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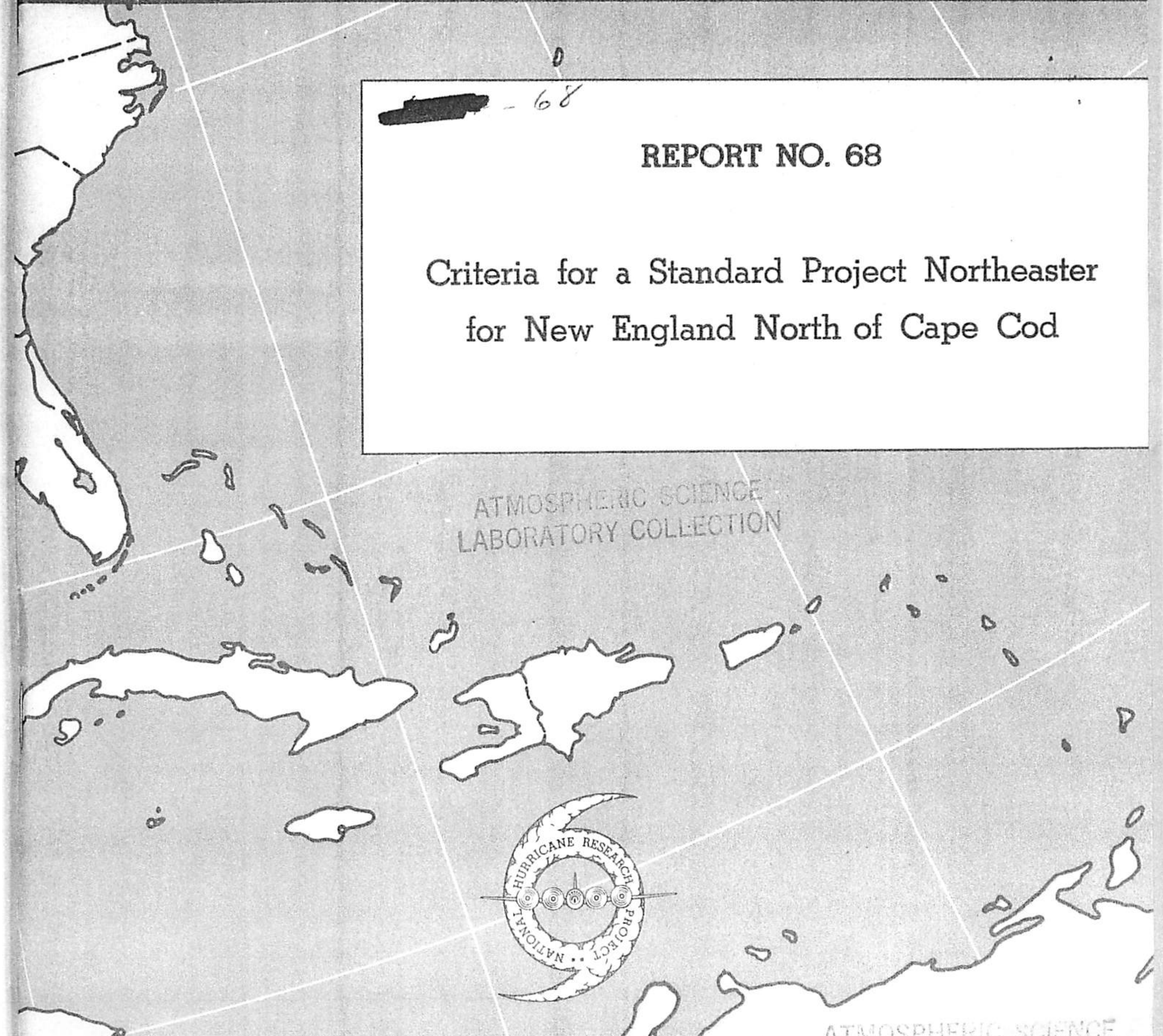
REPORT NO. 68

Criteria for a Standard Project Northeaster for New England North of Cape Cod



U. S. DEPARTMENT OF COMMERCE
Luther H. Hodges, Secretary
WEATHER BUREAU
Robert M. White, Chief

NATIONAL HURRICANE RESEARCH PROJECT

REPORT NO. 68

Criteria for a Standard Project Northeaster for New England North of Cape Cod

by

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Hydrometeorological Section, Hydrologic Services Division, Washington, D. C.

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NATIONAL HURRICANE RESEARCH PROJECT REPORTS

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CRITERIA FOR A STANDARD PROJECT NORTHEASTER FOR NEW ENGLAND NORTH OF CAPE COD

Hydrometeorological Section
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Washington, D. C.

ABSTRACT

Statistical frequency analyses of tide heights at Boston, Mass. and Portland, Maine, and the characteristics and intensities of coastal storms that produced abnormally high tidal surges (1914-1960) in New England north of Cape Cod are presented.

Standard Project Northeasters are developed using the most severe characteristics of cyclones that actually caused high tidal surges north of Cape Cod, or were deemed potentially capable of producing the high surges.

Isovel patterns of the Standard Project Northeasters are presented and compared with isovel patterns in previously developed Standard Project Hurricanes. These are intended to assist engineers in assessing the risks from tidal flooding and in designing possible countermeasures against such flooding.

1. INTRODUCTION

Purpose of Report

The purpose of this report is to present the characteristics and intensities of coastal storms that produce high tides in New England north of Cape Cod. This study was originally prepared for use by the U. S. Corps of Engineers in surveying the damage potential from high tides and waves and in designing means of alleviating such damage. The authors feel that the material may also be of value to meteorologists interested in comparing the behavior of northeasters with hurricanes, along the New England coast.

Authorization

The 84th Congress (1955), first session, through enactment of Public Law 71, authorized and directed the Secretary of the Army, in cooperation with other Federal agencies as necessary, to cause an examination and survey to be made of the eastern and southern seaboard of the United States with respect to hurricanes, especially where severe damage has occurred. One of the objectives was ... "the securing of data on the behavior and frequency of hurricanes, and the determination ... of possible means of preventing loss of human lives and damages to property, with due consideration of the economics of proposed breakwaters, seawalls, dikes, dams, and other structures..." Such surveys have suggested that north of Cape Cod severe extratropical storms (known as "northeasters") may be potentially as damaging to coastal areas as the hurricanes that occasionally move through this area. Accordingly, the Corps of Engineers, in a letter dated August 26, 1960, directed the Hydrometeorological Section to prepare a study or survey of northeasters north of Cape Cod, with the viewpoint of "developing standard project[1] flood criteria and isovel charts, isobaric charts and various parameters necessary to make tidal surge and wave analyses..."

Scope of Report

Severe storm criteria are presented in two ways. First, isovel patterns are developed that are comparable to the most severe storms of approximately the past 50 years, and are shown in figures 15 through 23. These are tentatively deemed to be of "Standard Project" category.

Second, a statistical frequency analysis and extrapolation is made of tide heights at Portland, Maine. This involves analyses of tide and surge heights, followed by the combination of surge frequencies with astronomical tide frequencies on a probability basis. A less comprehensive analysis is included for Boston, Mass. This material is found in table 4 and figures 24 through 31.

The history, morphology, and climatology of northeasters as well as the techniques used in reconstructing surface wind fields are summarized in other sections. Also included are reconstructed isovel patterns of several actual severe storms. The study, in line with specifications in the letter of referral mentioned in the paragraph on authorization, is restricted to the New England coast between Provincetown, Mass., and the Canadian border.

Isovels for standard project hurricanes in the New England region, constructed from the criteria in National Hurricane Research Project Report No. 33, are included in section 6.

Definitions and Symbols

Fetch. Fetch, in this report, refers to an area over water wherein the surface winds are fairly strong, say 25 knots or stronger, and reasonably constant in direction both in time and space.

Fetch length. The linear distance along which conditions as described in Fetch, above, prevail.

Marigram. A plot of tide height, with time as abscissa and height as ordinate.

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[1] See definition on page 3.

Neap tide. An astronomical tide of less than normal range occurring about the first and third quarters of the moon when the sun and moon are at right angles with respect to the earth.

Northeaster. The extratropical storms which occur along the northern part of the Atlantic Coast of the United States accompanied by strong winds blowing from a northeasterly quadrant over the coastal area, have been called "northeasters." By tradition it has become commonplace to refer to any east coast storm (except a hurricane) of the Middle Atlantic and New England States which produces strong onshore winds as a northeaster. The latter definition will be used throughout this report.

Spring tide. An astronomical tide of greater than normal range, occurring when the moon is about full or new and the sun, moon, and earth are nearly in line.

Standard Project. The phrase "standard project" has been used by the Corps of Engineers to designate and describe the most severe occurrence of some meteorological phenomenon (hurricane, rainfall, wind field, flood, etc.) that is considered reasonably characteristic of a particular region.

Surge. The surge is defined as the excess (or deficiency) due to meteorological causes of the actual tide over the predicted or normal astronomical tide.

A - Astronomical (also normal or predicted) tide. The periodic rise and fall of the ocean due to the gravitational attraction of the sun and moon and climatological factors.

CPI - Central pressure index, refers to the estimated minimum pressure for individual hurricanes, in designated latitudinal zones along the U. S. Atlantic Coast.

A_x - The height of the astronomical high tide.

S - Storm surge. The same as surge.

S_x - The maximum value of S in a storm.

SPH - Standard Project Hurricane (see standard project).

T - Observed tide. The height of the ocean level measured at a fixed point above a selected datum plane.

T_x - The maximum value of the observed or total tide, T, on any given day.

2. HISTORICAL COMMENTARIES ON NEW ENGLAND COASTAL STORMS

Coastal storms in New England, commonly referred to as northeasters, have been recorded in the history of the region from the time of the first settlers. Nearly all of the more destructive northeasters have occurred in the period from November through April. Their occurrence in late fall, winter, or early spring further distinguishes these extratropical storms from the less frequent hurricanes that have occasionally reached New England in August and September and rarely in October. Of the 160 gales recorded at Boston during the 75-year period, 1870-1945, 50 percent were classified as "northeast gales" [1]. An appreciation of the havoc created by a northeaster is imparted by the language used to describe the storm of December 15, 1839 [2]:

> "At noon of the 15th the wind had increased greatly in violence and in the afternoon blew a gale in many places. The ocean had rarely been seen in such violent agitation, and possessed of such terrible power. It continued to storm and rage, however, until late Monday night... The whole shore of Massachusetts was strewn with wrecks and dead bodies, and the harbors of Newburyport, Salem, Marblehead, Boston, Cohasset, Plymouth and Cape Cod were almost literally filled with disabled vessels. On the land the force was terrific, many buildings being blown down and hundreds of chimneys overturned. The tide rose higher than many of the highest water marks then known.
>
> "At Boston the tide rose higher than the old water-marks, and swept completely across the Neck, the force of the wind being so great that at the south part of the city on Sunday there was no apparent fall of the water for 3 hours."

With the advent of radio communication, shipwrecks associated with northeasters have become infrequent. Losses today are more in the nature of flooded and wrecked homes and business establishments, with fewer injuries and deaths. Concomitant damages consist of breached seawalls, grounded and broken boats, and eroded beaches. The impact of northeasters on New England is vividly portrayed by the reports in the local newspapers [3] and in publications [4], [5], of which some typical excerpts are given in appendix A.

3. CHARACTERISTICS OF NORTHEASTERS

Surge-Producing Storms

The purpose of this section is to describe the general characteristics of northeasters with particular emphasis on the range of those characteristics relevant to the development of the Standard Project Northeaster.

The primary characteristics of surge-producing storms in northern New England are revealed by the storms that have caused high surges at Boston, Mass., and Portland, Maine. These stations are the only ones north of Cape Cod with nearly complete recording tide-gage data for a period of more than 30 years. The 51 storms which produced "high surge", arbitrarily defined as being 2.5 ft. or greater at Portland (from 1914 to 1959) and/or 2.9 ft. or greater at Boston (from 1922 to 1960), comprised a group for special study. Surge was defined in the Introduction.

Each of the 51 storms, with but one exception, consisted of a single cyclone moving in a direction between north and east. The characteristics of these storms summarized in this section are amplified by climatological characteristics of eastern United States cyclones from several authorities.

Morphology of Northeasters

Northeasters producing strong winds and high surges along the New England coast are well-developed and mature extratropical Lows. The gross features of the more common northeaster consist of a single center of low pressure associated with one cold and one warm front. These storms are usually in the initial stage of occlusion. An example of such a Low is shown in figure 1. The more complex northeasters are characterized by more than one center of low pressure (sometimes two, or rarely, three low centers) associated with a multiplicity of fronts. An example of the complexity that these low systems can have is the northeaster of March 1, 1914; see figure 2.

Asymmetry of pressure field. Pressure fields associated with surge-producing northeasters are noticeably asymmetrical. The degree of asymmetry is dependent upon many diverse factors, such as the extent to which the storm has occluded, the nature of the underlying surface (when part of the storm circulation is over land), the effects of the upper air circulation, and the influence of surrounding pressure systems.

Many of the more notable surge-producing northeasters were associated with blocking high pressure located in advance of the storm and acting to block its forward motion. The blocking phenomenon acts to tighten the isobaric spacing (to increase the gradient) and lengthen the radius of isobaric curvature, creating an unusually long fetch in the forward semicircle of the storm; see, for example, figure 8.

Central pressures. Central pressures in the selected group of 51 northeasters described earlier in this section ranged from 957 mb. to 1006 mb.

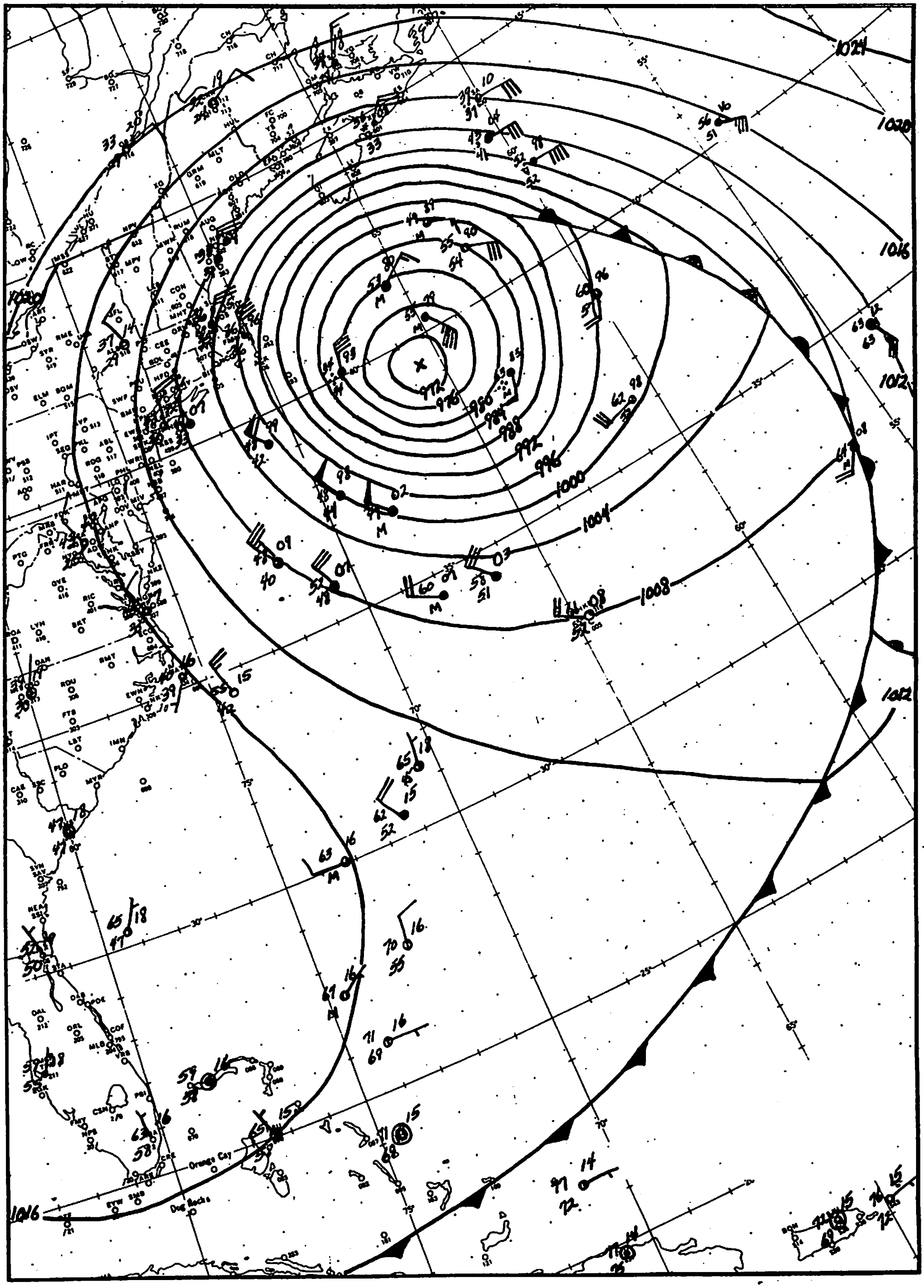


Figure 1. - A typical northeaster with a single center and a single frontal system, occurring 0100 EST, April 2, 1958, four hours before a peak surge of 3.5 ft. at Boston, Mass.

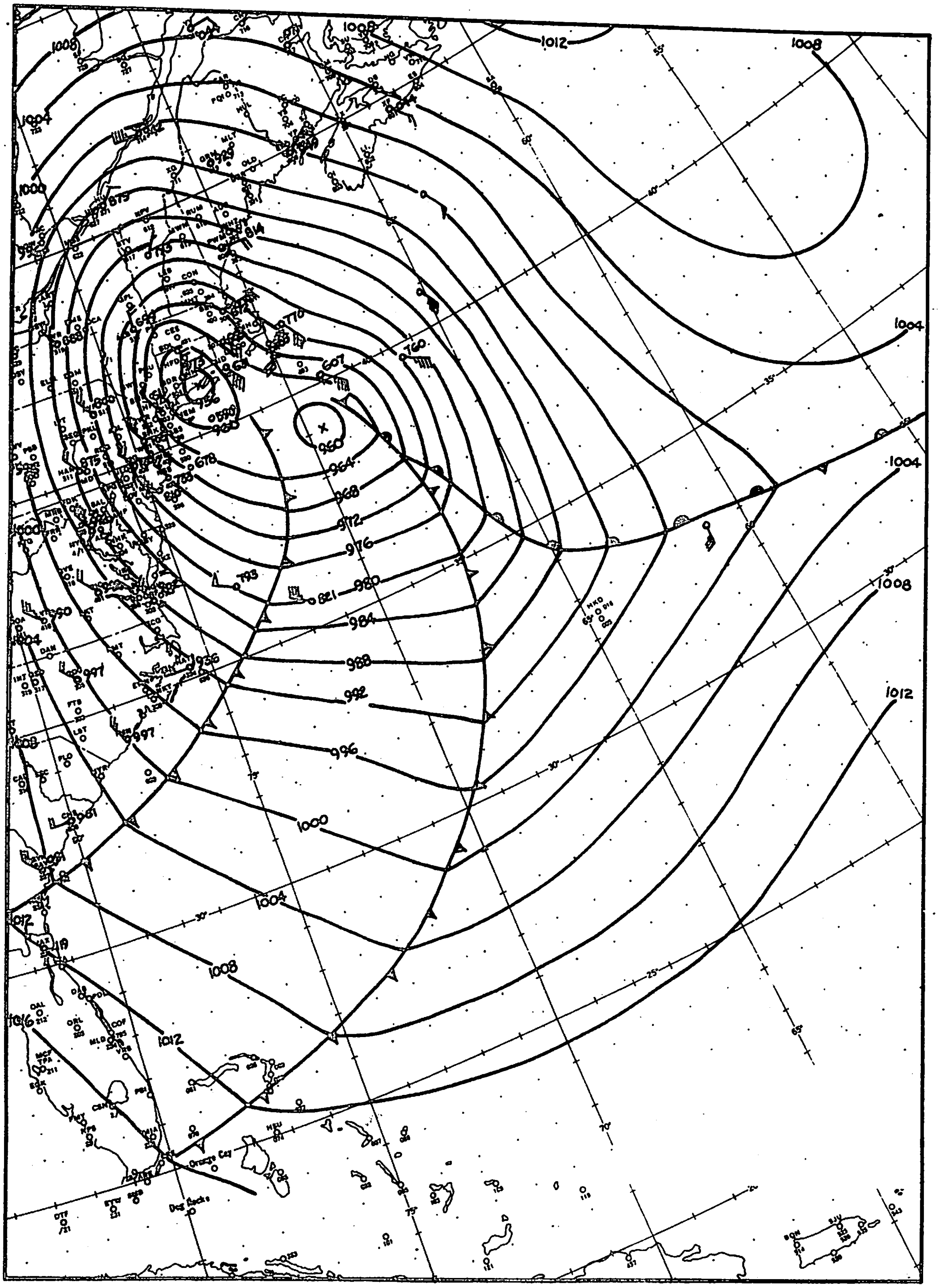


Figure 2. - A complex northeaster with two low centers and a double frontal system, occurring 1900 EST, March 1, 1914, three hours before a peak surge of 4.1 ft. at Portland, Maine.

The minimum observed pressure (957 mb.), recorded at New Haven, Conn., occurred during the northeaster of March 1, 1914, when the storm center was about 20 miles SE of the station. Other northeasters with notable minimum central pressures were: December 2, 1942 (959 mb.), March 4, 1931 (961 mb.), and March 4, 1960 (961 mb.). At the other end of the range, the February 20, 1927 storm had a central pressure of 1006 mb. The mode and median as given in the histogram in figure 3, are 987 mb. and 981 mb., respectively. The average of these 51 cases was 983 mb. during the 6-hr. period before the tidal surge reached its maximum.

It is interesting to note that the central pressures of all but one of these 51 cyclones decreased during the 12-hr. period just before the surge reached its peak at either Boston or Portland. The mean rate of deepening was about 9 mb./12 hr., with two storms (December 1942 and March 1956) deepening 20 mb. during the 12-hr. period. In general, the storms moving along a more northerly track deepened at a greater rate (average of 11 mb./12 hr.) than those traveling along a more easterly track (average of 6 mb./12 hr.).

Winds. The zone of strongest winds in any particular surge-producing storm is most often found in the forward semicircle of the moving storm; but it is not unusual to find it in the rear semicircle, particularly to the left. The distance of this zone from the center is variable. In the 11 northeasters for which isotach charts were constructed, this distance averaged 194 nautical miles, ranging from 90 to 340 n. mi.

There is often a secondary belt of maximum winds (of lesser value, but still distinct and well-substantiated by observations). The lesser maximum is usually at a greater distance from the center than the principal maximum belt.

Observed wind speeds of 55-65 kt. are not unusual in these mature storms. Wind speeds close to 70 kt. were observed in the northeaster of March 1, 1914. In many of the more severe northeasters the zone or area of strongest winds covers large portions of coastal regions.

To illustrate the variation in the configuration of isovel patterns in northeasters, the wind fields were synthesized for the four severe storms which produced the highest and second highest tide of record at Boston, Mass., and Portland, Maine. The dates, tide heights, and ranks are given in table 1. The maximum surge heights occurring with these storms are also listed. Although these surges are not particularly high, coincidence with spring high tide was a major factor in producing the record high tides.

The wind fields of these storms were synthesized using available ship observations, supplemented by winds obtained from trajectories, as described in appendix C. The isovel patterns, shown in figure 5, indicate the large variation in wind directions and speeds which are possible from northeasters.

Table 1. - Highest tide heights observed at Boston, Mass. and Portland, Maine

Date	Tide Height (ft. above msl)		Rank		Surge (ft.)	
	Boston	Portland	Boston	Portland	Boston	Portland
April 21, 1940	8.9		2		2.9	-
November 30, 1944		8.7		1	2.6	2.8
November 20, 1945		8.7		1	-	2.9
December 29, 1959	9.3		1		2.8	-

Fetch lengths. Two of the northeasters studied were found to have a fetch length of about 1400 n. mi; these storms were associated with very strong blocking Highs. Fetch lengths of 500 n. mi. or less are commonly observed.

Pressure gradients. As a measure of relative storm intensity, the value of maximum surface winds occurring just offshore from where high-surge was experienced was estimated for the 51 cases studied. Since actual observations were scarce, an indirect approach was used, which involved measuring the maximum pressure gradient, at a map-time about 6 hr. before the maximum surge occurred at either Boston or Portland. The maximum pressure gradients were measured along a line perpendicular to the isobars, passing through a point within 300 n. mi. upwind from Boston or Portland. "Upwind" is taken to be at an angle of 20 degrees to the isobars. The measurement was taken in units of millibars per 150 n. mi. This procedure is illustrated in figure 4.

