.70	4	4.58	1.40
Sandy Hook, NJ	38	1.71	0.52	7	2.71	0.83	3	2.97	0.91	1	5.70	1.74	2	5.15	1.57
Atlantic City, NJ	44	1.75	0.53	6	3.52	1.07	4	2.58	0.79	0			3	3.80	1.16
Breakwater Harbor, DE	48	1.75	0.53	4	2.82	0.86	3	2.30	0.70	0			1	5.30	1.62

Source: Burton et al 1965

Further study of tropical cyclones affecting the Bight area can be made by considering the climatology of storm paths, such as given by Cry (1965), who presents a tropical storm track chart for the North Atlantic for each year from 1871 through 1963. Similar charts for subsequent years are available in issues of the *Monthly Weather Review* (for example, Simpson and Hope 1972). During the 103-year period, 1871-1973, only 22 tropical storms crossed the coast of New York Bight. This averages out to about one storm in 4.7 years. Of course the storms are not evenly spaced in time; indeed, they are quite irregular. For instance, no tropical storms crossed the coast between 1905 and 1933; on the other hand, two storms crossed the coast in three different years—1934, 1944, and 1960.

Tropical storms not crossing the coast but moving alongshore also cause storm surges. This type is much more frequent. In a study of storm-tide frequency at Atlantic City and Long Beach Island, NJ, Myers (1970) determined the number of storms crossing the fortieth parallel at various distances from the coast (Table 6) by using Cry's storm track charts.

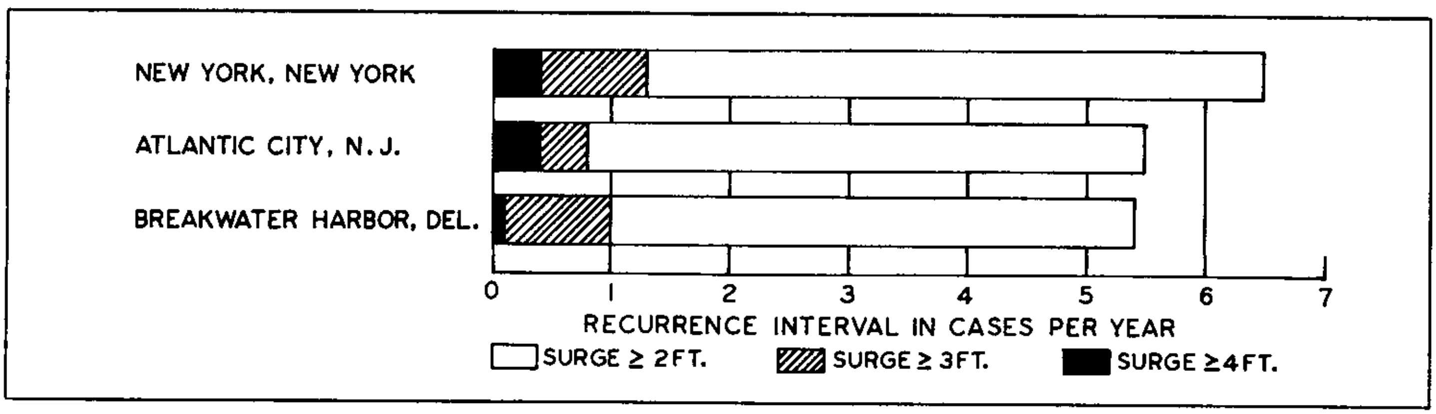
In a report on the development of an extratropical storm surge forecast method, Pore, Richardson, and Perrotti (1974) tabulated the frequency of extratropical storm surges for several locations from 1956 to 1969 (Figure 35). November through April were used because nearly all extratropical storm surges occur during those months.

Table 6. Distance from coast of hurricanes and tropical storms, 1871-1969

	Distance from coast along 40th parallel (nmi) 0-60	60-120	120-180	180-240	Total No. of Storms
1871-1885	1	5	4	1	11
1886-1899 total	5	3	3	3	14
Hurricanes	3	3	2	3	11
Tropical storms	2	0	1	0	3
1900-1969 total	5	6	8	8	27
Hurricanes	2	4	7	4	17
Tropical storms	3	2	1	4	10
Total	11	14	15	12	52

Source: Myers 1970

Figure 35. Frequency of extratropical storm surges based on data for November through April, 1956-1969



Source: Pore, Richardson, and Perrotti 1974

Maximum Storm-Tide Conditions

Just how high will sea level rise during the most severe storm that might occur? This essential question cannot yet be clearly answered. Two other important questions are: what geographic areas can be inundated by storm tides, and how much property damage can occur? Property damage depends upon how much development has taken place in the coastal areas. Certainly the Bight shores are heavily built up.

A study prepared for the Corps of Engineers (Tippets et al 1958) treats the subject of hurricane tide damage in the New York Harbor area. The authors estimated damage from a potential water level of 15 ft (4.6 m) above mean sea level (MSL), based on the hurricane of 3 September 1821 in which the storm surge was estimated at 10 to 11 ft (3.1 to 3.4 m), occurring at low astronomic tide. Tannehill (1944) points out there were reports of the water rising 13 ft (4 m) in one hour at New York during this storm. The 15 ft (4.6 m) above MSL used in the appraisal report considered the possible recurrence of the September 1821 hurricane, but at high astronomic tide. The conclusion was that a tide of 15 ft (4.6 m) above MSL would inundate about 23% of the New York City land area (Manhattan, Bronx, Brooklyn, Queens, and Staten Island) and about 8% of six New Jersey counties (Bergen, Essex, Hudson, Middlesex, and Union). Transportation would be greatly affected: rail transportation to and from New York City would be stopped, over 50 mi (80 km) of the New York subway system would be flooded, and the principal airports would be inoperative.

