Storm Damage Hazard Along the East Coast of the United States[1]

JOHN R. MATHER,[2] RICHARD T. FIELD AND GARY A. YOSHIOKA

C. W. Thornthwaite Associates, Elmer, N. J.

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ABSTRACT

Study of the frequency of damaging storms along the east coast of the United States during the past 40 years has revealed a significant increase in the past decade. Reasons for this increase are analyzed. It is concluded that man's generally unrestricted development of the outer coastal margin as well as a slight intensification of coastal cyclones have both contributed. Assuming no change in coastal development or meteorological conditions in the future, a storm damaging as much of the coast as the one in March 1962 would be expected once every 20 years. Based on recent storm damage experience, the New England coastal area and the region around Cape Hatteras appear to be particularly vulnerable to storm damage. The New Jersey, Maryland, Delaware coast and the coast from South Carolina to Florida seem to have a relatively low storm damage potential.

1. Introduction

The actual damage from a storm of a given intensity depends on a large number of physical factors. Some coastal sites may be more vulnerable than others by virtue of elevation, aspect, or orientation with respect to the storm surge and waves, offshore bottom conditions, the condition of natural and man-made coastal defenses, type and pattern of human development, and other factors. Proximate sites may differ markedly in vulnerability due to one or a combination of these factors of which we have only a very general understanding.

For this reason, it is extremely difficult to determine the vulnerability of particular sites along the coast. At present we lack satisfactory meteorological criteria for judging the damage potential of a given storm center. It is possible, however, to develop a notion of the relative storm hazard for different portions of the coast by examining the history of damage during the past several years. This has been done in an effort to integrate the many independent meteorological and environmental factors that, in combination, determine the destructive potential of a given storm. Inherent in this procedure is that its usefulness is limited to the broad scale of time and space. Such an analysis will not be especially useful for understanding the hazard at particular sites. Local hazard can be known only through detailed historical and physical studies of each site. Such detailed studies would, of course, be difficult to use for purposes of generalization because of the variability in the experience of neighboring sites. This study is therefore primarily concerned with the climatology of the hazard of coastal storm damage rather than with coastal storms themselves.

Coastal storm damage is defined here as damage due to the peculiar conditions existing at the sea coast (flooding, tides, and waves). Storms which cause damage *only* by wind or precipitation are not included. The approach we have adopted has sought to determine where along the coast damage (or presumed damage in the absence of actual reported damage)is most frequent; how this frequency of damage has changed in the past several decades; and to determine insofar as possible whether the observed changes in damage frequency during the years are due to meteorological changes, changes in reporting of damage, or changes in human use (or abuse) of the coast. A previous contribution (Mather *et al*, 1964) sought to identify the overall pattern of storm damage on the east coast of the United States and to classify the sorts of meteorological conditions that are responsible for coastal damage.

2. Frequency of damaging coastal storms

Records of coastal storms and related damage during the past 44 years are contained in a number of different periodicals, newspapers and weather summaries. The prime sources for all storm data during the period 1921–1964 have been U. S. Weather Bureau climatological publications. From 1921 until the end of 1949, brief records of severe storms were published in the *Monthly Weather Review*, while more detailed articles on storms of significance were included in the *Review* itself when warranted. From 1950 until the end of 1958, these storm records were included in the publication *Climatological Data, National Summary*. Since 1959 an

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[2] Also Department of Geography, University of Delaware, Newark.

expanded record of all severe storms has been published monthly in a special report entitled *Storm Data*.

Table 1 gives the yearly record of all storms that have resulted in some damage to part of the Atlantic coastal margin during the period 1935 to 1964. The record shows a marked increase in the number of such storms in the past two decades. If the 30-yr record is divided into three 10-yr periods, the average number of storms per year increases from 1.3 in the 1935–1944 period, to 3.6 in the 1945–1954 period, and to 7.2 in the 1955–1964 period. The real changes in the record appear to occur in the late 1940's and again in 1956 although the record shows a generally consistent increase over the whole 30-yr period.[3]

Because of the type of record that is available, it is not possible to say whether this increase in frequency of damaging storms is only the result of random climatological variation. It is certainly possible that the great increase in coastal occupancy and the resulting importance of damage-producing storms has led to a certain bias in reporting. This question will be considered in more detail in a later section.

[3] This record of number of damaging storms differs slightly from the record included in an earlier publication (Mather *et al.*, 1964) because of the definition of damaging storms. In the earlier paper all storms that were reported in the literature sources studied were included. Some of these brought insignificant damage. In the present study only those storms that resulted in some significant coastal damage were included. The terms significant and insignificant damage as used in this paper can only be subjectively applied. From the accounts and estimates of coastal damage done by a storm, an interpretation of whether the damage was severe enough to be significant, or so light as to be insignificant or of no general consequence, was made. In most cases this determination had to be made on the basis of written descriptions of damage and not on the basis of dollar values.

3. Lateral extent of storm damage

Figures indicating the damage frequency at a point along the coast give some idea of the relative hazard along different reaches of the coast, but they give no indication of the lateral extent of coast that might suffer damage from a single meteorological event. If one could predict the frequency with which coastal storms damage various lengths of coastline, such information, together with estimates of damage levels, would suggest the magnitude of the total damage risk from a national rather than a local point of view. An indication of the probabilities to be attached to storms damaging various lengths of coastline would suggest how often to expect total damage of various amounts and the geographic extent of such damage. This information might be helpful in the planning of coastal disaster programs and estimating overall levels of insurance risk that would be required for a national insurance program.

TABLE 1. Distribution of lateral extent of storm damage by years (1935–1964).