The ranges of pressure gradients measured for the 51 storms which produced high surge at Boston and/or Portland are shown in table 2. Also listed are the approximate equivalent surface wind speeds, computed by first converting the gradients to geostrophic wind speeds and then using curve VI of figure 37, appendix C, to obtain estimated surface wind speeds.

Origin of Northeasters

Using the zone classification of Bowie and Weightman /‾6/, (fig. 6), 73 percent of the 51 surge producing northeasters studied developed in the Texas-East Gulf and South Atlantic regions. Lows from these regions often develop rather quickly and intensify into severe storms over the mid-Atlantic and New England States. Maximum occurrence of cyclogenesis in these regions takes place during the colder months when the temperature contrast between maritime and continental air masses along these southern coasts is greatest.

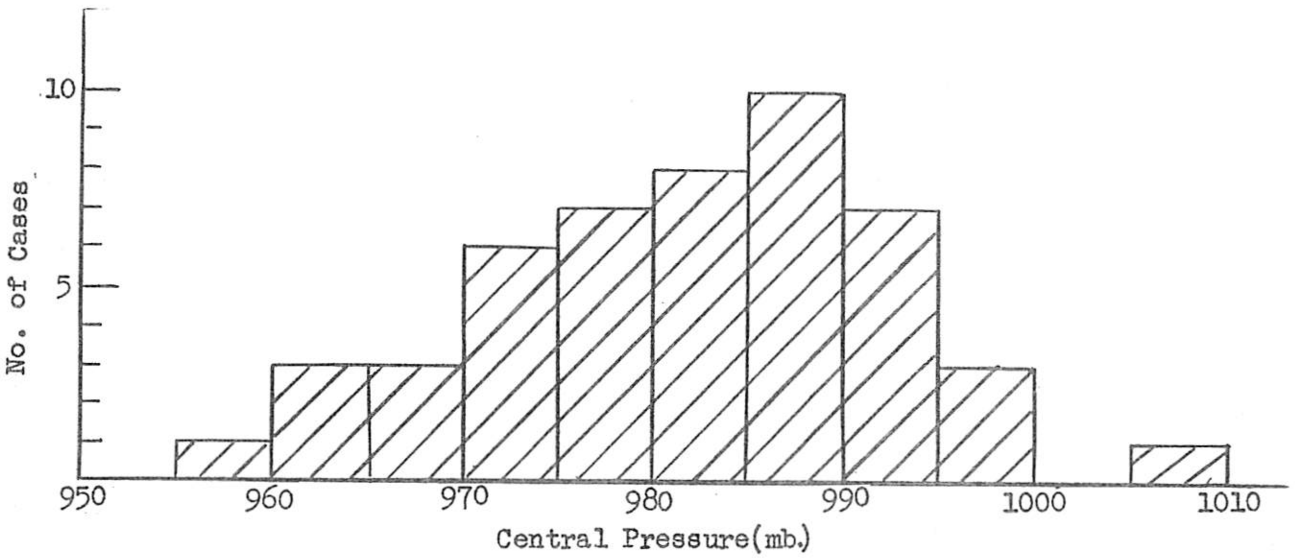


Figure 3. - Histogram of central pressures for northeasters producing high surge.

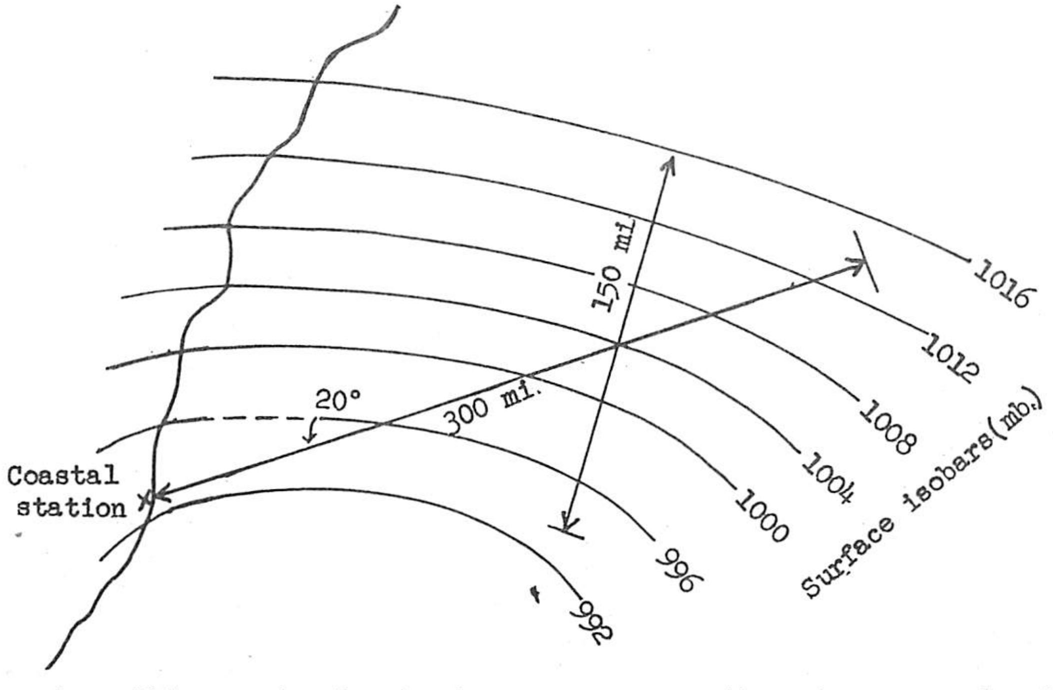
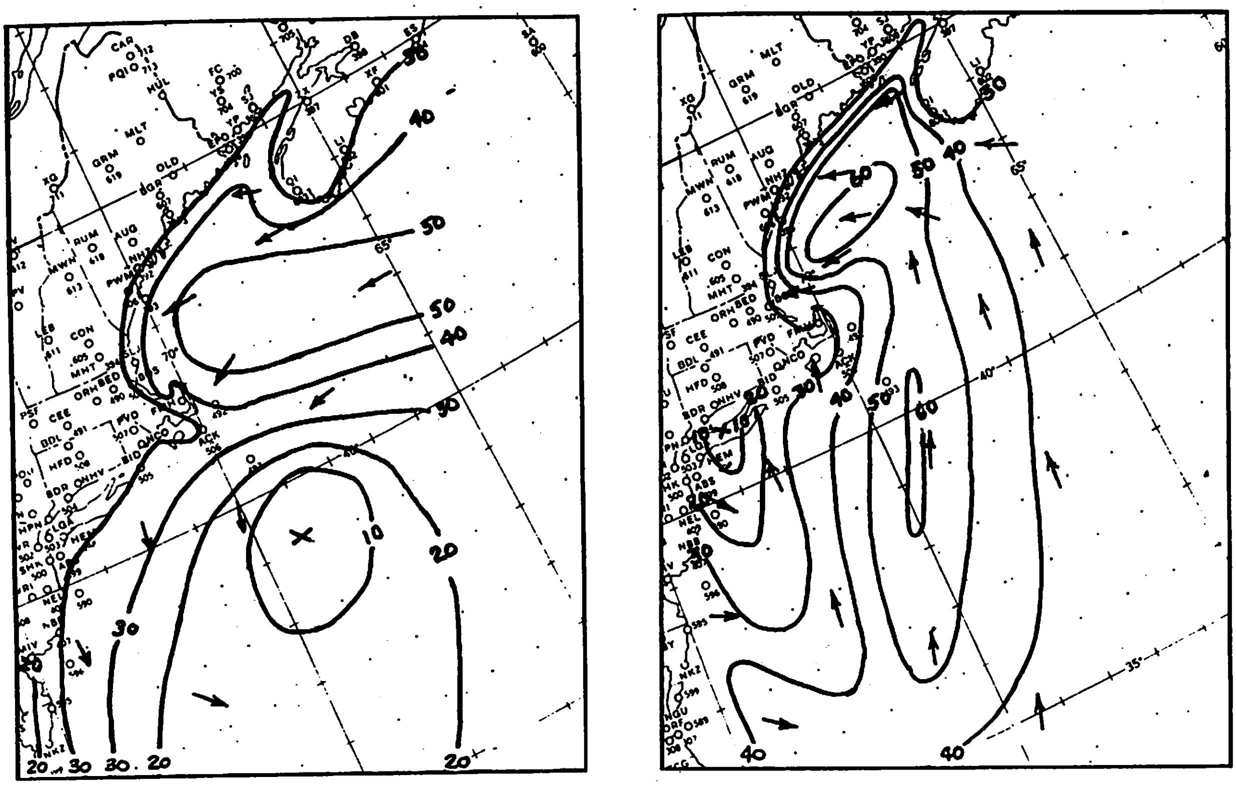
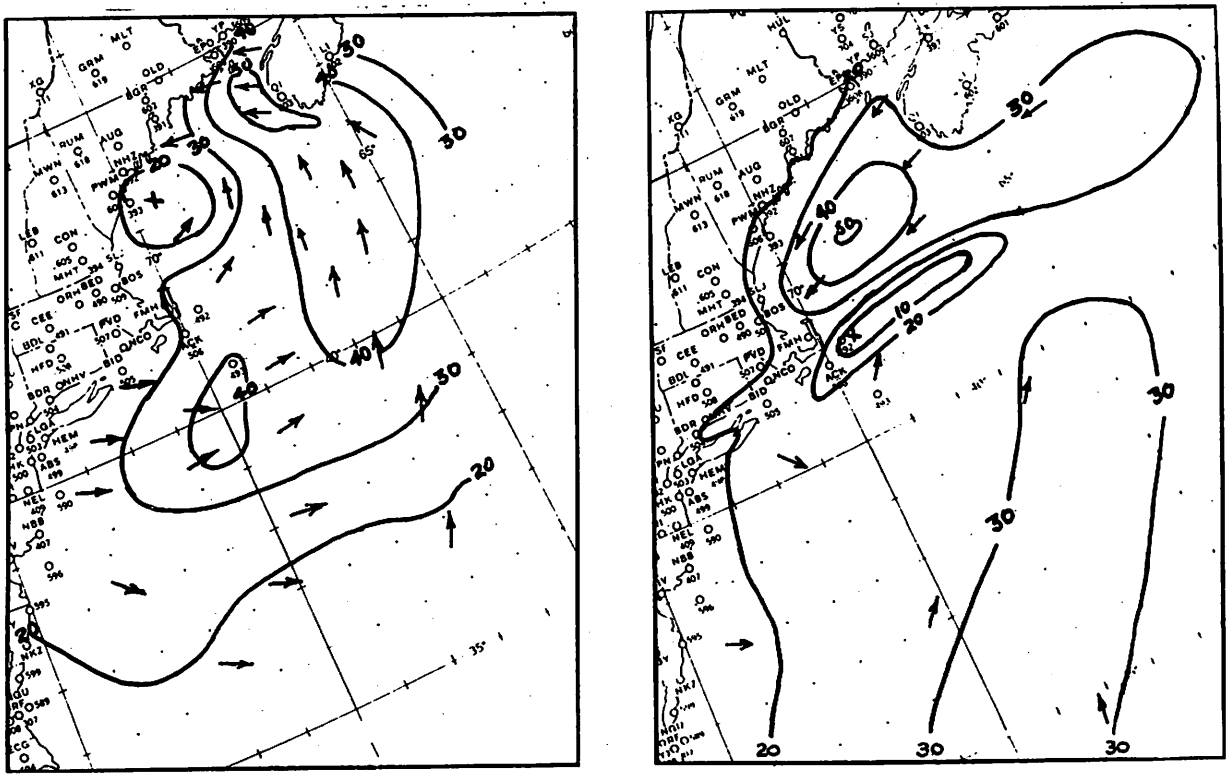


Figure 4. - Illustrating how maximum pressure gradient is measured. In this example, max. gradient = 22 mb./150 n. mi.



a. 1330 EST, April 21, 1940.

b. 0730 EST, November 30, 1944.



c. 1030 EST, November 20, 1945.

d. 1000 EST, December 29, 1959.

Figure 5. - Isovel maps illustrating the variation in the configuration of northeaster wind patterns. Isovels are in knots.

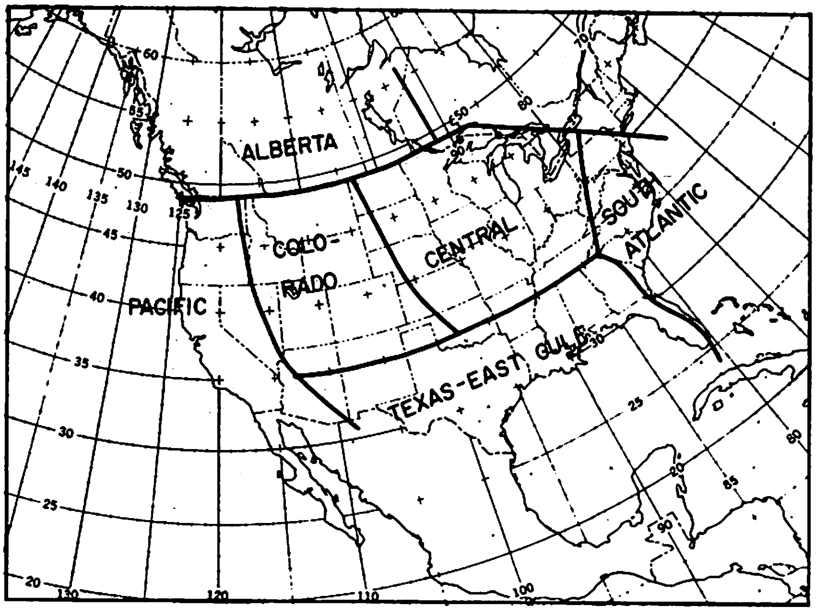


Figure 6. - Regions where extratropical cyclones first appear or develop in the United States.

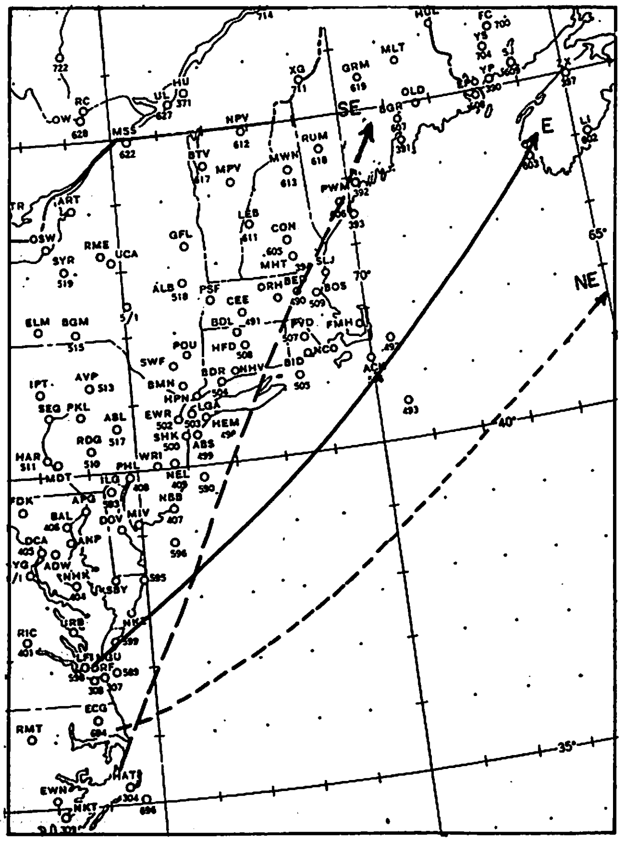


Figure 7. - Mean tracks of 51 northeasters which produced high storm surge at Boston or Portland. Tracks were grouped according to wind direction at coast shortly before peak surge.

Table 2. - Range of pressure gradients measured in 51 surge-producing northeasters.

	Boston		Portland	
	Min.	Max.	Min.	Max.
Pressure gradient (millibars per 150 n. mi.)	11.0	24.0	13.5	25.0
Approximate equivalent surface wind speed (kt.)	40	63	46	65

Cyclones which first appeared or developed in the Pacific Coast, Alberta, Colorado, and Central regions produced only 27 percent of the high surges in the New England coastal area.

Average Tracks of Northeasters

Figure 7 shows the average tracks followed by the 51 northeasters that produced high surge. These were obtained by computing the mean position of the storm centers at several times beginning 6 hr. before, and ending 6 hr. after the occurrence of the highest surge at either Boston or Portland. In this figure the storms have been grouped into three categories, according to the wind direction produced near the coast shortly before the time the surge reached its maximum value. This grouping is explained in greater detail in the following section.

Mean Speed

The speeds of the surge-producing northeasters were measured from tracks published in the Monthly Weather Review [7] and Climatological Data for the United States (8). The measurements were taken over a 12-hr. period just before the time of peak surge. The average speed of these 51 storms was 22 kt. This mean agrees with the mean speed of coastal storms found by Weightman [9]. The range was from nearly stationary to a maximum speed of 43 kt.

4. STANDARD PROJECT NORTHEASTER FOR NORTHERN NEW ENGLAND

Plan for a Standard Project Northeaster (SPN)

The previous section has set forth the characteristics of northeasters. The purpose of this section is to investigate those storms which have one or more of those characteristics which are conducive to high surge, and by means of reasonable combinations and adjustments, prepare a hypothetical storm which will possess the strongest individual characteristics of all the storms investigated. We will call this the Standard Project Northeaster.

The final choice of a project storm does not necessarily have to come from the 51 storms selected for special study, either singly or as composites, simply because these actually caused the surges at the places of interest. The period covered by the study is roughly 1914 through 1960. It is entirely possible that a particularly severe storm that passed nearby, either before or after this period, but did not cause a "high surge", might be a wiser choice for a project storm, assuming the storm can be transposed to a more favorable path. See appendix B.

The storm of March 1962, one of the most severe to affect the Atlantic seaboard in recent history, occurred after this study was well under way. It appeared that with moderate transposition the March 1962 storm might be as severe as any of the 51 storms already under study.

Accordingly, after a special study of this storm had been completed, its characteristics were compared with those of the composite storms derived from the 51 northeasters.

Classification System

Because of the peculiar geography of the New England coast north of Cape Cod, a southeast wind blows directly onshore at Eastport, Maine, while near the eastern end of the Cape Cod Canal a northeast wind blows onshore. Therefore, it was decided that a single Standard Project Northeaster would not be sufficient - that three SPN's were necessary and each could be applied to different parts of the coast, depending upon the coastal configuration. From this point on, the 51 northeasters designated in section 3, were grouped into three categories or types - NE, E, and SE, depending upon the onshore wind direction within 300 mi. of the northern New England coast about 6 hr. before the time of peak surge. Where wind observations were not available, an over-water wind deflection angle of 20 degrees across the isobars was assumed.

Example of Types

Typical examples of surface pressure patterns for NE and SE types have been shown in figures 1 and 2 respectively. A typical E type is shown in figure 8. The isobaric configurations of the NE and E types are approximately the same; that is, they are roughly oval-shaped. However, for the

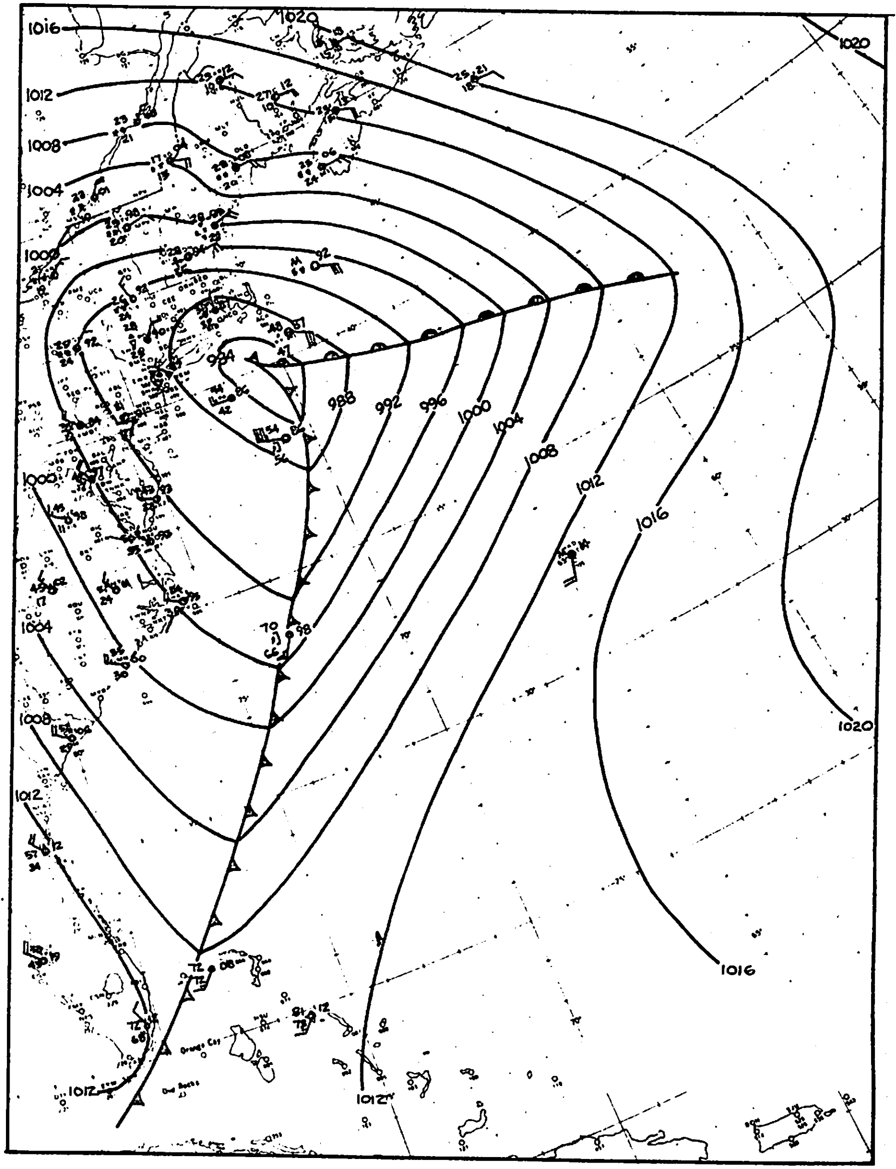


Figure 8. - A typical East type northeaster, occurring 1600 EST, March 12, 1959, six hours before a peak surge of 2.8 feet at Portland, Maine.

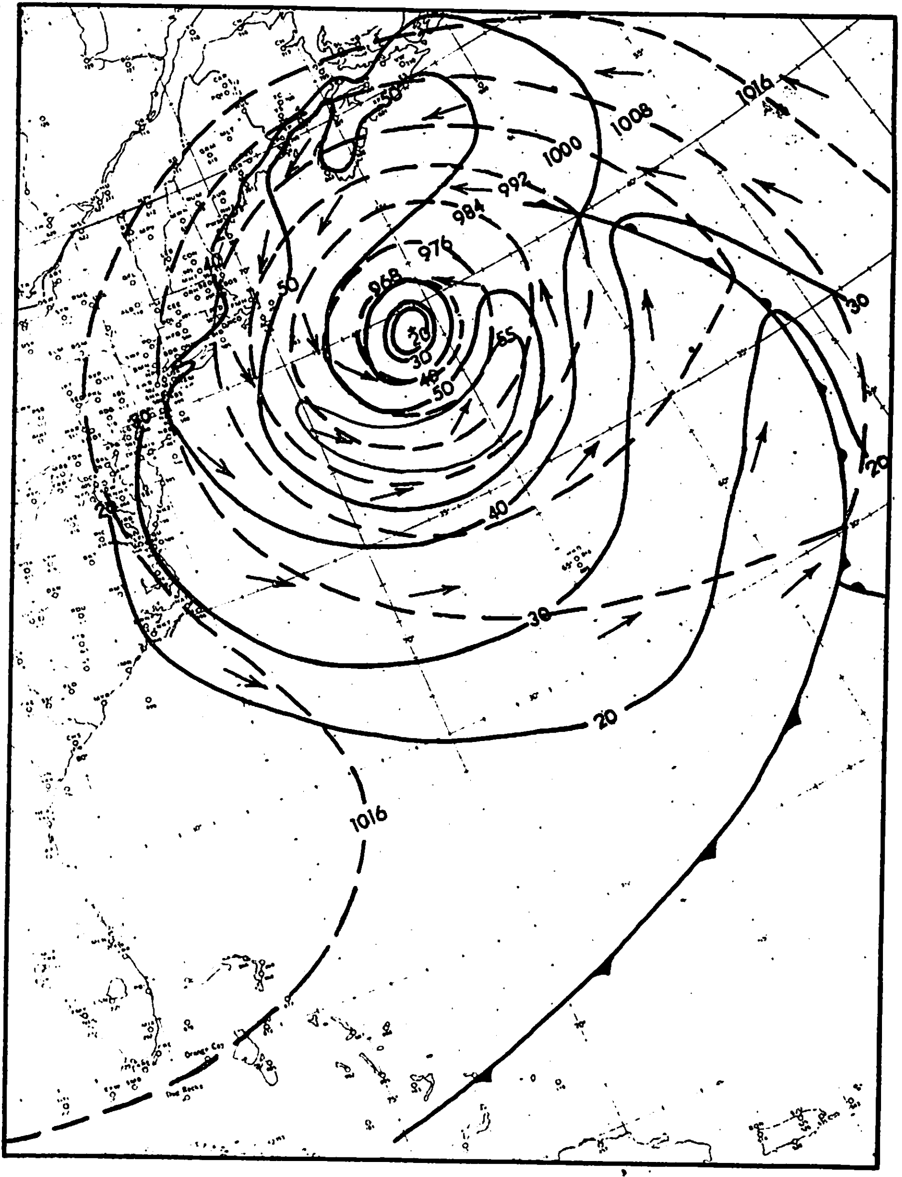


Figure 9. - Composite NE type northeaster, made up of storms occurring March 4, 1931 and April 2, 1958. Dashed lines are isobars; solid lines are isovels (knots).