NOAA is involved in performing flood frequency analyses for certain coastal areas to specify probabilities of occurrence of flood levels and flood-risk zones. This work is being done for the Federal Insurance Administration to support the calculation of flood insurance rates. The formulation of local zoning ordinances is also based on this type of information. The program was initiated by the National Flood Insurance Act of 1968 (PL 448), which provides for a national program for insuring residences and small businesses against damage or destruction by floods.

Myers (1975) has comprehensively described seven approaches to assessing future storm-tide frequencies.

Highest of Record. The simplest method is to determine from memory or records what has been the highest water level in the past and to assume that it can be repeated.

Statistical Analysis of Single-Station Data. A statistical analysis of high storm-tide levels can be made assuming that past, present, and future storm-tides fit a specific probability distribution.

Random Timing of Hurricanes with Respect to Astronomic Tide. This approach considers storm surges arriving at various phases of the astronomic tide. Thus, where equal surges occurred, the one at astronomic high tide would be more important than the one at astronomic low tide. The maximum water levels from these combinations of storm surge and astronomic tide can then be statistically analyzed.

Variation of Strike Point of Hurricanes on Coast. This method requires the profile of the highest tide height for a storm along the coast and assumes that where the hurricane actually strikes the coast—within a region homogenous in climatology and bathymetry—is accidental.

Shoaling Factor Adjustments. This approach further refines the preceding method by considering shoaling factor corrections in areas not homogenous in bathymetry.

Hydrodynamic Synthesis. This method applies a hydrodynamic model to calculate the storm surge from atmospheric input data. This makes storm surge information available from past storms in which surge data were not actually recorded. Useful for this purpose is the SPLASH (Special Program to List Amplitudes of Surges for Hurricanes) model of Jelesnianski (1972, 1974), which is also used for operational forecasting by the National Weather Service.

The Climatological-Hydrodynamic (Joint Probability) Method. In this method, the significant hurricane variables—central pressure, radius of maximum wind, directional approach to the coast, and forward speed—are considered as climatological variables having probability distributions at each coastal point, with smooth variations in these probabilities from point to point. This storm climatology is then converted to storm-tide climatology by applying the hydrodynamic model. In this approach, *storm-tide envelopes* (curves of maximum storm-tide along the coast) are synthesized from a variety of storms that could occur. These storms vary in strength, speed, size, and direction and also arrive at different phases of astronomic tide. This synthetic storm-tide climatology depends on the climatological specification of atmospheric hurricane variables, the smoothed bathymetry for use in the hydrodynamic model, shoaling correction curves, and the hydrodynamic model.

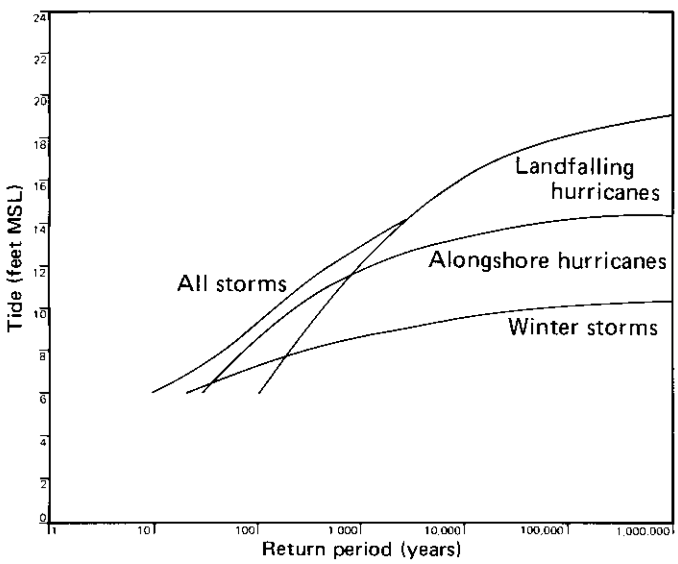
Such a joint probability method was applied to the storm-tide frequency problem at Atlantic City and Long Beach Island, NJ, by Myers (1970). Landfalling hurricanes and alongshore hurricanes were considered. Winter extratropical storm surge frequencies were derived from the record of past surges and not calculated from storm variables. These surges were then combined with the various phases of astronomic tide in the same manner as for hurricane surges.

The resulting storm-tide frequency curves for Atlantic City for the three types of storms and the combination of all storms are shown in Figure 36 from Myers (1970). The all-storm frequency curve of Figure 36 is compared to an earlier storm-tide frequency analysis by the Corps of Engineers (1963) in Figure 37. Myers' curve shows a lower tide height at the 500-year return period than the Corps of Engineers study. As pointed out by Myers, this is expected and is due in part to the assumption in the Corps of Engineers report that the Standard Project Hurricane* peak surge is coincident with astronomic high tide, whereas Myers' study considers variable phases of astronomic tide and storm surge.