	Lateral extent in nautical miles													
	1–100	101–200	201–300	301–400	401–500	501–600	601–700	701–800	801–900	901–1000	1001–1100	1101–1200	1201–1300	Number of storms
1964	6	1	1	1										9
1963	3	2	1		1									7
1962	2	3		3	1					1			1	11
1961	2	1	1	1		1								6
1960	3	2		1	1							1		8
1959	2		3			1								6
1958	2	1	1	2	3		1							10
1957	3	1		1										5
1956	1	1	1	1		2								6
1955			3	1										4
1954		1			2		1							4
1953		2	1	1		1								5
1952		1		1										2
1951	2													2
1950	2	1		2		1								6
1949	1						1							2
1948		2												2
1947	3	4												7
1946	2	1	1											4
1945	1						1							2
1944			1				1	1						3
1943	1		1											2
1942														0
1941														0
1940	1													1
1939														0
1938				1										1
1937	1													1
1936			1											1
1935	4													4
Totals	42	24	16	16	8	6	5	1	0	1	0	1	1	121

The length of coastline affected by a particular storm will, of course, depend largely on the intensity and size of the storm, its track, and speed of movement. A large storm of only moderate intensity moving slowly up the coast can generate destructive storm surges and seas persisting for several successive high tides. Such storms will often affect 400 or more miles of coastline and prove extremely destructive simply because of their persistence and extensive area of wave generation.

Using the reports of damage that are available for each of the 121 damaging storms that occurred during the 30-yr period from 1935 to 1964, supplemented by the tide records from the gaging stations where available, it has been possible to prepare maps of the lateral extent of damage from each storm. For this analysis, the lateral extent of damage was defined as the not necessarily continuous length of coast line, in nautical miles, for which any significant water damage was reported for a single storm event.

Table 1 shows the lateral extent of significant damage produced by the 121 storms by year. It is seen that 81 per cent of the storms damaged less than 400 n mi of coast. Only 4 storms during the period significantly affected more than 700 n mi of coast.

The overall trend toward a higher incidence of damaging storms previously noticed has been reflected in an increase in the frequency of storms in all classes of lateral extent. In Fig. 1, the lateral extent of damage per storm has been plotted against the logarithm of the average number of storms per year having that extent. For the 30-yr period, this plot seems to be fairly well represented by a straight line on semi-logarithmic paper, implying that frequency per year is a negative

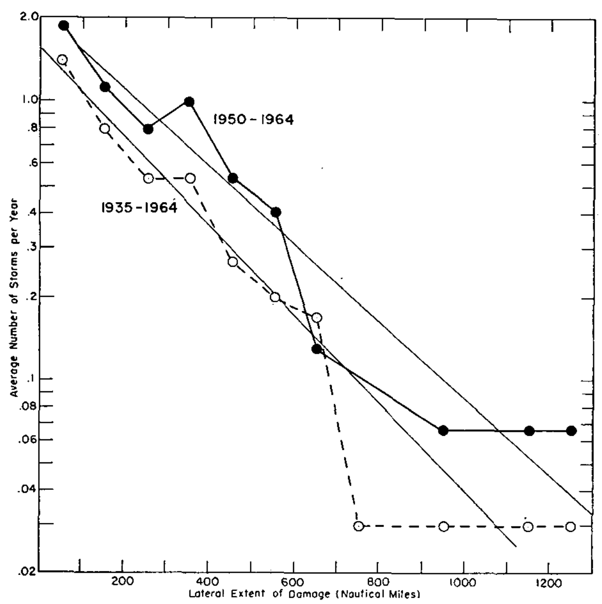


FIG. 1. Relation between average number of storms per year and their lateral extent of damage along the east coast of the United States for two different time periods.

exponential function of damage extent. Because there are so few very extensive storms, the quality of the fit deteriorates for very extensive storms.

One might be inclined to use this record to predict expected frequencies, assuming that the past may be relied upon as a satisfactory guide to the future. That there has been a change during the period of study is clear in Fig. 1 where the history of the latter 15 years is compared to the whole period. The same general relationship between frequency and damage extent appears to hold for the more recent years, except that the incidence per year of storms in almost all classes has been higher than for the whole 30 years. Consequently, prediction would require assuming the pattern and level of coastal development to be frozen at the present state. The prediction should be based on the most recent storm record. Under these conditions, there would be some reason to believe that a storm damaging about 600 n mi of coast would be expected to occur on the average every 1/0.3 or 3.3 years, and a storm damaging about 1300 miles (such as the March 1962 storm) might be expected about once in 1/0.035 or 29 years.[4] The need to assume no change in the rate of human occupance and no change in climatic conditions along the coast, of course, weakens the value of these figures as predictors of future events.

A more realistic prediction would require recognizing the random nature of storm events. Thus, a more useful prediction might be based on the theory of extreme values. The statistical theory of extreme values applies to the frequency distribution of the largest observation per sample of N primary samples, each of which primary sample contains n observations of unspecified number, but assumed to be large and equal.

In the present case, this stipulation of n large and equal is not applicable since we are actually dealing with relatively unlikely events, i. e., damaging storms per year that have occurred only around 0–11 times per year. We are trying to predict the magnitude of damage extent of these events. The applicability of the theory in such a case can only be tentative and will depend on the goodness of fit of the data. There is some reason to suppose that a double exponential distribution will adequately describe the extreme values of the data since the basic distribution does appear to be exponential.

The method described by Gumbel (1954) was used to fit the extreme value curves in Fig. 2 to the most extensive damaging storms per year for the two 15-yr periods, 1935-49 and 1950-64. Comparison of the two plots clearly shows an increase in the extent of the most extensive storms. During the former 15-yr period, the probability of a storm during a year that would damage 600 or more nautical miles of coast was about

[4] The east coast of the United States can be considered to be approximately 1600 n mi in extent if bays and other minor indentations are disregarded.

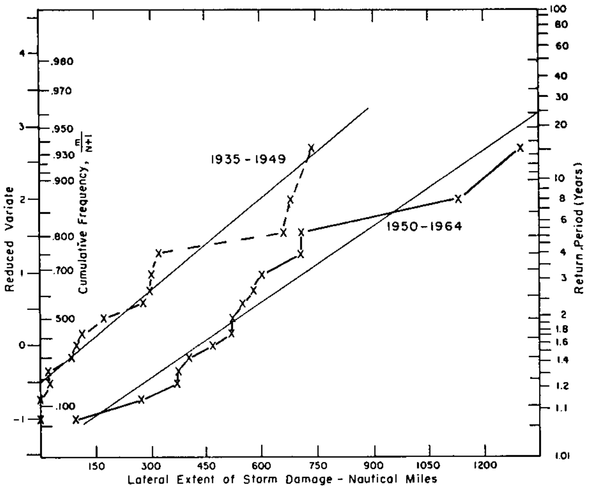


FIG. 2. Cumulative frequency of lateral extent of largest storm per year along the east coast of the United States, 1935–1949 and 1950–1964.