NE type the low center is more to the east and farther away from the station than for the E type. The SE type is distinguished for having elongated isobaric configurations.

Intensity Parameters

Of the several parameters one might use to assess the surge-producing potential of a storm, probably the most useful are the central pressure, the maximum pressure gradient (measured as in fig. 4), and the fetch length measured in the same area. The first two are not entirely independent of each other, but both are important for different reasons.

The storm, either actual or composite, possessing the highest values of these parameters (i.e., lowest central pressure, the strongest maximum pressure gradient, and the longest fetch length) would have the highest surge-producing potential. These parameters have been measured and listed for every storm in each type, and the highest values chosen.

Table 3 indicates the magnitude and date of occurrence of the intensity parameters used to prepare composite charts. It will be noticed that the northeaster of March 1, 1914 is, in itself, the SE composite (transposed 140 n. mi. northward) because it exceeded all other SE types with respect to intensity parameters. The characteristics of the storm of March 1962 have been included for comparison.

Table 3. - Northeaster parameters used in preparing composites

	Type			
	NE	E	SE	March 1962 Storm
Lowest central pressure (mb)	960	974	955	974
Date	3/4/31	2/14/40	3/1/14	3/7/62
Maximum pressure gradient (mb/150 n. mi.)	25.0	23.0	22.0	25.5
Date	3/4/31	3/16/56	3/1/14	3/7/62
Longest fetch (n. mi.)	470	450	540	1250
Date	4/2/58	11/17/35	3/1/14	3/7/62

Some of the weaker storms surveyed had longer fetch lengths than those selected, but the maximum pressure gradients and other factors of these storms were such that it was thought these particular fetches were not characteristic of storms of greater intensity.

Composite Storms of Each Type

Briefly, the procedure for preparing a composite surface map involved the following steps. (1) Superpose all the analyzed surface charts of a particular type (N, NE, or E). (2) Orient these so that the maximum fetch in each exerts its fullest effect on the New England coast. (3) From table 3, assign the minimum pressure from that type. (4) Sketch in the isobars so that the longest fetch line and strongest gradient, also from table 3, are correctly positioned relative to coast and storm center, using the actual storms as guides. (5) Draw in the mean frontal positions and the rest of the isobars carefully, scaling so as to retain the typical features of the storms. The last closed isobar inclosed as much area as that of the largest storm in the set.

The pressure maps were used to prepare isovel fields. Two techniques were employed, one based upon numerical solution of the equilibrium wind equations by an electronic computer and the other based upon a percentage correction to the geostrophic wind, as derived from the equilibrium wind equations. These methods are discussed in appendix C.

Figures 9 through 11 show surface pressure and isovel charts for NE, E, and SE composite types. The dashed lines are isobars and the solid lines are isovels. Wind direction arrows are true at the tip of the arrow.

Storms Offshore

The questions were raised, "Are storms that pass too far offshore to produce a high surge at Boston and Portland characteristically more intense than storms closer inshore? If so, should they be taken into account in developing the Standard Project Northeaster?" To investigate these questions a study was made of all northeasters whose centers passed within about 10° of longitude of the coast north of Cape Hatteras during the years 1951-1960 (when the more reliable surface maps were available). Also included was the notable March 1962 storm. The storms mentioned in section 3 were excluded. The maximum pressure gradient was considered the most important measure of relative northeaster intensity. Historical maps were searched for storms whose maximum pressure gradient approached that of the composite storms and whose centers were 300 n. mi. or more away from the New England coast. Only the few storms that met both these conditions were subsequently transposed, by application of the procedures described in appendix B. Subsequently the transposed maximum pressure gradients were compared with that of the composite storms.

Although a few storms had higher maximum pressure gradients (across 150 n. mi.) than the storms selected on the basis of surges, upon closer inspection it was apparent that, with the exception of the March 1962 northeaster, these storms had very narrow belts of maximum winds or extreme isobaric curvature (leading to shorter fetches).

The surface pressure analyses for the March 6-8, 1962 northeaster indicated a long, persistent fetch of strong winds blowing against the

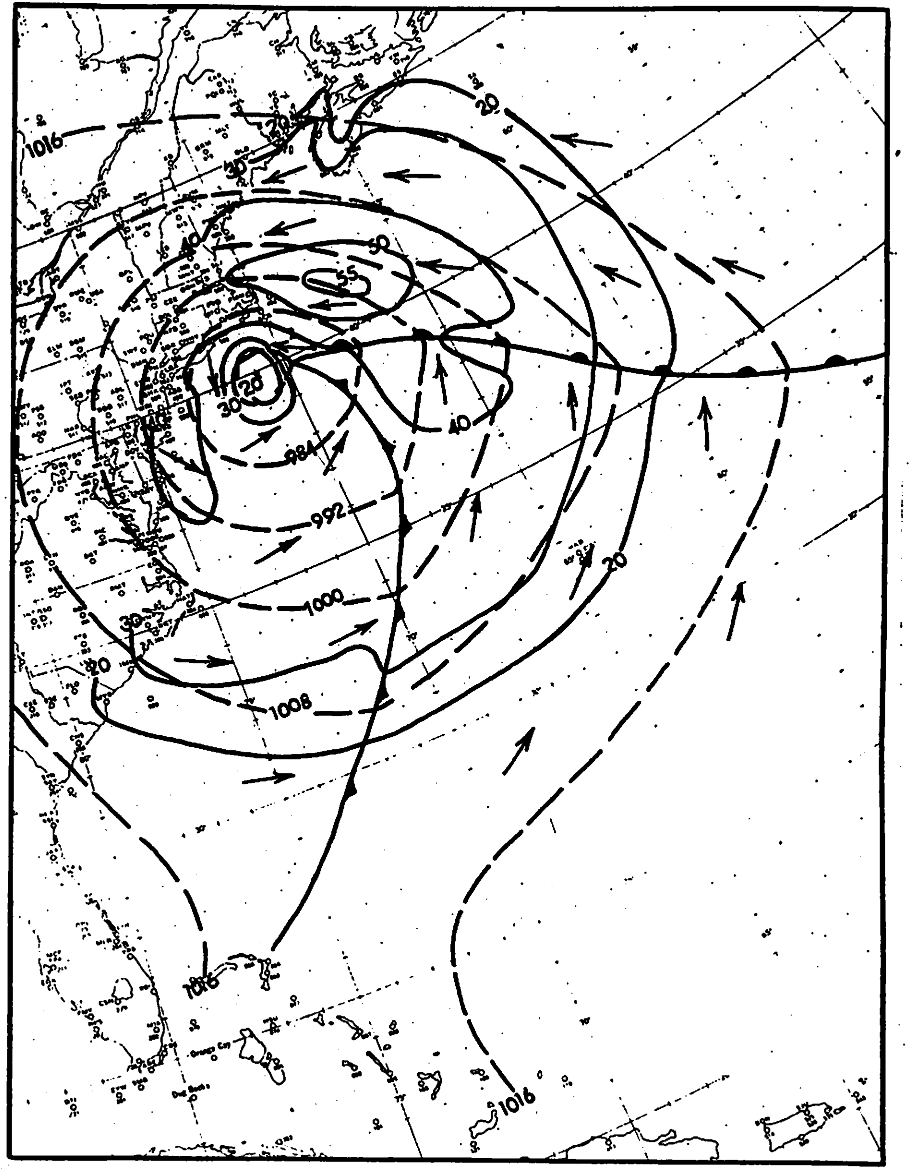


Figure 10. - Composite E type northeaster, made up of storms occurring November 17, 1935, February 14, 1940 and March 16, 1956. Dashed lines are isobars, solid lines are isovels (knots).

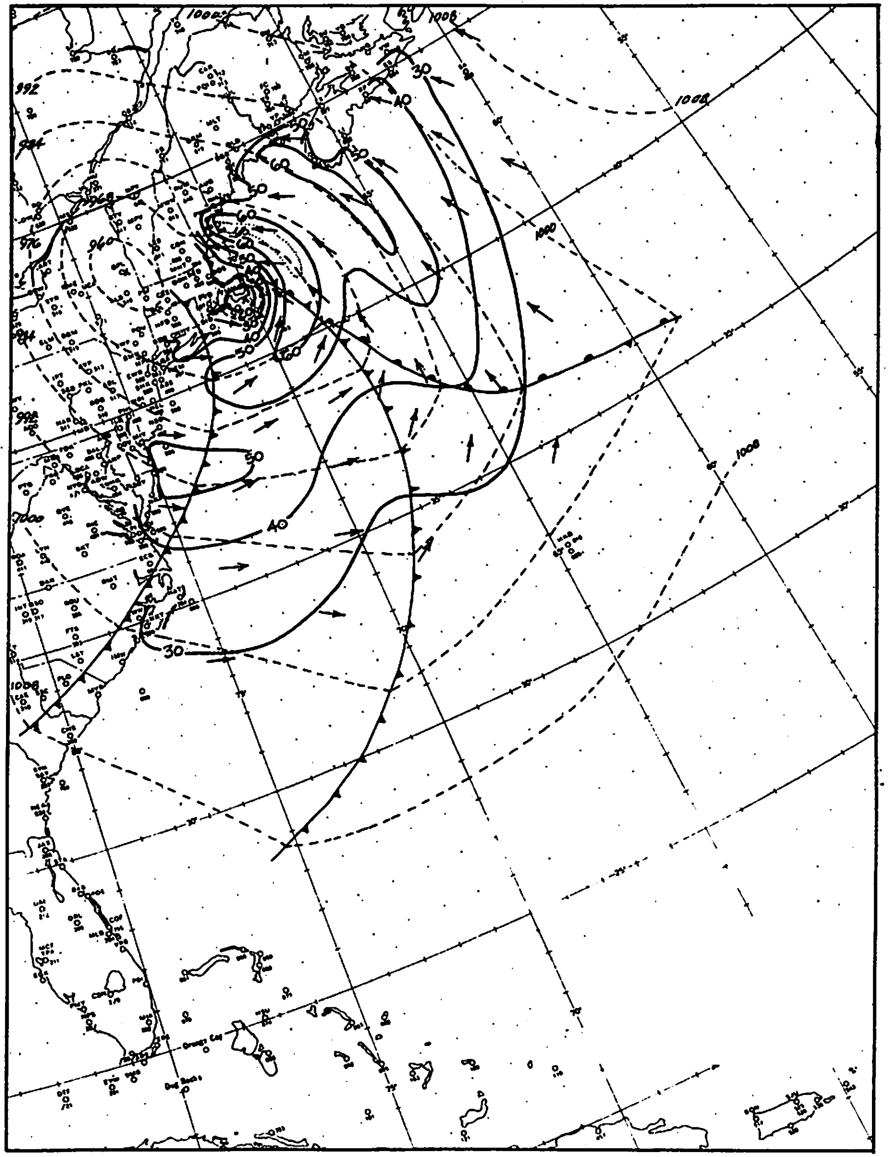


Figure 11. - Composite SE type northeaster, occurring March 1, 1914. Dashed lines are isobars; solid lines are isovels (knots).

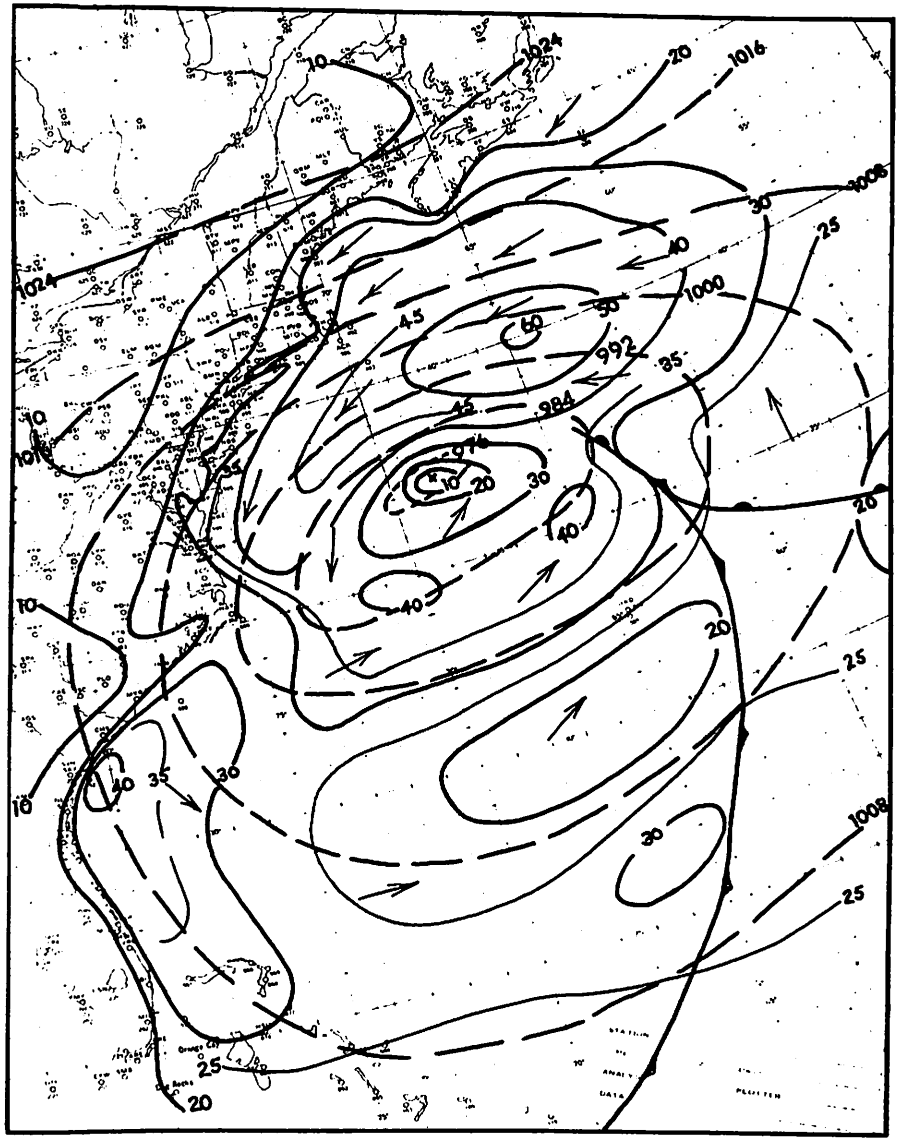


Figure 12. - Surface map for 0100 EST, March 7, 1962, six hours before the storm reached its maximum intensity. Dashed lines are isobars, solid lines are isovels (knots).

Figure 13. - Surface map for 0700 EST, March 7, 1962, at the time of maximum storm intensity. Dashed lines are isobars; solid lines are isovels (knots).

Middle Atlantic Coast. Isovel maps based on observed winds, computed equilibrium winds, and the empirical technique described in appendix C, verified these features. From the standpoint of wind speed and fetch, this storm exceeded all storms investigated in both the 47-year study involving storm surges and the 10-year study of all storms within about 10° of longitude of the coast north of Cape Hatteras, as well as the composite charts (figs. 9 through 11). Table 3 lists the intensity parameters for this storm. The combined surface pressure and isovel maps are shown for the time of maximum intensity, and for 6 hr. before and after this time, in figures 12, 13, and 14.

The examination indicated that northeasters occurring offshore, and not producing high surges at Boston or Portland, possess in general the same characteristics as, and are no more intense than, northeasters which do produce significant surges. This is true of these storms both before and after transposition. Although this is generally true, it is wise to look for the exceptionally severe cases, as the March 1962 storm.

Standard Project Northeasters of Each Type

Isovel charts for the Standard Project NE type are shown in figures 15 through 17. The March 1962 storm was classified as a NE type. Although the composite NE type had a lower central pressure, the maximum pressure gradient is considered to be the principal intensity criterion in comparing northeasters. If the isovel pattern of the March 1962 storm at the time of its greatest intensity is moved about 135 n. mi. northward with no rotation, it is considered to be the Standard Project NE type. The figures show the isovels for the maximum condition and for 6 hr. before and after this time. Since NE types are more prevalent at Boston than at Portland, the isovel patterns have been placed so that the strongest winds blow onshore near Boston.

Isovel charts for the Standard Project E type are shown in figures 18 through 20, and are for the March 1962 storm at its greatest intensity. The storm has been moved about 100 n. mi. northwestward and rotated 40 degrees clockwise. The figures show the isovel charts for the time when the storm was at its maximum and for 6 hr. before and after this time. The strongest winds produced by the storm in this location blow onshore near Portsmouth, N. H.

The isovel charts for the Standard Project SE type are shown in figures 21 through 23, and are for the time of maximum intensity and for 6 hr. before and after this time. It is not considered meteorologically feasible to move the March 1962 storm northward as a SE type since it would involve an unreasonable amount of rotation. Comparison of this storm and the composite SE type indicates that, in the region of maximum winds, both storms are of about equal intensity. Therefore, the composite SE storm (which is actually the storm of March 1, 1914 moved northward) is considered to be the Standard Project SE type. The isovel patterns have been placed so that the strongest winds blow onshore near Portland. It will be noted that figure 22, for the time of maximum intensity, has the same isovel pattern as figure 11, the SE composite.

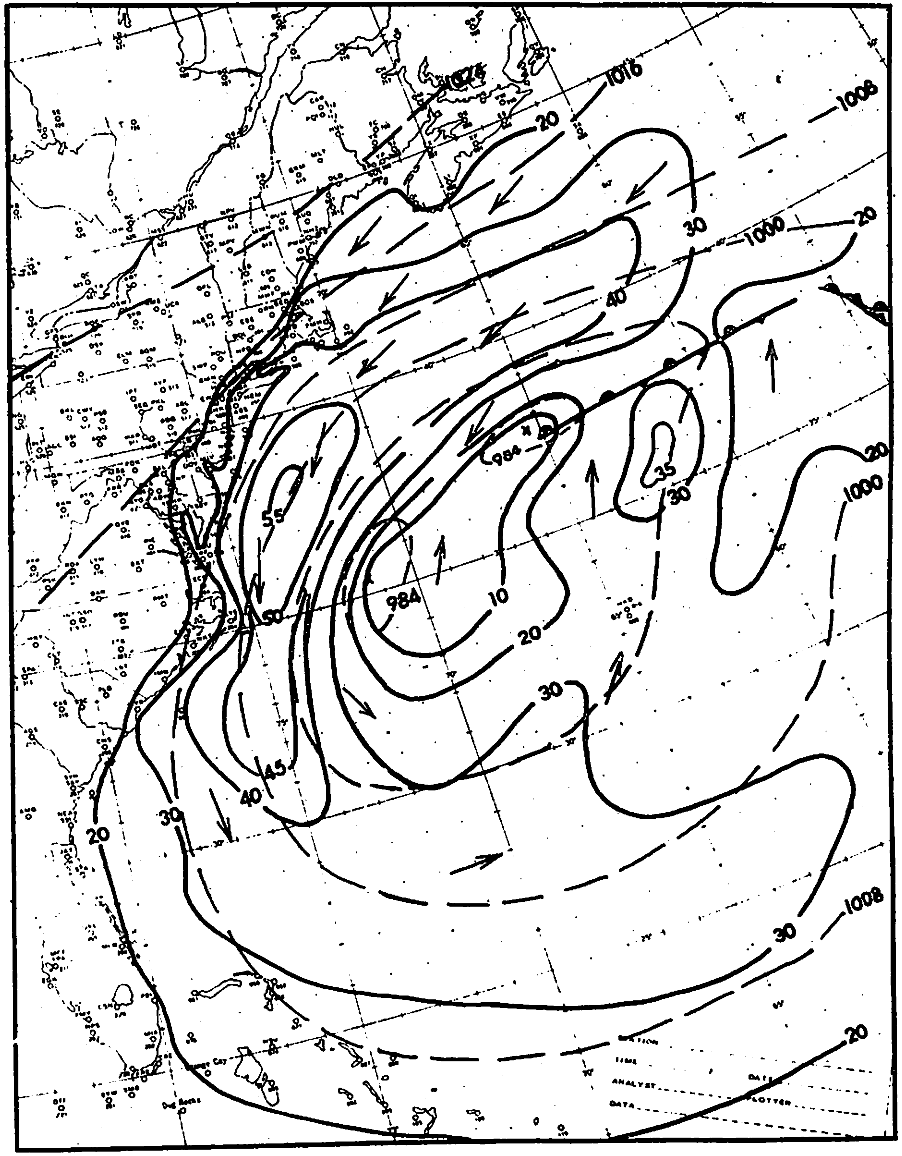


Figure 14. - Surface map for 1300 EST, March 7, 1962, six hours after the storm reached its maximum intensity. Dashed lines are isobars, solid lines are isovels (knots).

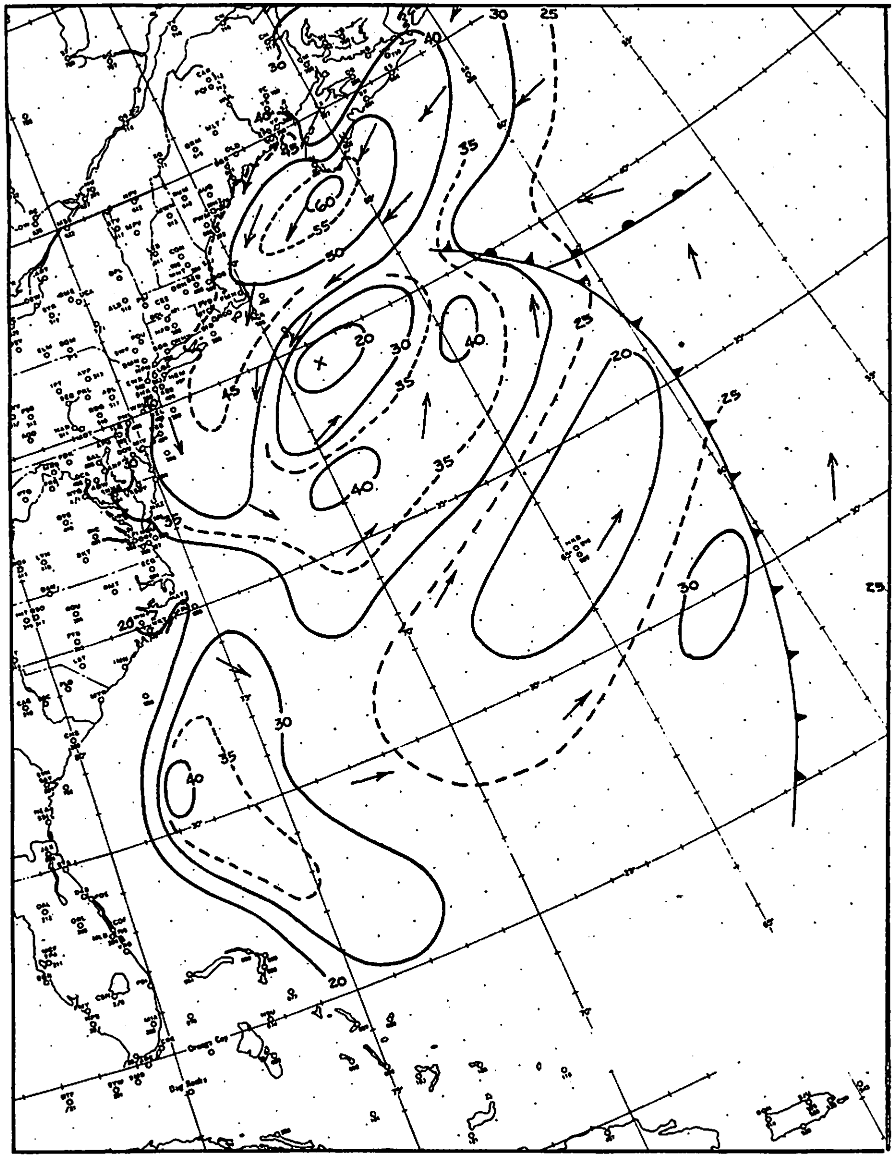


Figure 15. - Standard Project Northeaster isovels, NE type, six hours before maximum storm intensity. Isovels in knots.