The joint probability method of determining storm-tide frequencies has been applied to other parts of the US Atlantic coast (Ho 1974; Ho and Tracy 1975; Myers 1975) and it will probably be applied in the future to additional coastal areas of the Bight besides Atlantic City and Long Beach Island.

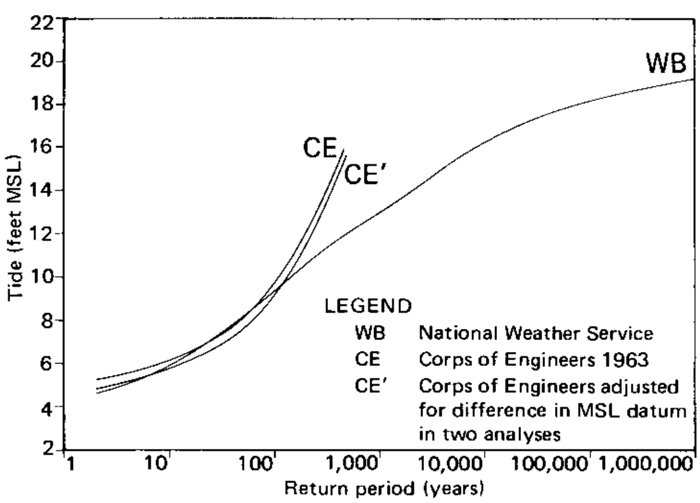
*Standard Project Hurricane is defined as a hypothetical hurricane representing the most severe combination of hurricane variables reasonably characteristic of a specific region, excluding extremely rare combinations.

Figure 36. Storm-tide frequencies for Atlantic City, by joint probability method



Source: Myers 1970

Figure 37. Storm-tide frequencies for all storms, Atlantic City



Source: Myers 1970

Forecasting Storm Surges

Storm surge forecasts are valuable and essential to plan for protection of life and property in areas subject to storm surges. The Weather Service's National Hurricane Center is responsible for predicting storm surges associated with hurricanes and tropical storms for the Gulf of Mexico and Atlantic areas, including the Bight coasts. Successful forecasting of hurricane storm surges depends, of course, upon accurate forecasts of the intensity, size, and movement of the hurricanes themselves. Actual storm surge forecasts are made with the SPLASH computerized numerical model for the east and Gulf coasts from Long Island to Texas (Jelesnianski 1966, 1967, 1972, 1974). This model consists of a storm traveling across a rectangular basin of variable depth. The storm surge driving forces from pressure and wind are determined from a tropical storm model. The driving forces are applied to a version of the storm surge equations. Numerical calculations are generally made for a grid distance of 4 mi (6 km) with a 2.5 min time interval between computations. The SPLASH model can be used for two types of storms: those that cross the coast and those that travel along the coast but do not actually landfall. For storms expected to cross the coast the following information is given to the model: the landfall position of the storm; pressure drop in the storm while it traverses the continental shelf; the mean compass direction in which the storm will traverse the continental shelf just prior to landfall; the average storm speed just prior to landfall; and the radius of maximum wind, which is a measure of storm size.

For storms that do not landfall, five storm positions at 6-hr intervals are supplied to the model. Pressure drop and radius of maximum wind can also be varied in this version of SPLASH.

The results of the model computation–the expected storm surge–are displayed by programmed computer output. This includes a resume of storm variables given to the model, a list of correction factors to update the surge forecast for a variation of storm pressure drops, a plotted graph of the envelope of the highest storm surges along the coast, and a listing of the astronomic tide levels for selected locations for several hours before and after the predicted time of maximum surge. A sample computer printout from Jelesnianski (1974) is shown in Figure 38. Here the calculated surge envelope is shown for the hurricane of 14 September 1944 for the coast from Virginia Beach to Long Island; the calculations agreed reasonably well with observations. This was not a forecast but rather a computation based on analyzed meteorological data. In operational use, the accuracy of actual real-time forecasts depends greatly on the accuracy of the meteorological forecasts.

The first versions of SPLASH treated the coastline as straight. The latest improvement in the model is a modification in which the storm surge equations of motion and the driving forces of the storms are transformed to correspond approximately to a curvilinear coordinate system. This allows the model to consider coasts with moderate curvature and will extend the model's usefulness to areas such as New England. Figure 39 shows storm surge calculations made by SPLASH, with the curvilinear coordinate system, for several locations during hurricane Donna in 1960.

For extratropical storms, National Weather Service Forecast Offices are responsible for issuing storm surge warnings. Computerized statistical forecasts are used as guidance at these forecast offices (Pore et al 1974). This automated forecast technique, which became operational in October 1971, is a statistical method based on actual storm surge data from November through April, from 1956 through 1969, using storms that produced surges of 2 ft (0.6 m) or more.

Separate forecast equations were determined by the statistical screening procedure for each of the forecast locations so that local effects were considered. The six forecast locations in and near the Bight area are Newport, RI, Stamford, CN, Willets Point, NY, The Battery, NY, Atlantic City, NJ, and Breakwater Harbor, DE. Figure 40 shows, as an example, the forecast equation derived for storm surge at New York.