0.13; while during the latter period, the probability for such a storm had increased to about 0.42. Relying on the record of the recent 15 years, the return period implied for a storm of *at least* 600 mi extent is 1/0.42 or about 2.4 years and for a storm damaging at least 1300 mi of coast, 1/0.05 or 20 years.

4. Causes for increasing storm damage frequency

The foregoing analysis of damaging storms along the east coast of the United States has shown a great increase in the number of such storms in recent years. The cause of this increase needs real study. Is the present high number of damaging storms the result of better reporting? Is it the result of a real climatic change? Or is the increase the consequence of more intensive development of the coastal margin so that storms that formerly would have been benign now result in damage?

There is some reason to believe that improved reporting or a larger number of reporters is not the major cause of the increase in reported damage. If there were a marked improvement in reporting, an increase in the number of reported storms causing comparatively insignificant damage would be expected. The right-hand column of Table 2 shows no such increase in the number of insignificant damage storms during two 5-yr periods although the number of significant damage storms has increased. Of course, it could be argued that improved reporting may have resulted in the "promoting" of all reported storms. That is, storms now assigned significant damage might previously have been listed inaccurately as insignificant as a result of poor reporting. Storms now called insignificant might not even have been reported in earlier years. However, there is no evidence that this has occurred.

In order to have a preliminary check on whether the change in the number of damaging storms could have resulted from a climatic trend affecting the frequency of storms, daily weather maps for two 5-yr periods (1949-1953 and 1960-1964) were examined. There were reports of 25 storms in the earlier period and 47 in the more recent period.

The appearance of the weather map of a closed low within 100 mi of the east coast (either inland or seaward) was accepted as a criterion for a possible coastal storm. All such lows for which there was no report of water damage were considered non-damaging. Both the midnight and noon maps were examined for each day of the two 5-yr periods (except for ten days when the maps in the files being examined were missing). If two or more closed lows appeared within 100 mi of the coast on the same map, and if they appeared to be part of a single meteorological disturbance, they were counted as only one cyclone center. If a particular low appeared on more than one map, it was, of course, counted only once.

The number of damaging storms for each year is compared with the total number of closed lows in Table 2. Despite the increase in number of damaging storms in recent years, the total number of closed lows moving within 100 mi of the coast has remained essentially the same. Consequently, if the increase in damaging storms is to have a climatological origin, there must have been a change in some other statistic such as storm intensity or storm track.

To test the possibility that the circulation in the low pressure systems has tended to be more intense during recent years, the central pressures of all the closed lows occurring within 100 mi of the coast during the period 1952 to 1962 which produced significant

TABLE 2. Number of cyclonic centers and damaging storms during two different periods.

	Number of closed lows within 100 mi of coast	Number of cyclone centers resulting in Significant damage*	Number of cyclone centers resulting in Insignificant damage
1949	68	2	0
1950	56	5	2
1951	65	2	4
1952	66	2	3
1953	61	5	0
	316	16	9
1960	62	8	1
1961	57	5	2
1962	64	11	1
1963	61	7	2
1964	67	8	2
	311	39	8

* For the purposes of this study, the damage occurring along 25-mi reaches of coastline based on reports in the literature and on records of tide heights at gaging stations was considered. If at least one 25-mi reach indicated significant coastal damage, the storm was so-classed. If no sectors reported damage other than minor the storm was classified as insignificant damage.

damage were studied.[5] The average minimum central pressures for these storms (within the confines of the map) are given in Table 3. The table shows that:

1) The number of extratropical storms resulting in significant damage has increased, a fact previously established.

2) Central pressures of such damaging extratropical storms tend to be lower in more recent years. In fact, the average minimum central pressure of all extratropical storms occurring during the years 1958-1962 and resulting in significant damage is 11 mb lower than the average minimum central pressure of such storms for the years 1952-1957. Students t test shows this difference to be significant at the 1 per cent level.

Is there any significance that might be drawn from this difference in minimum central pressure or is this just normal climatic variation? Several different lines of evidence have been examined.

The frequency of significantly high tides by years at selected east coast points is shown in Table 4. The expected decrease in tidal range at southern stations is reflected in the data. The table shows that there has been only a small increase in the average height of abnormally high tides at five of the seven stations during the eleven years. However, totaling the number of tides in the greatest tidal range shows that there has been a marked increase in the frequency of very high tides. For example, at Portland between 1952 and 1956 there was only one tide over 3.5 ft above mean high water (MHW), but there were seven in the 1957-1962 period. Montauk had three tides over 3.0 ft above MHW during the early period and six between 1957 and 1962. Atlantic City had one tide over 3.5 ft above MHW in the first period and three in the second. A similar increase in the number of very high tides can also be seen at Portsmouth, Charleston, and Boston.

The occurrence of a very high tide is related either to astronomical or meteorological events rather than to the human development of the coast. Astronomical causes should not produce any great change in the number of very high tides from year to year since the opportunity for spring or perigean tides to occur will not vary greatly with time. Thus, an increase in the number of very high tides should be primarily related to meteorological factors. At the same time since damage is related to very high tides, this would suggest that we should seek at least in part for a climatic explanation of the recent increase in coastal damage. It does not, of course, rule out the possibility of increased vulnerability to storms due to the human development of the outer coastal margin. This latter factor will add to the influence resulting from climatic conditions.

