Chapter 41

THE ASH WEDNESDAY EAST COAST STORM, MARCH 5-8, 1962 A HINDCAST OF EVENTS, CAUSES, AND EFFECTS

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ABSTRACT

Hindcasts were made for winds, waves and tides for several east coast locations for the storm of 5-8 March 1962. A limited amount of recorded data and a considerable amount of other observations were available from near-by and remote stations. The data were analyzed for correlation or "calibration" purposes in order to improve the "state of the art" of wave and storm surge hindcasting for locations where recorded data were not available. Wind records were analyzed to obtain sustained wind speeds, average gust factors, and probability distribution of gust factors. Isobaric patterns were used to determine sustained wind speeds over the water fetch for deep and shallow water waves and storm surge hindcasts. Wave run-up calculations were made to determine the wave activity on the beach and the dunes and were used to estimate the probable rate of beach erosion and dune evolution. The off-water wind speeds were modified to determine wind speeds over the beach and over the top of the dunes. Finally, by summarizing the time-history of the various meteorological, oceanographic, and coastal engineering events, a very interesting scientific and engineering evaluation of the causes and effects can be made.

INTRODUCTION

The Ash Wednesday East Coast Storm, 5-8 March 1962, was perhaps the most severe storm of the century along the east coast of the United States. It occurred during spring tide conditions, and as a result produced near-record-breaking high tides enabling large waves to attack the shoreline and cause extensive beach erosion, and combined with exceptionally high winds caused a tremendous amount of property damage along the Atlantic coast from Long Island, New York, to Cape Hatteras, North Carolina. The effects of the storm even reached northern Florida where swell greater than 12 seconds was a record observed for the first time. In many cases the dunes were moved back 20 to 40 feet or more. Figure 1 shows the areas of interest along the east coast of the United States.

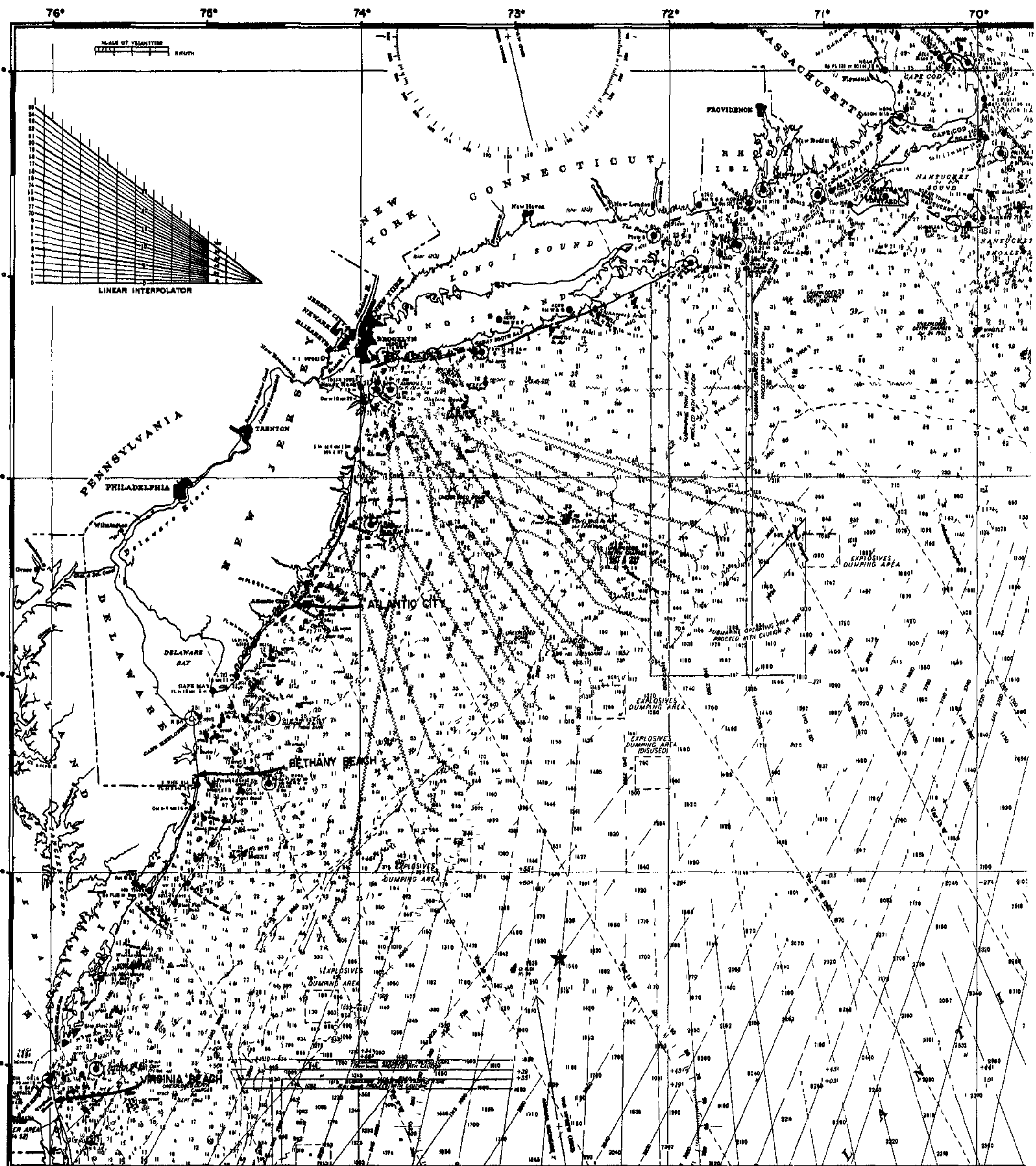


FIG. 1.--LOCATION MAP, EAST COAST OF UNITED STATES

The storm persisted through four to five high tide cycles, a situation which never before had been recorded. As compared to a hurricane, this storm can be considered greater in damage potential because a hurricane affects a much shorter reach of coastline at any particular time and usually lasts through only one high tide cycle at a particular location. Furthermore, in a hurricane the high tides usually precede the highest winds whereas in a steady-state type northeast storm the highest winds usually precede, and may last through, the highest tides.

Two particular areas were investigated in detail and a third qualitatively by use of hindcast techniques. The location of Atlantic City, New Jersey (Ventnor, N. J. to be exact) was investigated by Bretschneider and Collins (1963), and South Bethany, Delaware, was investigated by Bretschneider, Le Mehaute, and Allen (1963). The coast of Virginia was investigated qualitatively. In all cases the detailed hindcasts were correlated with available data.

The winds and tides in the area were comparatively well recorded giving a complete picture of the wind and water levels near the coast. The only actual waves recorded were for the early part of the storm at the Beach Erosion Board's wave gauge on the Steel Pier at Atlantic City, N. J. The gauge became inoperative on the second day due to power failure when a part of the Pier was destroyed by a drifting barge or ship. The U. S. Coast and Geodetic Survey tide recorder, also near the end of Steel Pier, operated throughout the storm since no outside power source was required. A number of Coast Guard lightships observed and logged wind and wave data. These wave data are for moderate water depths on the continental shelf and are not applicable to the shallower surf zone depths along the coastline.

The extent of damage caused by this storm has been summarized previously by O'Brien and Johnson (1962). The storm even affected shipping to a great extent. Some ships actually lost distance when navigating into the wind and waves.

This paper represents a hindcast of the causes and effects of the great northeast storm of 5-8 March 1962. Included in the hindcast are deep water waves; waves and tides over the continental shelf and in the surf zone; and wind, tides, waves, wave run-up and erosion over the beach and the dunes. In some respects this paper is more or less a case history study, and a test of hindcasting techniques. It should be apparent from this report that there are certain interesting aspects requiring further research.

THE PROBLEM

The problem is best defined in terms of a general problem coupled with individual local problems. The general problem pertains to the determination of wind, waves and swell, and tides from deep water to breaking wave or surf zone, and if more-or-less average physical coastal features are assumed, the general study can be extended from the surf zone to the coastline over the beach and dunes to the limits of the flooding. The local studies include any deviations from the general study as might be required for an engineering evaluation of the timing and causes of damage, whether wind or water or a combination of both. The type of engineering evaluation depends on whether the structure is a pier extending into the sea, a coastal bulkhead, a dune, or a building on top of or behind the dune, etc.

Specifically the problem consists of the determination of the time-history of many events. The following steps are generally considered important:

1. Analyze past weather maps for the particular storm of interest to determine wind and wind stress diagrams.

2. Analyze all other available data pertinent to the area of interest such as wind, tide, storm surge, waves, wave run-up, high water marks, beach and dune erosion, etc.

3. Hindcast deep water wave heights and periods and compare, where possible, with existing data.

4. Determine the normal or predicted tide using the appropriate tide tables.

5. Hindcast storm surge and compare with existing data, where possible.

6. Hindcast wave heights and periods over the continental shelf taking into account the combined effects of bottom friction, wave refraction, wind generation, and compare with existing data, where possible.

7. Hindcast the breaking wave heights and periods and depths of breaking waves in the surf zone coincident with total tides.

8. Hindcast wave heights and periods at the coastline coincident with the total tides.

9. Hindcast wave run-up on the beach, berm and dunes.

10. Hindcast the beach and berm erosion and dune evolution.

11. Hindcast the sustained winds and peak gusts along the coastline.

12. Hindcast the sustained winds and peak gusts over the dunes for the area of interest

13. Compute wave and wind pressures and forces for the type of structure being affected.

14. Analyze in detail each particular structure of interest subjected to all or some of the factors hindcasted above.

15. Based on all the available information, hindcast data and observed and/or recorded data, determine the most probable cause or causes and time of damage and/or destruction of various structures.

The above step-by-step procedure appears to be relatively straight-forward and somewhat idealistic. Depending upon the available facts, each particular problem can impose difficulties of various degrees. However, when the problem as a whole is finally analyzed in terms of good engineering judgment, then the many inherent difficulties are minimized and very sound conclusions can be drawn. Perhaps one of the most important reminders is that there must be coherence from location to location. Eyewitness accounts from people possessing no particular self-interest are a consolation to the accuracy of the hindcasts. Although the consistancies between reliable eyewitness accounts and a hindcast have a definite role in establishing the factual causes of damage during the storm, eyewitness accounts during the storm should not be considered as scientific data to be used in the calibration of the hindcast techniques.

AVAILABLE DATA

In order to perform the hindcast study, various sources of data must be investigated and the data must be studied. Important for this study were the following:

1. The official U. S. Weather Bureau maps, Northern Hemisphere charts, at 6-hourly intervals, 5-8 March 1962, were used to determine sustained wind speeds and direction over the water fetch. Figure 2 gives a typical example of the component of wind speed resulting in maximum wave generation, and figure 3 gives a typical example of the average wind stress diagrams resulting in maximum storm surge generation off the east coast.

2. The official U. S. Coast and Geodetic Survey recorded tide data for various locations along the east coast of the United States were used to determine the increase in total water depth during the storm. This information is of value to hindcast total water depths where recordings were not available. Figure 4, reproduced from Harris (1963), gives the storm surge hydrographs measured at various locations along the east coast. Figure 5, also reproduced from Harris (1963), shows high water marks which were indicative of wave set-up, and also maximum probable wave run-up.

3. The U. S. Coast and Geodetic Survey Tide Tables for 1962 were used to determine the normal predicted tides, sometimes called the astronomical tides. Neglecting the second order effects, the storm surge is obtained by subtracting the predicted tide from the recorded tide.

4. The Beach Erosion Board's analysis of the wave record for Atlantic City Steel Pier, 5-6 March 1962, was used to check the accuracy of wave hindcasts in shallow water near the coast, mean low water depth of about 17 feet. (The wave gauge became inoperative after 0400 GMT on 6 March 1962.)

5. The official U. S. Weather Bureau records and logs for various land stations near the coast were used to determine relations between average gust speeds and 1-minute average sustained wind speed, and were also used to determine the probability distribution of gust factors. The 1-minute average is the average of the last 1-minute of a 15-minute period, and the gust is the peak wind during the same 15-minute period.

6. Wind and wave data logged by U. S. Coast Guard lightships and other vessels at sea were used to check wind and wave hindcasts. The winds reported by ships at sea represent an average wind speed, and gusts are not normally reported. The waves are average of the maximum observed and are probably close to the significant wave.

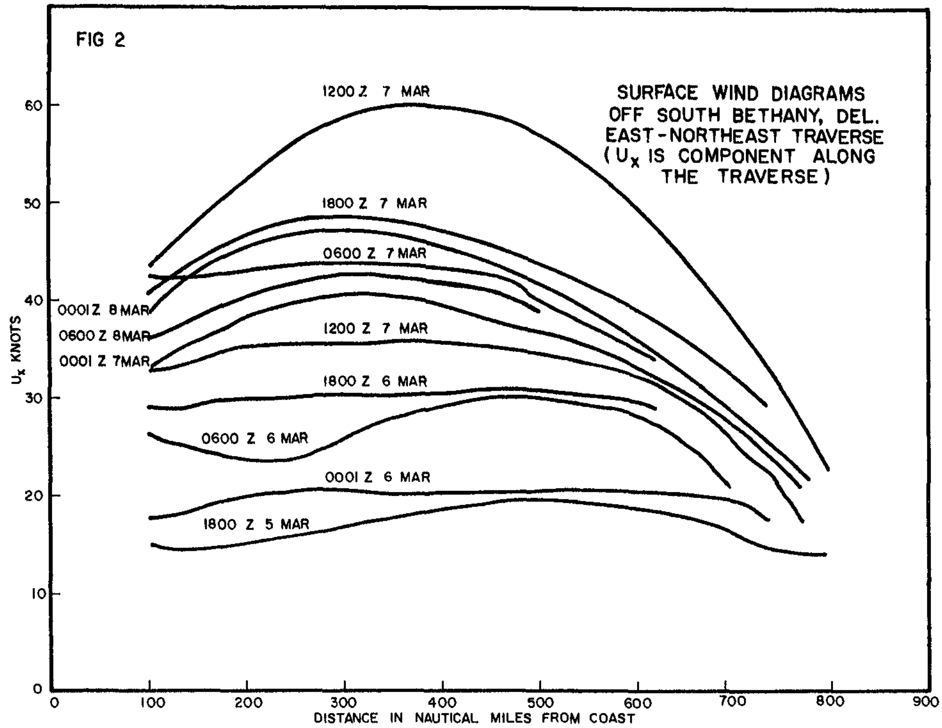


FIG 2
SURFACE WIND DIAGRAMS
OFF SOUTH BETHANY, DEL.
EAST-NORTHEAST TRAVERSE
(U_x IS COMPONENT ALONG THE TRAVERSE)
1200 Z 7 MAR
1800 Z 7 MAR
0600 Z 7 MAR
0001 Z 8 MAR
0600 Z 8 MAR
1200 Z 7 MAR
0001 Z 7 MAR
1800 Z 6 MAR
0600 Z 6 MAR
0001 Z 6 MAR
1800 Z 5 MAR
U_x KNOTS
0
10
20
30
40
50
60
0
100
200
300
400
500
600
700
800
900
DISTANCE IN NAUTICAL MILES FROM COAST