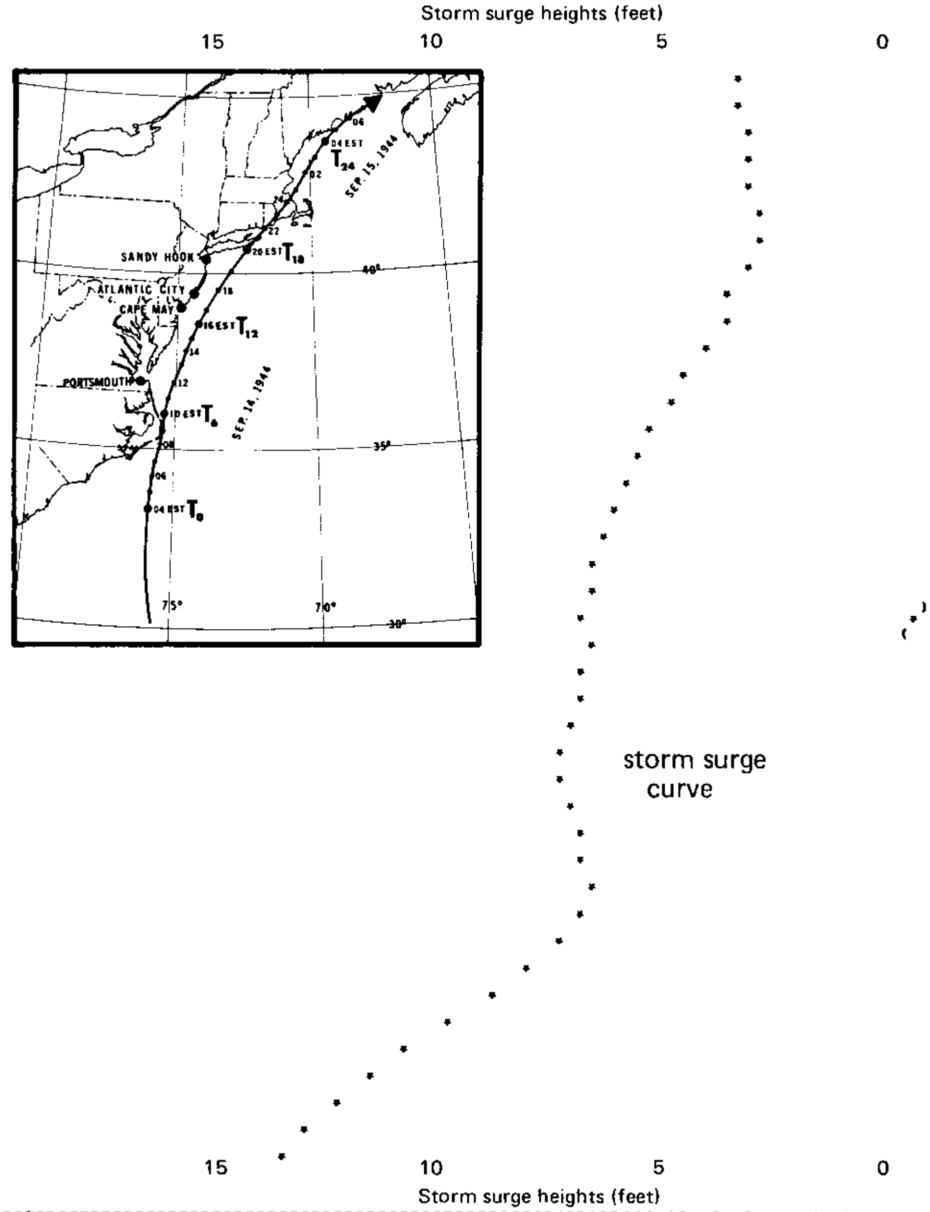
To test the method, it was applied to the devastating storm of 5-8 March 1962. Curves of observed storm surge and calculated storm surge are shown in Figure 41 for five locations in or near the Bight area. Note the considerable agreement between the calculated and the actual storm surge, demonstrating the accuracy of the method for even an intense, record-breaking storm like that in 1962.

In actual operation, sea-level pressure forecasts at the appropriate grid points are inserted in the storm surge equations. Pressure forecasts are available

Figure 38. Computed surge envelope of high waters on open coast generated by September 1944 storm. Inset shows storm track.

```
SPLASH CALCULATIONS PERFORMED ON  08/15/72  AT  21.37.19.

YOU HAVE CHOSEN THE FOLLOWING STORM AND BASIN SITUATION
THE NEAREST APPROACH OF STORM TO BASIN CENTER IS ----------------  51 MILES, ON THU, THE 14 OF SEP, 1944, AT 16 HOURS
THE BASIN,S CENTER IS LOCATED ------------------------------------  0 MILES TO THE RIGHT OF CAPE MAY
YOUR INITIAL, CLOSEST APPROACH, AND FINAL PRESSURE DROPS ARE------  100.0,   60.0,   20.0 MBS, RESPECTIVELY
YOUR INITIAL, CLOSEST APPROACH, AND FINAL STORM SIZES ARE --------   60.0,   42.5,   25.0 STATUTE MILES RESPECTIVELY
```