A decrease in the central pressure of damaging low pressure systems would also seem to be unrelated to possible changes in coastal vulnerability but such may not be the case. Low pressure areas at higher latitudes are generally more strongly developed and have lower central pressures than those in lower latitudes. Thus, it might be possible to explain the deepening of the central pressures of damaging storms by means of a northward shift in the locations of storm centers in more recent years. Figs. 3 and 4 show the location of the minimum low pressure observed for each destructive storm for the two periods 1952-1957 and 1958-1962. Aside from the more than twofold increase in storm frequency, two other changes are obvious.

1) The marked increase in the number of damage producing centers that attain greatest intensity outside of the zone 100 mi east and west of the coast.

2) The marked increase in number of damaging storm centers reaching their greatest intensity north of 40N.

Table 5 shows a 3–5 mb change in pressure between lows south of 40N and those north of 40N. This change is evidently related to the stronger development of cyclones at higher latitudes. The significant trend, however, is the change in pressure of all lows between the 1952-1957 period and the 1958-1962 period. There was a deepening of pressure of 9 mb during this time in those damaging lows south of 40N and of 11 mb in those north of 40N.[6]

The results would seem to support an increase in the intensity of damaging low pressure areas. There is, of course, no proof that this is the only factor responsible for the increase in damage along the coastal margin.

The increase in the number of damage-producing centers attaining their greatest intensity outside of the 100-mi zone might, for example, be related to the increased vulnerability of the coast. As coastal defenses are weakened by the building of marinas, leveling of dunes, etc., intense storms whose centers are farther from the coastal margins themselves will be able to

[5] It is recognized that pressures of cyclonic centers taken from synoptic charts may not be minimum pressures. Such pressures may not be known for centers located over the oceans. Thus, it may be that the reported differences in central pressures are biased by changes in the techniques of data collection and analysis of the synoptic maps.

[6] This figure for lows north of 40N has no real significance since there was only one damaging low in the 1952–1957 period. It is felt, however, that had more damaging lows been present, the same type of change in central pressure noted south of 40N would also have been found north of 40N.

TABLE 3. Average central pressures (mb) of significant damage extratropical storms by years, 1952–1962.*

	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962
Number of significant damage storms	1	2	1	1	4	5	9	5	6	4	9
Average minimum central pressure	1011	994	1005	1000	996	1004	989	982	990	988	993

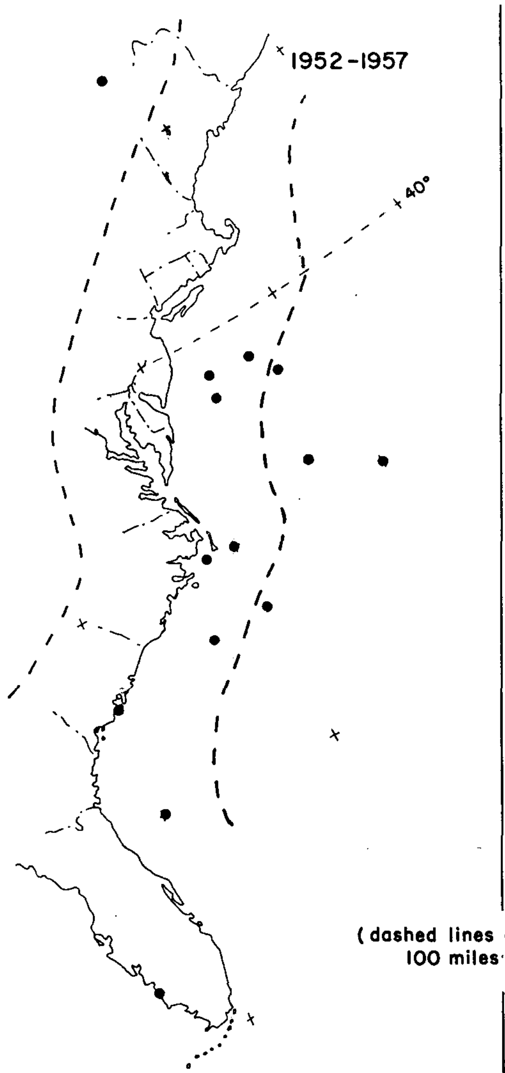
* Data are averages of the lowest pressure found on the synoptic map for each storm.

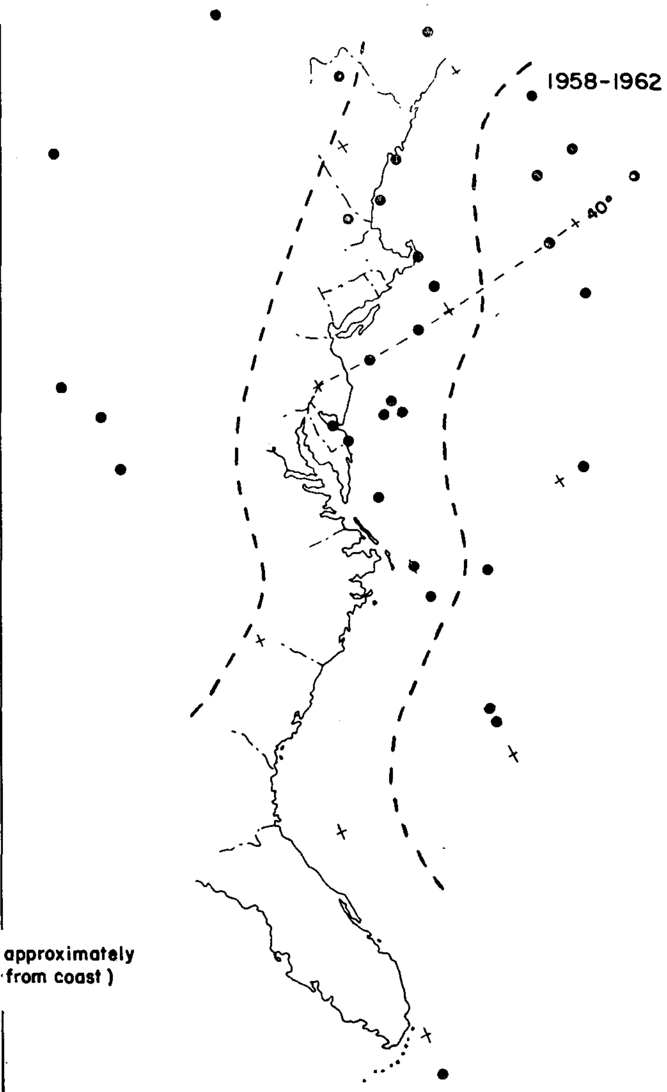
TABLE 4. Number of tides well above mean high water by year at selected east coast stations.