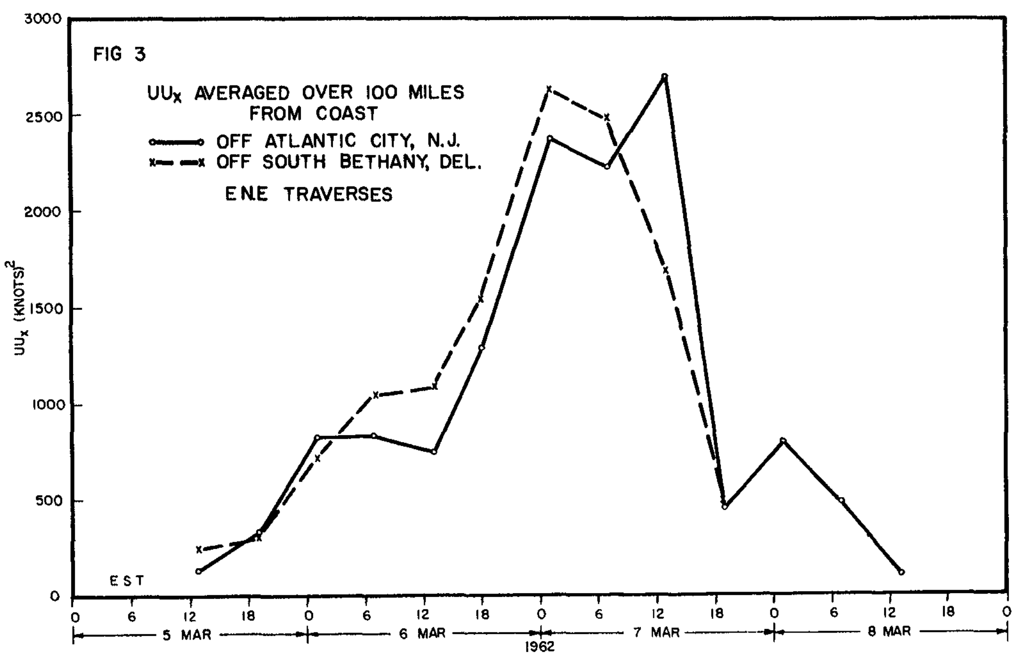


FIG 3
UU_x AVERAGED OVER 100 MILES
FROM COAST
OFF ATLANTIC CITY, N.J.
OFF SOUTH BETHANY, DEL.
ENE TRAVERSES
UU_x (KNOTS)^2
0
500
1000
1500
2000
2500
3000
EST
0 6 12 18 0 6 12 18 0 6 12 18 0 6 12 18 0
5 MAR
6 MAR
7 MAR
8 MAR
1962

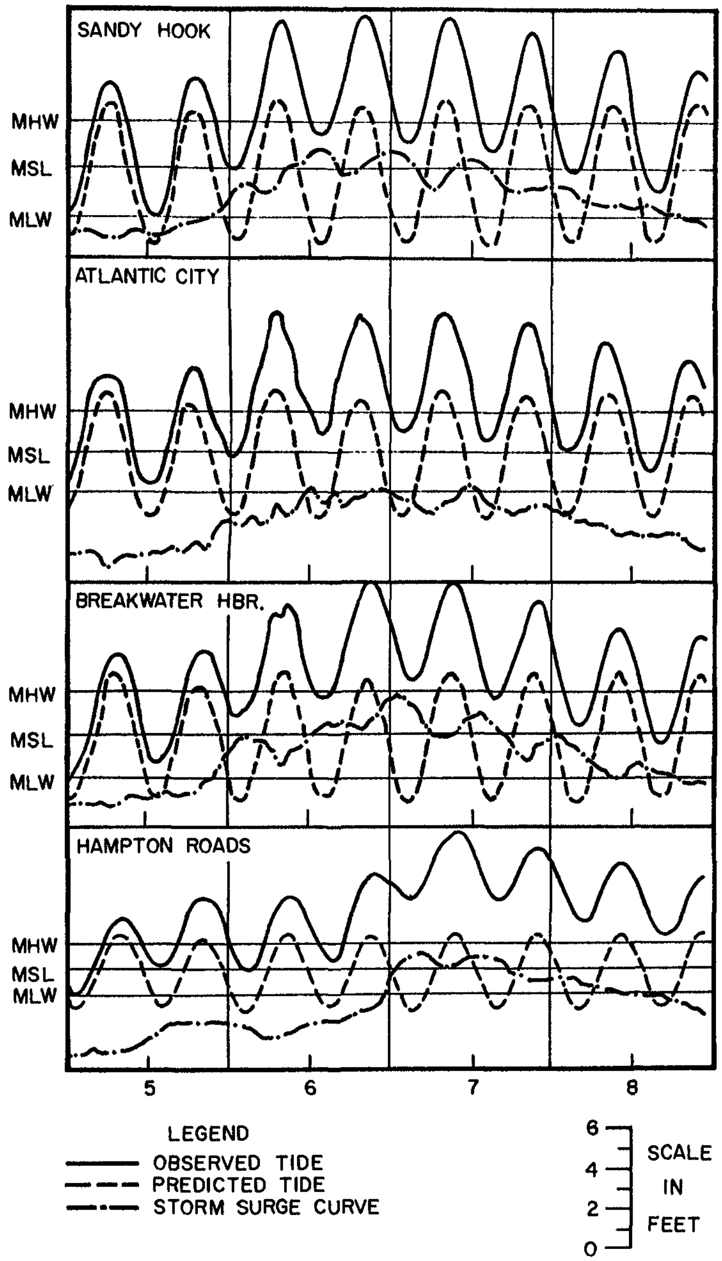
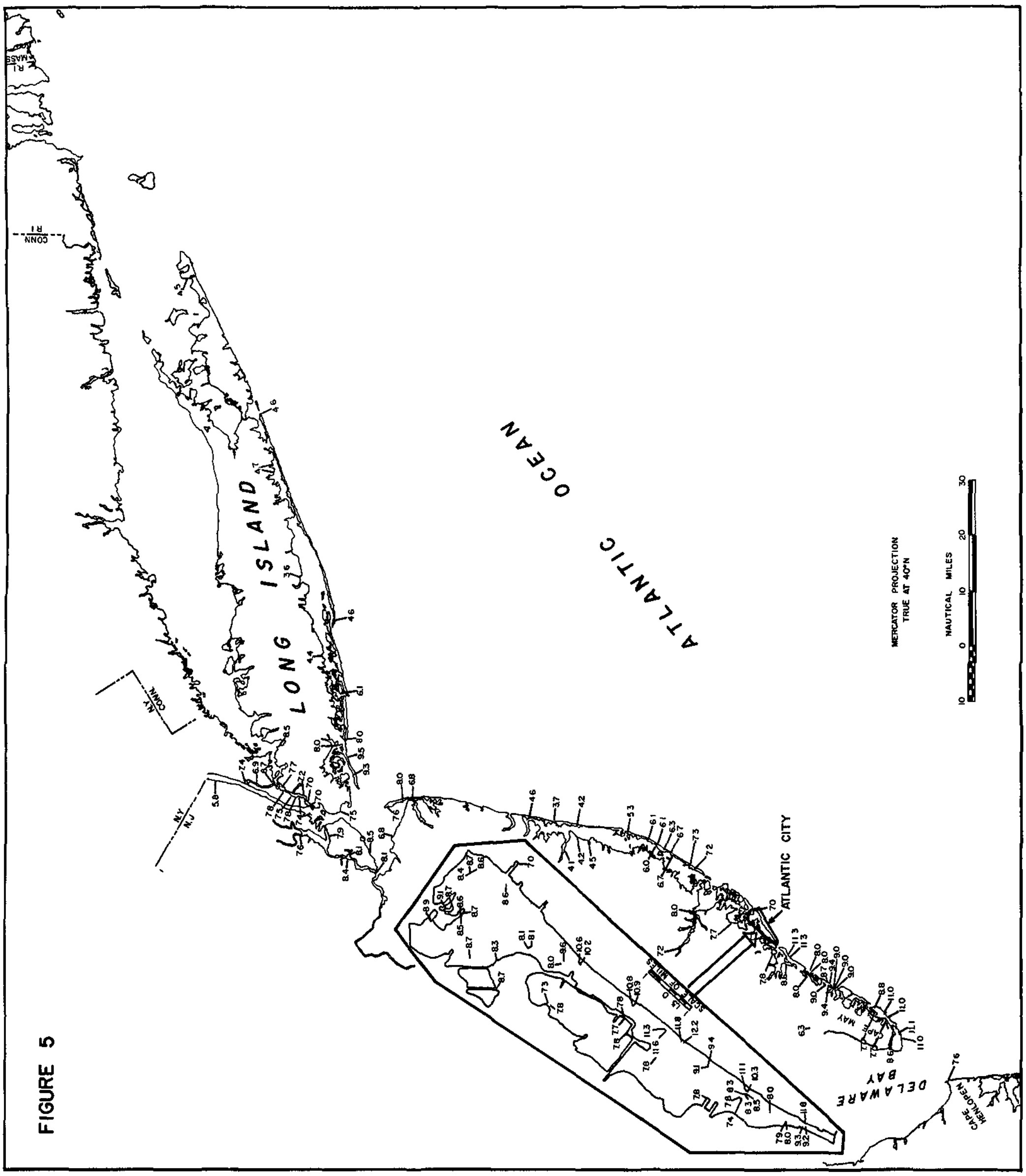


FIG. 4 OBSERVED TIDE, PREDICTED TIDE AND STORM SURGE, FOR SELECTED STATIONS MARCH 5-8, 1962. (AFTER HARRIS, 1963)

FIGURE 5



HIGH WATER MARKS FOR THE EARLY MARCH STORM, 1962 (REDRAFTED FROM HARRIS, 1963)

7. The U. S. Coast and Geodetic Survey hydrographic charts for the year 1954 were used to obtain the bottom profiles from deep water, over the continental shelf, through the surf zone, to the coastline. Figure 6 shows typical bottom profiles for various locations off the east coast of the United States, representative of the year 1954. Other sources of information were consulted in order to estimate the more recent changes near the coastline.

8. The U. S. Army Engineer District "Beach Erosion Control Survey Report, Kitts Hummock to Fenwick Island, Delaware," was used to obtain details of beach and dune profiles and soil conditions for the Delaware coast as of the year 1954. This report was also of use to hindcast the average change in bottom contours and the coastline after 1954 based on the corresponding changes prior to 1954. Some of this information also appears in House Document 216, 85th Congress, 1958. Figure 7 represents typical average dune and beach profiles prior to and after the 1962 storm.

9. The U. S. Army Engineer District post-storm survey and flood reports were used to examine the extent of flooding, beach and dune erosion, and the general extent of damage. This included three reports: "Post-Flood Report, Coastal Storm of 6-7 March 1962, Southern New Jersey and Delaware," prepared by the U. S. Army Engineer District, Philadelphia, December 1962; "The March 1962 Storm along the Coast of Maryland," prepared by the U. S. Army Enginee District, Baltimore, November 1962; "The March 1962 Storm on the Coast of Virginia," prepared by the U. S. Army Engineer District, Norfolk, August 1962.

10. Hearings before the Sub-Committee on Oceanography, 87th Congress, April 4, 1962, on "Improvement of Storm Forecasting Procedures," were examined for certain information and various degrees of opinions pertaining to the 6-8 March 1962 east coast storm.

11. The U. S. Army Engineer District Report, "Revised Report on Cooperative Beach Erosion Control Study for Atlantic City, N. J.," June 1962 (unpublished), was used to obtain the beach profiles at Ventnor, N. J. before and after the storm. Figure 8 is based on this report.

12. Estimates of beach and dune erosion along the Delaware coast were obtained from the Beach Erosion Board. Typical of this information is Figure 9.