3.2	160.		1900 LST
3.1			1900 LST
3.0		FIRE ISL	1900 LST
3.0			1900 LST
2.9			1900 LST
2.9	120.	SNDY HOOK	1800 LST
2.9			1800 LST
3.1			1800 LST
3.4		SEA GIRT	1800 LST
3.6			1800 LST
4.0	80.	SEASIDE PK	1700 LST
4.5		BARNGT IN_	1700 LST
4.8			1700 LST
5.2			1700 LST
5.4			1600 LST
5.8	40.	ATLANTIC C	1600 LST
6.1			1600 LST
6.2		CORSON IN_	1600 LST
6.4			1500 LST
6.6			1500 LST
6.6	0.	CP MAY	1500 LST
6.6		CP HENLOPN	1500 LST
6.7			1500 LST
6.8			1400 LST
7.1		OCEAN C,MD	1400 LST
7.2	-40.		1400 LST
7.2			1400 LST
7.0			1300 LST
6.8			1300 LST
6.7		ASSATEAGUE	1300 LST
6.5	-80.		1200 LST
6.8		MTMKN INL	1200 LST
7.3			1200 LST
8.0			1100 LST
8.9			1100 LST
9.8	-120.		1100 LST
10.6		CP CHARLES	1100 LST
11.4		CP HENRY	1000 LST
12.2			1000 LST
12.9		VIRG BCH	1000 LST
13.5	-160.		1000 LST

```
TIDE HEIGHTS ARE FT ABOVE MEAN SEA LEVEL .
HOURLY VALUES ARE PRINTED 12 HRS BEFORE TO
12 HRS AFTER NEAREST APPROACH TO BASIN,S CENTER.
ESTIMATED APPROACH TIME 1600 LCL STD TIME, 14 SEP 1944        ESTIMATED NEAREST APPROACH TIME (*) [at 16]
```

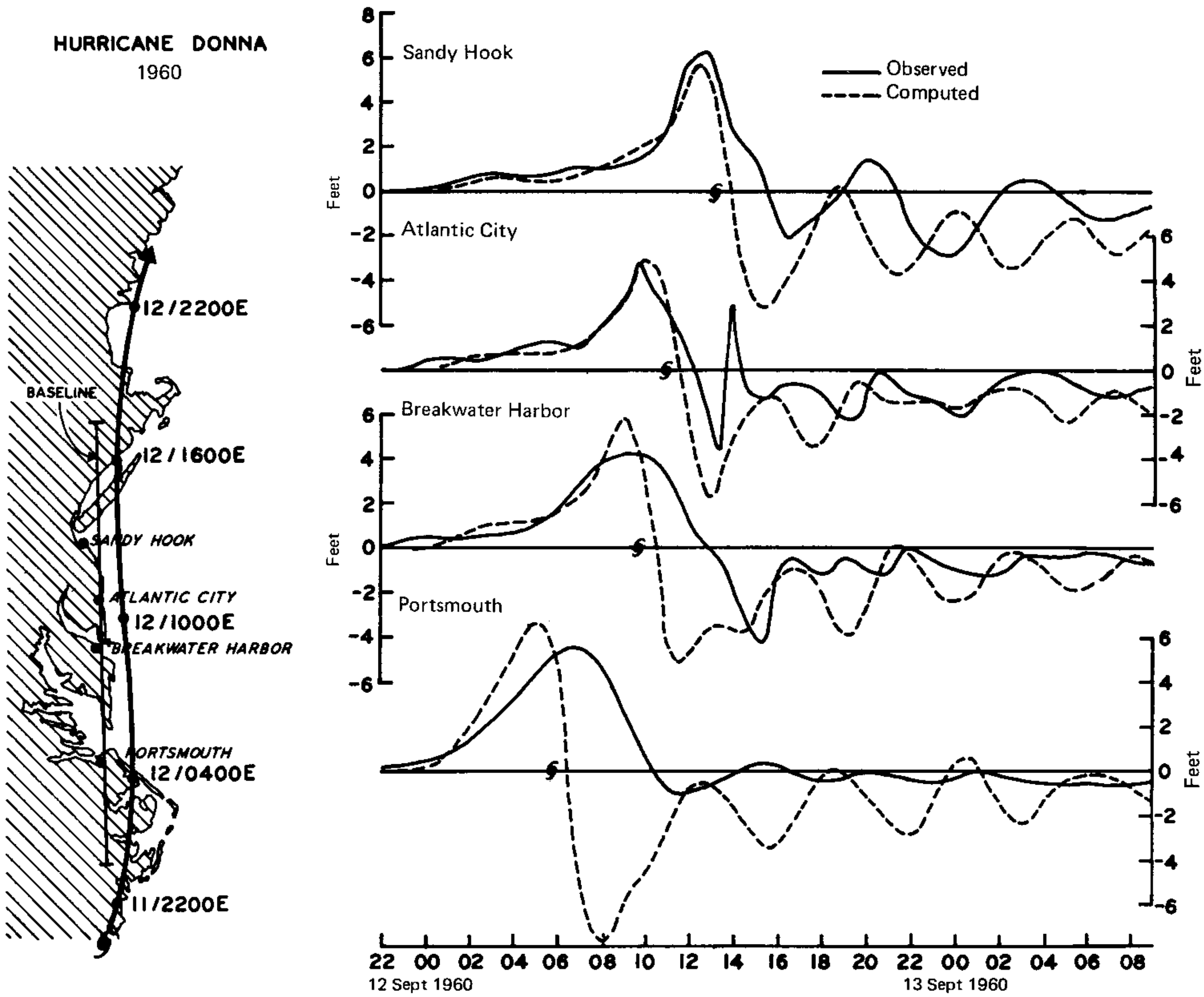
LCL STD TIME	4	5	6	7	8	9	10	11	12	13	14	15
MONTAUK PT	.4	.7	.8	.8	.6	.2	-.2	-.6	-.8	-.7	-.3	.1
SHNNCK INL	1.2	1.2	1.0	.5	-.1	-.7	-1.0	-1.1	-.8	-.2	.5	1.1
FIRE ISL	1.6	1.7	1.5	.9	.1	-.8	-1.4	-1.6	-1.3	-.6	.4	1.4
SNDY HOOK*	1.3	1.9	1.9	1.5	.8	-.2	-1.1	-1.6	-1.7	-1.3	-.4	.7
SEASIDE PK	1.6	1.8	1.6	1.0	.2	-.7	-1.3	-1.6	-1.4	-.7	.3	1.3
CORSON INL	1.1	1.5	1.6	1.3	.7	-.1	-.8	-1.4	-1.5	-1.1	-.4	.5
OCEAN C,MD	1.2	1.4	1.3	.9	.2	-.5	-1.0	-1.3	-1.2	-.7	.1	.9
MTMKN INL	.8	1.3	1.5	1.3	.9	.2	-.6	-1.1	-1.4	-1.2	-.6	.2
VIRG BCH	1.3	1.7	1.7	1.3	.6	-.1	-.7	-1.1	-1.1	-.7	.0	.8
KTTY HWK	1.4	1.6	1.5	1.1	.4	-.3	-.8	-1.1	-1.0	-.5	.2	1.0
CP HTTRS	1.6	1.8	1.6	1.1	.3	-.4	-1.0	-1.2	-1.0	-.4	.4	1.2