Tide above MHW (ft)	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962
Portland, Me.											
2.0–2.4	10	9	5	3	6	4	7	5	7	4	6
2.5–2.9	2	3	4	5	0	7	8	3	5	7	5
3.0–3.4	2	3	1	4	2	0	1	2	3	2	3
3.5–	0	0	1	0	0	0	2	1	1	3	0
Total	14	15	11	12	8	11	18	11	16	16	14
			Avg. ht. 2.54					Avg. ht. 2.65			
Boston, Mass.											
2.0–2.4	4	5	5	5	7	5	7	6	6	10	5
2.5–2.9	2	2	2	4	3	2	5	2	4	0	2
3.0–3.4	2	2	1	1	0	0	3	1	2	3	1
3.5–	0	0	0	0	1	0	1	1	0	1	1
Total	8	9	8	10	11	7	16	10	12	14	9
			Avg. ht. 2.50					Avg. ht. 2.55			
Montauk, Long Island											
1.5–1.9	5	2	4	4	5	3	6	0	4	4	3
2.0–2.4	1	1	1	0	2	1	7	1	5	3	1
2.5–2.9	0	0	0	1	0	0	0	1	0	3	1
3.0–	0	1	1	0	1	0	2	0	2	1	1
Total	6	4	6	5	8	4	15	2	11	11	6
			Avg. ht. 2.59					Avg. ht. 2.49			
Atlantic City, N. J.											
2.0–2.4	5	2	5	1	6	7	6	3	6	4	1
2.5–2.9	1	1	1	3	3	0	2	0	1	2	3
3.0–3.4	0	0	0	0	0	0	0	1	0	1	0
3.5–	0	1	0	0	0	0	0	0	1	1	1
Total	6	4	6	4	9	7	8	4	8	8	5
			Avg. ht. 2.41					Avg. ht. 2.45			
Portsmouth, Va.											
2.5–2.9	2	3	5	2	4	1	3	2	3	1	2
3.0–	0	0	0	0	2	1	1	0	1	1	2
Total	2	3	5	2	6	2	4	2	4	2	4
			Avg. ht. 2.58					Avg. ht. 2.73			
Charleston, S. C.											
2.0–2.4	1	2	5	3	5	6	8	4	8	6	9
2.5–2.9	0	2	1	1	0	1	1	2	2	1	1
3.0–	0	0	0	0	0	0	0	1	1	0	1
Total	1	4	6	4	5	7	9	7	11	7	11
			Avg. ht. 2.30					Avg. ht. 2.34			
Mayport, Fla.											
1.5–1.9	4	4	7	6	5	6	4	6	4	4	5
2.0–2.4	0	1	2	0	0	2	1	1	3	0	1
2.5–	0	1	0	0	0	0	0	0	0	0	0
Total	4	6	9	6	5	8	5	7	7	4	6
			Avg. ht. 2.32					Avg. ht. 2.20			

produce damage on the coast. If the rate of development of the coast north of 40N has been more rapid than along the coast south of 40N, then the number of damaging storms north of 40N could have increased without any change in the actual number of cyclone centers or any change in meteorological phenomena. The central pressures for the more recent damaging storm centers might be lower than those for earlier time periods merely because of their more northerly location.

Thus, certain of the changes noted on Figs. 3 and 4 can be explained in part by the assumption of increased vulnerability of the northern portion of the coastline. However, as Table 5 indicates, there has been a decrease in central pressure of all cyclones whether they are





(dashed lines approximately 100 miles from coast)

FIG. 3. Location of damaging extratropical storm centers at the time of minimum central pressure, 1952–1957.

FIG. 4. Location of damaging extratropical storm centers at the time of minimum central pressure, 1958–1962.

found north or south of 40N. The decrease in central pressure has been about the same for both groups of cyclones. It is difficult to explain this difference except on the basis of meteorological factors. Although the data are too sparse and the periods of analysis too short to base conclusions on meteorological or climatological trends, there do appear to be physical differences that are associated with the increase in damage during recent years.

TABLE 5. Changes in number and central pressure of damaging lows north and south of latitude 40N, 1952–1962.

	North of 40N		South of 40N	
Year	Number	Average min. pressure (mb)	Number	Average min. pressure (mb)
1952–1957	1	998	13	1001
1958–1962	17	987	16	992

5. Analysis of damage frequency

Thirty years of recorded storm damage covering 1935-1964 have been analyzed to determine the frequency of damage to all points along the east coast of the United States. The coastline as defined here omits the interior shorelines of bays and estuaries, such as the Delaware, Chesapeake, and Cape Cod Bays, and Long Sound. The coast thus defined extends 1600 n mi from Eastport, Me., to East Cape, Fla. It has been divided into 64 increments or reaches of 25 n mi each.

Descriptions of the damage sustained along the coast were obtained and evaluated for severity for each 25-mi reach of the coast. Damage reports for interior coastlines of bays and sounds were averaged with those for the exterior coastlines. Damage to property judged from the reports to be due to flood or wave action and incidents of beach erosion were mapped for each storm. Information on the heights of abnormal tides along the coast were also used to judge the severity of each storm at various points along the coast. The tide information aided in determining the lateral extent and intensity of the storm damage. It was used as a supplement to and a check on the actual damage reports. By using both damage and tide information, it was possible to obtain some idea of the broad pattern of the potential for damage along the coast including uninhabited places and sites between points of definite reported damage. The resulting pattern is therefore a combination of actual damage to vulnerable points along the coast and a generalization of this damage frequency to nearby points that may or may not be vulnerable at future times depending on local circumstances. In this way, it was hoped to free the analysis from excessive reliance on detailed local topographic and human occupance factors, and thereby to obtain a measure of the broad patterns of hazard along the coast.