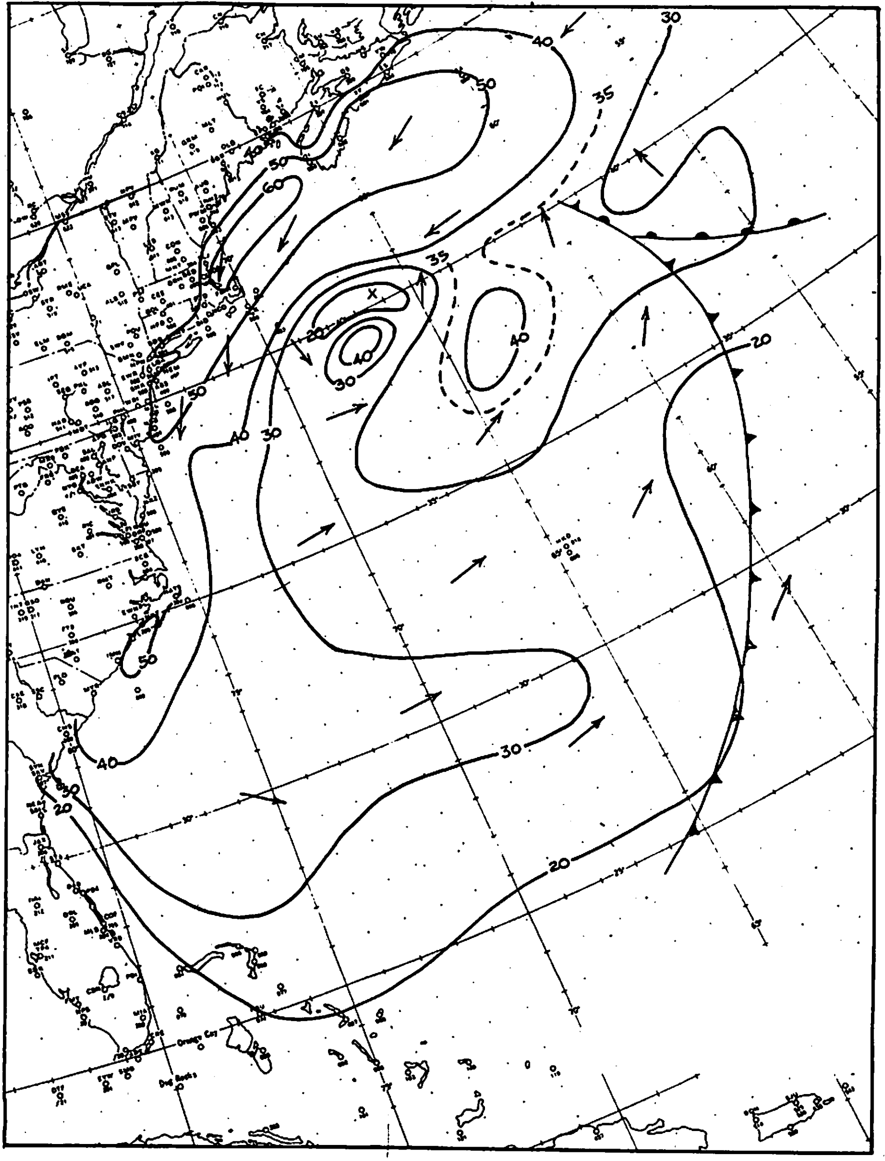


Figure 16. - Standard Project Northeaster isovels, NE type, at time of maximum storm intensity. Isovels in knots.

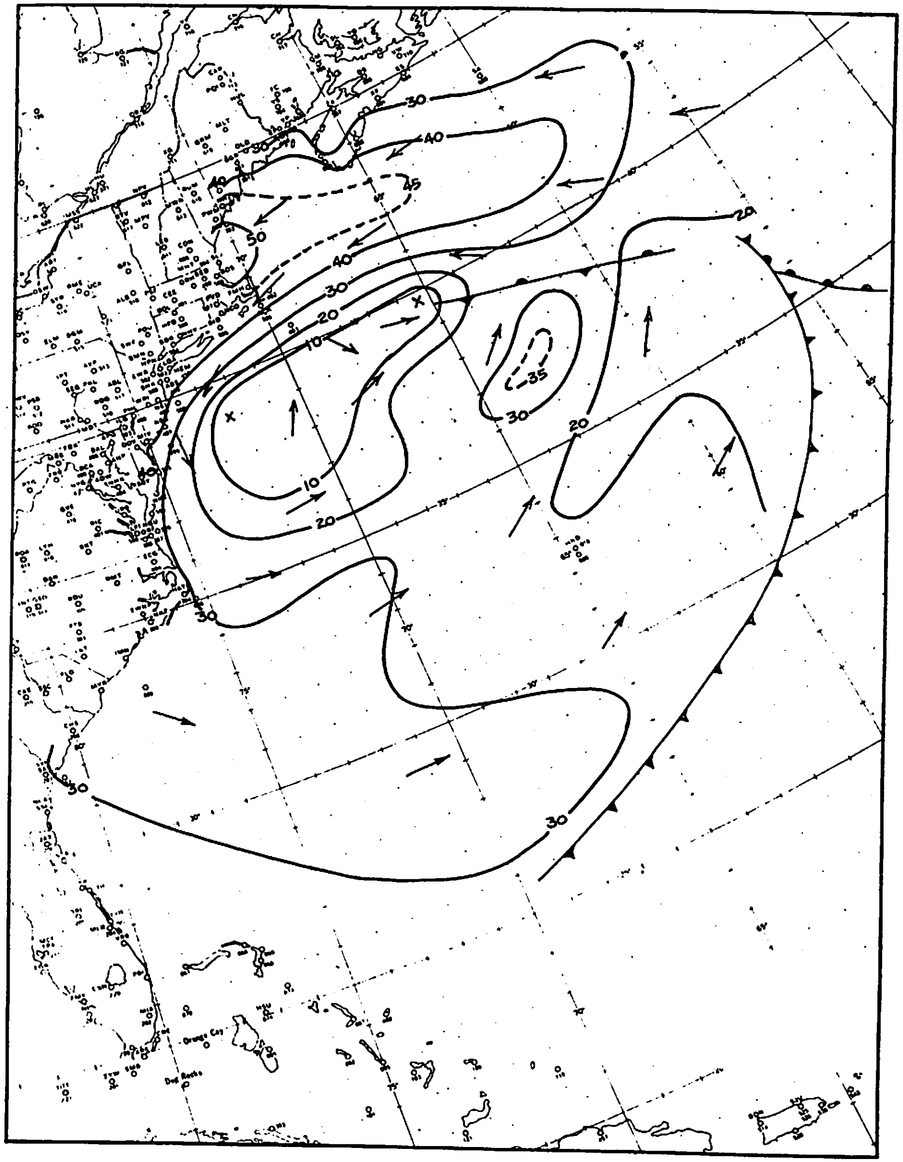


Figure 17. - Standard Project Northeaster isovels, NE type, six hours after maximum storm intensity. Isovels in knots.

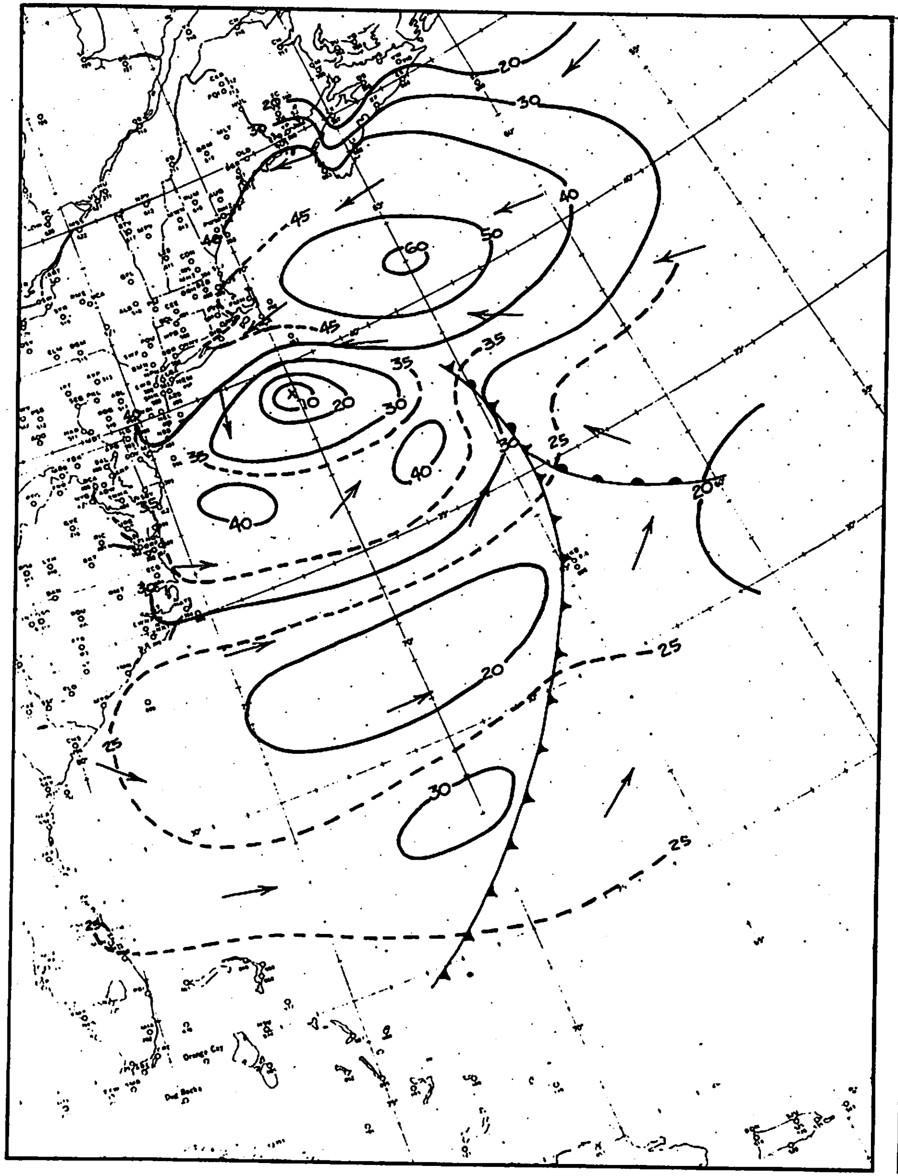


Figure 18. - Standard Project Northeaster isovels, E type,six hours before maximum storm intensity. Isovels in knots.

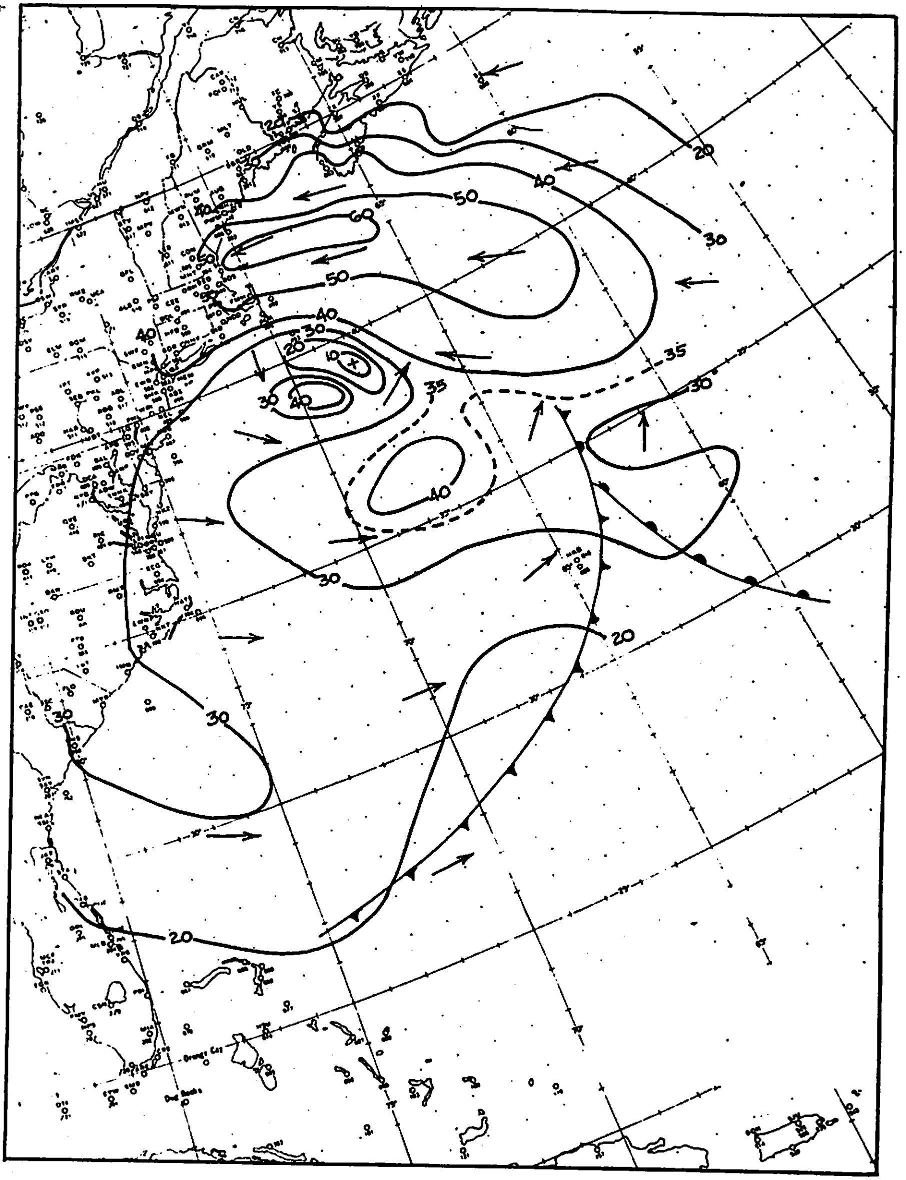


Figure 19. - Standard Project Northeaster isovels, E type, at time of maximum storm intensity. Isovels in knots.

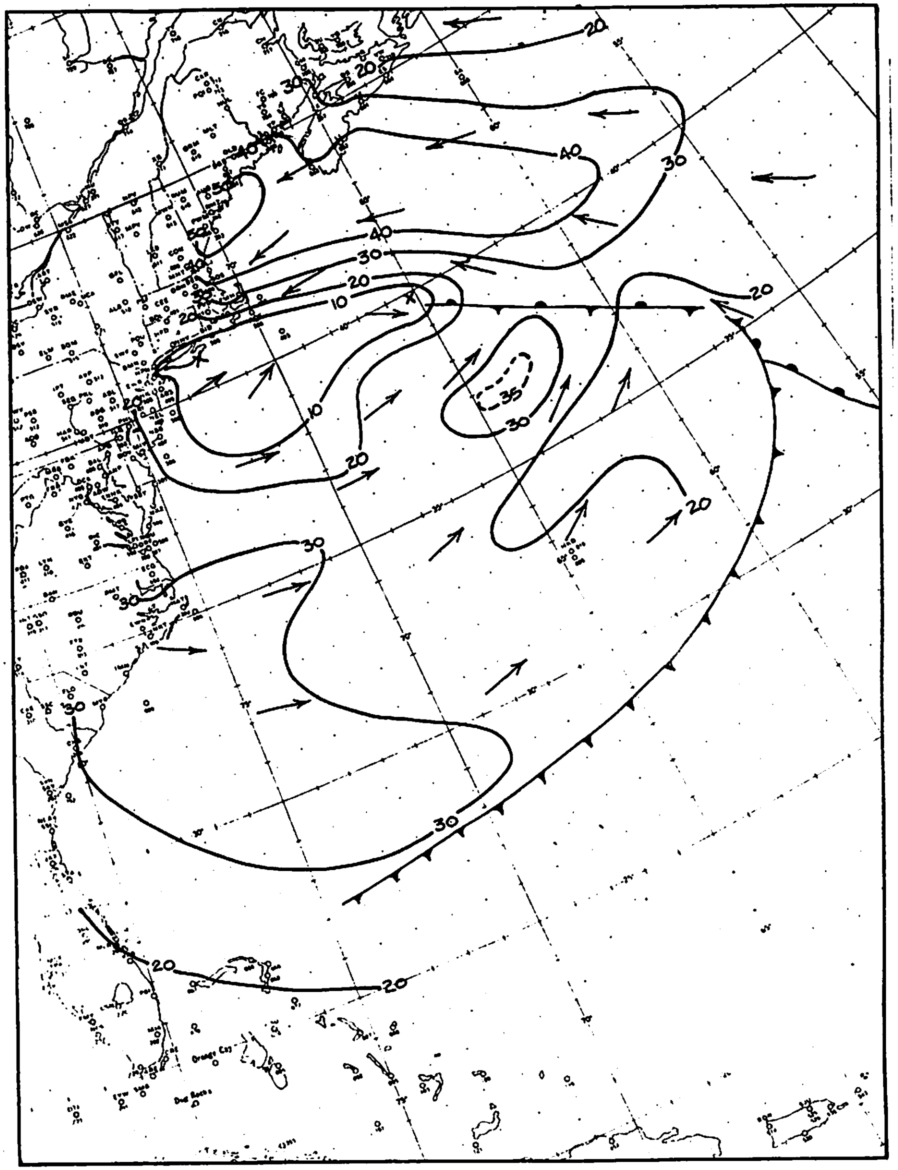


Figure 20. - Standard Project Northeaster isovels, E type, six hours after maximum storm intensity. Isovels in knots.

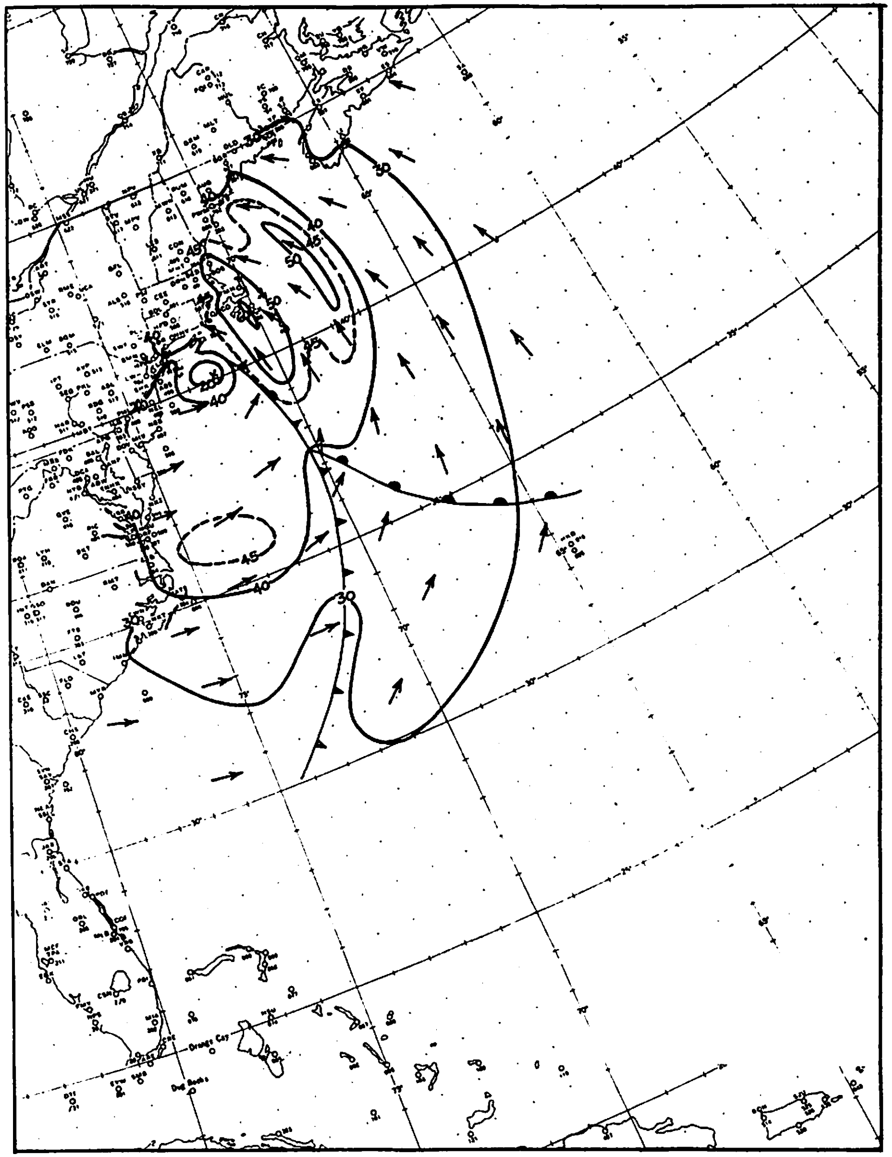


Figure 21. - Standard Project Northeaster isovels, SE type, six hours before maximum storm intensity. Isovels in knots.

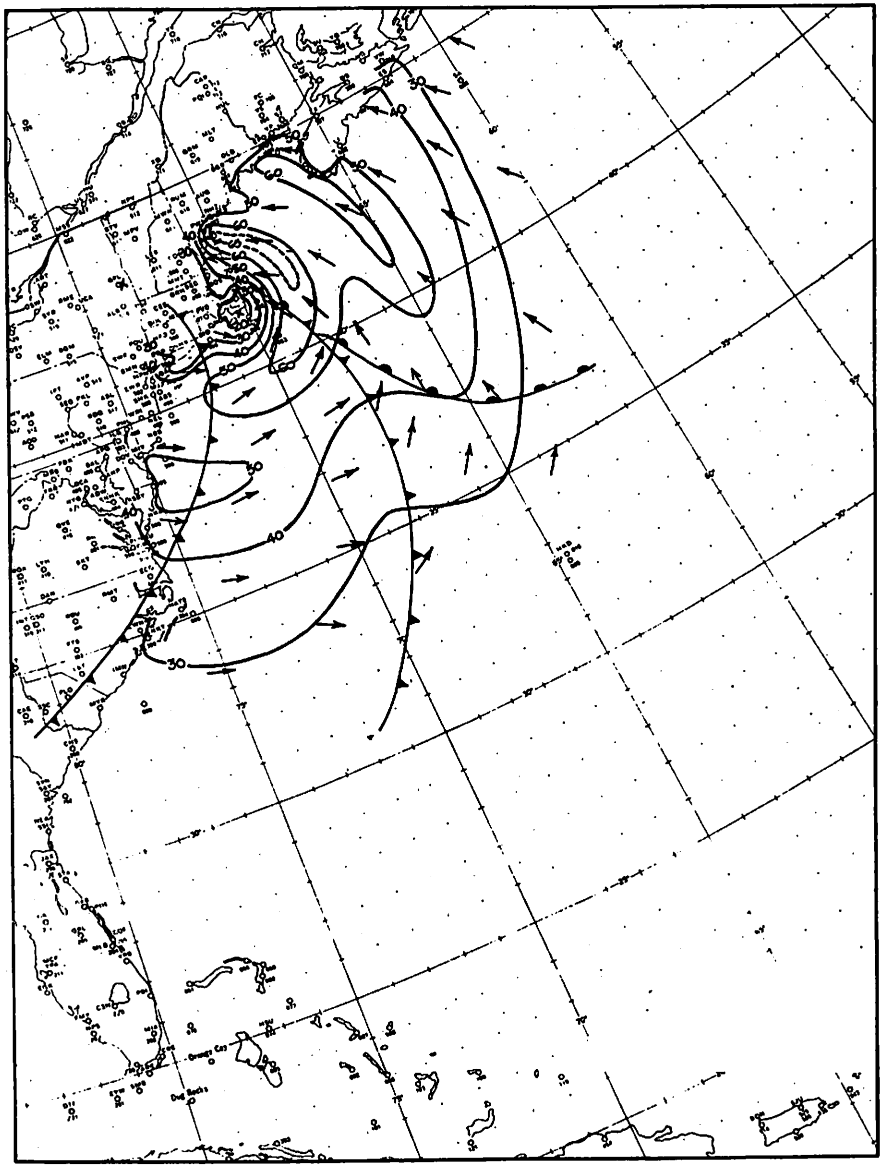


Figure 22. - Standard Project Northeaster isovels, SE type, at time of maximum storm intensity. Isovels in knots.