LCL STD TIME	16	17	18	19	20	21	22	23	24	1	2	3	4
MONTAUK PT	.6	.9	1.0	1.0	.8	.5	-.0	-.5	-.8	-.9	-.6	-.2	.2
SHNNCK INL	1.5	1.7	1.4	.9	.2	-.5	-1.1	-1.3	-1.3	-.8	-.2	.5	1.1
FIRE ISL	2.1	2.3	2.1	1.5	.6	-.4	-1.3	-1.8	-1.9	-1.4	-.5	.5	1.4
SNDY HOOK*	1.8	2.4	2.6	2.3	1.5	.4	-.8	-1.7	-2.1	-2.0	-1.3	-.3	.8
SEASIDE PK	2.1	2.4	2.2	1.6	.7	-.3	-1.3	-1.9	-1.9	-1.5	-.6	.4	1.3
CORSON INL	1.4	2.0	2.2	2.0	1.3	.4	-.5	-1.4	-1.8	-1.7	-1.2	-.3	.6
OCEAN C,MD	1.6	1.9	1.9	1.4	.7	-.1	-.9	-1.5	-1.6	-1.3	-.6	.2	1.0
MTMKN INL	1.1	1.7	2.0	1.9	1.4	.6	-.3	-1.1	-1.6	-1.7	-1.3	-.6	.3
VIRG BCH	1.6	2.0	2.1	1.8	1.2	.3	-.5	-1.1	-1.3	-1.1	-.5	.2	1.0
KTTY HWK	1.6	2.0	2.0	1.6	.9	.1	-.5	-1.1	-1.2	-.9	-.3	.4	1.1
CP HTTRS	1.9	2.3	2.2	1.7	.9	-.0	-.8	-1.3	-1.3	-1.0	-.3	.6	1.4

* PRIMARY TIDE PREDICTION SITE - IF AVAILABLE

Source: Jelesnianski 1974

Figure 39. Observed storm surges and storm surges calculated by SPLASH model using curvilinear coordinate system. (Courtesy of C.P. Jelesnianski)

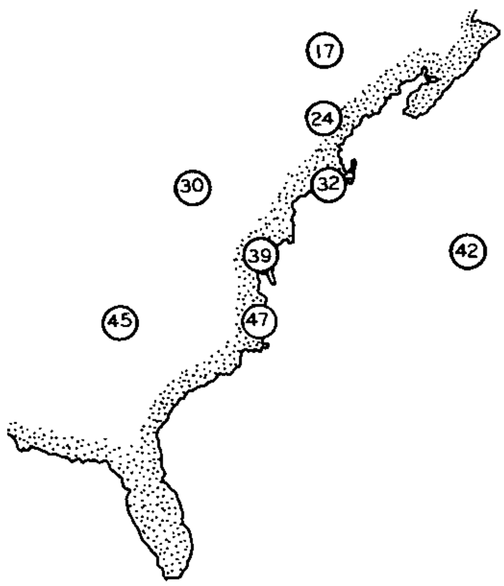


twice daily from a numerical weather model in the Weather Service's National Meteorological Center. Pressure forecasts to 48 hours at 6-hr intervals are used.