There were some storms in which the damage reports indicated only inconsequential damage. In other cases, it was difficult to distinguish between major and inconsequential beach erosion. Therefore, the 121 damaging storms analyzed here include only those storms in which there was judged to be greater than minimal damage to real estate or natural coastal defenses somewhere along the coast. Intermediate points were sometimes considered to have been damaged when tides were as high as the tides known to be associated with damaging storms.

A map of the damage produced by each storm was prepared for each of the 121 storms. The frequency of damage for each 25-mi reach of coast was determined from these maps.

The overall frequency of damaging storms for the whole length of coastline has increased over the 30 years from about 1 per year to a current frequency of about 8 damaging storms per year. The frequency of damaging storms per 25-mi reach of coastline is shown

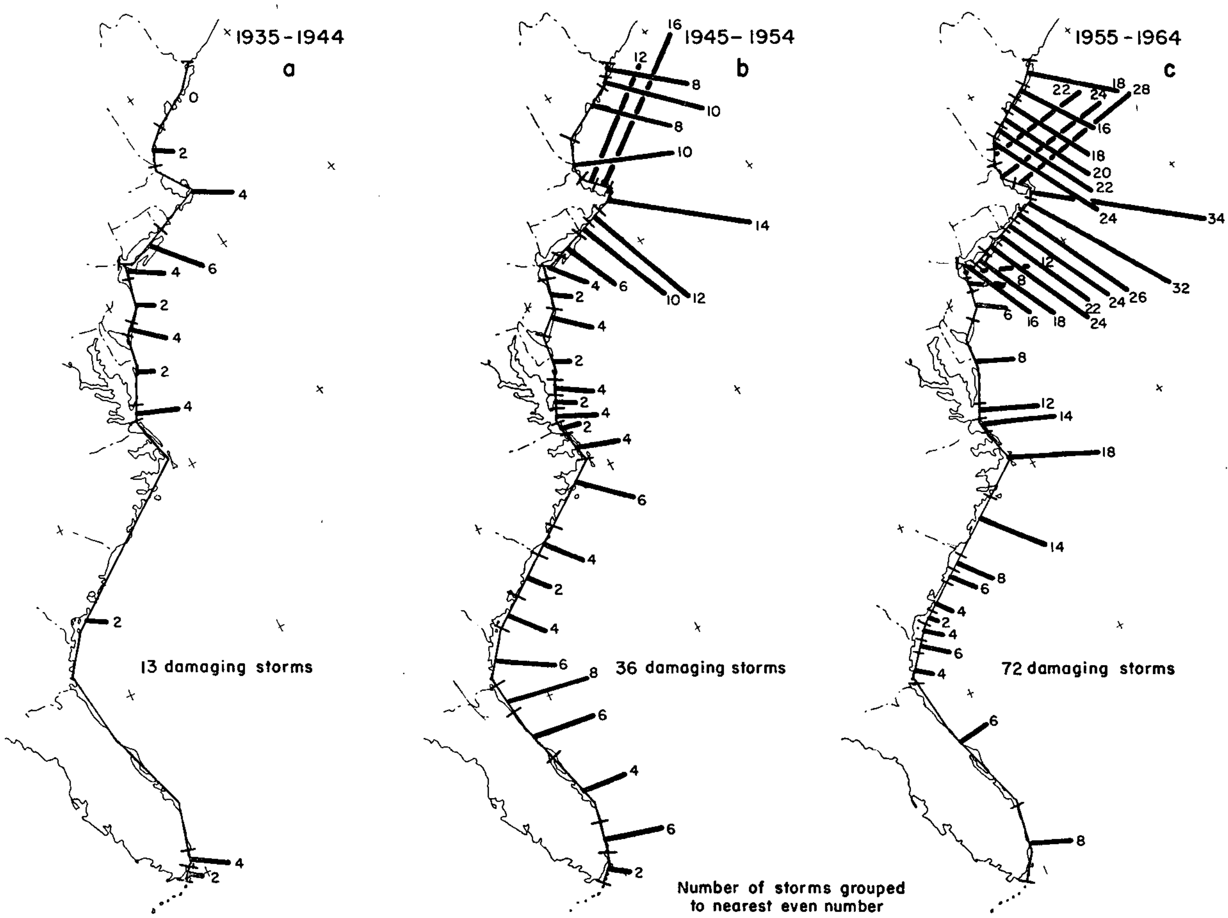


FIG. 5. Number of storms producing significant reported damage along indicated reach of coastline for three selected time periods: a) 1935–1944, b) 1945–1954, c) 1955-1964.