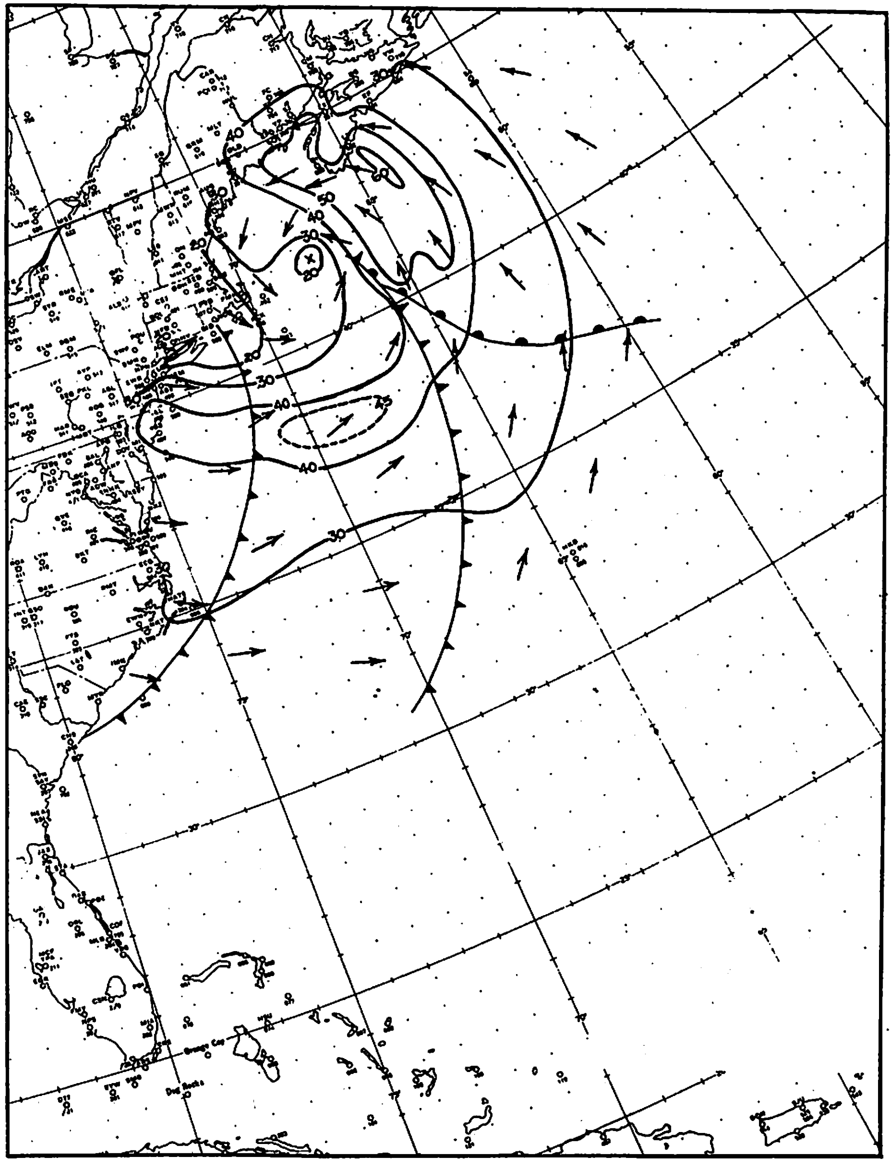


Figure 23. - Standard Project Northeaster isovels, SE type, six hours after maximum storm intensity. Isovels in knots.

5. TIDE AND STORM SURGE FREQUENCIES FOR NORTHERN NEW ENGLAND

A Statistical Approach

The previous sections have led to the development of standard project storms for three different northeaster types. The end result has been the preparation of isovel charts from which surge computations can be made. The present section examines the feasibility of a statistical analysis of observed tides and storm surge for Portland, Maine and for Boston, Mass. These stations were selected because of their length and completeness of record.

One advantage of this type of analysis is that it leads directly to tide or surge values for given return periods without the intermediate step of synthesizing wind fields. Another reason for including this material in the report is for its use as a check against surges which can be computed from the Standard Project Northeaster types presented in the previous section.

Data

The primary data available for this study were hourly and daily high and low tide observations at the Coast and Geodetic Survey gage at Portland, Maine from 1914 through 1959 and at Boston, Mass. from 1922 through 1960; published predictions of high and low astronomical tides at these gages /10/; and hourly astronomical tide heights computed for selected storms on the IBM 7090 computer at Suitland, Md. by the Storm Surge Unit of the Weather Bureau. The Coast and Geodetic high and low tides for a shorter period of record were also available at four other stations.

Tide Height Conversion

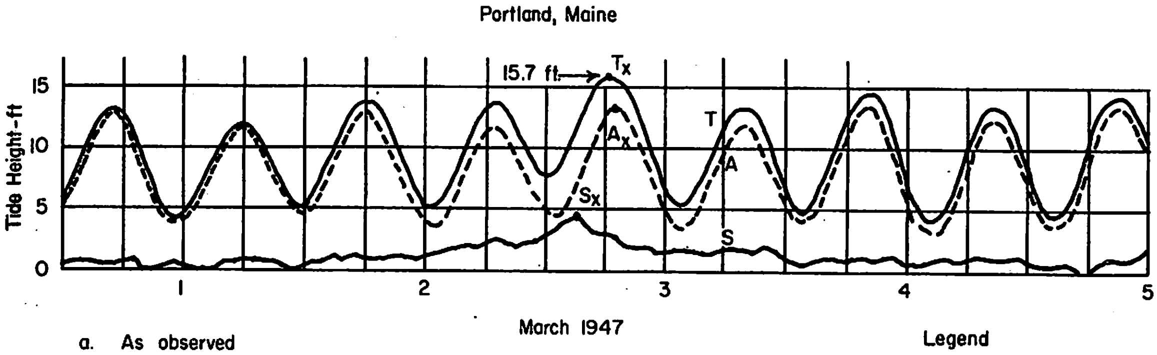
To convert tide heights at Portland, Maine from mean sea level datum to height above mean low water, add 4.5 ft; to convert to height above mean high water, subtract 4.5 ft. For similar conversions at Boston, Mass. add or subtract 4.9 ft., as applicable. All astronomical and total tide levels in this section are referred to mean sea level, except for figure 24.

Observed Tide, Storm Surge, and Astronomical Tide

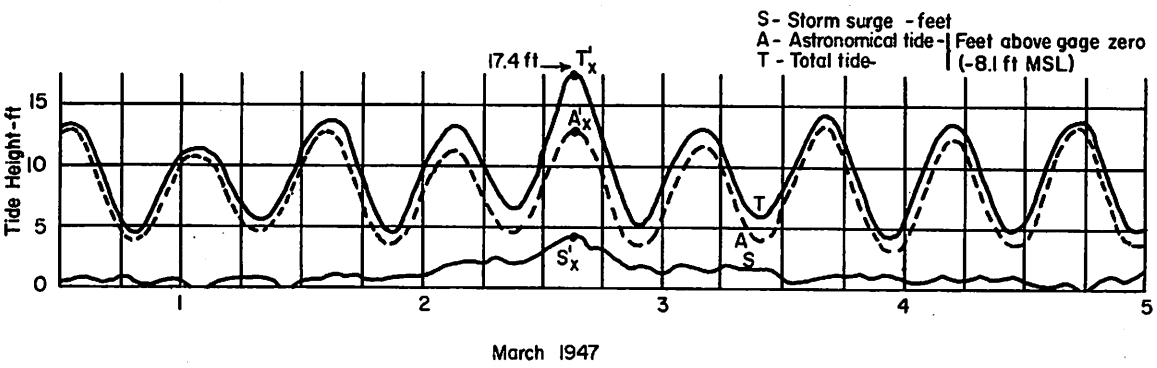
The observed tide, T, has two components - the storm surge, S, and the astronomical tide, A. Hence

$$T = S + A \tag{1}$$

An exceptionally high tide will be observed when a large storm surge occurs close to astronomical high tide. When the storm surge is negligible the observed tide will be close to the astronomical tide. Finally, when the wind blows strongly offshore, the surge will be measured in a negative sense and the observed tide will be less than the astronomical tide.



a. As observed



b. Peak surge and astronomical high tide occurring simultaneously

Figure 24. - Storm surge, astronomical tide and total tide, March 1-5, 1947 (a) as observed, (b) assuming peak surge and astronomical high tide occur simultaneously.

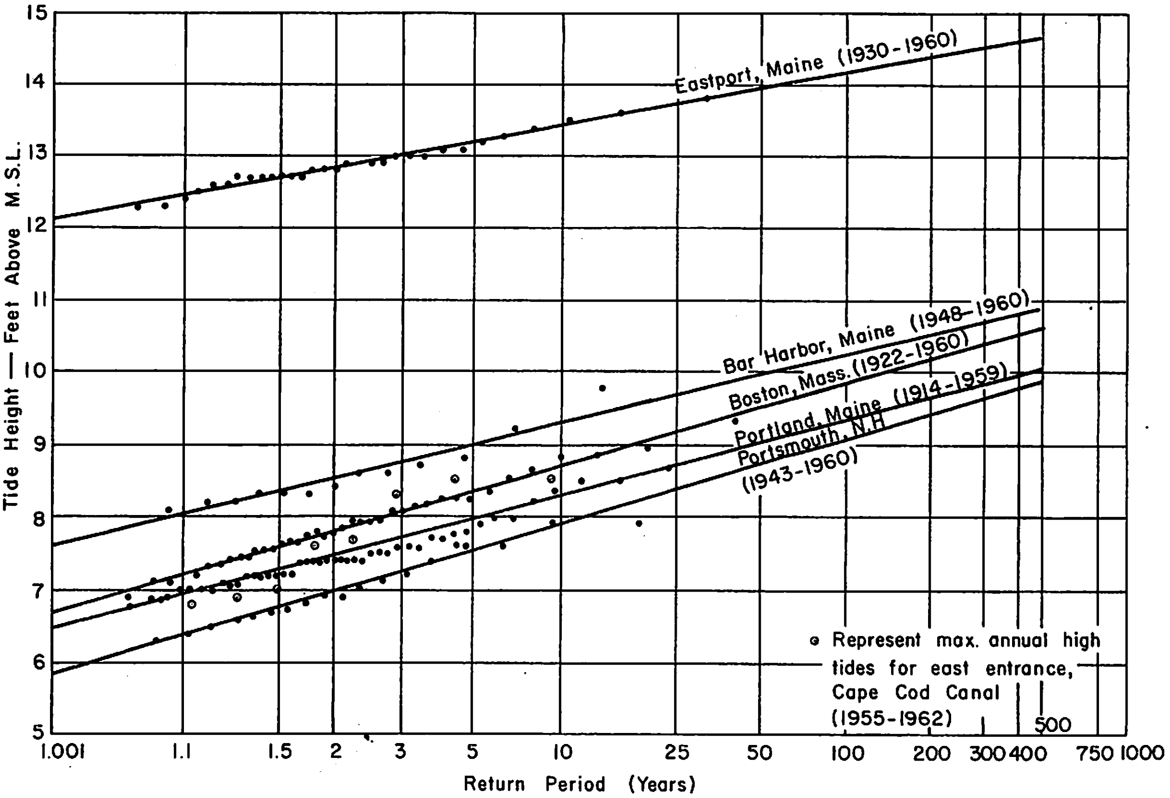


Figure 25. - Estimated probabilities of extreme tide heights based upon maximum annual high tides.

Although there is a tendency for slightly higher surge values at low tide than at high tide /11/ an exceptionally high surge can occur at the same time as an astronomical low tide, high tide, or at any other time during the tide cycle. This has a pronounced effect upon the observed tide, as is illustrated by figure 24. Part (a) shows the distribution of the S, A, and T curves as observed at Portland on March 1-5, 1947. The surge peak, S_x, occurred about 4 hr. before astronomical high tide, A_x. Part (b) of the same figure depicts the resulting T if S_x and A_x had occurred simultaneously. T_x is increased by 1.7 ft., to a tide higher than any of record.

The 1947 storm shown produced the highest observed surge at the Portland gage, but since the surge peak did not occur near astronomical high tide, it did not give the highest observed total tide.

The highest observed tides at Portland between 1914 and 1959 occurred in November 1944 and November 1945, both at a height 8.7 ft. above msl. (16.8 ft. above gage zero). If the surges associated with these cases had occurred at high astronomical tide, the total tide would have been 9.8 ft.

Frequency of Maximum Annual High Tide

The most direct method of estimating the recurrence interval of various tide heights is to extract the maximum annual values of the observed total tide from the tabulated tide records, rank and plot these values on extreme value probability paper such as that developed by Gumbel /12/, and fit a curve by eye to the points. Figure 25 shows such curves for Boston, Portland, Eastport, Maine, Bar Harbor, Maine, and Portsmouth, N. H. Points are also plotted for the east end of Cape Cod Canal; however, with only 8 years of data available no curve is drawn. The basic data for Boston and Portland are listed in table 4. The curves for these two stations also appear on figures 26 and 27, curve F.

Tide Probabilities from Components

The simple relationship of total tide being the sum of surge and predicted tide has application to a frequency analysis of extreme tides. Random combinations of observed surges with astronomical tide heights would serve to synthetically augment the data on extreme tides. Some of the outstanding floods from the sea in various regions have resulted from an extreme surge coinciding with spring tide. One advantage of tide probabilities from components is that this important combination is taken into account on a probability basis; there is no a priori assurance that the direct extrapolation of maximum annual tides does this.

One method, then, of extracting the maximum information on frequency of T_x from tide records is the following. Reconstruct the marigrams of all past surges, add each one at all time displacements to all marigrams of A, then summarize the frequency of the thousands of resulting T_x's. The equivalent of this was done for Portland as described in later paragraphs. Curve G of figure 26 indicates the results of such an analysis.

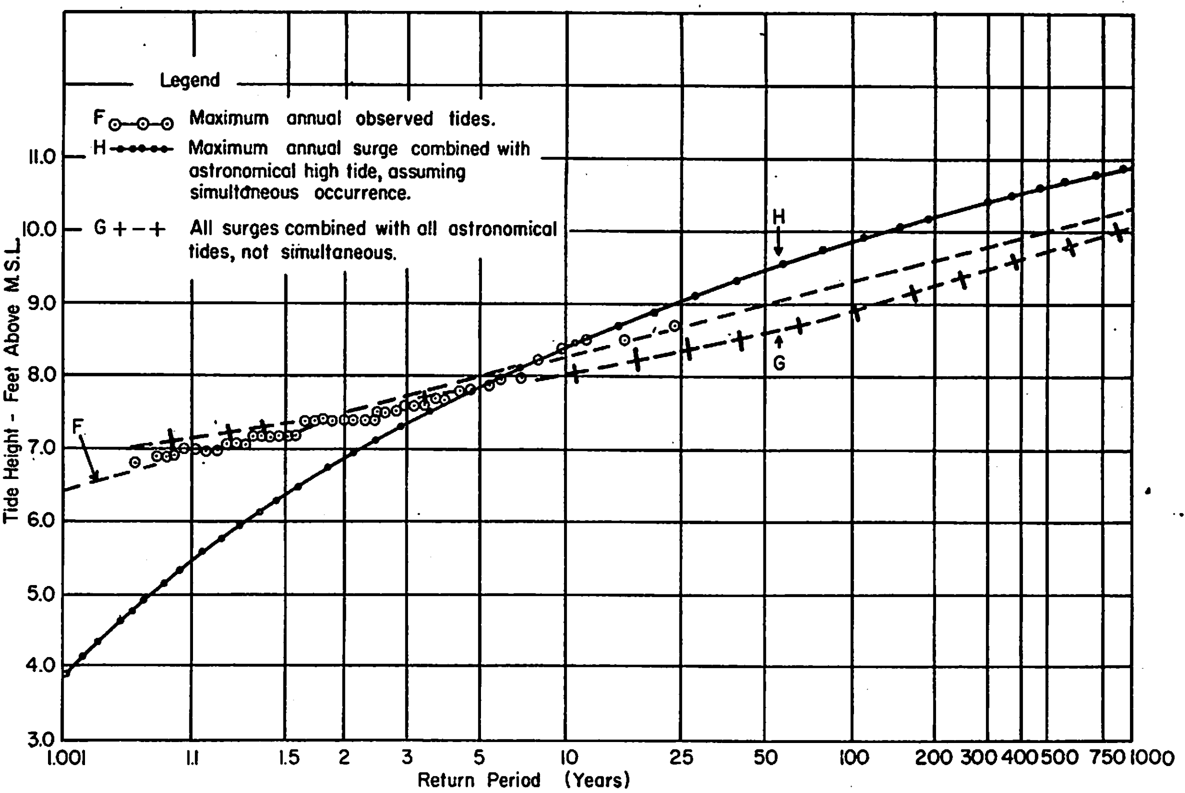


Figure 26. - Estimated probability of extreme high tide height at Portland, Maine. (Based on data for 1914-1959.)

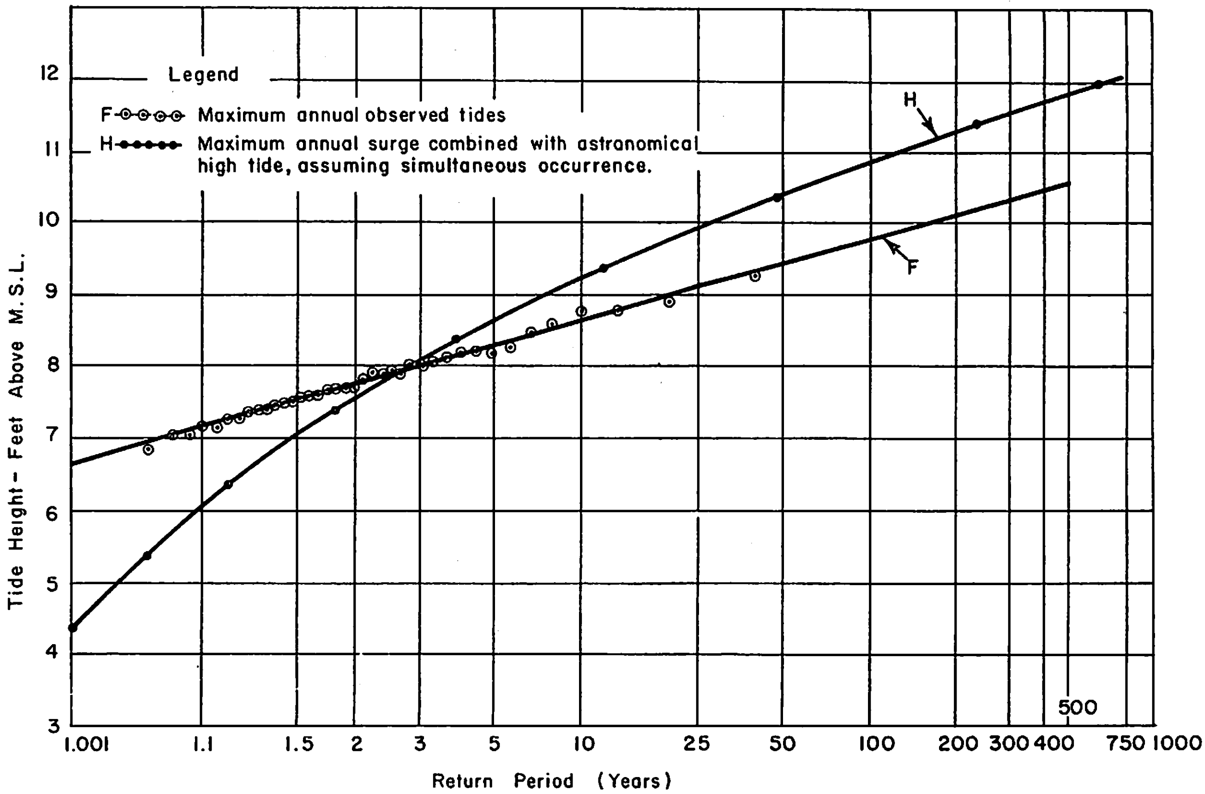


Figure 27. - Estimated probability of extreme high tide height at Boston, Mass. (Based on data for 1922-1960.)

Comparison of Direct and Reconstructed Frequencies of Extreme High Tide

It is found that the reconstructed frequency distribution, curve G, is fairly close to the direct frequency distribution, curve F. Curve F shows tides 0.3 ft. higher for any given return period beyond 25 years.

The significance of the comparison is that the F curve has been tested. It has been found that curve F, by extrapolation, does properly portray the risk of unfavorable coincidence of surge and astronomical tide, at Portland.

Whether the same correspondence would be found at other tide gages between direct and reconstructed tide frequencies has not been determined.

Surge Selection and Computation

For the surge contribution to the reconstructed T_x's at Portland it was decided to introduce the values in the form of frequency of maximum surge height in individual storms, S_x, together with empirically standardized shapes of the surge marigrams. This approach facilitated a statistical extrapolation of S_x beyond the record.

The surge cannot be observed directly but is obtained by subtracting the predicted tide from the observed tide hour by hour. The hourly predicted tides are not published, only the highs and lows. To minimize computations, a selection of significant surge dates was made by scanning the tabulations of daily high and low observed tide. First, all dates were listed on which the observed high tide increased 1.4 ft. or more from one day to the next. The same procedure was followed for day-to-day low tide increments greater than 1.4 ft. The threshold value was an arbitrary choice, chosen so as to provide at least 3 cases per year. Using these dates, a second screening was made by comparing the initial high or low tide of each pair with the monthly average high or low tide. The dates on which the high or low tide on the first day was close to or above the monthly average were retained while dates of distinctly below monthly average were eliminated. Such a departure suggested a strong offshore wind inducing a lowered water level on the initial day. This was verified by reference to sea level weather maps.

Hourly storm surge values were computed for a total of 122 selected storms for Portland. Computations for each case were made for about 7 days. Although the main part of the storm surge lasted one day or less it was desired to go back to the undisturbed state when the surge was negligible. Hurricanes were not excluded from the study; however, only three hurricanes (Sept. 14, 1944, Dog 1950, and Carol 1954) remained in the final selection of the maximum annual storm surges. These storms gave lower surges than many of the northeasters. Table 4 lists these maximum surges and their dates of occurrence.

Hourly values of the astronomical tide were computed on an IBM 7090 computer for all cases. The predicted tide was subtracted from the tide gage observation, thereby yielding the storm surge.