A sample teletype bulletin of storm surge height forecasts for 10 locations is shown in Figure 42. The forecasts are expressed in feet at time intervals of six hours for the 48-hr forecast period. Such messages are transmitted on a Weather Service teletype circuit to forecast offices where they may be modified by later observational data and past storm surge experience. Coastal flood warnings are based on these extratropical storm surge forecasts along with astronomic tide information.

This method will continuously be improved by including recent extratropical storm surge data beyond the original 14-year developmental information. More forecast points will also be added to the system.

Figure 40. Storm surge forecast equation for New York. SS is storm surge; number in parentheses is grid point (circled on map) for which sea-level pressure is used as predictor; subscript on each term is time lag of predictor in hours.



$$SS(NYC)_t = A - B(47)_{t-6} + C(17)_{t-6} - D(42)_{t-6} - E(30)_{t-6} + F(24)_{t-6} - G(39)_{t-6} + H(32)_{t-6} + I(45)_t$$

Source: Pore, Richardson, and Perrotti 1974

Figure 41. Observed and calculated storm surges, March 1962 storm. Solid lines are observed storm surges; dashed lines connect storm surges calculated at 6-hr intervals, based on analyses of sea-level pressure.

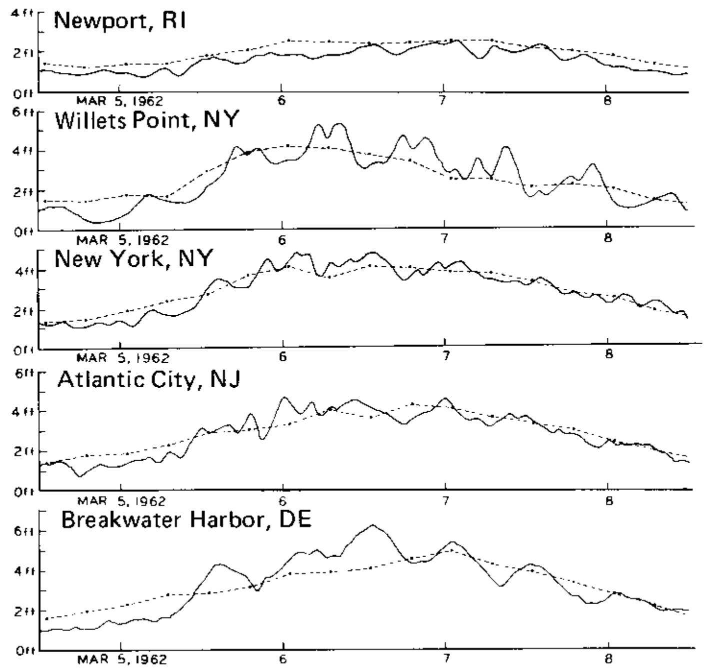


Figure 42. Storm surge forecast teletype message. Valid times indicated above each column; station call signs identified below message.

```
FZUS3 KWBC 021200
EAST COAST STORM SURGE FORECAST IN FEET
            12Z  18Z  00Z  06Z  12Z  18Z  00Z  06Z  12Z
   PWM      0.1  0.4  0.5  0.7  0.7  0.9  0.8  0.9  0.7
   BOS      0.1  0.2  0.3  0.4  0.4  0.5  0.4  0.6  0.3
   NWP      0.8  1.0  1.1  1.2  1.2  1.3  1.1  1.1  0.9
   SFD      1.0  1.1  1.2  1.2  0.9  0.7  0.6  0.1  0.0
   LGA      1.0  1.0  1.0  1.3  1.2  1.0  1.0  0.8  0.7
   NYC      1.2  1.3  1.4  1.4  1.3  1.2  1.0  0.9  0.7
   ACY      0.8  0.9  1.0  0.9  0.9  0.9  0.8  0.8  0.7
   BWH      1.1  1.1  1.2  1.0  0.9  0.9  0.7  0.7  0.6
   BAL      2.4  2.5  2.6  2.8  2.8  2.6  2.4  2.0  1.9
   ORF      0.9  0.8  0.9  0.8  0.8  0.8  0.7  0.6  0.9
   PWM  Portland, Maine
   BOS  Boston, Massachusetts
   NWP  Newport, Rhode Island
   SFD  Stamford, Connecticut
   LGA  Willets Point, New York
   NYC  Battery, New York
   ACY  Atlantic City, New Jersey
   BWH  Breakwater Harbor, Delaware
   BAL  Baltimore, Maryland
   ORF  Hampton Roads, Virginia
```

Source: Pore, Richardson, and Perrotti 1974

Summary

Storm surges are of great concern in the New York Bight area whenever hurricanes or intense extratropical storms approach or cross its coastline. Sea level can increase to more than 10 ft (3.1 m) above normal high tide level. Such abnormal water levels are a threat to human life. Extensive property damage to homes, boats, automobiles, businesses, recreation facilities, highways, airports, and industrial facilities has occurred during storm surge situations. Timely forecasts are valuable for safeguarding human lives and reducing such property damage.

Knowing the frequency of hurricanes, extratropical storms, and storm surges is important for planning purposes. Knowing frequencies of storm surges of various heights helps determine what flood levels should be protected against in new construction, such as power plants, factories, or private residences.

National Weather Service storm surge forecasts, although not perfect, are effective in protecting life and property. Forecasts are improving as refined techniques for both storm surges and storms are developed.