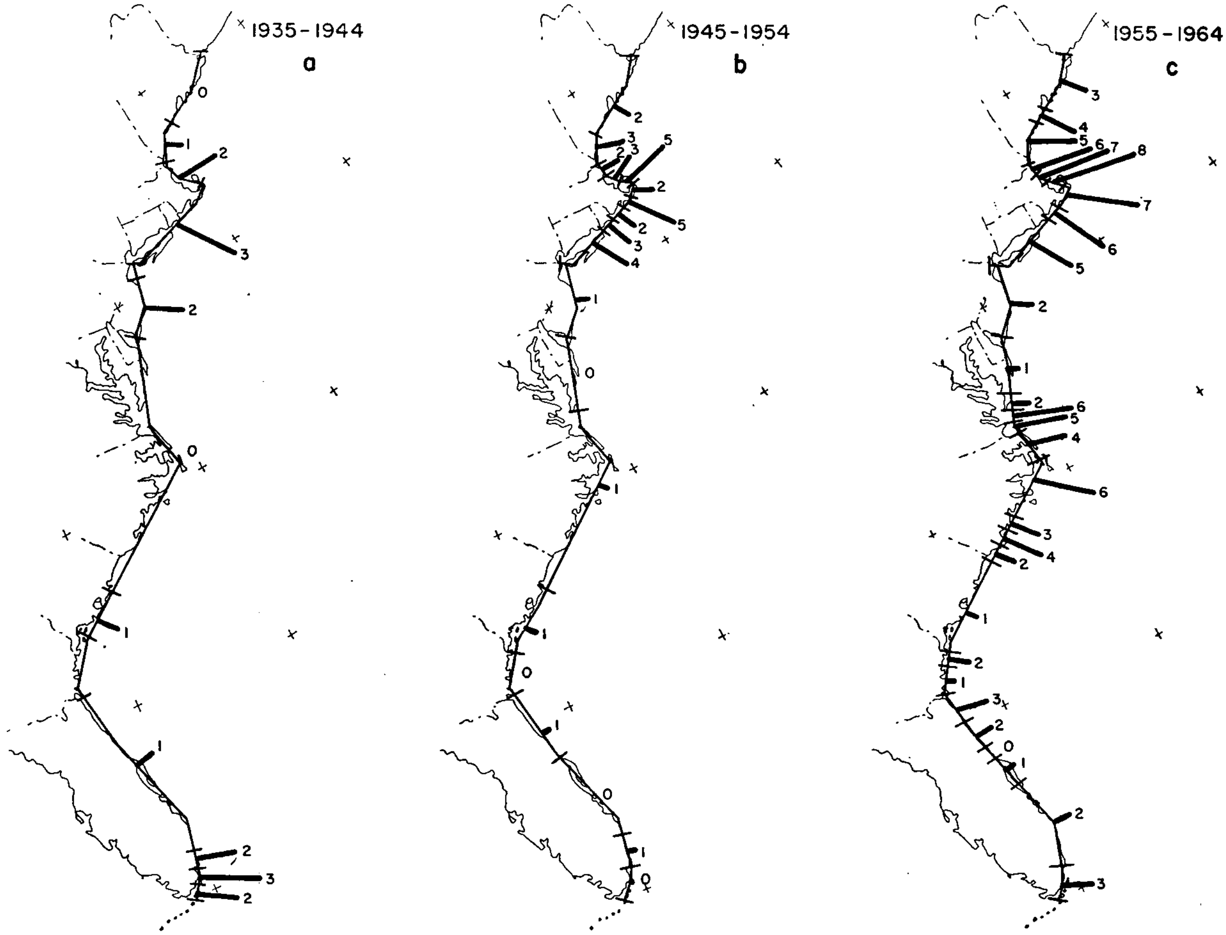


FIG. 6. Number of storms producing heavy damage along indicated reach of coastline for three selected time periods: a) 1935–1944, b) 1945–1954, c) 1955–1964.

in Fig. 5 for the three decades 1935 through 1964.[7] In each of the three decades, just under one-half of the storms seriously affected the vicinity of Cape Cod on the southern New England coast. It is clear from Figs. 5b and 5c that since 1945 the New York-New England coast has been significantly more subject to storm damage than has the remainder of the United States east coast lying to the south of New York City. During the most recent decade, for instance, there were an average of 22 damaging storms for each 25-mi segment of coastline between New York City and Eastport, Me. By contrast, there were only an average of 8.3 storms bringing damage to each of the 25-mi segments south of New York. Within New England, storm damage was most frequent along the Rhode Island-Massachusetts coastline, where there were an average of 28 damaging storms per 25-mi segment between Provincetown, Mass., and Groton, Conn. North of Provincetown, the number of damaging storms is only slightly lower.

Nowhere south of New York does the total number of damaging storms exceed the storm frequencies experienced in New England. And the average frequency, as noted above, is less than half that experienced in New England. Yet, within the southern coast (in this context, the whole coast south of New York), the region immediately north and south of Cape Hatteras, from Albemarle Sound to Cape Fear, not surprisingly, has been damaged more often than any other reach of the southern coast during the past ten years. It is interesting to note, however, that there has been a marked increase in the relative damage frequency along this reach of coast since 1955. The number of structures in the Nags Head area (near Cape Hatteras) has almost doubled in the period 1953-1963. This points up again the difficulty of separating climatic and human influences on coastal damage.

There are two reaches of the coast south of New York where damage frequency during the past ten years has been notably lower than the average for the whole coast. These include an extensive reach of the New Jersey coast north of Atlantic City and the bight of coast from the vicinity of Charleston, S. C., to the vicinity of Palm Beach, Fla. During the decade 1945-1954, however, the latter reach showed a greater rela-

[7] The number of storms per segment has been rounded upward to the nearest even number to simplify the plotting.

tive frequency of damaging storms than was observed during the other two decades of the 30 years under study.

Fig. 5 includes the information on all storms that brought some damage to the shore during the past 30 years of record. From the recorded descriptions of the damage done it has been possible to select those storms that produced heavy or very significant damage in contrast to the others that have only resulted in more moderate damage. Again only subjective criteria could be employed since dollar values of damage were not always available or reliable. Maps were prepared to show the frequency of very significant damage-producing storms for each of the three decades. Fig. 6 shows the frequency of very significant damage for comparison with the frequency of all significant damage shown in Fig. 5. Of the total 121 storms, 48 resulted in very significant damage somewhere along the coast.

Again, the whole New England coast is significantly prone to damage. During the last decade, each of the nineteen 25-mi segments between Eastport and New York City received an average of almost six heavy damage-producing storms during the ten years. To the south of New York, only in the Hatteras area, and the area near Norfolk, Va., is there found an equivalent frequency of very significant damage during the most recent 10-yr period.

Broad categories of relative storm hazard were assigned to individual segments of the coastline from the storm frequencies shown in these two sets of maps. In evaluating the relative hazard, it seemed appropriate to give more weight to storms producing very significant damage. Thus, double weight has been given to these storms.

Fig. 7 shows the relative coastal storm hazard by 25-mi sections of coastline for the three decades. The relative hazard is simply the total number of damage occurrences per reach, with very significant damage occurrences being given double weight.[8] The weighted damaging storm frequencies were broken down into four classes of hazard: 1-10 (light hazard), 11-20 (moderate hazard), 21-30 (considerable hazard) and >31 (great hazard).