Table 4. - Maximum annual observed tides and surges at Boston and Portland

	Boston		Portland		Boston		Portland	
Year	Max. Obs. Tide (ft. abv. msl.)	Date	Max. Obs. Tide (ft. abv. msl.)	Date	Max. Surge (ft.)	Date	Max. Surge (ft.)	Date
1914			7.5	12-14			4.1	3-1
15			7.5	12-7			2.6	12-14
16			7.1	1-5			2.1	3-8
17			7.2	12-14			3.9	12-14
18			8.0	11-19			2.2	1-12
19			8.0	12-7			2.3	11-5
1920			7.2	6-6			2.6	12-14
21			7.2	11-29			0.6	2-21
22	7.4	4-11	7.6	4-11	2.9	12-29	2.5	1-11
23	7.1	4-30	7.0	4-30	3.3	3-7	2.0	3-7
24	7.2	2-6	7.0	7-17	3.4	3-11	2.3	4-2
1925	6.9	6-9	6.8	6-9	1.9	1-20	2.9	11-13
26	7.7	2-10	7.0	1-15	2.6	2-4	2.0	2-4
27	7.4	3-3	7.6	12-8	3.3	2-20	2.3	2-20
28	7.6	12-28	7.4	12-28	2.2	1-20	2.3	1-20
29	7.5	4-13	7.0	4-13	3.0	4-16	2.0	4-16
1930	7.2	1-15	7.1	1-15	2.5	10-25	2.8	12-28
31	8.8	3-4	8.4	3-4	3.0	3-8	2.5	3-4
32	7.7	11-30	7.4	11-30	2.5	3-7	1.6	11-30
33	8.3	1-28	7.4	1-27	2.3	12-4	1.4	4-7
34	7.1	10-23	6.9	1-16	2.2	2-20	2.6	1-14
1935	7.3	12-9	6.9	12-9	4.3	11-17	2.6	11-17
36	7.7	10-1	7.4	10-1	3.3	1-19	2.7	1-19
37	7.9	11-20	7.4	11-20	2.1	2-17	2.4	4-11
38	7.9	1-17	7.1	1-16	2.5	10-30	1.6	1-25
39	8.0	4-2	7.2	4-2	3.4	1-31	2.2	3-13
1940	8.9	4-21	8.2	4-21	4.4	2-14	3.0	1-15
41	7.4	5-11	7.2	5-11	2.6	3-1	1.7	12-14
42	7.5	3-3	7.4	3-3	2.4	3-3	3.2	12-2
43	7.5	8-17	7.4	8-17	1.4	3-6	1.5	2-11
44	8.8	11-30	8.7	11-30	3.9	9-14	2.8	11-30
1945	7.9	12-30	8.7	11-20	5.1	11-30	3.3	11-30
46	7.7	5-31	7.4	5-7	2.7	2-20	1.7	12-21
47	8.2	11-12	7.7	2-5	4.0	3-3	4.3	3-3
48	7.8	1-2	7.2	12-31	2.9	12-31	2.8	12-31
49	7.3	10-22	7.2	10-22	2.6	3-1	2.6	4-6
1950	7.9	12-11	7.8	12-9	3.2	11-25	3.5	11-26
51	7.6	5-24	7.5	11-3	2.3	3-11	3.0	2-7
52	8.2	2-28	7.5	1-28	3.4	2-18	2.8	2-18
53	8.1	4-13	7.8	4-13	3.2	11-7	2.6	2-15
54	8.2	8-31	7.9	8-31	3.7	8-31	3.3	8-31
1955	8.0	4-26	7.6	11-1	1.8	3-22	2.3	2-12
56	8.6	3-17	7.7	3-17	3.6	3-16	3.1	3-16
57	7.6	2-15	7.2	2-15	2.5	3-8	1.9	12-26
58	8.5	4-7	8.5	4-7	3.7	2-16	2.7	3-2
59	9.3	12-29	8.5	12-29	3.1	3-12	2.8	3-12
1960	8.1	3-4			4.0	3-4		

There is little doubt that the selection procedure yielded the maximum annual surge, S_x, for each of the 47 years 1914 through 1960 and that the sample of annual maxima is statistically reliable. Also, all or nearly all surges of 2.5 ft. or greater are thought to have been identified.

Probability of maximum annual surge, S_x. The maximum annual surges for Portland, plotted on extreme value probability paper, are shown in figure 28.

Partial duration series. The synthetic combination of tide components requires the heights of all surges, not just maximum annual values. For Portland all surges of 2.5 ft. or more were arranged in order of magnitude (partial duration series) and the corresponding frequency curve was drawn. This curve was identical with the maximum annual curve above 3.0 ft. Below 2.5 ft. the curve was smoothly extrapolated to lower surge heights. The final tide probabilities are not sensitive to the exact frequencies assigned the surges in the very low range of heights.

Probability of astronomical high tide height. The contribution of the astronomical tide to reconstructed T_x's was handled in a manner similar to the surge.

A frequency distribution of astronomical high tide height can be readily constructed from published tide tables since the cycle is virtually complete for engineering purposes within a period of 19 years. Furthermore, the maximum annual astronomical high tides for Portland vary only a few tenths of a foot from year to year during this 19-year period. Thus a sufficiently accurate frequency distribution of daily astronomical high tide can be determined by suitable combination of the predicted high tides for only a few selected years. Frequency distribution of astronomical high tides was obtained by determining a weighted average of all the predicted high tides for 1950 (below normal range), for 1955 (normal range) and 1959 (above normal range). The 1955 data were weighted double.

The data plots as a straight line on normal probability paper for most of the range (fig. 30) but departs from a straight line at the extremes. Since there is an upper and lower limit to the astronomical high tide height, both dependent upon astronomy, such departure is to be expected.

Boston Tide and Surge Frequencies

The frequency distribution of maximum annual surge at Boston is shown in figure 29, while the distribution of high astronomical tide is found on figure 31. These graphs may be compared with the corresponding Portland curves, and were prepared by the same techniques. At the time of preparation of this report these had not yet been combined into reconstructed tides at Boston.

Combination of Coincidental Surge Peak and Astronomical High Tides

To select storm characteristics with return periods such as 100 years from probability curves, is but one approach to designation of design values.

A method which adds perspective is to presume an unfavorable combination of circumstances. A coastal engineer could pose the question, for such perspective, "What tides would result over the next several hundred years if the surges occurred as they had in the past but with each of the major surges coincident with astronomical high tide?" Curve H, figures 26 and 27, provides the probability distribution of extreme tide under such a regime. Curve H was obtained by combining the probabilities of maximum annual surges, figures 28 and 29, with the probability distribution of astronomical high tides from figures 30 and 31*. The combination was effected by a convolution method developed by Cramer /13/, a systematic numerical integration procedure.

Topographic Effect

An extreme high tide has a physical upper limit dependent upon the topography of the region, and is related to the ground elevation at which the ocean water can flood back from the normal shore for great distances. Extreme tide probability curves should become asymptotic to the prescribed upper limit. No such upper limit has been taken into account in this analysis.

Another topographic effect is that tide heights during severe storms are often greater on beaches than at tide gages because of set-up due to breaking waves. The tide observations analyzed in this paper were taken at pier locations. The tide heights developed herein, if applied to a beach location, should possibly be increased somewhat.

Conclusions

It has been shown that the extreme probability distribution of maximum annual observed tides over 46 years at the Coast and Geodetic Survey gage at Portland, Maine is close to and no less severe than the probability distribution of extreme tides that would result from the combination of all surges during the 46 years with all possible astronomical tides at all possible time displacements. The probability distribution of the maximum annual observed tide is shown for several other gages, and of the surge at Boston and Portland.

It was found that if extreme surges at Portland were all to be coincident with astronomical high tide, the tide level of any given return period would be about 0.7 ft. greater than with random time combination of surge and astronomical tide. The difference at Boston would be greater.

---

*Curve H drops below curve F at lower tide heights because it is a probability distribution of the quantity <u>total tide at time of maximum annual surge</u> and not the quantity <u>maximum annual total tide</u>. These quantities are the same for high tide heights but not for low tide heights.

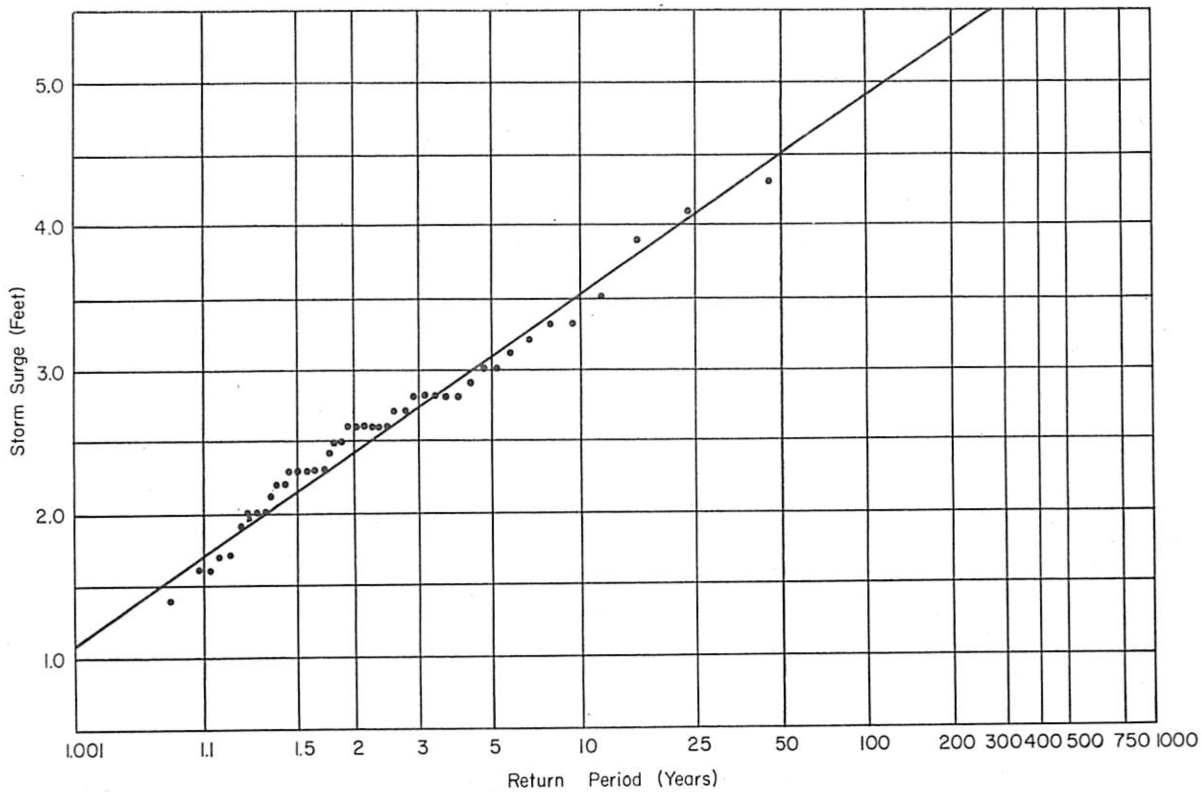


Figure 28. - Maximum annual storm surge vs. return period. Portland, Maine (1914-1959).

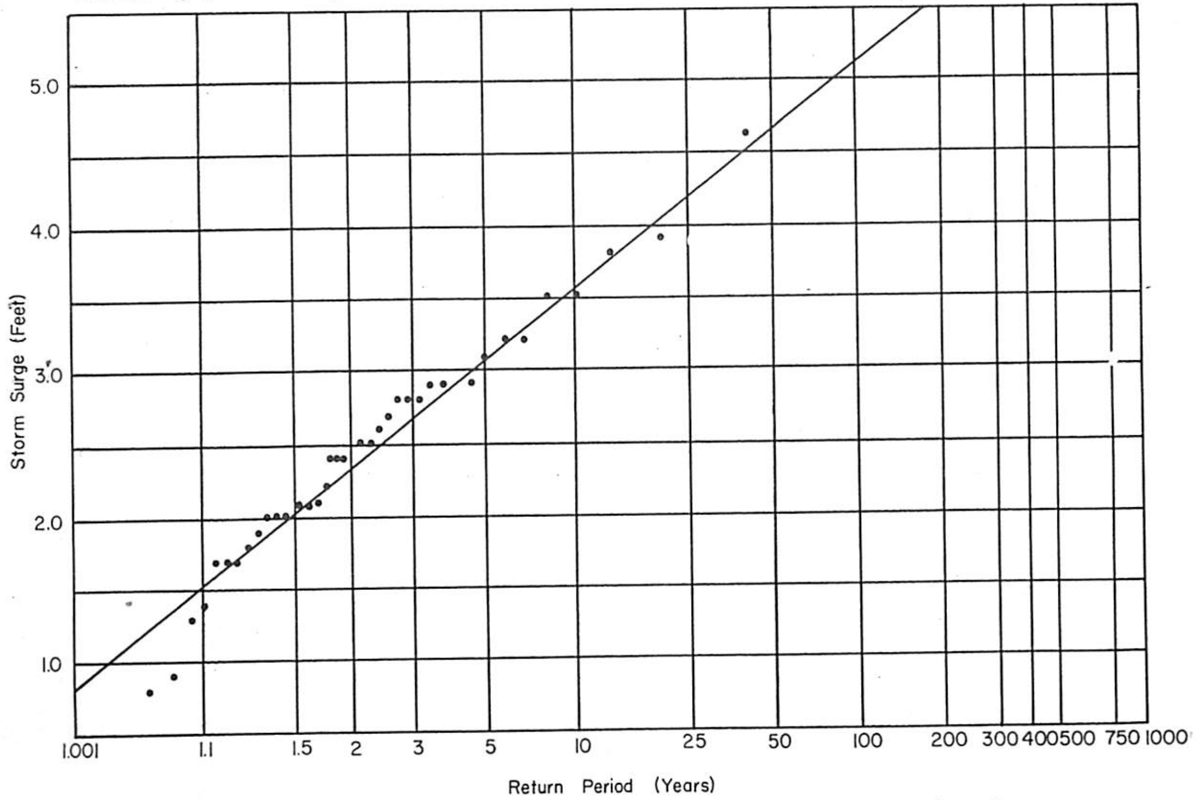


Figure 29. - Maximum annual storm surge vs. return period. Boston, Mass. (1922-1960).

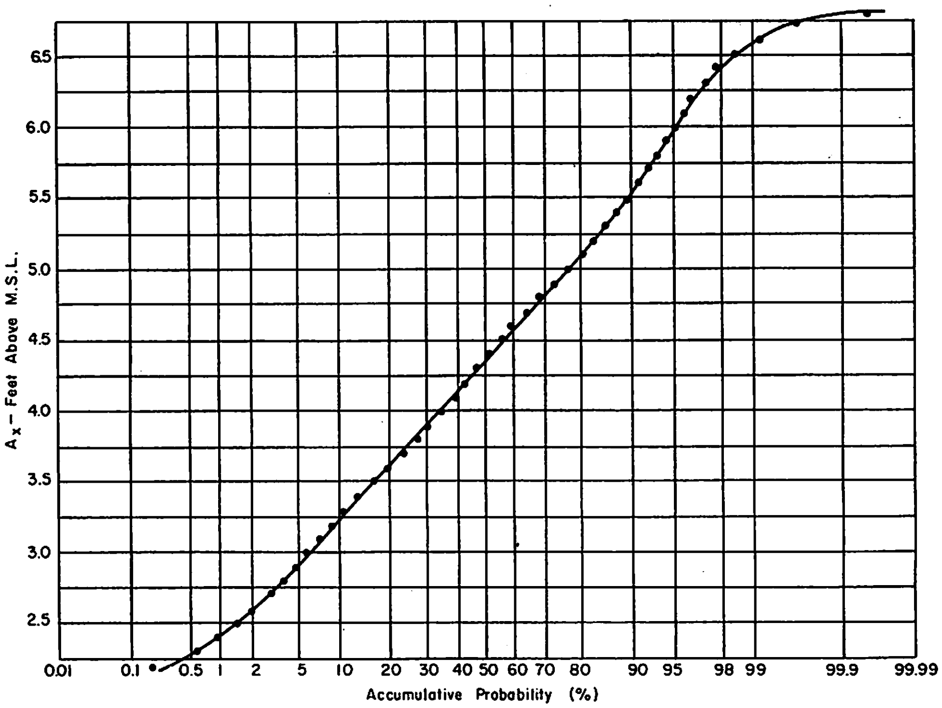


Figure 30. - Accumulative probability of an astronomical high tide height at Portland, Maine being equal to or less than a particular value.

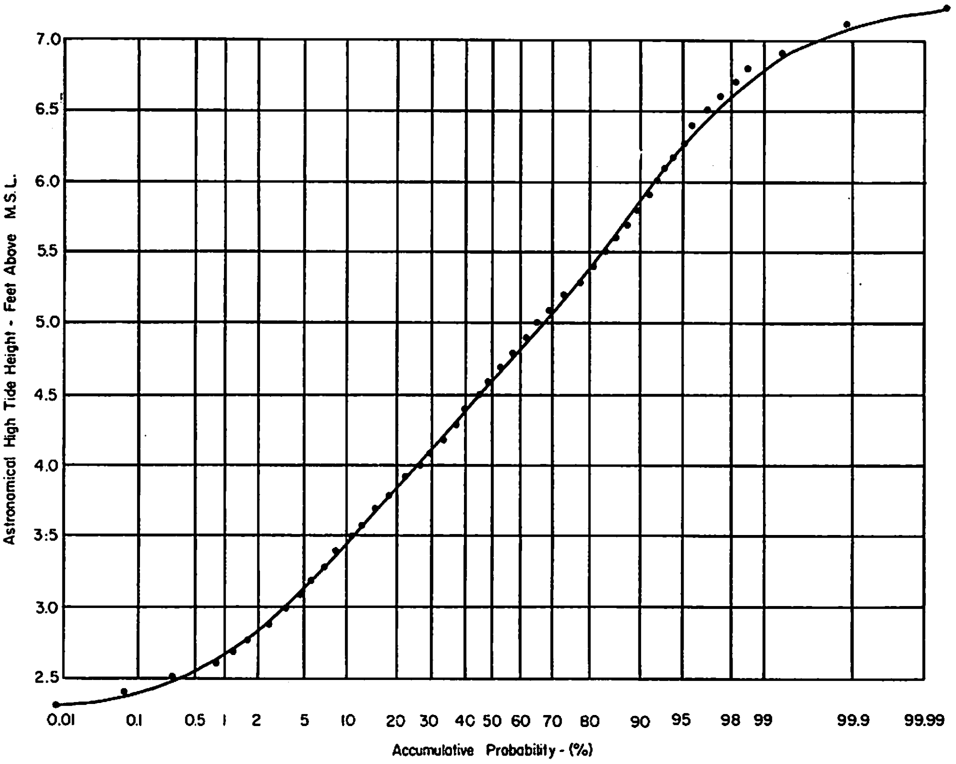


Figure 31. - Accumulative probability of an astronomical high tide height at Boston, Mass. being equal to or less than a particular value.

6. STANDARD PROJECT HURRICANE CRITERIA FOR NORTHERN NEW ENGLAND AND COMPARISON OF HURRICANES AND NORTHEASTERS

Introduction

The Standard Project Hurricane criteria for New England are presented not only as a basis of comparison with the Standard Project Northeasters but also to offer a wider choice of design storms.

It seems surprising that hurricanes, with maximum wind speeds usually much higher than the maximum winds in northeasters, have not produced higher surges north of Cape Cod. This is possibly because the zone of maximum winds is restricted to a relatively small area and the speed of translation is somewhat greater in hurricanes than in northeasters. The storm of September 14, 1944, hurricane Dog (1950) and hurricane Carol (1954) were the only hurricanes since 1914 to have given comparatively high surges. The observed surge values for these hurricanes are shown in table 5.

Table 5. - Observed surge values for hurricanes affecting northern New England.

	Surge Height (ft.)	
Hurricane	Boston	Portland
September 14, 1944	3.9	2.6
Dog (1950)	3.0	2.0
Carol (1954)	3.7	3.3

Standard Project Hurricanes for Northern New England

Hurricane characteristics. The characteristics to be expected of severe hurricanes along the coast of New England from Provincetown, Mass. to Eastport, Maine, are summarized in tables 6 and 7. The values for northern New England were obtained by extrapolation of the Standard Project Hurricane criteria in National Hurricane Research Project Report No. 33 / 14/. That report, and tables 6 and 7 give Standard Project Hurricane criteria for varying radii (small, medium, and large) of maximum winds, and storm speeds (slow, moderate, and fast). A variation in either radius of maximum winds or storm speed will produce different wind fields.

Hurricane tracks. The hypothetical tracks which are both meteorologically feasible and of greatest significance in producing onshore winds are portrayed in figure 32. For northern New England, paths producing the strongest onshore winds would be from a south through east direction. However, since 1887, only two weak tropical storms moved into northern New England from a direction east of south. Therefore, a path moving toward the

Table 6. - Characteristics of New England SPH for tracks A and B, moderate radius, forward speed = 30 knots

Track	Hour Before or After Crossing Coast	Latitude (°N.)	Longitude (°W.)	CPI* (Inches)	Radius of Max. Winds (N.Mi.)	Max. Wind 30 ft. Over Water (m.p.h.)
A	-4	39.5	71.0	27.68	20	109
	-3	40.0	71.0	27.71	21	108
	-2	40.5	71.0	27.74	22	107
	-1	41.0	71.0	27.78	24	104
	0	41.5	71.0	27.82	25	102
	+1	42.0	71.0	28.01	27	96
	+2	42.5	71.0	28.13	29	88
	+3	43.0	70.9	28.23	31	85
	+4	43.4	70.6	28.31	33	82
	+5	43.7	70.2	28.39	34	80
	+7	44.2	69.0	28.48	37	76
	+9	44.7	67.8	28.60	40	71
	+11	45.1	66.5	28.65	42	67
B	-9	39.4	69.6	27.68	20	109
(1 and 2)	-8	39.9	69.6	27.70	21	108
	-7	40.4	69.6	27.74	22	107
	-6	40.9	69.6	27.74	23	106
	-5	41.4	69.6	27.81	25	105
	-4	41.9	69.6	27.84	27	103
	-3	42.4	69.6	27.89	29	102
	-2	42.9	69.6	27.92	31	101
	-1	43.4	69.6	27.96	33	100
	0	43.8	69.5	27.99	35	99
	+1	44.2	69.0	28.16	37	92
	+2	44.5	68.4	28.28	39	88
	+3	44.7	67.8	28.34	40	83
	+5	45.1	66.5	28.49	42	75

*Adjusted for filling

Table 7. - Standard project hurricane index characteristics, east coast United States

Location		CPI (Inches)	Radius of Max. Winds (n. mi.)			Forward Speed (kt.)			Representative Max. Wind Speed (m.p.h.)		
Zone	Latitude (°N.)		RS	RM	RL	ST	MT	HT	V_{gx} (for RL)	V_x	
										T=30 kt.	T=50 kt.
4	40	27.71	8	21	43	14	32	50	101	104	116
	41	27.78	8	24	48	15	34	51	98	102	114
	42	27.85	8	27	52	16	36	52	95	99	111
	43	27.93	9	31	57	17	37	52	92	97	109
	44	28.01	9	36	61	18	38	53	89	94	106
	45	28.10	9	41	66	19	39	53	85	91	103

CPI = central pressure index, estimated minimum pressure
RS = representative small radius to region of maximum winds
RM = representative mean radius to region of maximum winds
RL = representative large radius to region of maximum winds
ST = representative slow speed of translation of hurricane center
MT = representative moderate speed of translation of hurricane center
HT = representative high speed of translation of hurricane center
V_{gx} = maximum theoretical gradient wind *
V_x = estimated maximum 30 ft. wind speed *
T = speed of translation of hurricane center

*See p. 16 NHRP No. 33

north and later curving northeastward was chosen as being the track that is both meteorologically feasible and conducive to producing the highest onshore winds. The lower portions of Tracks A and B are similar to the track of the September 1938 New England hurricane, transposed eastward, while the upper portions of the tracks bear a similarity to the September 1944 hurricane as it occurred. Directions of motion of past hurricanes in the New England region have been summarized in figure 10 (see zone 4) of National Hurricane Research Project Report No. 33 /14/.

Track B_1 is selected to give severe conditions from Provincetown, Mass. to Cape Cod Canal, B_2 from Brunswick, Maine to Eastport, Maine and A from Cape Cod to Portsmouth, N. H. For severe conditions at a particular point on the Maine coast, Track B can be transposed by keeping the lower part of the track oriented north-south and shifting the point of coastal entry of the hurricane center up or down the coast. This transposition is possible from 67.5° to 70.5°W. with slight adjustment for frictional effects at the coast. For severe conditions from Portsmouth, N. H. to Brunswick, Maine, interpolation can be made between the isovel patterns of tracks A and B_2.

Construction of hurricane isovels. The basic SPH isovel pattern for the North Atlantic Coast, figure 35 of /14/, was oriented in the most favorable direction for producing surge. Adjustments were then made for latitudinal variation of the CPI and radius of maximum winds, and for filling after the center crossed the coast and friction over land. The adjustments and the wind directions were accomplished using techniques described in /14/.

Hurricane isovels. The isovel analyses presented in figures 33 through 35 are all based on a mean radius of maximum winds and a moderate speed of translation as given in table 7. It should be kept in mind that these winds are in miles per hour while northeaster wind fields are shown in knots. (To convert m.p.h. to kt. multiply by 0.868.) A speed of translation of 30 kt. was selected to keep the strongest winds over the critical region for a relatively long time. This speed is near the lower boundary of the range of moderate speeds of translation. During the period 1900-1956 the lowest observed speed of translation of a hurricane as it crossed the New England coast was 29 kt. (/14/, fig. 9). The mean radius of maximum winds was chosen as an average condition. Other tracks, forward speeds, and radii of maximum winds might be more severe than those selected.

Comparison of Hurricanes and Northeasters in Northern New England

From a comparison of hurricanes and northeasters in northern New England one can conclude that although hurricanes have higher wind speeds, they move with a faster forward speed, have a smaller area of strong winds, and shorter fetch lengths than northeasters. Therefore the surge-producing effects of hurricanes last a shorter length of time with the result that, in the past, northeasters have produced higher surges north of Cape Cod. This may, however, be due to the relatively short period of record. A summary of the characteristics of hurricanes and northeasters affecting northern New England is given in table 8.