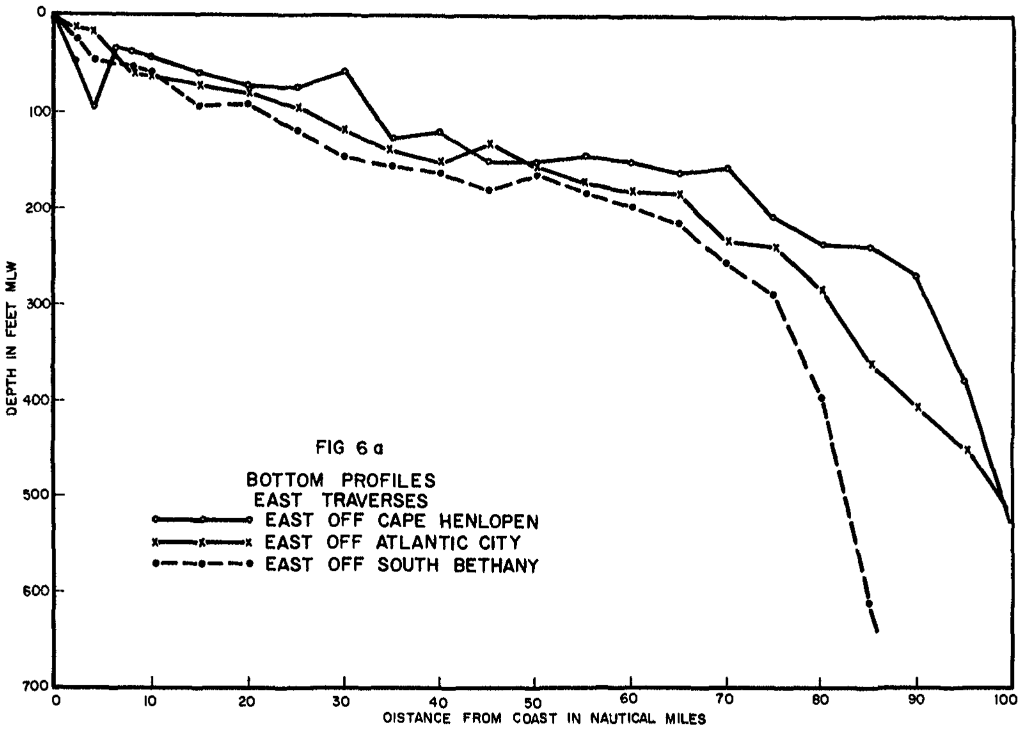


FIG 6 a

BOTTOM PROFILES
EAST TRAVERSES

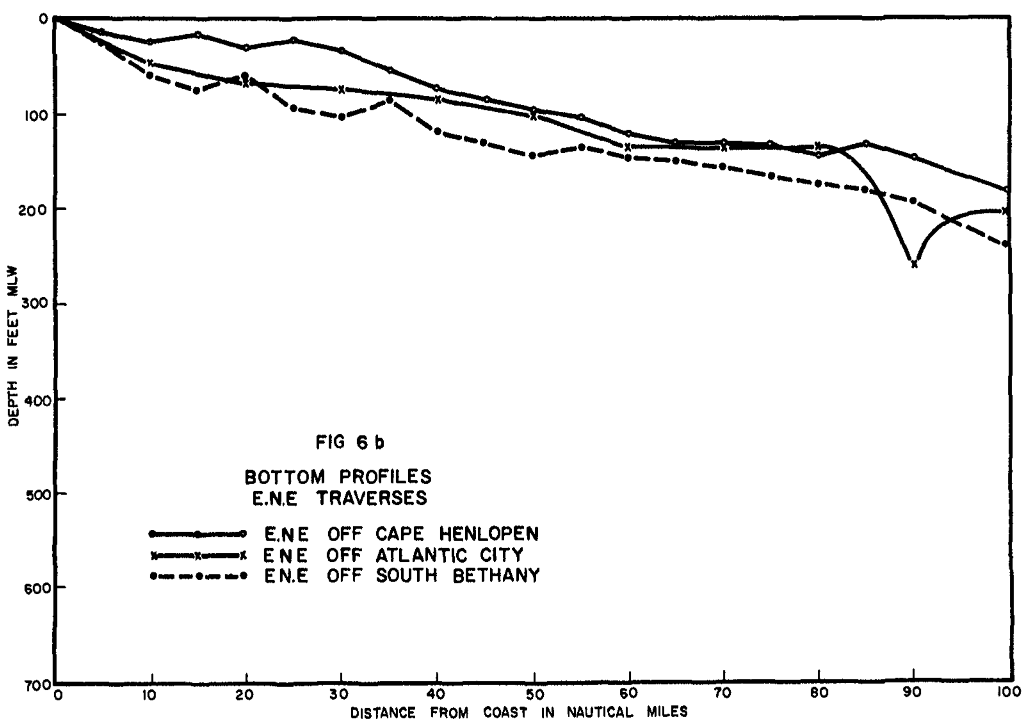
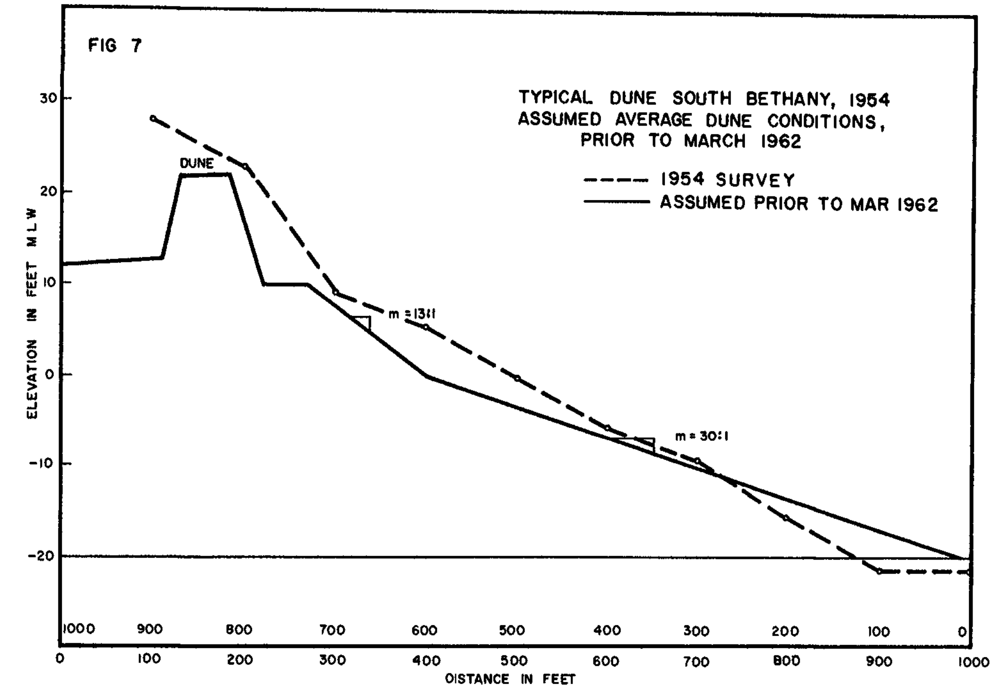


FIG 6 b

BOTTOM PROFILES
E.N.E TRAVERSES



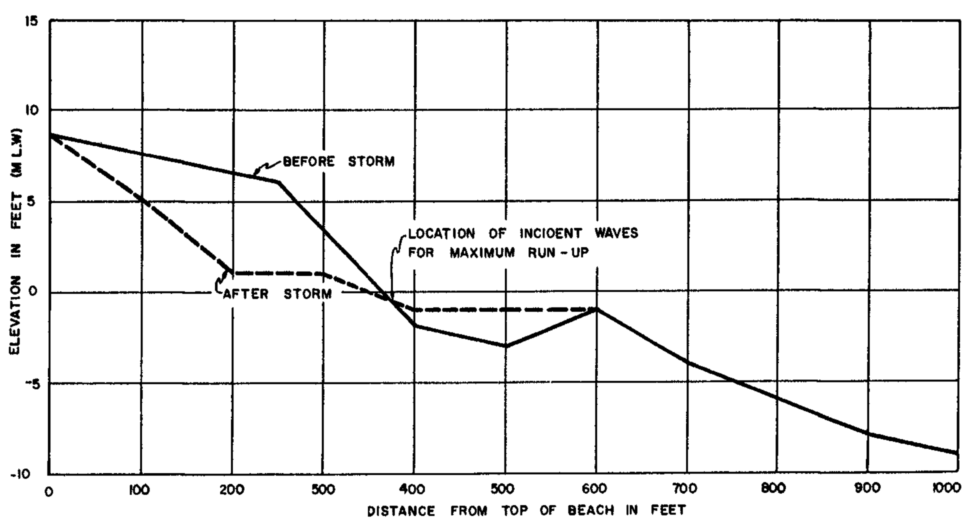


FIGURE 8 BEACH PROFILES AT VENTNOR, BEFORE AND AFTER STORM OF MARCH 1962

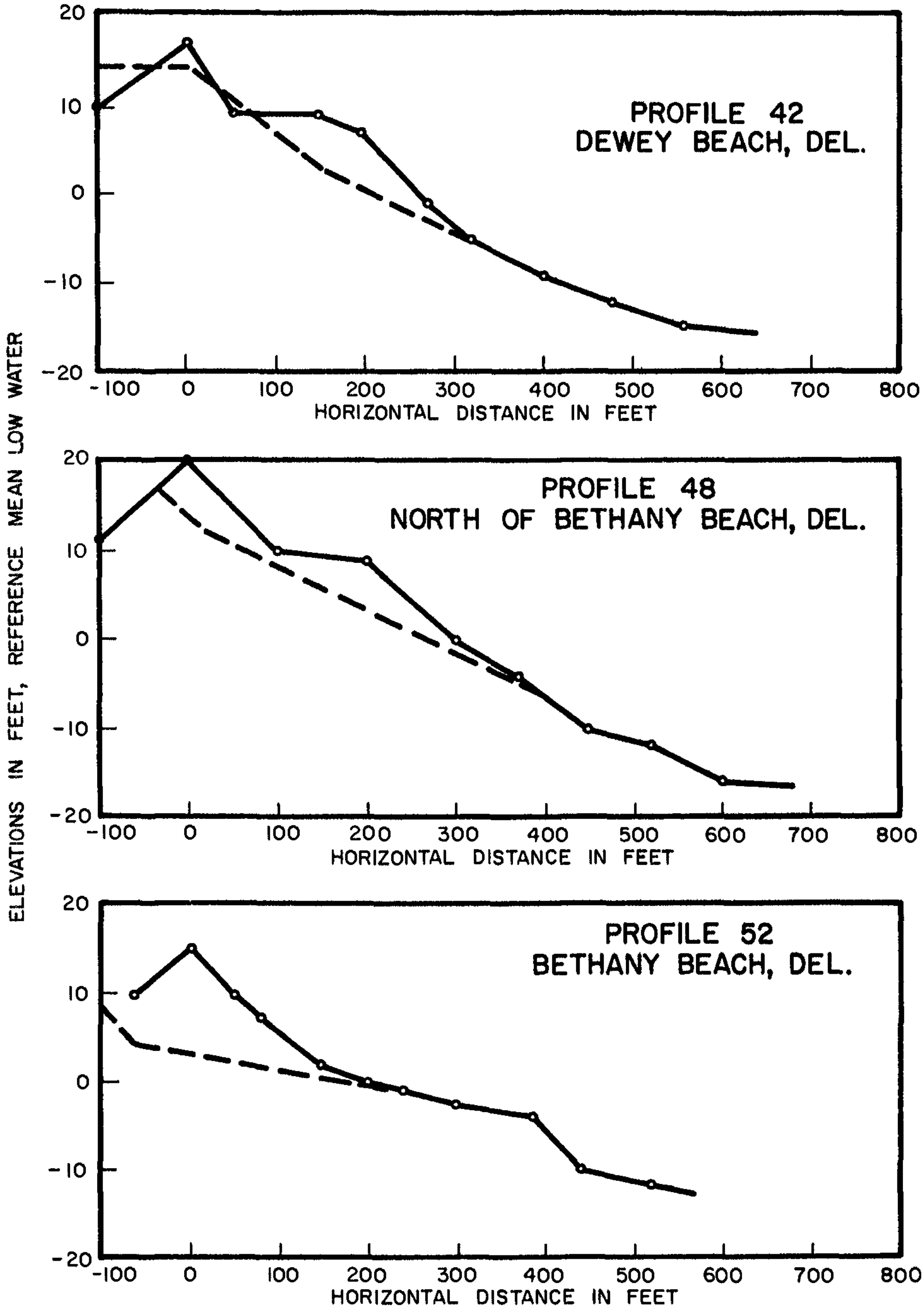


FIG. 9 TYPICAL BEACH PROFILES FOR DEL. COAST
(BEFORE AND AFTER STORM)

1954 SURVEY
ESTIMATED 15 MAR, 1962

13. Various U. S. Weather Bureau publications (given in the references at the end of this paper) were used for supplemental data.

14. Numerous U. S. Coast and Geodetic Survey aerial photographs of the coastline before and after the storm were used to estimate the extent of flooding and erosion. Figure 10 shows typical photgraphs taken before and after the storm.

15. Numerous storm reports, including many photographs published by various newspapers, were used with great interest. References to this material are given at the end of this paper.

16. Supplemental data and text material, given in the references, were used to support the interpretations and conclusions of the study. For example, an analysis of winds for Hurricane Carla, 1961, was made in order to verify the relationships of gust speed to wind speed for high winds for coastal and inland stations. This information aids in the conclusion for various relationships established for the east coast storm, and is consistent with the relationships found in literature for other storms.

17. Data on model tests by Ning Chien, et. al. (1951) were investigated to determine the behavior of wind over various shaped objects. Also of particular interest were the results of a very elaborate field experiment by Landsberg (1942) along the west coast of Lake Michigan, which included relationships for the vertical distribution of winds over the beach and over a typical Michigan sand dune.

AVAILABLE THEORY AND PROCEDURES

When making wind, wave, tide and wave run-up hindcasts, it is necessary to use selected theories and procedures, coupled with any reliable available data, and the hindcast procedures may be altered accordingly. In some respects the formulations may be considered more or less semi-theoretical or semi-empirical. Regardless of the terminology, the theory and procedures used must be of sound engineering judgment. For this particular study the following determinations were included.

1. Over-water wind speeds were computed from the pressure gradients obtained from the U. S. Weather Bureau maps, using the procedures outlined in Beach Erosion Board Technical Report No. 4 (BEB T. R. 4), "Shore Protection Planning and Design" (revised ed., 1961).

AERIAL PHOTOGRAPH - 1962

FIGURE 10A DUNES - 1954

1 2 3 3 2

BEFORE AFTER

FIGURE 10 B SOUTH BETHANY, DELAWARE

Winds were also estimated by averaging the observed wind speeds which were entered on the weather charts. Both the computed winds and the winds averaged from the observations represent a 10 to 15 minute average sustained wind at 10 meters above the water surface, such as those defined by the U. S. Weather Bureau (Goodyear, 1963, for example). Figure 11 shows typical 1-minute average winds based on the wind data from weather maps for Ventnor, N.J. The mean of 1-minute average peak wind speeds is equal to about 1.15 to 1.25 times the 10-minute average. The variability of several-minute average to computed 10- to 15-minute average is demonstrated in figure 12, reproduced from Goodyear (1963).

2. The total tides -- storm surge plus normal predicted astronomical tide -- were calculated according to the procedures given by Bretschneider (1958) in "Engineering Aspects of Hurricane Surge." In addition, wave set-up on the beach was estimated according to the material and data presented by Saville (1961) and Longuet-Higgins (1963). The important consideration is the instructions on calibration, taking into account the available recorded tide data. Figure 13 shows the results for storm tide hindcasts off the New Jersey and Delaware coasts. Figure 14 accounts for wave set-up on the beach based on wave height hindcasts obtained later in this paper.

3. Deep water waves were hindcast according to the methods proposed by Bretschneider (1958). The significant waves were hindcast and compared with the available data from ship reports, and were also compared with the wave contours presented by Cooperman and Rosendall (1962). Some of this information is given by O'Brien and Johnson (1963). In addition, deep water wave spectra were hindcast, but were used only for calculations to determine the wave spectra in shallow water. Figure 15 and 16 are the results of deep water wave hindcasts for Ventnor City, N.J. and South Bethany, Delaware, respectively.