[8] The actual, unrounded storm frequencies were used. Consequently, there may be a discrepancy of one storm between the hazard value and the sum of storm frequencies in the two sets of maps.

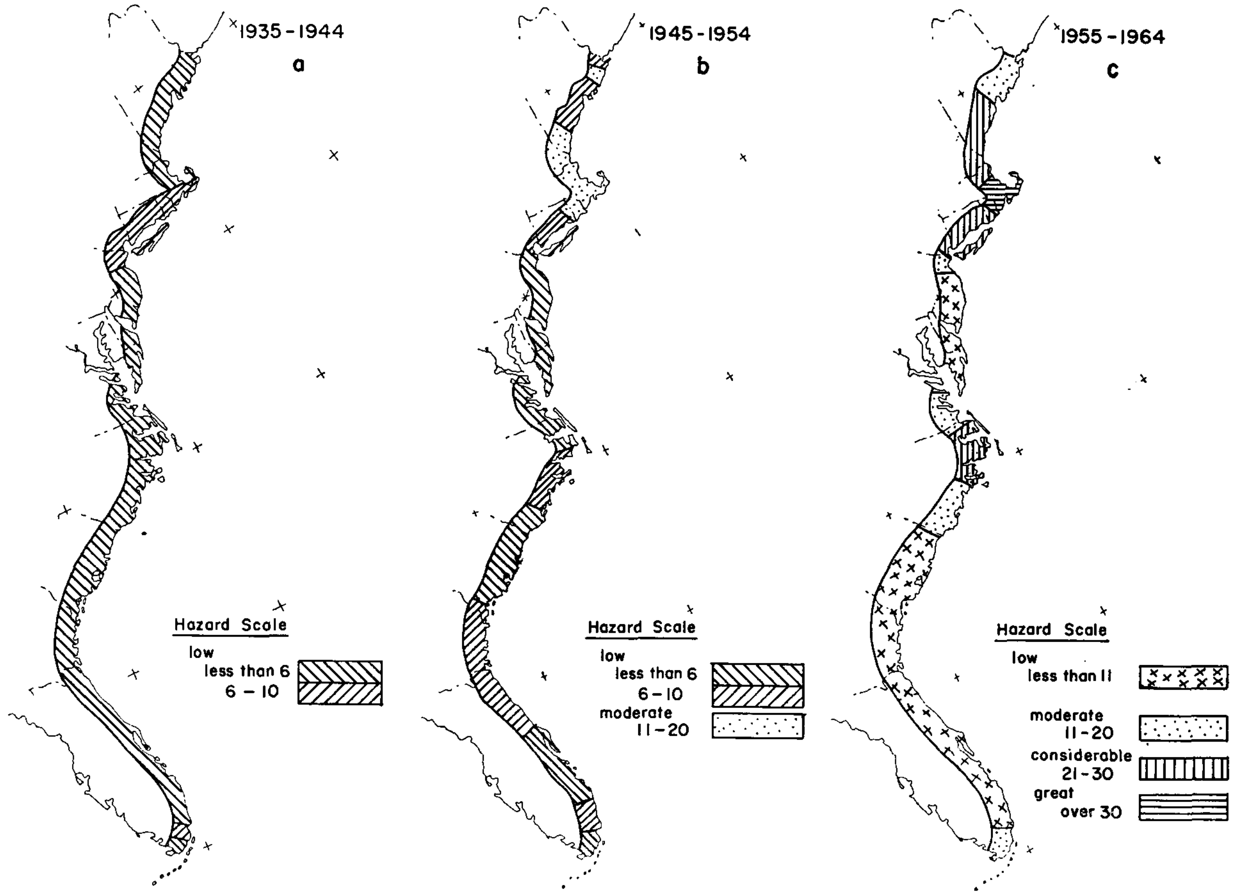


Fig. 7. Regions of relative coastal storm damage hazard, east coast of the United States, for three selected time periods: a) 1935–1944, b) 1945–1954, c) 1955–1964.

Fig. 7c indicates the relative hazard from coastal damage at the present time based on the history of the last ten years. The New England coast around Cape Cod is the only reach of coast that experiences great hazard. Two other regions, the balance of the New England coastline south to New York together with the region from Albemarle Sound to Morehead City are found to be considerably hazardous. The coasts of New Jersey, the Delmarva peninsula, South Carolina, Georgia, and Florida are all found to experience only low hazard. Of course, it is to be remembered that these definitions have been made in terms of frequency of damage. Occasional highly damaging events do occur on these low hazard coasts. The high damage caused by the occasional severe storms along a low hazard coast may be more a consequence of the pattern of coastal development than the severity of the storm.

6. Conclusions

There has been a rapid and, in most cases, unplanned and possibly even unsound, human development of much of the east coast during the past ten or more years (Burton *et al.*, 1965). This development has undoubtedly resulted in a weakening of the natural coastal defenses against storms and, of course, made possible the greatly increased dollar values of damage. The recent increases in the number of storms bringing damage to the coast undoubtedly results in part from the increased vulnerability of the coastal margin. It appears, however, that certain trends in the intensity of cyclones and in their paths of movement may also contribute to this increased storm frequency. Both the meteorologic and human factors must thus be considered in any evaluation of future coastal problems. A more intensive study of possible climatological trends in storm characteristics seems to be justified.

Analysis of the record of damaging storms over the past 30 years indicates that the likelihood of a devastating storm like the one of March 1962 is about one in 20 years. The more frequent storms of restricted extent result in an overall frequency of damage that is much greater. Continued action by man in developing the coastal margin whether or not coupled with changes in the intensity of cyclone development and paths of movement can only increase this damage potential unless great care is exercised in the future development of the coast.

The significant and disastrous effects of man's actions along the coastal margins are clear and well documented. It would seem that only through education of the coastal inhabitants and builders to the damage potential from coastal storms can any permanent and effective solution to this serious problem be achieved.

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