A decision as to whether hurricanes or northeasters north of Cape Cod have the greater damage potential must await surge computations (based upon SPH and SPN isovel charts) which are outside the scope of this report.

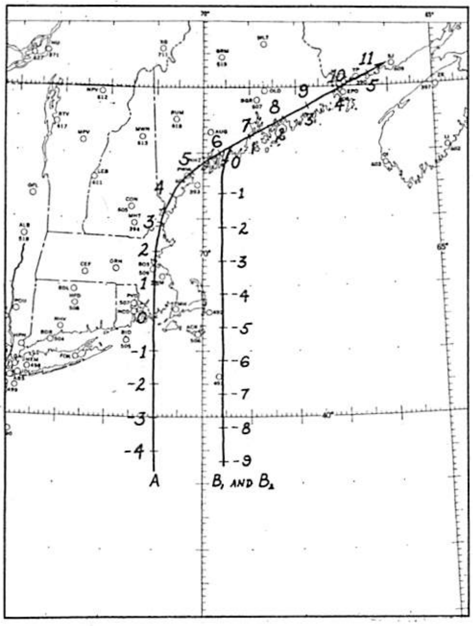


Figure 32. - Northern New England Standard Project Hurricane tracks. Track A critical from Cape Cod to Brunswick, Me; track B_1, critical from Provincetown, Mass. to Cape Cod Canal; track B_2 critical from Brunswick, Me. to Eastport, Me.

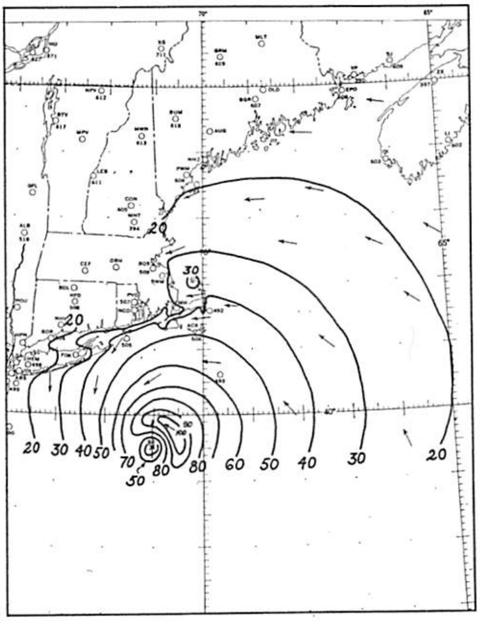


Figure 33a. - Standard Project Hurricane isovels. Track A, four hours before center crosses coast. Units in m.p.h.

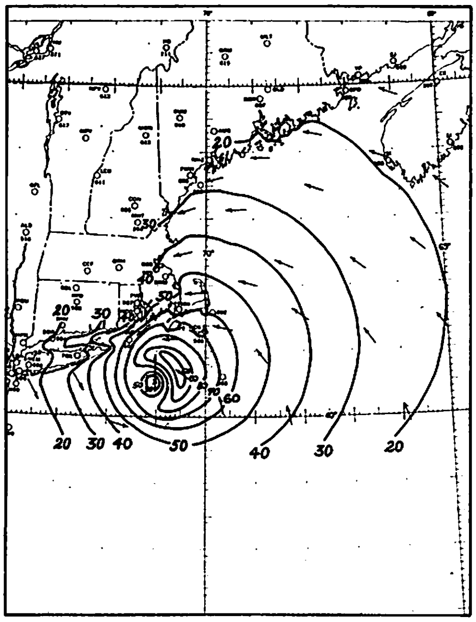


Figure 33b. - Standard Project Hurricane isovels. Track A, two hours before center crosses coast. Units in m.p.h.

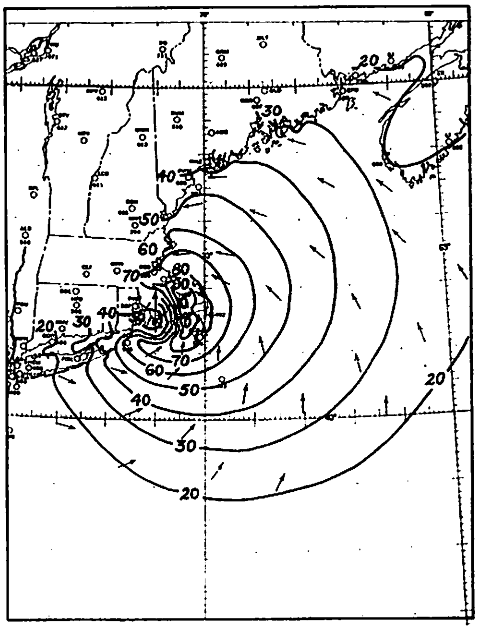


Figure 33c. - Standard Project Hurricane isovels. Track A, at time center crosses coast. Units in m.p.h.

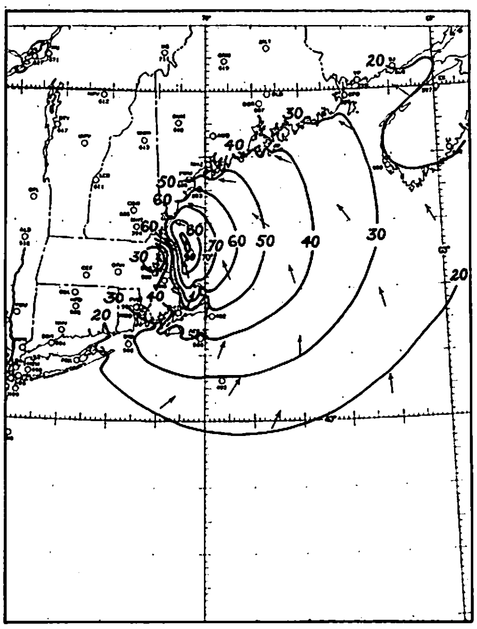


Figure 33d. - Standard Project Hurricane isovels. Track A, two hours after center crosses coast. Units in m.p.h.

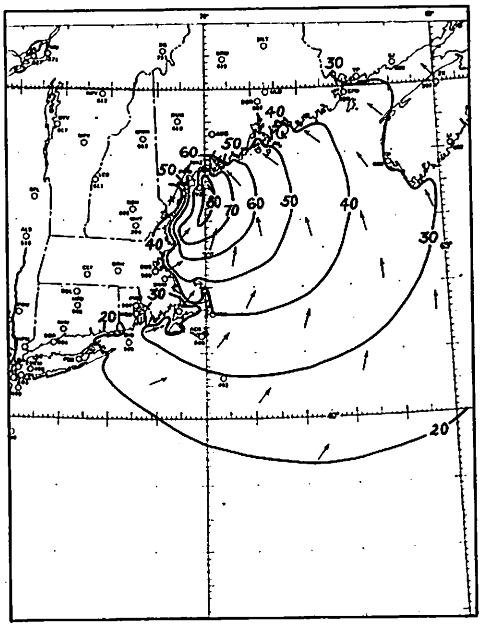


Figure 33e. - Standard Project Hurricane isovels. Track A, four hours after center crosses coast. Units in m.p.h.

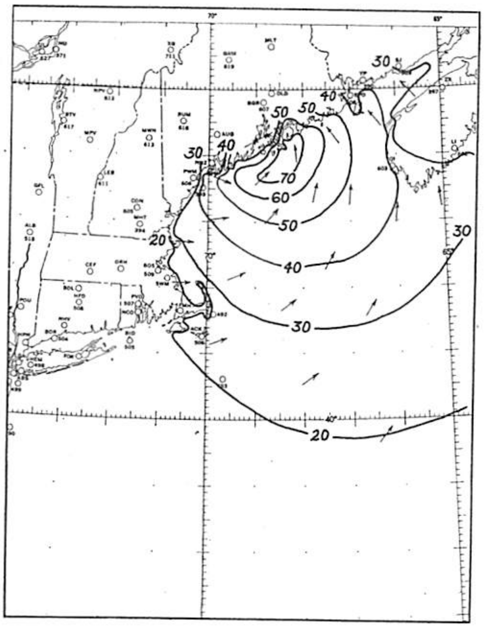


Figure 33f. - Standard Project Hurricane isovels. Track A, seven hours after center crosses coast. Units in m.p.h.

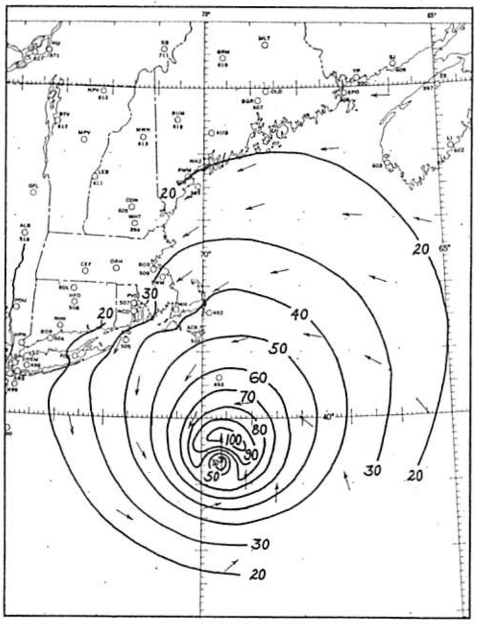


Figure 34a. - Standard Project Hurricane isovels. Track B_1, nine hours before center crosses coast. Units in m.p.h.

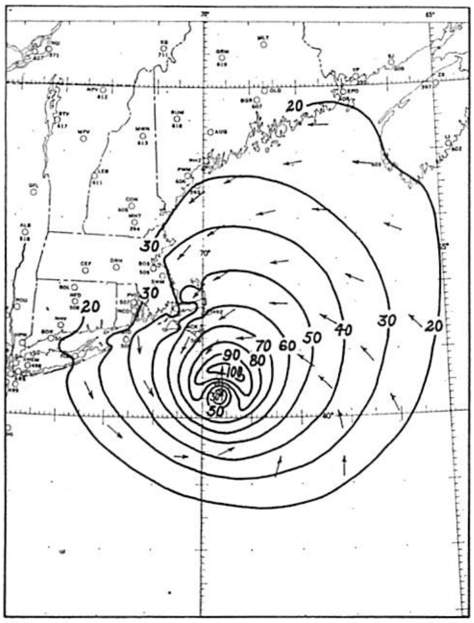


Figure 34b. - Standard Project Hurricane isovels. Track B_1, seven hours before center crosses coast. Units in m.p.h.

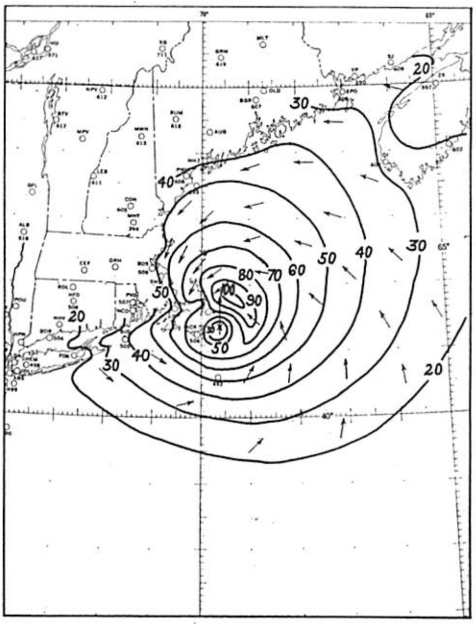


Figure 34c. - Standard Project Hurricane isovels. Track B_1, five hours before center crosses coast. Units in m.p.h.

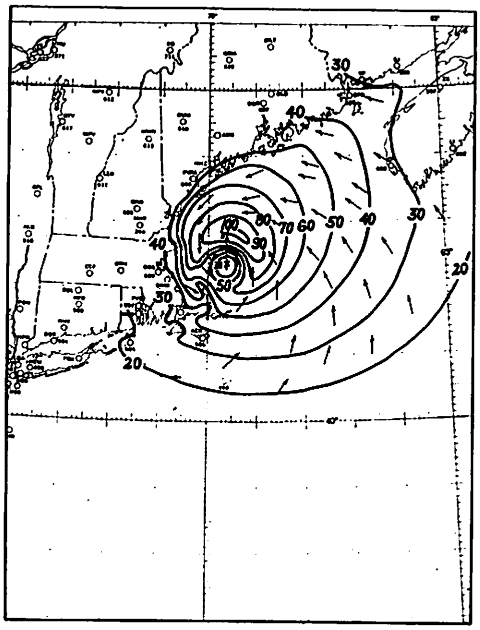


Figure 34d. - Standard Project Hurricane isovels. Track B_1, three hours before center crosses coast. Units in m.p.h.

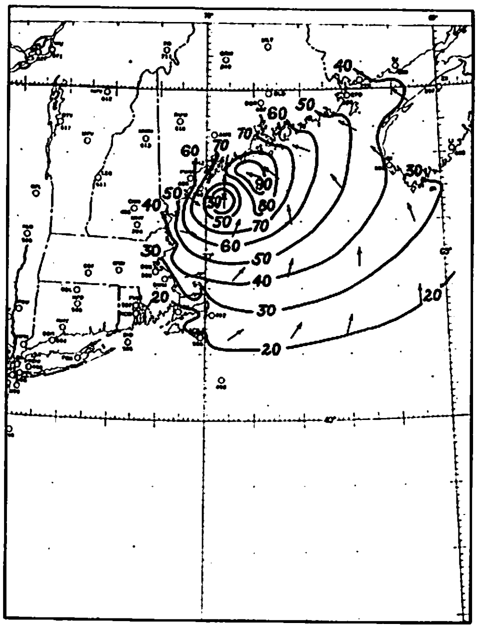


Figure 34e. - Standard Project Hurricane isovels. Track B_1, one hour before center crosses coast. Units in m.p.h.

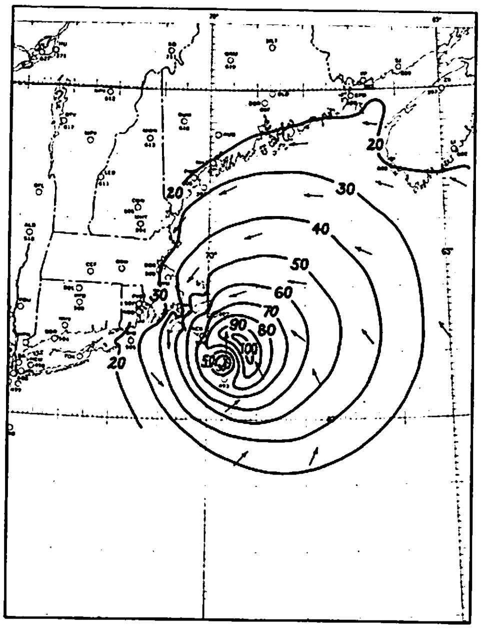


Figure 35a. - Standard Project Hurricane isovels. Track B_2, six hours before center crosses coast. Units in m.p.h.

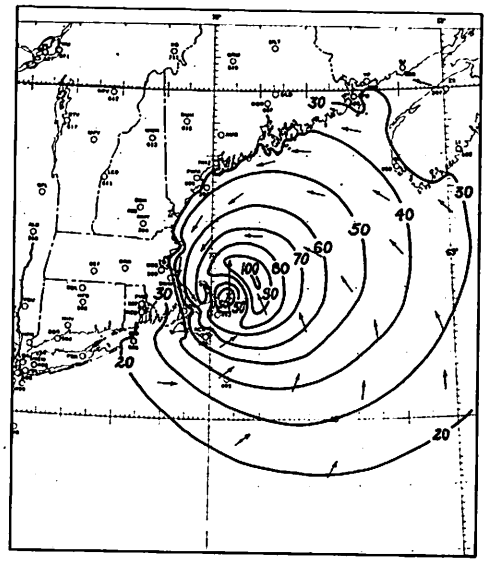


Figure 35b. - Standard Project Hurricane isovels. Track B_2, four hours before center crosses coast. Units in m.p.h.

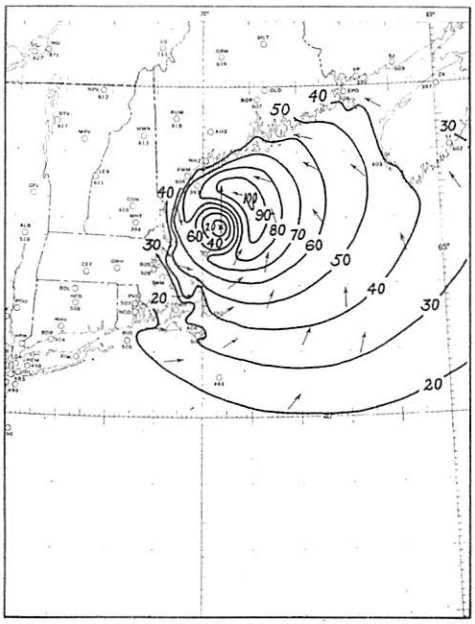


Figure 35c. - Standard Project Hurricane isovels. Track B_2, two hours before center crosses coast. Units in m.p.h.

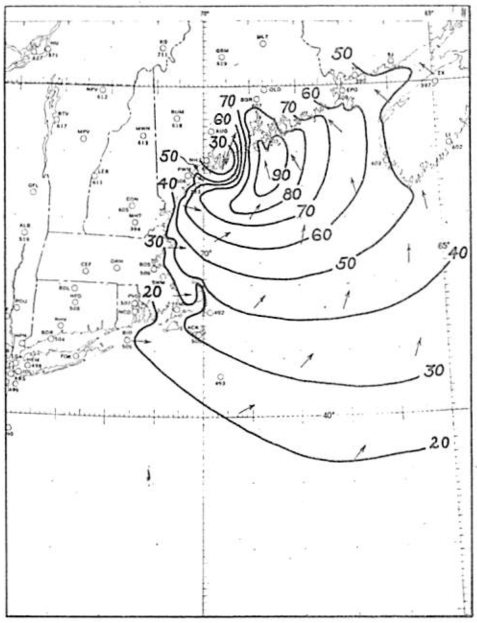


Figure 35d. - Standard Project Hurricane isovels. Track B_2, at time center crosses coast. Units in m.p.h.

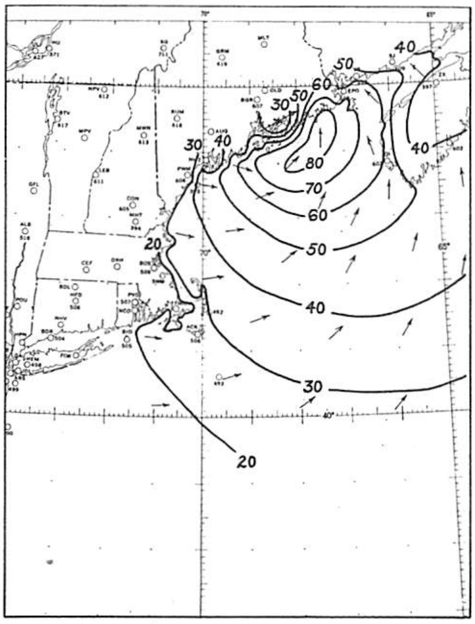


Figure 35e. - Standard Project Hurricane isovels. Track B_2, two hours after center crosses coast. Units in m.p.h.

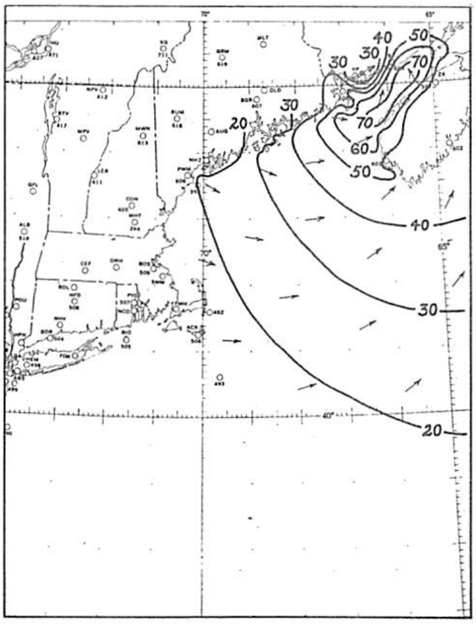


Figure 35f. - Standard Project Hurricane isovels. Track B_2, five hours after center crosses coast. Units in m.p.h.

Table 8. - Comparison of hurricanes and northeasters in northern New England

Characteristics	Hurricanes	Northeasters
<u>Climatology</u>		
Origin	Tropics, always over water	Mostly Gulf of Mexico or South Atlantic regions, usually near coast
Season	August-October**	October-April*
Development	Reach greatest intensity south of New England and then diminish	Reach greatest intensity as they pass New England
Frequency	Average of 1 per 6 yr.	1-2 per yr. with surge ≥ 2.0 ft.*
<u>Track</u>		
Direction	N to NE**	N to E*
Speed	Avg. 36 kt.; range 29-48**	Avg. 22 kt.; range 6-43*
<u>Pressures</u>		
Central pressure	Avg. 958 mb.; lowest 943 mb.**	Avg. 983 mb.; lowest 957 mb.*
Pressure pattern	Usually symmetrical	Usually asymmetrical
Average storm diameter	Small (400-600 n. mi.)	Large (600-1500 n. mi.)
<u>Winds</u>		
Maximum speeds	80-100 kt. not uncommon	70 kt. is rare
Radius of maximum winds	22-66 n. mi., well-defined**	90-340 n. mi., not well-defined, sometimes more than one*
Fetch lengths	Short	Long, 300-1400 n. mi.*

Table 8. (cont'd.) - Comparison of hurricanes and northeasters in northern New England

Characteristics	Hurricanes	Northeasters
<u>Surge</u>		
Surge heights	3.7 ft. highest observed*	Up to 5.1 ft. observed*
Duration of high surge and strong wind	6-12 hr.	12 hr. to 3 days*
Inverted barometer effect	May give important contribution to surge	Relatively unimportant contribution to surge
Topographical considerations	Cape Cod protects northern New England to some extent	Little protection afforded by Cape Cod

Sources: *51 northeasters which produced high surge as described in second paragraph of section 3.

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ACKNOWLEDGMENTS

Work on this project was carried out by Kendall R. Peterson and Hugo V. Goodyear. Collaborating with the project leaders were William Malkin, Sydney Molansky, Charles E. Schauss, and Alan R. Simmons.

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APPENDIX A

HISTORICAL ACCOUNTS OF NOTABLE NEW ENGLAND STORMS

In attempting to put together a panorama of descriptive elements, recourse was made both to historical records and diaries printed in newspapers and books. For much of the history of these storms, the early writers are quoted verbatim below. The numbers following the dates indicate the reference.

April 26, 1717 [2]. "The winds were so strong and the waves were so great and powerful that the sea forced its way across the Cape, which was very narrow at this place (near Wellfleet), creating a channel so large that a whaleboat passed through it at the time."

February 24, 1723 [2]. "The wind was strong and from the northeast, which, blowing at the time of a very high tide, was probably the cause of the flood... at Dorchester, Mass... It was most severe in those parts where the coast ran north and south on the Massachusetts and New Hampshire shores. On the inside of the Cape, the tide rose 4 feet, and outside, it was said, from 10 to 12 feet higher than was ever known before. At Plymouth, it was from 3 to 4 feet above the highest water mark ever known there."

The (Boston) Newsletter of that time said the inundation in Boston "looked very dreadful... the tide rising to a height of 16 ft... At Hampton, New Hampshire, the storm caused the great waves of the full sea to break over its natural banks for miles together, and the ocean continued to pour its water over them for several hours."

Cotton Mather's account of this storm sent to the Royal Society in London relates "... It was on Feb 24, 1723, when our American philosophers observed an uncommon concurrence of all those causes which a high tide was to be expected from. The moon was then at the change, and both sun and moon together on the meridian. The moon was in her perigee, and the sun was near to his having past. There was a great fall of snow and rain... finally the wind was high and blew hard and long... Then veering eastwardly it brought the eastern seas almost upon them (the shore)... They raised the tide unto a height which had never been seen in the memory of man among us... The City of Boston particularly suffered from its incredible mischiefs and losses..."

October 20, 1770 [2, 3]. One of the most violent and destructive storms of wind and rain that ever occurred on the New England coast prevailed on Saturday, October 20, 1770. It began Friday night and continued most of the following day, the wind blowing from the north-northeast. From The Boston Evening-Post, Monday, October 22, 1770. "Last Saturday (October 20) we had here a very violent storm of wind and rain, which continued most of the day at about NNE attended at noon with the highest tide that has been known at this place for near 50 years past, by which great damage has been sustained by the loss of sugars, salt and other articles in store on the wharves, which were overflowed in all parts of the town.