4. Wave hindcasts were made for the continental shelf and the surf zone, taking into account the combined effects of deep water waves propagated shoreward, wave refraction, wave energy loss due to bottom friction, and the regeneration of waves by wind in shallow water. The procedures for modification of wave spectra over the continental shelf, given by Bretschneider (1962), have been extended to take into account the wind regeneration of wind waves in shallow water. Hindcasts over the continental shelf were compared with the available data from ship reports. Figure 17 shows the results of wave hindcasts over the

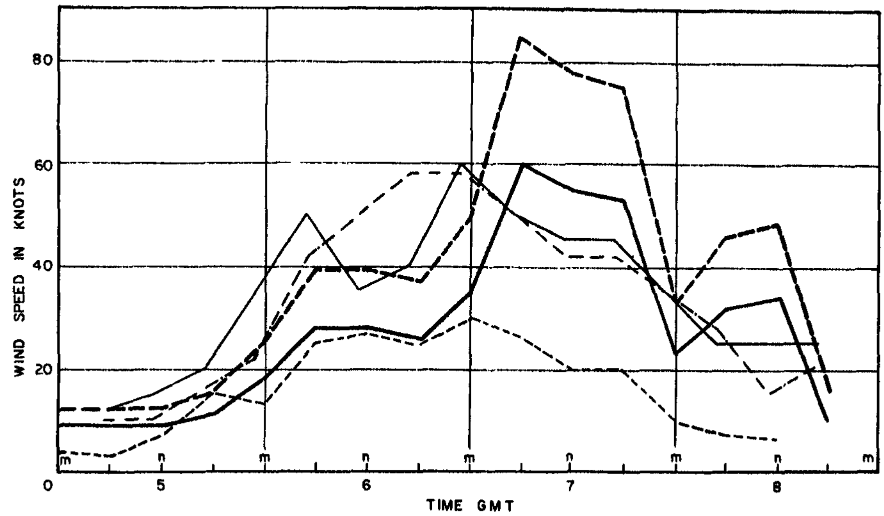


FIGURE 11 WINDS AND GUSTS DURING STORM, MARCH 1962

VENTNOR CITY, SYNOPTIC CHARTS
VENTNOR CITY, GUSTS (CALCULATED)
BARNEGAT LIGHTSHIP
FIVE FATHOM LIGHTSHIP
ATLANTIC CITY, NATIONAL AVIATION EXPERIMENTAL CENTER

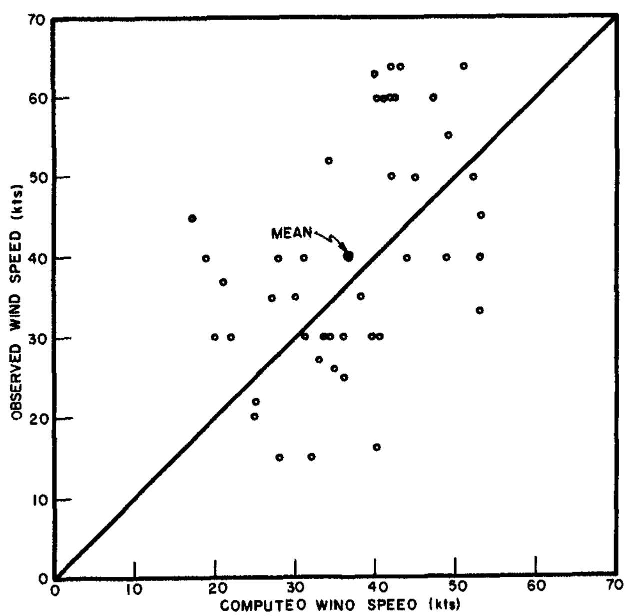


FIG. 12 - COMPUTED vs OBSERVED SURFACE WIND SPEED FOR 43 RANDOMLY SELECTED POINTS (AFTER GOODYEAR, 1963)

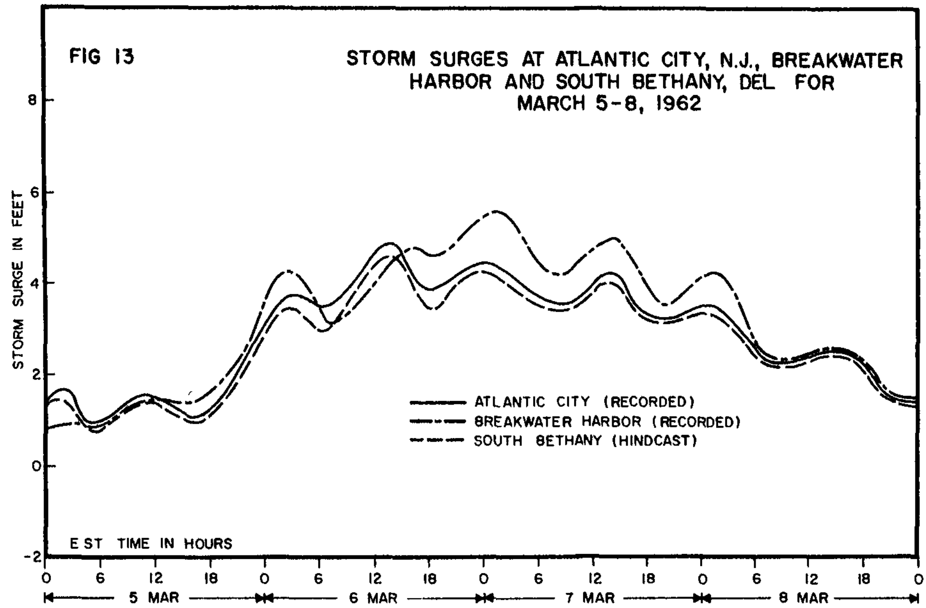


FIG 13
STORM SURGES AT ATLANTIC CITY, N.J., BREAKWATER HARBOR AND SOUTH BETHANY, DEL FOR MARCH 5-8, 1962
STORM SURGE IN FEET
ATLANTIC CITY (RECORDED)
BREAKWATER HARBOR (RECORDED)
SOUTH BETHANY (HINDCAST)
EST TIME IN HOURS
5 MAR
6 MAR
7 MAR
8 MAR

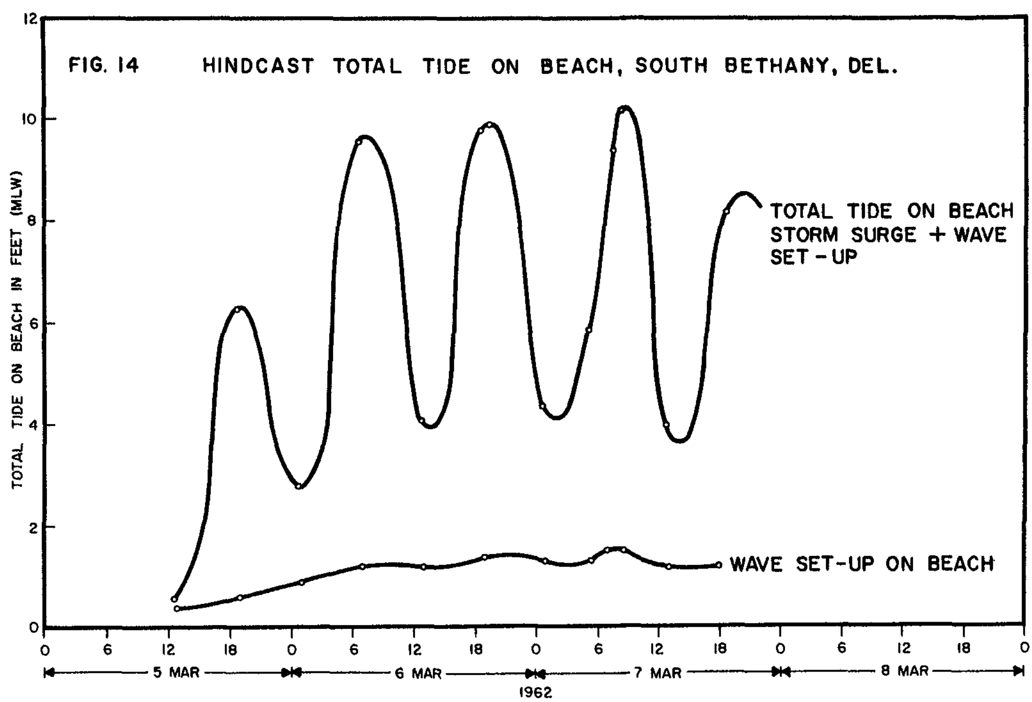
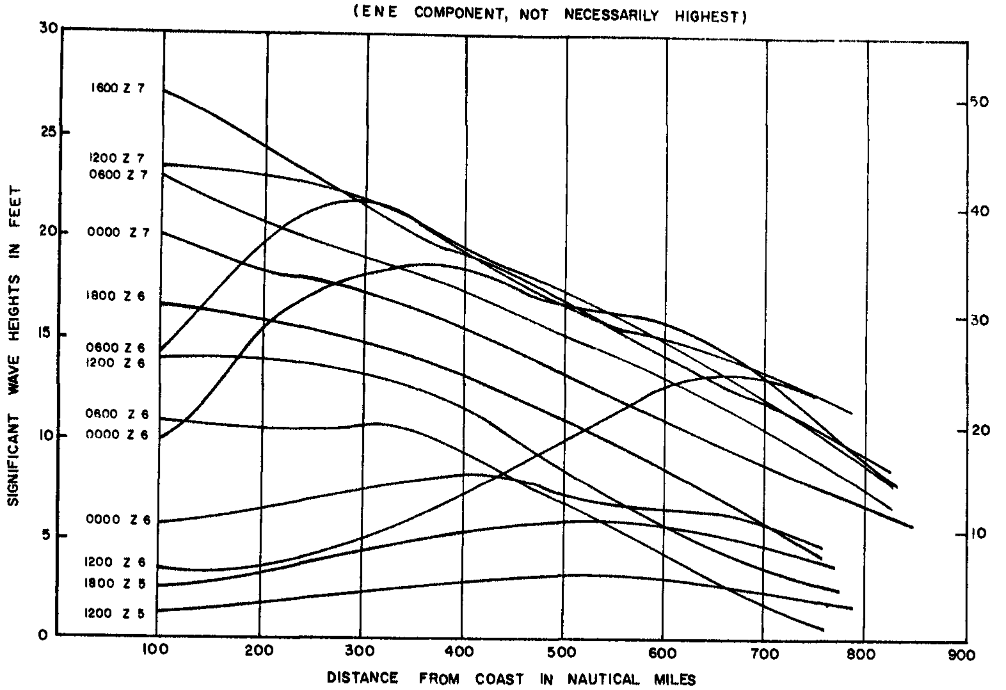
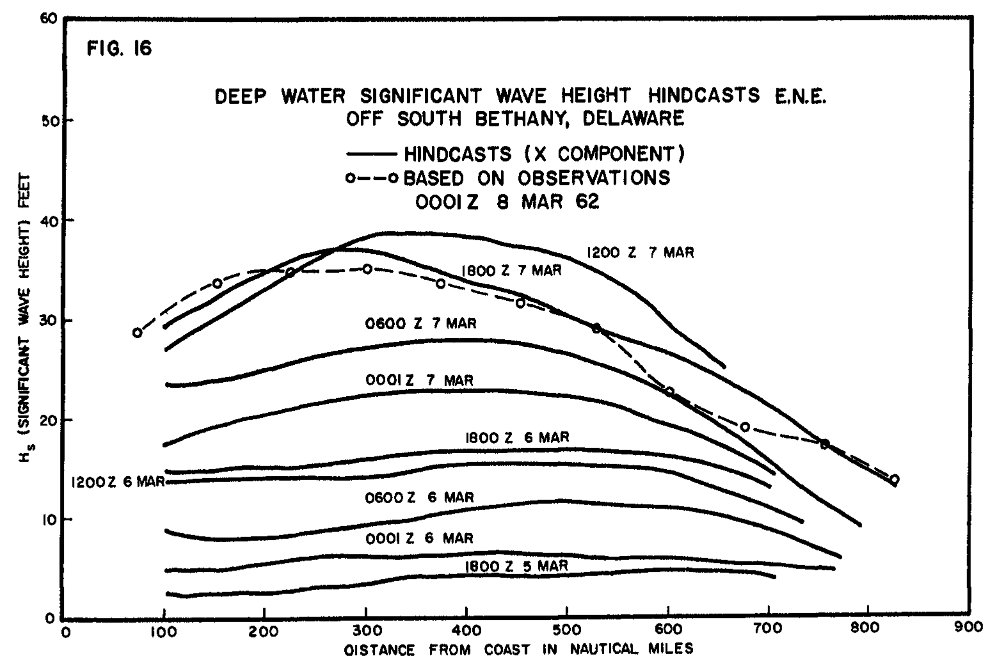


FIG. 14 HINDCAST TOTAL TIDE ON BEACH, SOUTH BETHANY, DEL.
TOTAL TIDE ON BEACH IN FEET (MLW)
TOTAL TIDE ON BEACH
STORM SURGE + WAVE
SET-UP
WAVE SET-UP ON BEACH
5 MAR
6 MAR
7 MAR
8 MAR
1962

FIG. 15 DEEP WATER WAVE HINDCASTS E.N.E. OFF NEW JERSEY COAST
(ENE COMPONENT, NOT NECESSARILY HIGHEST)