Bristor, C.L. 1951. The great storm of November 1950. *Weatherwise* 4(1):10-16.

Burton, I., Kates, R.W., Mather, J.R., and **Snead, R.E.** 1965. *The shores of megalopolis: coastal occupance and human adjustment to flood hazard.* Elmer, NJ: C.W. Thornthwaite Assoc., Lab. Climatol.

Cooperman, A.I., and **Rosendal, H.E.** 1962. Great Atlantic coast storm, 1962. *Climatol. Data, Nat. Sum.* 13(3):137-45. Washington, DC: Dep. Com. Weather Bur.

Cry, G.W. 1965. *Tropical cyclones of the North Atlantic Ocean.* Tech. Paper 55. Washington, DC: US Dep. Com. Weather Bur.

Davis, W.R. 1954. Hurricanes of 1954. *Monthly Weather Rev.* 82(12):370-73.

Dunn, G.E. 1961. The hurricane season of 1960. *Monthly Weather Rev.* 89(3):99-108.

Harris, D.L. 1963*a.* Coastal flooding by the storm of March 5-7, 1962. Unpub. ms. of US Weather Bur. Washington, DC: US Dep. Com.

_____. 1963*b. Characteristics of the hurricane storm surge.* Tech. Paper 48. Washington, DC: US Dep. Com. Weather Bur.

_____, and **Lindsay, C.V.** 1957. *An index of tide gages and tide gage records for the Atlantic and Gulf coasts of the United States.* Nat. Hurricane Res. Proj. Rep. 7. Washington, DC.

Ho, F.P. 1974. *Storm tide frequency analysis for the coast of Georgia.* NOAA Tech. Mem. NWS HYDRO 19. Silver Spring, MD.

_____, and **Tracey, R.J.** 1975. *Storm tide frequency analysis for the coast of North Carolina, south of Cape Lookout.* NOAA Tech. Mem. NWS HYDRO 21. Silver Spring, MD.

Jelesnianski, C.P. 1966. Numerical computations of storm surges without bottom stress. *Monthly Weather Rev.* 94(6):379-94.

_____. 1967. Numerical computations of storm surges with bottom stress. *Monthly Weather Rev.* 95(11):740-56.

_____. 1972. *SPLASH (special program to list amplitudes of surges from hurricanes),* pt. 1, *Landfall storms.* NOAA Tech. Mem. NWS TDL 46. Silver Spring, MD.

_____. 1974. *SPLASH (special program to list amplitudes of surges from hurricanes),* pt. 2, *General track and variant storm conditions.* NOAA Tech. Mem. NWS TDL 52. Silver Spring, MD.

Malkin, W., and **Holzworth, G.C.** 1954. Hurricane Edna, 1954. *Monthly Weather Rev.* 82(9):267-79.

Munk, W., Snodgrass, F., and **Carrier, G.** 1956. Edge waves on the continental shelf. *Science* 123 (3187):127-32.

Myers, V.A. 1970. *Joint probability method of tide frequency analysis applied to Atlantic City and Long Beach Island, NJ.* ESSA Tech. Mem. WBTM HYDRO 11. Silver Spring, MD.

_____. 1975. *Storm tide frequencies on the South Carolina coast.* NOAA Tech. Rep. NWS 16. Silver Spring, MD.

Pierce, C.H. 1939. The meteorological history of the New England hurricane of September 21, 1938. *Monthly Weather Rev.* 67(8):237-85.

Pore, N.A. 1964. The relation of wind and pressure to extratropical storm surges at Atlantic City. *J. Appl. Meteorol.* 3(2):155-63.

_____, **Richardson, W.S.,** and **Perrotti, H.P.** 1974. *Forecasting extratropical storm surges for the northeast coast of the United States.* NOAA Tech. Mem. NWS TDL 50. Silver Spring, MD.

Simpson, R.H., and **Hope, J.R.** 1972. Atlantic hurricane season of 1971. *Monthly Weather Rev.* 100(4):256-67.

Smith, C.D. 1950. The destructive storm of November 25-27, 1950. *Monthly Weather Rev.* 78(11):204-09.

Stewart, J.Q. 1962. The great Atlantic coast tides of 5-8 March 1962. *Weatherwise* 15(3):116-20.

Tannehill, I.R. 1938. Hurricane of September 16-22, 1938. *Monthly Weather Rev.* 66(9):286-88.

_____. 1944. *Hurricanes.* 5th ed. Princeton, NJ: Princeton Univ. Press.

Tippets-Abbett-McCarthy-Stratton (Engineers). 1958. *Hurricane tide inundation damage survey—New York Harbor, including New York metropolitan area, New York, and New Jersey.* Revised Rep. for Corps of Eng., NY Dist.

US Army Corps of Engineers. 1963. *Report of hurricane study, Atlantic City, NJ.* Philadelphia Dist.

_____. 1973. *Shore protection manual.* Vol. 1. Ft. Belvoir, VA: Corps of Eng. Coastal Eng. Res. Cent.

Weather Bureau, US Department of Commerce. 1968. *Climatological Data, National Summary* 19(11). Washington, DC.

Winston, J.S. 1954. The weather and circulation of August 1954—including a discussion on hurricane Carol in relation to the planetary wave pattern. *Monthly Weather Rev.* 82(8):228-36.

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