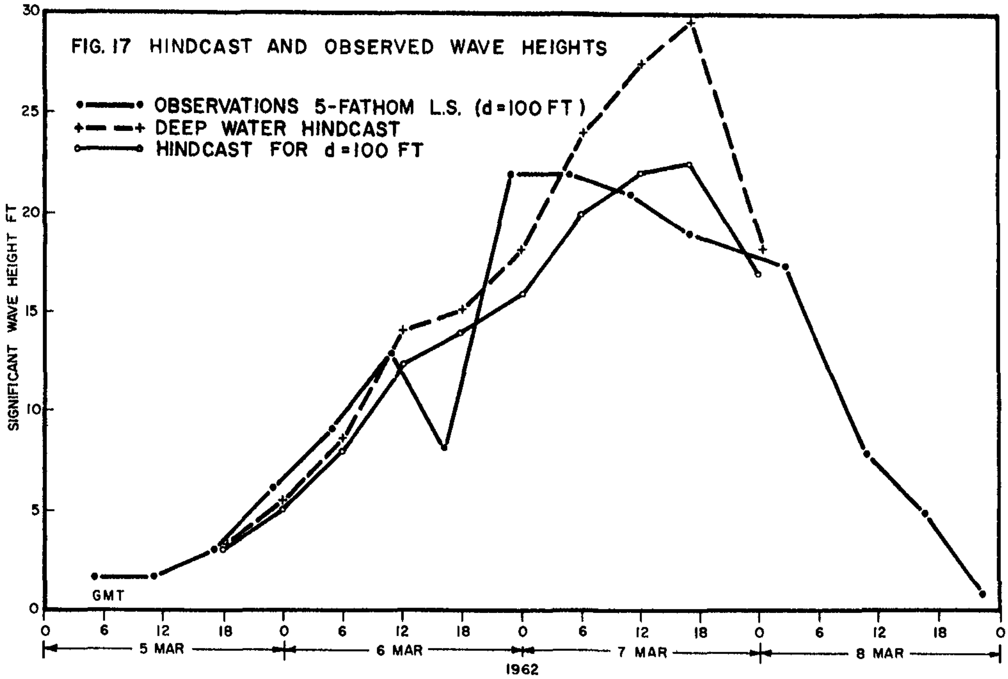


FIG. 17 HINDCAST AND OBSERVED WAVE HEIGHTS

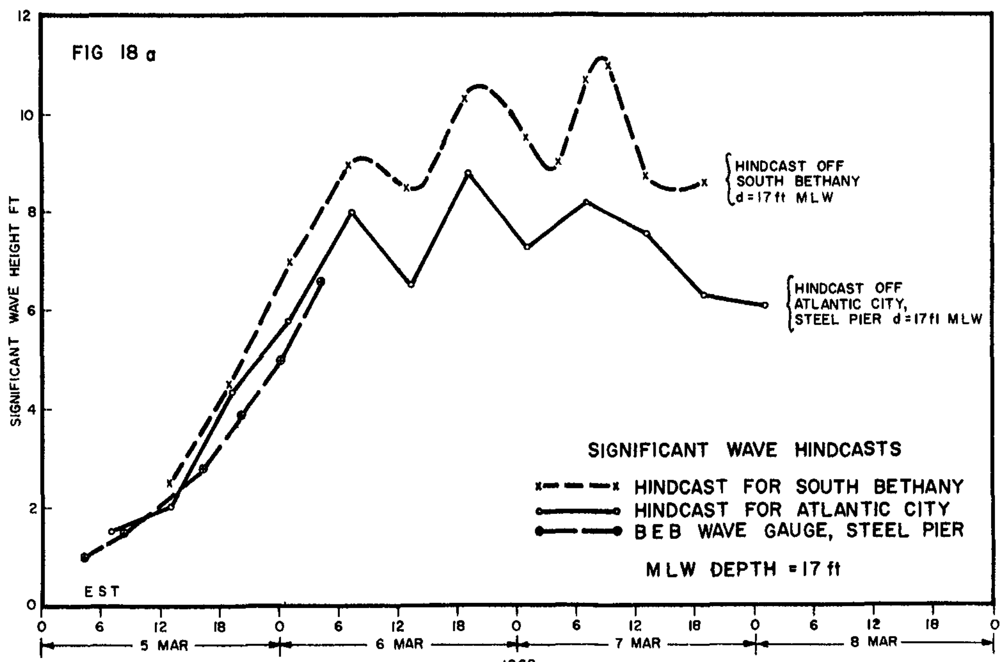


FIG 18 a

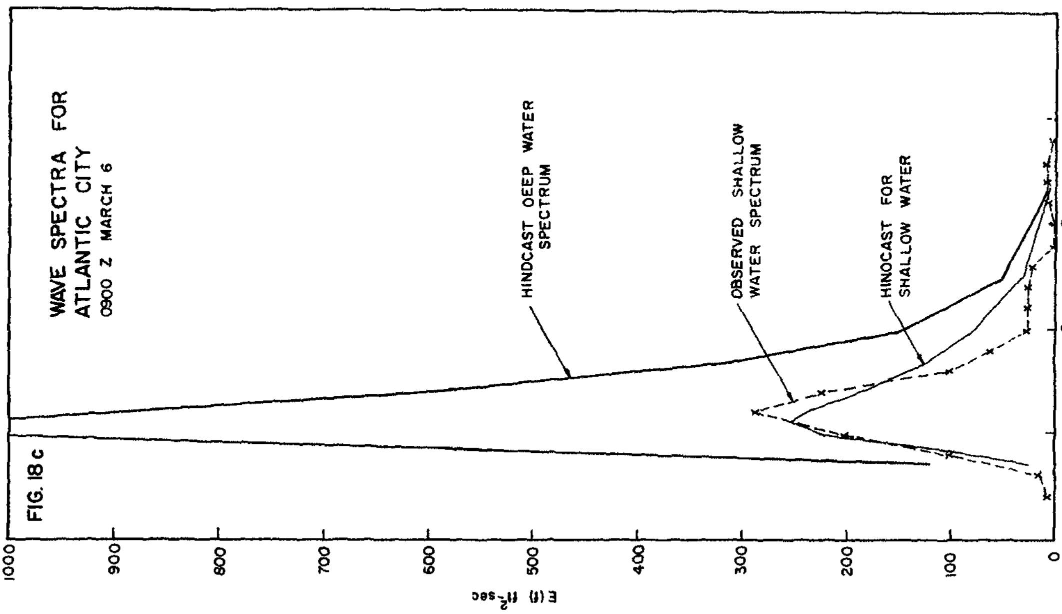


FIG. 18 c
WAVE SPECTRA FOR ATLANTIC CITY
0900 Z MARCH 6
HINDCAST DEEP WATER SPECTRUM
OBSERVED SHALLOW WATER SPECTRUM
HINDCAST FOR SHALLOW WATER
1000
900
800
700
600
500
400
300
200
100
0
E (f) ft²-sec

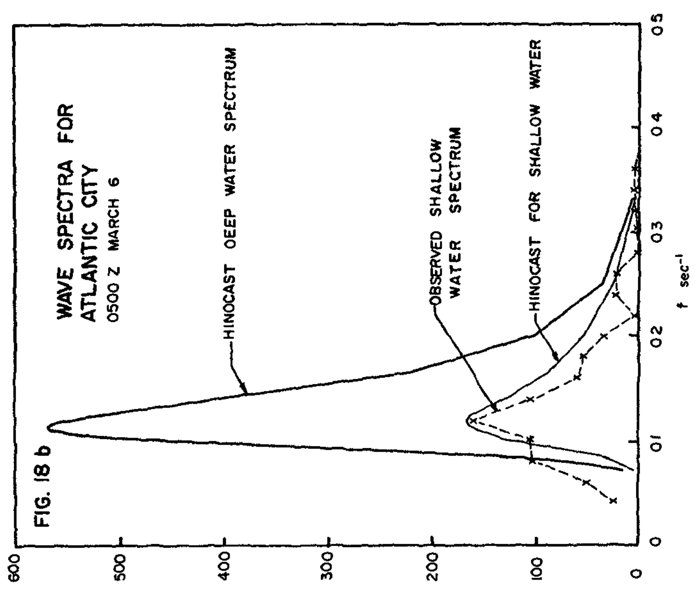


FIG. 18 b
WAVE SPECTRA FOR ATLANTIC CITY
0500 Z MARCH 6
HINDCAST DEEP WATER SPECTRUM
OBSERVED SHALLOW WATER SPECTRUM
HINDCAST FOR SHALLOW WATER
600
500
400
300
200
100
0
E (f) ft²-sec
0
01
02
03
04
05
f sec⁻¹

continental shelf compared with the data reported by the Five Fathom Lightship in 100 feet of water depth off the coast of Delaware. The hindcasts in shallow water were compared with the data recorded at Atlantic City Steel Pier. Figure 18 shows the results of wave hindcasts and recorded data in shallow water at Atlantic City Steel Pier, mean low water depth of 17 feet. The periodic increase in wave height is an indication of change in total water depth as a function of tide and not as a change in storm intensity. Figure 18 also shows the results of hindcasts of the wave spectrum for several periods of time. The recorded wave data for Atlantic City were also used to calculate the wave spectra according to the simplified method proposed by Bretschneider (1961).

5. The breaking wave zone was determined for the water depth and individual breaking wave heights according to the breaking wave index criteria as given by Bretschneider (1958). Because a spectrum of wave heights and periods exists, the breaking waves occur over a broad zone instead of a single line of breakers. These conditions should result in a spectrum of breaking depths. In the present study the first most probable maximum wave breaks first at a far distance from the coast, followed by all other waves breaking shoreward from this first point of breaking. Eventually the smallest waves break on the beach. Because the total tide is a function of time, depending upon the twice-daily normal predicted tides, the breaking wave zone moves seaward and shoreward, alternating with time. Figure 19 shows a typical example of how the point of breaking moves in and out from the coastline as a function of time.

6. The wave run-up calculations were made according to the procedures of Saville (1958), taking into account the composite slope techniques. For these calculations average conditions (see figure 7) were assumed to consist of a 20-foot high dune above mean low water, the slope of the dune as 1-foot horizontal and 3-foot drop to the berm at 10 feet above mean low water. The berm was 50 feet wide, followed by a beach slope of 1 foot on 13 to the coastline, and a bottom slope of 1 foot on 30 to the minus 20-foot contour, and a gradual slope to the minus 100-foot contour. Figure 20 shows the results of wave run-up calculations for the typical composite slope given in figure 7.

Waves which arrived at the 20-foot mean low water contour result in essentially the same maximum wave run-up as those waves which break at the coastline during high tides. The spectrum of wave run-up was determined according go the Rayleigh distribution, suggested by Saville (1962). The most probable maximum wave run-up

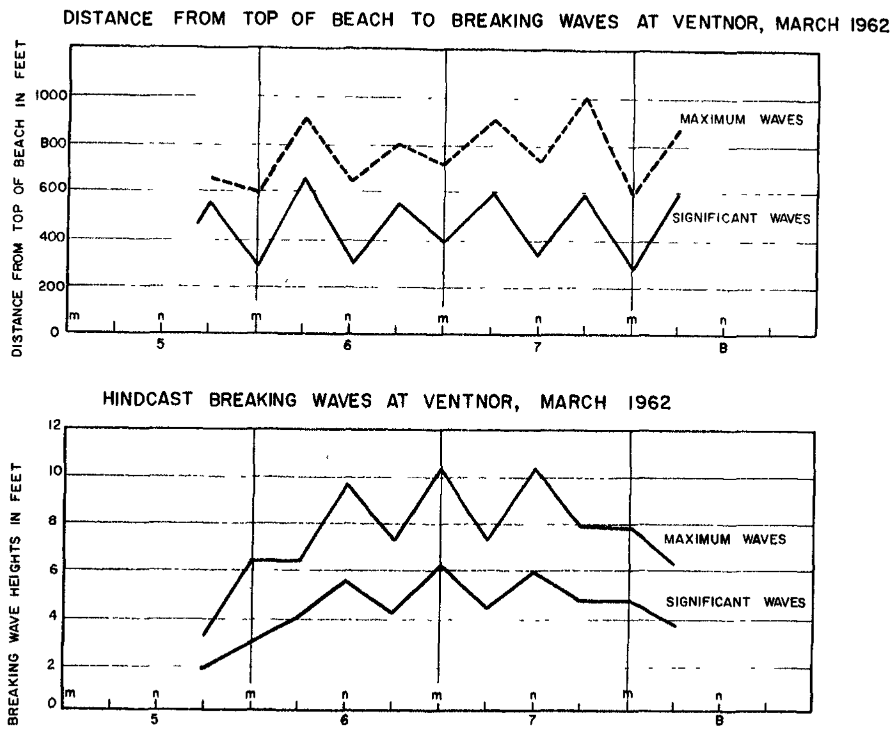


FIG 19 HINDCASTS FOR BREAKING WAVE HEIGHTS AND LOCATIONS

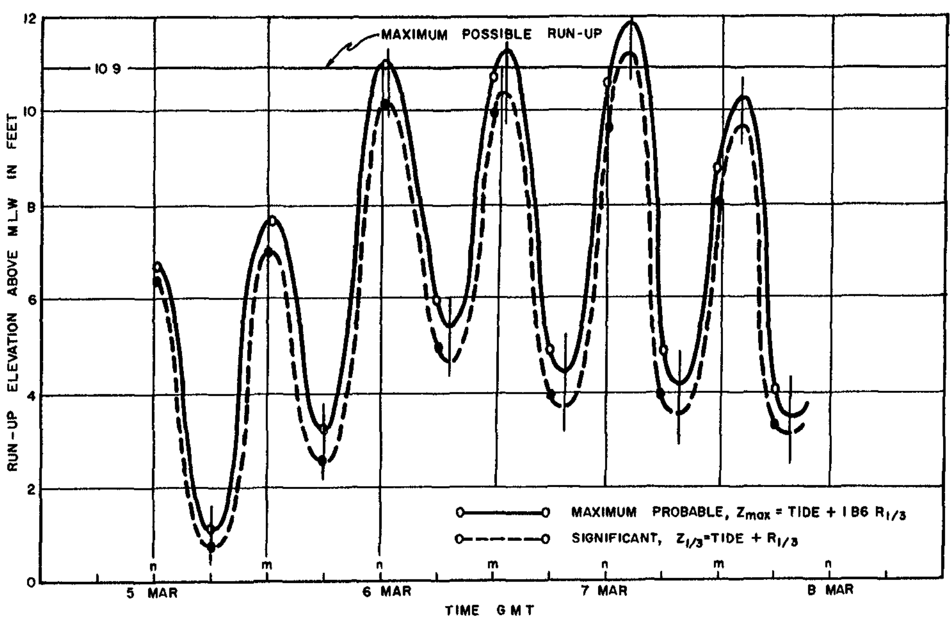


FIGURE 20a WAVE RUN-UP ON THE BEACH AT VENTNOR, NJ

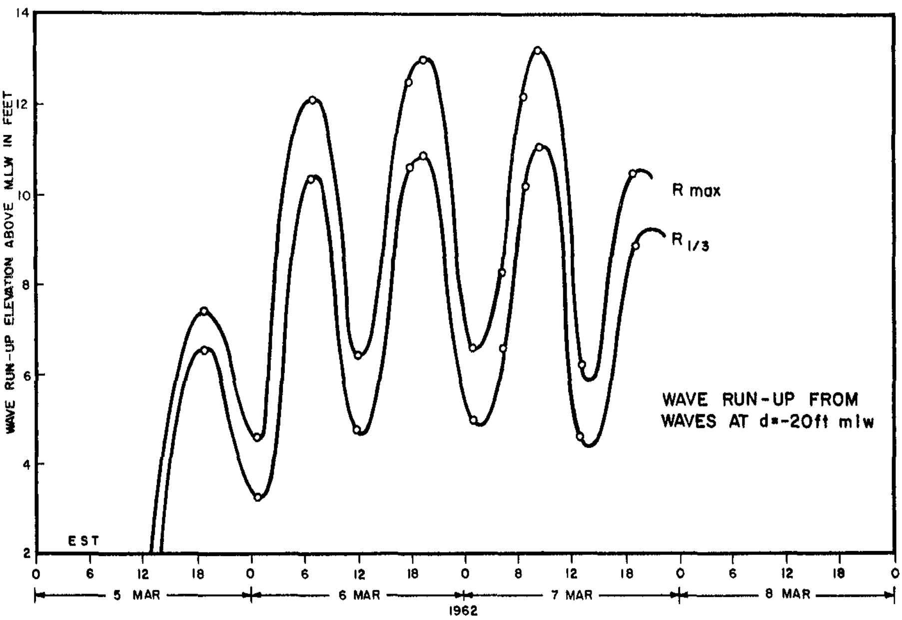


FIG 20 b WAVE RUN-UP ON THE BEACH AT SOUTH BETHANY, DELAWARE

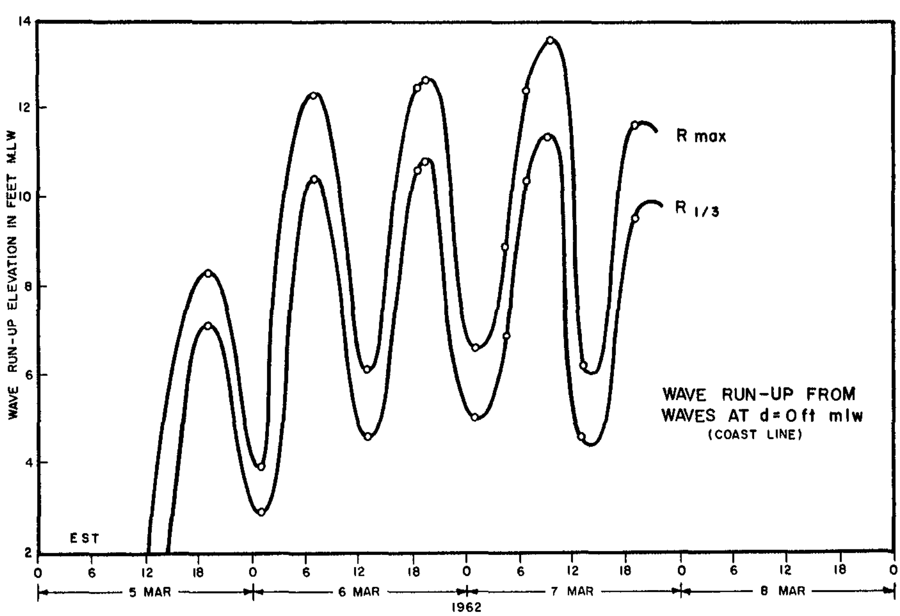


FIG 20 c WAVE RUN-UP ON THE BEACH AT SOUTH BETHANY, DELAWARE was compared with the high water marks reported by Harris (1963) and also given in the U. S. Army Engineer District Post-Storm Survey Reports. Calculations also show that during the final phases of the storm the maximum probable wave run-up was very close to the maximum possible wave run-up governed only by the maximum possible wave height as a function of total water depth.

7. The beach, berm, and dune activity can be defined in terms of the relative wave energy reaching above 10 feet mean low water elevation. Local observers have stated that the erosion of the dune was a gradual process. No previous theory or available data exist in regard to the rate of dune erosion. It might be postulated that the rate of erosion for an average dune can be related to the relative wave energy reaching above 10 feet mean low water. The exact nature of erosion of a factual dune will depend upon deviations from the average dune, such as height, width, type and amount of grass cover, etc. The U. S. Army Engineers Post-Storm Survey Reports state that in some areas along the east coast the dunes were moved back 20 to 40 feet or more along the Virginia coast. Wave and wave run-up calculations were essentially the same for New Jersey, Delaware and Virginia.

One method for estimating the rate of dune erosion is to assume as a first approximation that the cumulative erosion is proportional to the cumulative wave energy reaching above 10 feet mean low water. Probably more erosion takes place during a falling tide when the erosion forces are aided by the hydrostatic pressure directed outward from the dune and less erosion during a rising tide when the erosion forces are opposed by the hydrostatic pressure directed into the dune. For this particular study it appears that the average dune corresponding to figure 7 has a width of 40 feet, corresponding to 100 percent wave energy erosion. Other considerations remaining the same, wider dunes would not be breached, whereas narrower dunes would have been destroyed prior to the end of the last high tide. Figure 21 shows histograms of wave energy (arbitrary scale in feet squared) and percent cumulative energy as a function of time for waves reaching above 10 feet mean low water.

8. Winds, which were hindcast over water at the coastline, were adjusted to off-water winds over the beach. The appropriate reduction factors can be estimated based on the data obtained by the U. S. Army Engineers from the Lake Okeechobee, Florida, experiments and summarized by Meyers (1954) in the U. S. Weather Bureau Hydrometeorological Report No. 32. The reduction factor varies between

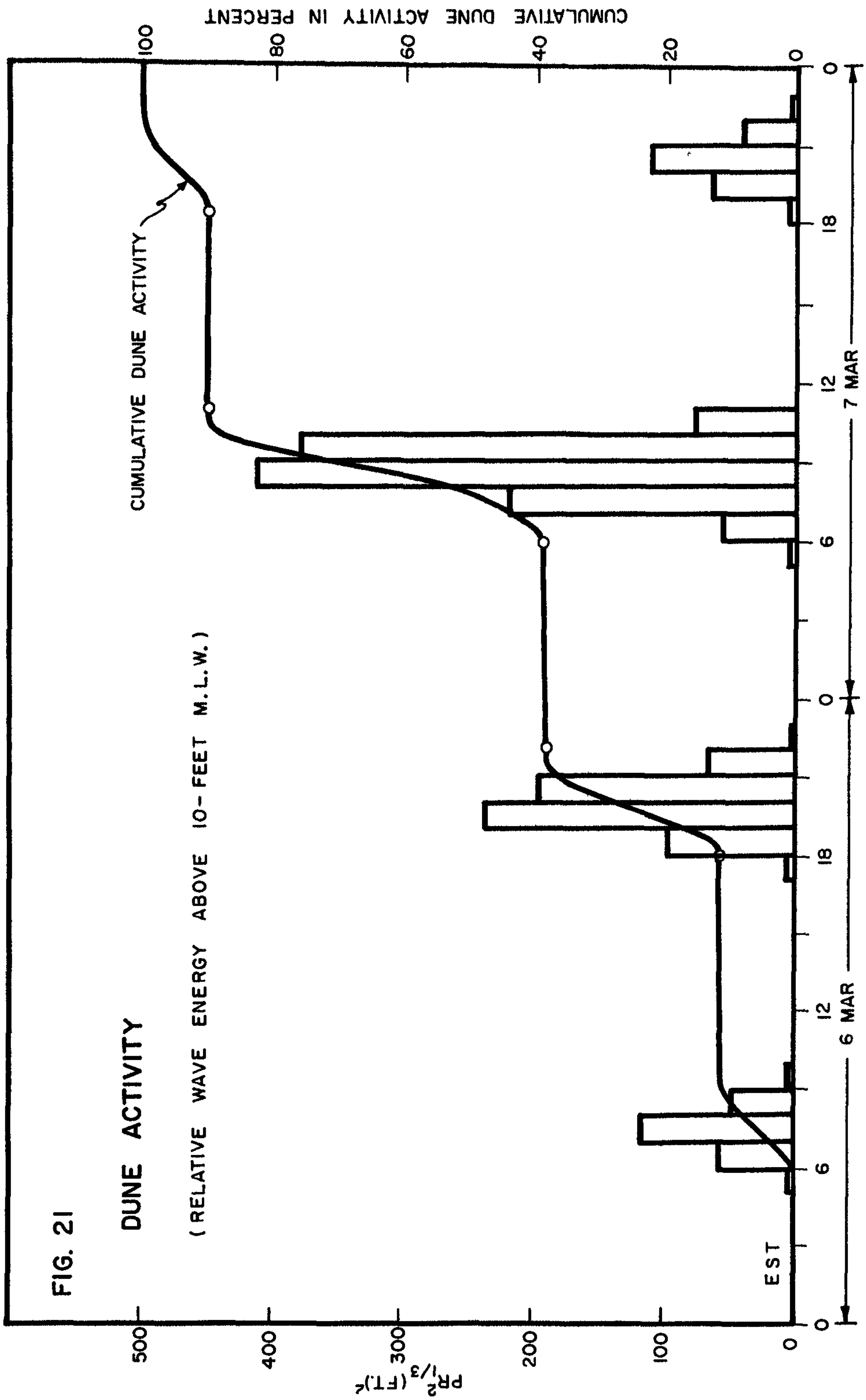


FIG. 21
DUNE ACTIVITY
(RELATIVE WAVE ENERGY ABOVE 10-FEET M.L.W.)
CUMULATIVE DUNE ACTIVITY
CUMULATIVE DUNE ACTIVITY IN PERCENT
EST
6 MAR
7 MAR
1962

1.0 and 0.9, depending upon the distance from the coast. In a U. S. Weather Bureau report Graham and Nunn (1959) recommend using a gradual reduction factor from 1.0 to 0.9 over the first two miles from the coast. Ten-minute average wind speeds over the beach of South Bethany, Delaware, were calculated from the over-water wind speeds using a reduction factor of 0.9. The 1-minute average peak winds are 1.15 times the 1-minute average.

9. The vertical distribution of wind speed above the water and above the beach were estimated in accordance with the 1/7th power law; that is:

$$U_Z = U_{10} (Z/10)^{1/7} \tag{1}$$

where U_Z is the wind speed at elevation Z meters above the surface, and U_{10} is the wind speed at 10 meters above the surface. The above formula seems applicable above wet sandy beaches as well as above water surfaces. For example, the data by Sheppard (1958) follows very nearly the 1/7th power law for velocity distribution over water, and the experiments of Landsberg (1942) follow very nearly the 1/7th power law for velocity distribution over a Michigan beach.

10. Wind gust speeds were investigated using the U. S. Weather Bureau data for the East Coast Storm and for Hurricane Carla, 1961. Except for low wind speeds, linear relationships were found between gust speed and wind speed. These results were also in agreement with other data given in the literature (Huss, 1946, for example). Numerous results on gust factors are also summarized in the U. S. Air Force Handbook of Geophysics (1961).

A summary of gust factors is given in Table 1. In this table U_{max} and G_{max} respectively are the maximum values during the storm of the 1-minute average and the peak gust, which do not necessarily occur during the same 15-minute period of time. $\overline{U}$ and $\overline{G}$ are respectively the average of the 1-minute average sustained wind and the average of the corresponding peak gusts.

Figure 22 shows typical results of gust determinations for the east coast storm and figure 25 is based on hurricane Carla. The analysis was made by averaging gust speeds for 3-knot intervals and the corresponding averages of the 1-minute average sustained wind

TABLE 1

SUMMARY OF GUST FACTORS

EAST COAST STORM, MARCH 6-8, 1962

Station	U_{max} Knots	G_{max} Knots	G_{max}/U_{max} U_{max}	$\overline{U}$ Knots	$\overline{G}$ Knots	$\overline{G}/\overline{U}$
Dover, Del.	35	49	1.40	18.5	27.6	1.49
Salisbury, Md.	35	47	1.34	20.4	31.7	1.55
Atlantic City, N. J.	38	49	1.29	25.0	36.3	1.45
Nantucket, Mass.	44	60	1.37	29.8	41.9	1.41
AVERAGE			1.35			1.47

HURRICANE CARLA, 1961

Station	U_{max} Knots	G_{max} Knots	G_{max}/U_{max} U_{max}	$\overline{U}$ Knots	$\overline{G}$ Knots	$\overline{G}/\overline{U}$
Port Arthur, Tex.	34	47	1.38	25.5	34.8	1.37
Galveston, Tex.	52	75	1.44	36.5	50.6	1.38
Victoria, Tex.	87	130	1.50	37.2	49.1	1.32
Houston, Tex.	45	67	1.49	25.1	37.3	1.48
Corpus Christi, Tex.	55	75	1.36	31.5	44.0	1.40
Freeport, Tex.	73	100	1.37	48.2	66.9	1.39
AVERAGE			1.42			1.41

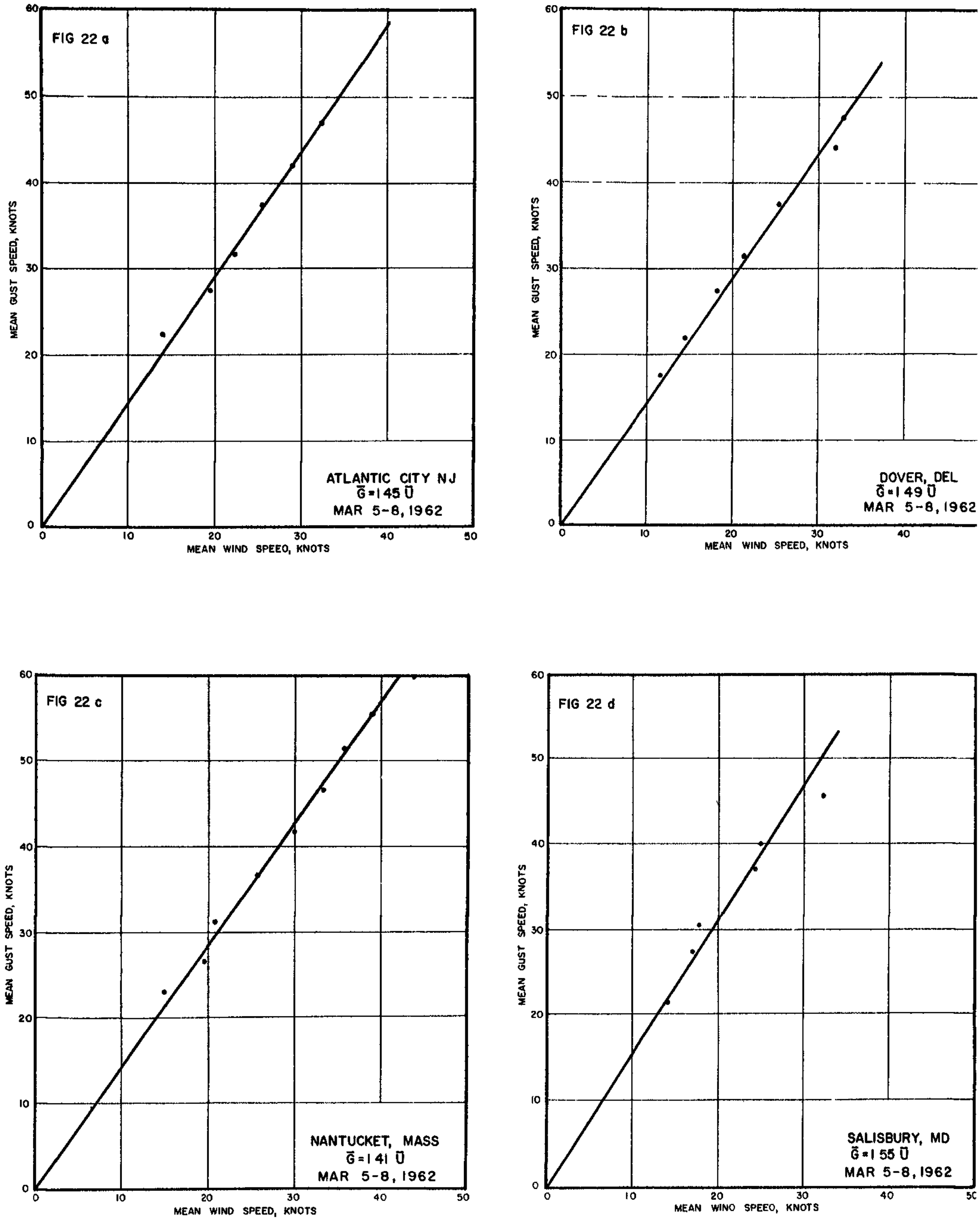


FIG. 22.--AVG. GUST SPEEDS VS. AVG. 1-MIN AVG. WIND SPEEDS FOR EAST COAST STATIONS

speed. Figure 23 shows histograms of gust factors and figure 24 the cumulative probability distribution of gust factors for the east coast storm. The data for hurricane Carla reduces to similar relationships.

The vertical distributions of gust speed above the land were estimated in accordance with the 1/12th power law as obtained from the results of Sherlock (1953) and Deacon (1955); that is:

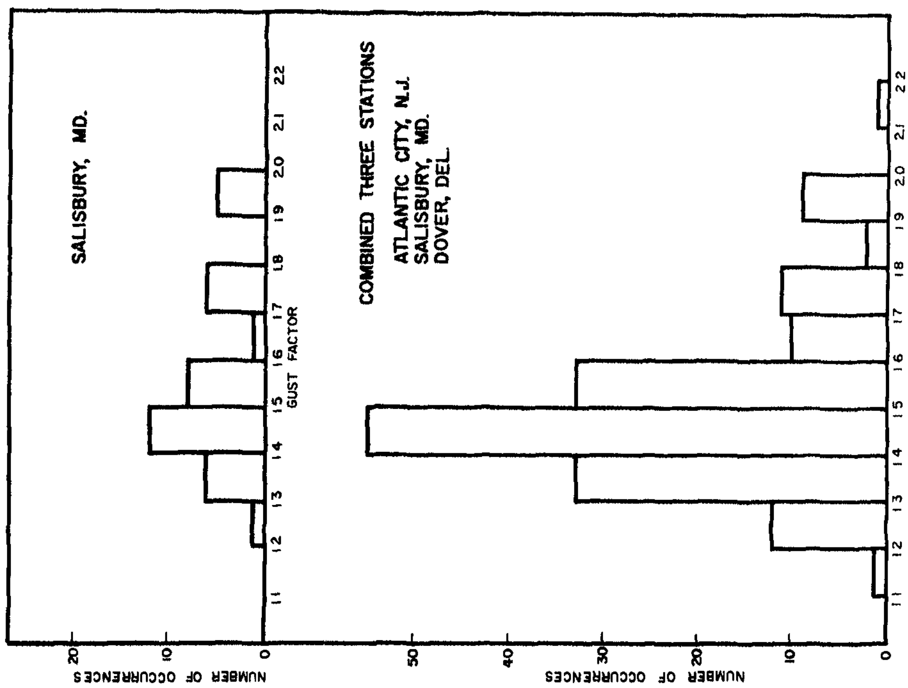
$$G_Z = G_{10} (Z/10)^{1/12} \qquad (2)$$

where G_Z is the average gust speed at elevation Z and G_{10} is the average gust speed at 10 meters above the surface.

11. Sustained wind speeds and gust speeds will be greater over the top of the dunes than at the coastline. This follows from the fact that the flow is convergent, and the principle of continuity and Bernoulli's equation must apply, and the air can be treated as incompressible fluid. Unfortunately no data are available for this particular storm to determine the exact flow of air over the dunes. However, it must be expected that there is a considerable increase in wind speed over the top of a dune, similar to that associated with the flow of air over any type of obstacle. (Ning Chien, et. al., 1951)

Sutton (1953) states that the inviscid fluid theory (potential flow) gives a first approximation to the solution of the problem of finding the increase in horizontal velocity caused by a half-parabolic ridge. In fluid mechanics (Rouse, 1938, for example), it can be found, based on experiments, that there is a considerable increase in speed for incompressible flow over a half-cylinder and a vertical wall. This is also true for high Reynolds numbers, even though separation of the flow takes place on the back side of the obstacle. In the present study it is only of interest to consider the incident face of the dune where convergent flow exists and separation of the flow does not exist. Therefore, except for the small laminar boundary layer, potential theory can be applied. In this respect one must also take into account the vertical velocity distribution, which otherwise is normally assumed to be constant for potential theory.

For demonstration purposes, one can assume that a dune has the shape of a half-cylinder, an ellipse, a parabola, or a vertical flat plate. For example, it can be found in Lamb (1945), or more easily in Valentine (1959), that for potential flow the increase in



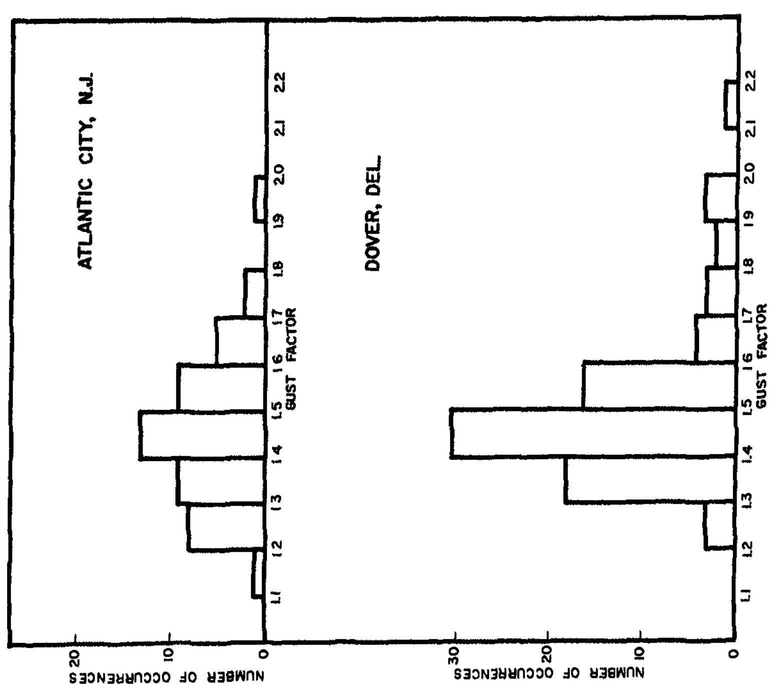


FIG. 23 HISTOGRAM OF GUST FACTORS FOR EAST COAST STATIONS, MARCH 5-8,1962

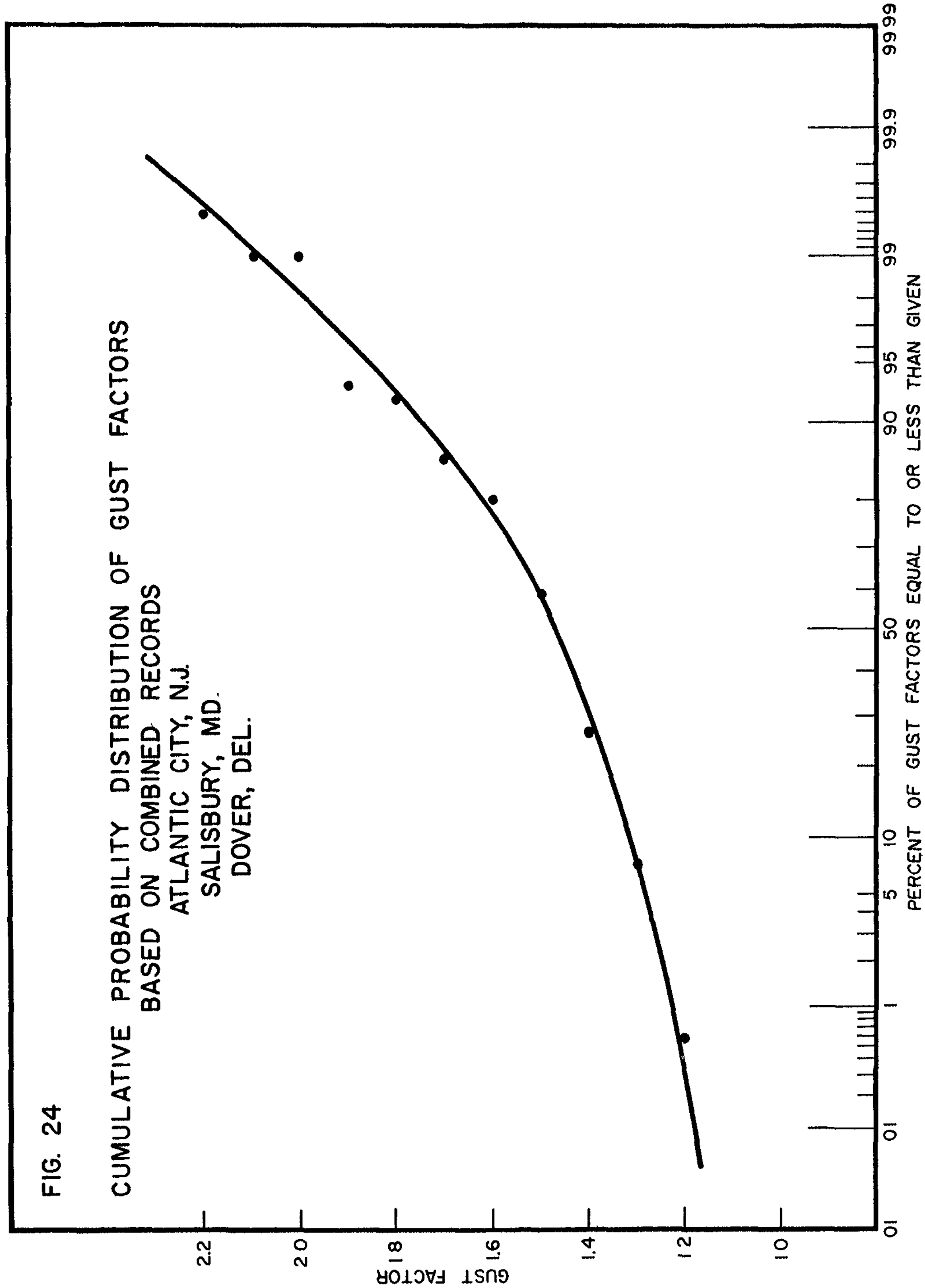


FIG. 24

CUMULATIVE PROBABILITY DISTRIBUTION OF GUST FACTORS
BASED ON COMBINED RECORDS
ATLANTIC CITY, N.J.
SALISBURY, MD.
DOVER, DEL.

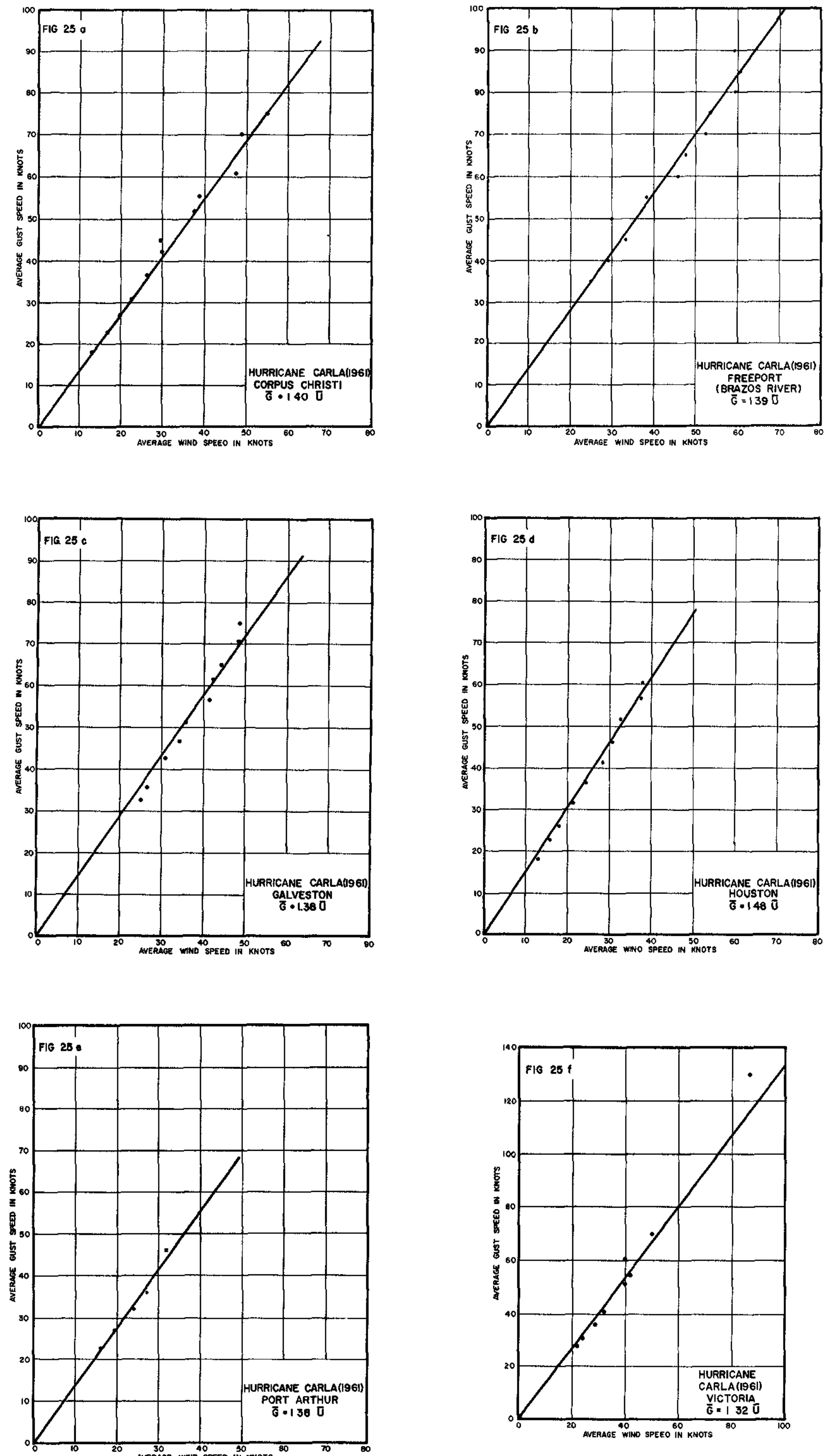


FIG. 25. --AVG. GUST SPEEDS VS. AVG. 1-MIN AVG. WIND SPEEDS FOR HURRICANE CARLA, 1961

horizontal wind speed over a half-cylinder (wind perpendicular to the dune) is given by:

$$U = U_{\infty}\left[1 + h^2 \frac{y^2 + x^2}{(y^2 + x^2)^2}\right] \qquad (3)$$

where U is the wind speed above the dune; h is the height of the dune; x is the horizontal distance measured from the center of the dune; y is the vertical distance measured upward from ground level in absence of the dune, and U_{∞} is the horizontal wind speed in absence of the dune. Figure 26 is based on the solution of equation 3 in non-dimensional form.

Of immediate interest in this study is the maximum horizontal wind speed in the vertical plane which occurs at $x = 0$, and referencing the coordinate system from the top of the dune, let $y = Z + h$, whence for a half-cylinder dune:

$$U = U_{\infty}\left[1 + \left(\frac{h}{Z + h}\right)^2\right] \qquad (4)$$

Similarly, for a vertical flat plate dune one obtains

$$U = U_{\infty}\left[\frac{Z + h}{\sqrt{(Z + h)^2 - h^2}}\right] \qquad (5)$$

Either of the above equations can be used to estimate a first approximation to the solution of the maximum wind speeds over the top of the dunes. Because of friction and turbulence, the incident wind speed U_{∞} is not constant with elevation and a second approximation can be obtained by replacing U_{∞} with U as a function of elevation Z. It will be convenient to refer all elevations measured upward from the free surface streamline instead of from a horizontal plane; i.e. $Z = 0$ all along the beach from the coastline to the toe of the dune, up the face of the dune to the top of the dune. Assuming that continuity is approximately satisfied and that additional frictional losses in the convergent flow are negligible from the beach to the top of the dune, then the second approximation can be estimated by replacing U_{∞} in the above equations with U_Z from equation 1, whence for a half-cylinder dune

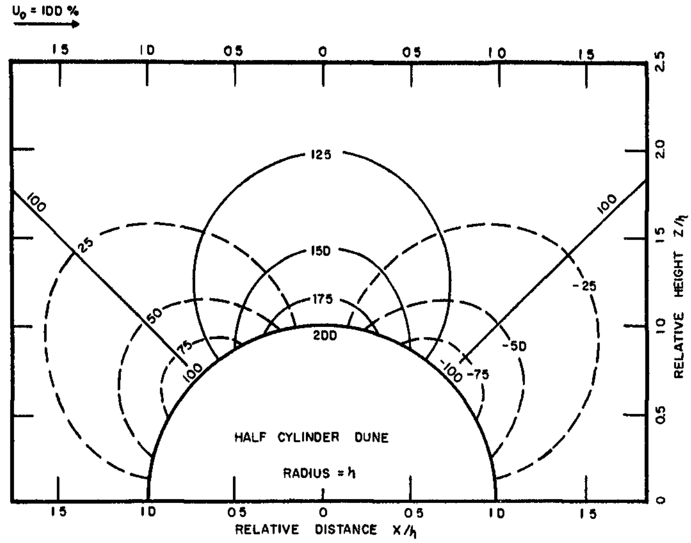


FIG 26 VERTICAL AND HORIZONTAL WIND SPEED COMPONENTS FOR IDEALIZED FLOW

SOLID LINES ARE HORIZONTAL COMPONENTS IN PERCENT OF U_0
DASH LINES ARE VERTICAL COMPONENTS IN PERCENT OF U_0
U_0 = 100 PERCENT AWAY FROM DUNES
POSITIVE SIGN ON VERTICAL COMPONENT IS UP
NEGATIVE SIGN INDICATES DOWNDRAFT

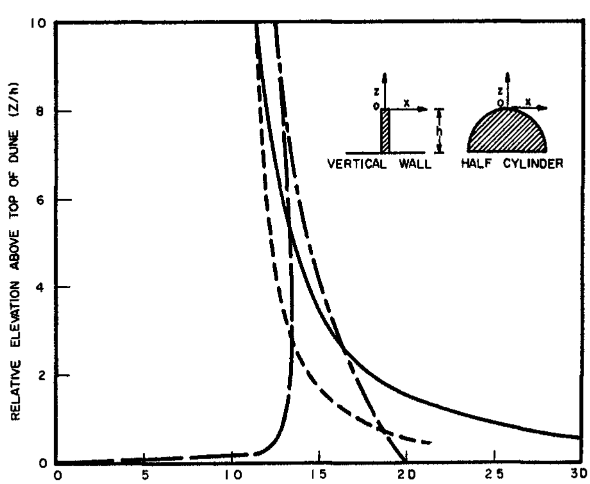


FIG 27— DEMONSTRATION OF INCREASE IN WIND SPEED OVER TOP OF A DUNE

VERTICAL WALL POTENTIAL THEORY
HALF CYLINDER POTENTIAL THEORY
VERTICAL WALL MODIFIED FLOW
HALF CYLINDER MODIFIED FLOW

$$U_Z = U_h \left(\frac{Z}{h}\right)^{1/7} \left[1 + \left(\frac{h}{Z+h}\right)^2\right] \tag{6}$$

and for a vertical flat plate dune

$$U_Z = U_h \left(\frac{Z}{h}\right)^{1/7} \left[\frac{Z+h}{\sqrt{(Z+h)^2 - h^2}}\right] \tag{7}$$

Landsberg (1942) conducted an elaborate experiment on "The Structure of Wind Over a Sand Dune." The vertical and horizontal distributions of winds were investigated over a typical Michigan dune near Stevensville, Michigan. The dune was a so-called "blow-out" that had been cut through an older chain of grown-over dunes. The measurements were made where the dune had been cut above 100 feet below the level of the grown-over portion of the dune. The "blow-out" formed a fairly narrow channel about 75 feet wide at the base, which was at an elevation of about 80 feet above the level of Lake Michigan. The channeling effect of the front slope and the two ridges to either side of the blow created much higher velocities nearer the ground than elsewhere. Over the top of the "blow-out" the velocities were practically uniform from 1/2 to 10 meters.

In the analysis of the data Landsberg (1942) used the logarithmic vertical distribution of wind speed given by the following equation

$$U_Z = 2.5\sqrt{\tau/\rho} \;\ln Z/Z_o = 2.5\sqrt{\tau/\rho}\;\ln\left[\frac{Z}{h}\cdot\frac{h}{Z_o}\right] \tag{8}$$

where τ is the shear stress, ρ is the density, and Z_o is the friction length parameter. The height of the dune h is introduced in the present paper.

From the data of Landsberg for winds over the beach, $Z_o = 0.155$ cm and $U = 2.8$ meters per second in 1 meters height, and over the top of the "blow-out" $Z_o = 0.09$ cm and $U = 4.2$ meters per second in 1 meters height, representing a 50 percent increase in wind speed in 1 meters height.

Figure 27 represents the solution of equations 4, 5, 6 and 7 in non-dimensional form. The increase in wind speed over the top of the dunes determined from equations 6 and 7 is in reasonable agreement with the measurements made by Landsberg, allowing for the fact that the theoretical dunes and the actual Michigan dune are not necessarily in similitude.

The ratio of the average wind speed over the top 5 or 10 feet of the dune to the average wind speed in absence of the dune is called the average "dune factor". The general conclusion is that the average dune factor for a 10 to 20 foot high dune is between 1.35 and 1.45. Since the gust factor varies between 1.35 and 1.45, it is probable that the combined gust and dune factor is on the order of 2.0. Without the dune, 50 percent of the gust factors (see figure 24) will be as high as 1.45, and only 2 percent of the gust factors will be as high as 2.0. For a dune factor of 1.35 times a gust factor of $1.45 \cong 2.0$, one might expect that about 50 percent of the gust speeds over the top of the dune will be on the order of twice the incident 1-minute average wind speeds over the beach. This presumes that the dune and gust factors can be combined linearly.

Since the pressures acting on an object vary as the square of the wind speed, and since the dune factor is on the order of 1.35 to 1.45, the pressures acting against a house on top of the dune should be about twice that of a similar house located some distance ahead of or behind the dune.

SUMMARY

The material presented in this paper represents a hindcast of events during the March 6-8, 1962, storm along the east coast of the United States. Specifically the hindcasts include (1) deep water waves, waves over the continental shelf, waves in shallow water, and waves at the coastline; (2) total tide, including normal predicted tide, storm surge and wave set-up; (3) wave run-up on the beach and an estimation of beach berm and dune erosion; (4) wind speeds over water, over the beach, and over the top of the dunes. The hindcasts were checked with available data for the storm. Numerous sources of information on the storm were available to improve the accuracy of the "state of the art" in forecasting. Theory was required for various aspects of the problem for which little or no data were available.

The summary of this study leads to a time-history of the many events stated above. Figure 28 presents a brief summary of the more important determinations. This includes the normal predicted tide obtained from the tide tables; the total tide which includes the storm surge, the wave run-up of the maximum waves, the cumulative

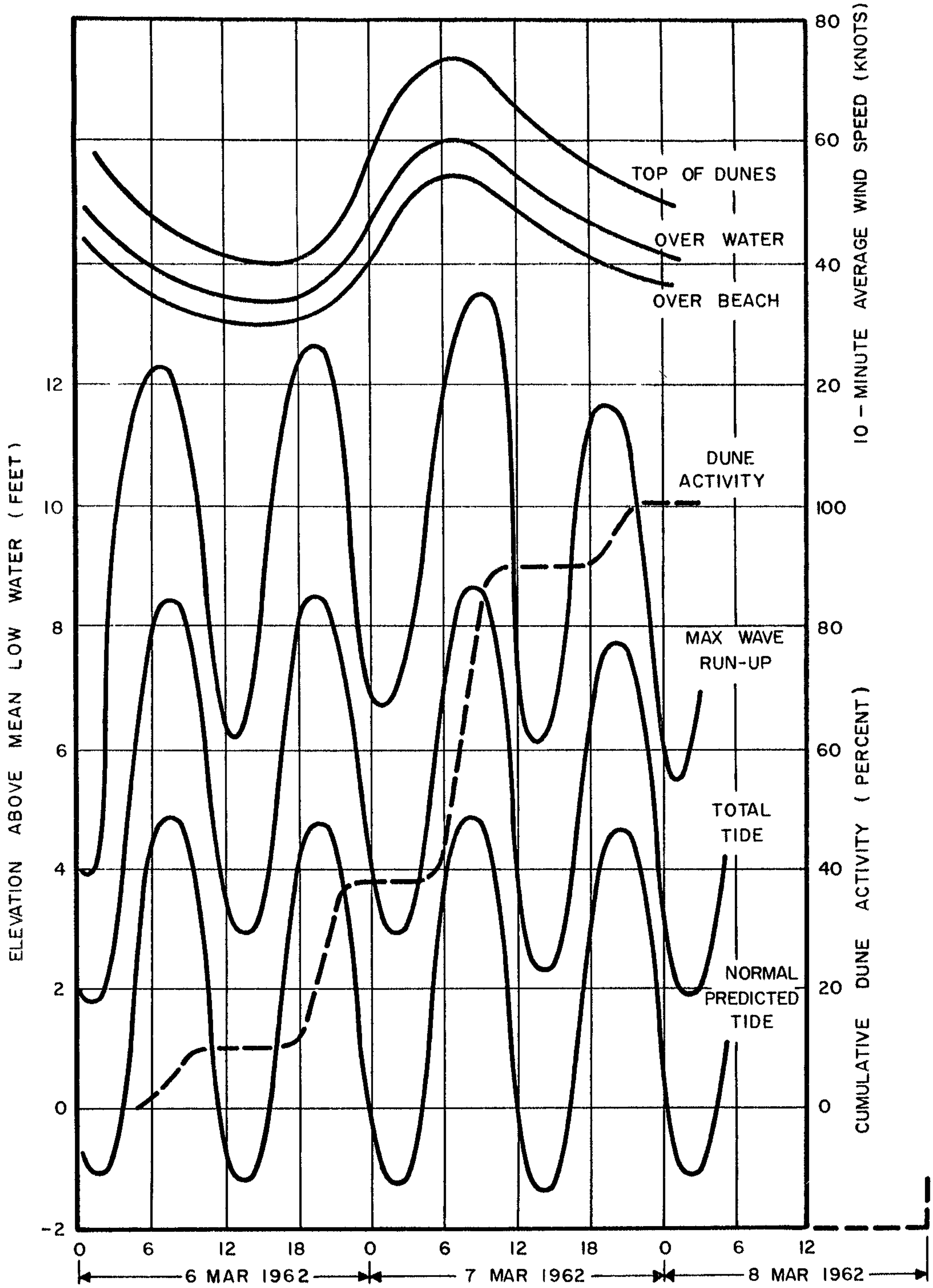


FIG. 28 TIME-HISTORY SUMMARY OF WIND, TIDES, WAVE RUN-UP AND DUNE ACTIVITY

presentation of estimated dune activity, and wind speeds over water, over the beach, and over the top of the dunes.

The over-water winds and winds over the beach are referenced to the 10-meter elevation. The winds over the dunes are averaged over the top 5 or 10 feet above the crown of the dune and are calculated to be about 1.35 times the incident wind speed. All winds represent the standard 10-minute average sustained wind speed. The peak one-minute average wind speeds average about 1.15 times the 10-minute average. The peak gusts are given approximately by 1.45 times the peak one-minute average wind speed.

The so-called "calibrated methods" for hindcasting were quite suitable for the present storm conditions. It is not necessarily recommended that these same methods be applied to some other factual storm or a design storm of different orientation direction and speed of wind, and direction and forward translation of the storm.

The state of the art of wave and storm surge hindcasting and forecasting is being advanced considerably by taking advantage of the data of both the east coast storm and hurricane Carla, as well as data from other storms along the Gulf coast and the east coast of the United States.

ACKNOWLEDGEMENTS

This paper represents a condensation of a number of reports pertaining to the east coast storm of 6-8 March 1962. Much of the work pertaining to the New Jersey coast was supported by the U. S. Naval Civil Engineering Laboratory under Contract No. NBy-32235. Much of the work pertaining to the Delaware coast was supported by more than 40 citizens of the Delaware Beach Rehabilitation Association under a letter agreement with Brookhart, Becker and Dorsey. The work performed pertaining to additional work beyond the requirements of the above contracts, including the work on wave spectra concepts and the drafting of this paper, was performed under contract with the Office of Naval Research under Contract No. Nonr-4177(00). Otherwise this paper could not have been documented. Of particular appreciation are numerous photographs and documents furnished by Mr. Garnett D. Horner, White House correspondent for the Washington Star. Appreciation is also extended to Mr. Louis Allen for his interpretation of wind speeds over the South Bethany, Delaware beaches. Those at NESCO who have contributed to this work include, among others, Dr. Bernard Le Mehaute, Dr. J. Ian Collins, Mr. Raymond Hurt and Prof. Raymond Fox.

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