"And it is feared great damage is done at other seaport places and by vessels who might happen to be upon this coast."

The New-Hampshire Gazette, Portsmouth, October 26, 1770 reported: "Last Friday night (October 19) came on here and continued the next day a violent N. E. storm which blowed down several buildings and many fences in this and neighboring towns: about twelve o'clock at noon, the tide rose higher than has been known for 40 years past, which did considerable damage in some wharehouses (sic) by melting of salt, etc. and floating lumber - wood, etc. from off the wharves---Many small vessels from the shoals had sailed, the preceding day, most of which tis feared are lost, as not more than two or three have been since heard of---We hear they have sustained great damage at Newbury, by the above storm, the particulars of which we have not heard."

December 4, 1786 [37]. "On Monday evening last (December 4) came on and continued without intermission until Tuesday evening, as severe a snowstorm as has been experienced here for several years past-The wind at east, and northeast, blew exceeding heavy, and drove in the tide with such violence on Tuesday, as over-flowed the pier several inches, which entering the stores on the lowest part thereof, did much damage to the sugars, salt, etc. therein-considerable quantities of wood, lumber etc. were carried off the several wharfs-The shipping in the harbour, we are happy to find, received but little injury."

March 26, 1830 [27]. "A cold, northeast storm of wind, rain and snow raged along the coast of New England during the latter part of March 1830, producing a great tide, which in some parts exceeded the highest tide remembered there. The storm began on the morning of Friday the 26th, and continued until 1 o'clock in the afternoon, the tide being at its height at noon of that day.

"At Portland, Maine several wharves were carried away, and many vessels lost their fastening, some being driven on shore and others greatly damaged by being beaten against the wharves...At Portsmouth, New Hampshire wharves were injured and several vessels driven ashore.

"At Gloucester, the water was 2 or 3 feet deep on the wharves and much moveable property was washed away, the waves being covered with articles and debris of all kinds.

"The tide rose at Boston 1 and 1/2 inches higher than the great tide of December 1786 which was 10 inches higher than that any person then living remembered. The water broke through the dam along the Roxbury Canal...sweeping away fences and outhouses, and prostrating buildings.

"Much property was set afloat at Charlestown and Cambridgeport. The Navy Yard was overflowed, and the tide broke through the coffer-dam, about 3 feet of water coming into the dry dock."

December 22, 1839 [2]. "The second severe snow storm of this month began on Sunday, the 22nd, and the next morning the wind was fiercely blowing from the northeast. The snow continued all through the day, ...and great damage was done on both land and sea, many vessels being driven ashore...

"Sand hills 20 feet high were carried off, and others equally large were formed."

December 27, 1839 [2]. "During the middle of the week the weather was unusually fine for the season, but just before noon on Friday another terrible storm began...It was more tempestuous than the other storms had been, and the wind came from the east-southeast, increasing during the night to a violent gale and reached its height toward morning. It continued 30 hours in all, and brought in the tide to a great height, overflowing the wharves, and doing more or less damage to nearly all of them.

"At Portland, Maine, the storm was very violent... In Gloucester the storm was severer than it was on the 15th, the wind being extremely fierce. At Salem, all the wharves suffered more or less and everything was swept off them... In Boston, more damage was done than in the storm of the 15th. The injuries to shipping were very extensive, wharves were overflowed...The causeway leading to Dorchester, and the lower streets of the city were submerged, so much damage being done that crowds came from the surrounding towns to see it.

"The storm was so severe at Provincetown, on Cape Cod, that the damage done to shipping and property on the wharves amounted to $50,000 and many of them were entirely carried away, several persons being injured. The month of December, 1839, was indelibly fixed in the minds of the multitudes as one of the most awful seasons that they have ever known... We do not put it too strongly when we say that upwards of 300 vessels were wrecked, one million dollars worth of property destroyed and more than 150 lives lost..."

April 14, 1851, The Lighthouse Storm [2]. "It (the storm) commenced at Washington, D. C. on Sunday (the 13th), reached New York Monday morning, and during the day extended over New England... The moon was at its full, and the water having been blown in upon the shores for several days, the tide rose to a greater height in many places than was remembered by the people then living. It swept the wharves and lower streets like a flood and at Dorchester, Mass. rose nearly 7 feet higher than the average tide... On all parts of the coast where the northeast wind could exert its force the tide rose over wharves from 1 to 4 feet. At Provincetown on Cape Cod, many wharves and salt mills were swept away; and in several places people left their houses which were flooded, water being 6 inches deep on the lower floors in some of them.

"At Boston where the tide averaged 15.62 feet, the water was 3 or 4 feet deep on Central and Long Wharfs and the wooden stores on the latter wharf were completely inundated...

"Deer Island in Boston Harbor, suffered extensively by the great tide which made a complete breach over the island, covering nearly the whole of it. The sea wall that had been built there a few years before by the government, was washed away; and 3 buildings were carried out to sea, one of them being the schoolhouse.

"At Newcastle, New Hampshire, the sea broke through the beaches, and made an island of Jaffrey point... The great storm and tide are known in history as the 'Lighthouse storm and tide,' from the fact that in it the Minot's Ledge Lighthouse was carried away. Minot's Ledge is one of the rocks off Cohasset, Mass., which, before the Light was established, had sent to destruction many a vessel that had been driven upon them by northeasterly gales."

<u>March 12-13, 1888</u>. This storm, often referred to as the "Great Blizzard of "88" is mainly noted for the fury with which it struck New York and Boston, paralyzing both major cities with great falls of snow. In addition many ships, coastal tugs and barges were lost in the fury of the seas, and the coastal areas suffered much wind and tide damage. Listed below are excerpts from Boston newspaper accounts [3] of some of these occurrences.

(<u>Boston, Mass</u>.)

"The storm of last night and this morning is the worst that has been known on the north shore for the last 20 years, and the damage alongshore is greater than ever before. From Point Shirley to the Point of Pines the beach is strewn with the wreck of bulkheads, cottages and fences. At Cottage Hill, near the terminus of the Boston, Winthrop and Shore Railroad, the scene is one of desolation; the tracks are down and the cottages on the other side are in a dilapidated condition..."

(<u>Lynn, Mass</u>.)

"Old fishermen in Swampscott stated this morning that they had no record of so high a sea in the bay for 18 years, the ice cakes are tossed up and lie 60 to 75 feet beyond high water line well up towards the roadway... Beach Street in Lynn was submerged by the tide at various points... Part of Frank W. Breck's seawall at Red Rock was undermined and thrown down..."

(Gloucester, Mass.)

"The storm was the severest of the season on the Cape. The sea at Pavilion Beach washed Western Avenue, doing much damage to property..."

(Cohasset, Mass.)

"The storm of the past 48 hours has had the effect of creating the heaviest seas off the south shore which have been seen since the destruction of Minot's Lighthouse on April 15, 1851. At an early hour this morning the seas were sweeping over Minot's in almost a solid body..."

(Newburyport, Mass.)

Captain Elliot of the life-saving service at Plum Island sent the following report to the city today (13th): "The northeast gale commenced yesterday and blew with terrific fury throughout the night with heavy snow and sleet. The sea at midnight broke through all the valleys between the hills and inundated all the low parts of the island filling our well with sea water."

November 26-27, 1898. Known as the "Portland Gale", this storm caused much loss of shipping and lives at sea including the excursion steamer "Portland" which was wrecked with the loss of 100 to 150 persons while on a trip from Boston to Portland, Maine. A small sample of the severity of this storm may be constructed from portions of the report of J. W. Smith, Weather Bureau Observer at Boston, Mass., appearing in the Monthly Weather Review of November, 1898.

"November 27, 1898 /4/. The storm increased greatly in severity during the night becoming one of the most severe for years. From 3 A.M. to 1 P.M. the hourly wind velocity ranged from 40 to 50 miles, with a maximum velocity of 60 miles at 11 A.M., and an extreme velocity at the rate of 72 mph for one mile at 11:20 A.M. The storm caused great damage along the coast in this vicinity. Many vessels were wrecked and summer cottages blown down." Perley /2/ adds:

"Giant breakers swept through many thoroughfares and the tide at Cohasset, Mass. rose even higher than during the storm which destroyed Minot's Light in 1851... Wharves were submerged at Nantasket during this gale.. at Scituate, Mass., the mighty surf broke through between the 3rd and 4th cliffs... At the same time, the original North River sealed its mouth and is now marked by a tablet on the Humarock shore... High water mark, Boston, Mass., 14.3 above mean low water."

December 26, 1909, The Christmas Gale /57. "The morning tide of December 26, 1909, attending the severe storm of this date on the New England coast, was one of the highest ever recorded in Boston Harbor.

"At Boston Light the predicted time of high tide was 10:20 a.m. The wind from the late afternoon of the 25th until nearly noon of the 26th, was from the east and northeast over Boston Harbor and Massachusetts Bay, rapidly increasing in force during the evening of the 25th to very high velocities soon after midnight, which continued undiminished through the morning and day of the 26th. At Cape Cod, Highland Light, the velocity at 8 a.m. of the 26th was 48* miles northeast; noon 72* miles; 2:15 p.m., 84* miles; at 5 p.m. 66* miles all from the east-northeast and at midnight was 60* miles north. At Boston the hourly movements from midnight to noon of the 26th ranged between 25* and 39* miles. The hourly maximum rates between 32* and 45* mph, the latter occurring at 5:10 a.m., from the northeast.

"The increasing and high wind, occurring with the rising tide, together with a high run of tide, caused the water in Boston Harbor to reach approximately the record height of the tide of April 14, 1851 (The Lighthouse Storm), which at the U. S. Navy Yard was 15.0 to 15.1 ft., the height of the tide of December 26, 1909, being, at the same station 14.98 ft. In general the tide in Boston Harbor and Massachusetts Bay was approximately 3.5 feet about the predicted height. The actual height as given by the U. S. Engineers and other reliable authorities at the following places was as follows: Newburyport, Massachusetts, Harbor, Black Rock Wharf, 12.68'; Sand Bay, Rockport Harbor, 13.64'; Boston Harbor, Deer Island, 14.56'; Plymouth Harbor 14.8'; Barnstable Bay, 13.25'; Provincetown Harbor, 14.35'; the tide at all these stations with the exception of Plymouth and Barnstable was approximately 5 feet above mean high water."

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*These are uncorrected wind values (not adjusted for instrumental error.) Corrected values are about three-fourths of the values given.

APPENDIX B

STORM TRANSPOSITION IN THE NEW ENGLAND AREA

Introduction

Adjustments for transposition were considered necessary in the development of composite or Standard Project Northeasters when transposing storms 300 n. mi. or more. In several instances during the 10-year study of offshore extratropical cyclones (see section 4) it was found necessary to transpose storms beyond this range. The concept behind transposition is that the relocation of a storm can be demonstrated to be feasible and reasonable, usually after applying adjustments determined from meteorological principles. The basic assumption was that if the storm being transposed had moved along a different track, it would have occurred with the adjusted characteristics at the transposed site. Those characteristics which were modified during transposition were the central pressure and the pressure profile.

Transposition of Storm Center

The observed storm center was moved to a location where the strongest observed pressure gradient in the forward semi-circle of the storm and the winds (associated with the pressure gradient) would blow onshore at about the center of the coastline between Eastport, Maine and Cape Cod, Mass.

Adjustment of Central Pressure

Central pressures were adjusted by maintaining equal departures of the central pressure (in terms of the standard deviation) from the average central pressure of Lows at the respective locations. The following equation will illustrate this concept more clearly.

$$\frac{\bar{p}_{c(i)} - p_{c(i)}}{\sigma_i} = \frac{\bar{p}_{c(t)} - p_{c(t)}}{\sigma_t} \qquad \text{(B-1)}$$

where,

$\bar{p}_{c(i)}$ = mean central pressure of all Lows passing over the point where the Low occurred.

$p_{c(i)}$ = observed central pressure of Low before transposition.

σ_i = standard deviation of all $p_{c(i)}$.

$\bar{p}_{c(t)}$ = mean central pressure of all Lows passing over the point to which the Low is being transposed.

$p_{c(t)}$ = transposed central pressure.

σ_t = standard deviation of all $p_{c(t)}$.

Solving for the transposed central pressure,

$$p_{c(t)} = \bar{p}_{c(t)} - \frac{\sigma_t}{\sigma_i} (\bar{p}_{c(i)} - p_{c(i)}) \quad \text{(B-2)}$$

The means and standard deviations of the lowest central pressures of all cyclones traversing the area of interest during October through March between 1940 and 1950 are indicated at the center of each 5 degree "square" in figures 36(a) and 36(b). Isolines are drawn to aid in interpolation of $\bar{p}_{c(i)}$, $\bar{p}_{c(t)}$, σ_i and σ_t.

As an example, let us transpose a storm the center of which is at 36°N., 68°W. (point A in the figures) to 41°N., 68°W. (point B in the figures). Assume that the observed central pressure, $p_{c(i)}$, is 970 mb. From figures 36(a) and 36(b),

$\bar{p}_{c(i)}$ = 1000.5 mb.

σ_i = 9.25 mb.

$\bar{p}_{c(t)}$ = 997.3 mb.

σ_t = 10.9 mb.

and from equation B-2, the transposed central pressure, $p_{c(t)}$, is

$$\begin{aligned} p_{c(t)} &= 997.3 - \frac{10.90}{9.25} (1000.5 - 970.0) \\ &= 961.3 \text{ mb.} \end{aligned}$$

Adjustment of Peripheral Pressures

Pressure profiles were constructed along several radial directions and were adjusted at the center (as described above) and at the peripheries (where the isobaric curvature is negligible).

The peripheral adjustment is accomplished by employing the following equation, where normal sea level pressure is used as a standard and the peripheral pressure is for a particular radius:

$$p_{p(t)} = \bar{p}_{p(t)} \cdot \frac{p_{p(i)}}{\bar{p}_{p(i)}} \quad \text{(B-3)}$$

where

$p_{p(t)}$ = adjusted peripheral pressure, after transposition.

$\bar{p}_{p(t)}$ = normal (monthly) sea level pressure at the peripheral point after transposition.

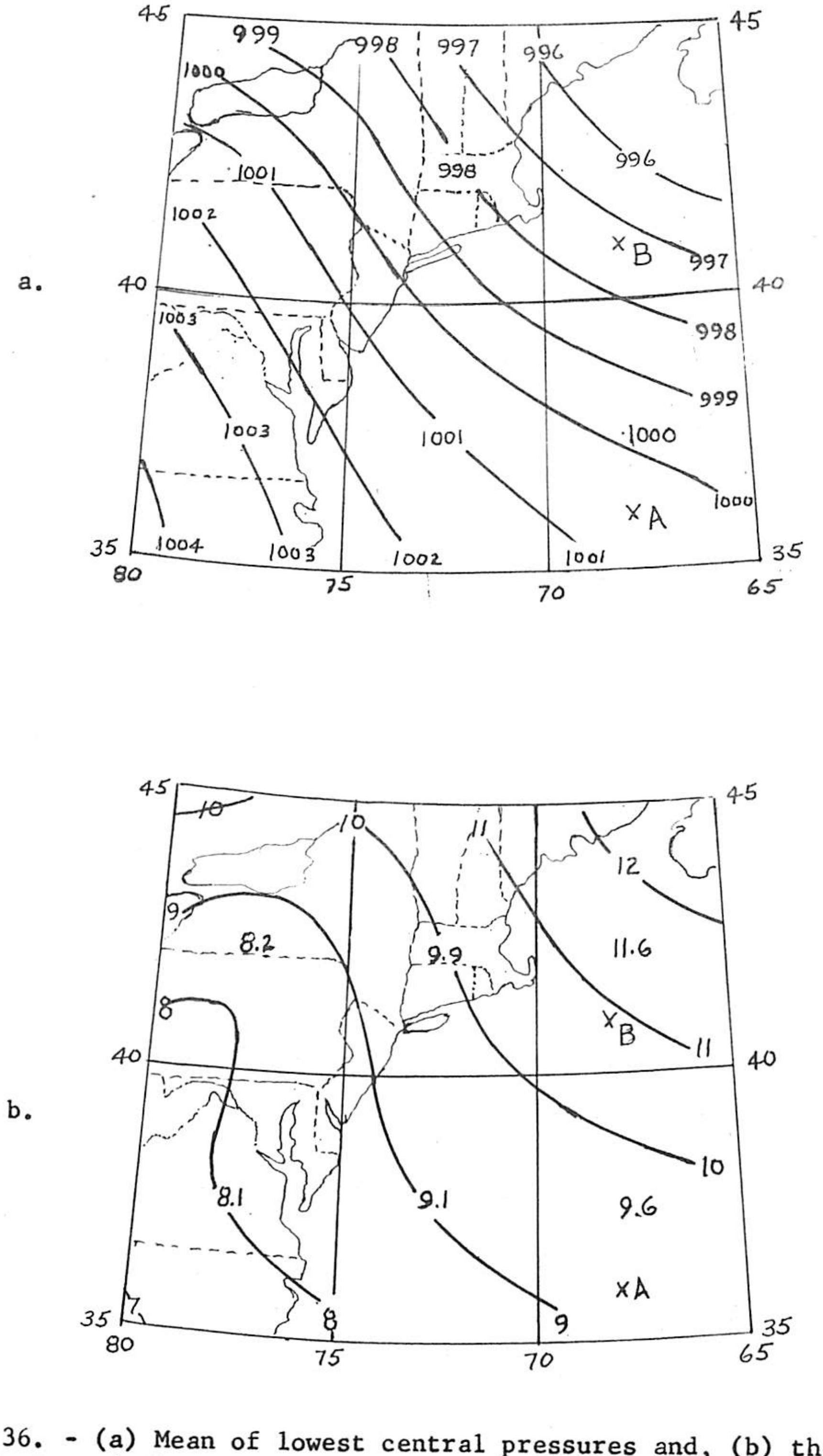

Figure 36. - (a) Mean of lowest central pressures and, (b) the standard deviations (mb), of all cyclones traversing the 5° squares, October through March, 1940-50.

$p_{p(i)}$ = peripheral pressure before transposition.

$\bar{p}_{p(i)}$ = normal(monthly) sea level pressure at the peripheral point before transposition.

Adjustment of Pressure Profiles

Adjustments of the pressure profiles are made using the transposed central and peripheral pressures, maintaining as closely as possible the original shapes of the profiles. This last step agrees with a study by James [15], who concluded that "the profile shape varies little if at all from occlusion to occlusion." Storms considered for transposition are usually in some stage of occlusion.

Preparation of Transposed Isobars

Holding the areal extent and the orientation of the storm constant, the transposed central pressure and the adjusted profiles are transferred to a base map and new isobars are sketched, using the shape of the original isobars as a guide.

Limits of Transposition

Application of this transposition technique is recommended for transpositions of 300 n. mi. or more between the limits 35°N. to 45°N. and within 10° of longitude of the coast.

APPENDIX C

TECHNIQUES OF RECONSTRUCTING SURFACE WIND FIELDS FROM PRESSURE FIELDS

Introduction

In synthesizing storm wind fields over the sea it is always necessary to augment the scarcity of direct observations of wind by indirect computations. These computations are usually made from the pressure field. Four such methods were employed in this study, both to synthesize wind fields of past storms and to develop the recommended Standard Project wind patterns.

Since, in synthesizing wind fields, heavy reliance is put on the pressure field, a series of surface pressure charts are analyzed with care, taking advantage of the fact that a few pressure observations determine the pressure field more reliably than the same number of wind observations determine the wind field. This series of charts usually begins several standard map times before the first map time for which wind computation will take place so that the continuity of such characteristics as pressure, pressure gradients, and fronts may serve as a check on the reliability of the analyses.

Estimating Over-Water Surface Winds from Trajectories

Trajectories. Trajectories are the paths followed by particles of matter, in this case air, as they act in response to forces imposed upon them. Air particles in motion are commonly referred to as wind. If one can trace the path of an air parcel, he will know the wind speed at a particular time at each point over which the parcel passes. Consequently, if one draws enough trajectories, it is possible to define the wind field over a specific area for any given time. Although this procedure is laborious and time-consuming, such computed winds agree well with observations.

The equations of motion. Trajectory computations may be made by graphical techniques using nomograms which represent solutions of the simplified equations of motion. Goodyear /16/ has devised such nomograms for the special case where surface friction is neglected. However, because friction terms are lacking, results are reliable only when computation is carried out over relatively short periods of time, say up to six hours, initial wind is close to dynamic balance, and the isobaric gradient is not changing rapidly with time.

Refinement of the equations of motion so as to include friction greatly increases the accuracy of wind values determined from trajectory computations. These equations, including friction, are:

$$\frac{du}{dt} = fv - fv_g - \sqrt{u^2 + v^2}\left(uK_t - vK_n\right) \qquad (C-1)$$

and

$$\frac{dv}{dt} = fu_g - fu - \sqrt{u^2 + v^2}\left(vK_t - uK_n\right) \qquad (C-2)$$

where:

u = the east-west component of wind speed,

v = the north-south component of the wind speed,

f = the Coriolis parameter,

t = time,

K_t = empirical constant relating tangential frictional force to square of wind speed,

K_n = empirical constant relating normal frictional force to square of wind speed,

g = subscript for components of geostrophic wind (defined in a following paragraph).

Although equations (C-1) and (C-2) may be solved graphically when friction (the complex term at the extreme right end of each equation) is neglected, as they stand they can be solved with any reasonable rapidity only with the aid of an electronic computer.

Comments. The trajectory technique is probably the most realistic of the techniques described in this appendix for computing surface winds. When properly used it can take account of changes in the pressure field due to either local changes or storm motion, and effects due to curvature of the wind trajectory. The assumption that frictional forces are proportional to the square of the wind speed has been verified by several authorities.

Winds derived using the coefficients of friction are not sensitive to small changes in the coefficients. For further remarks see the subsequent subsection on frictional coefficients.

Estimating Surface Winds Using a Percentage of the Geostrophic Wind

Introduction. One of the most direct techniques for obtaining surface winds from the pressure field is to multiply the geostrophic wind by a constant factor. Opinions of previous investigators as to the value of this factor vary from 0.60 to 0.80 /17 through 23/.

Geostrophic wind. The geostrophic wind may be defined as the theoretical wind speed realized under conditions of straight, parallel isobars, steady-state flow, and no friction. It is proportional to the pressure gradient, and may be computed from the expression:

$$V_g = \frac{1}{\rho f}\frac{dp}{dn} \qquad (C-3)$$

where V_g = geostrophic wind speed,

ρ = density of air at sea level,

f = Coriolis parameter, and

$\frac{dp}{dn}$ = pressure gradient.

In practice, the geostrophic wind is usually computed by means of nomograms which convert distance between isobars to wind speed.

Constant factor. Since the surface wind over the sea is influenced by friction in an approximately uniform manner, using a constant percentage of the geostrophic wind as an estimate of the surface wind is a conventional approach. However, this method gives poor estimates of the surface wind when the geostrophic wind is very high or the curvature of the trajectory of the wind becomes great.

Variable factor. If a variable percentage of the geostrophic wind speed is used as an estimate of the surface wind speed, improved estimates can be obtained for a wider range of geostrophic wind speeds. In order to find the proper values of this variable percentage or factor to be applied to pressure gradients in northeasters affecting New England, a study was made of the ratio between measured geostrophic winds and observed surface winds. The study consisted of measuring geostrophic winds between 35° and 60°N. latitude in the western Atlantic at places where two or more ships located within 120 n. mi. or less of each other reported both winds and pressures which were consistent. This requirement was waived for reports from USCG stationary weather ships. Additionally, in all cases, it was necessary that there be reports from a sufficient number of other ships in the vicinity to define the pressure field closely.

Inspection of surface pressure maps for selected winter months over several years yielded 180 cases which satisfied the above conditions. For each case, a record was made of the location, date and time, observed wind speed and direction, geostrophic wind speed and direction, and curvature of the isobars.

The 180 observed speeds versus geostrophic speeds were plotted and a curve fitted by using the means of the plotted values within 10 kt. intervals. The mean curve is shown as curve V in figure 37. It is apparent from this curve that a constant percentage is not valid at high geostrophic wind speeds. However, there is good agreement between curve V and curves (actually straight lines) developed by other investigators (using constant factors) for the relation between actual and geostrophic wind speeds up to about 50-60 kt.

A distribution of inflection angles showed a good mode at one compass point: 22.5° (on a 32-compass-point basis) toward low pressure, and this incurvature value was used on the isotach charts synthesized by this method.

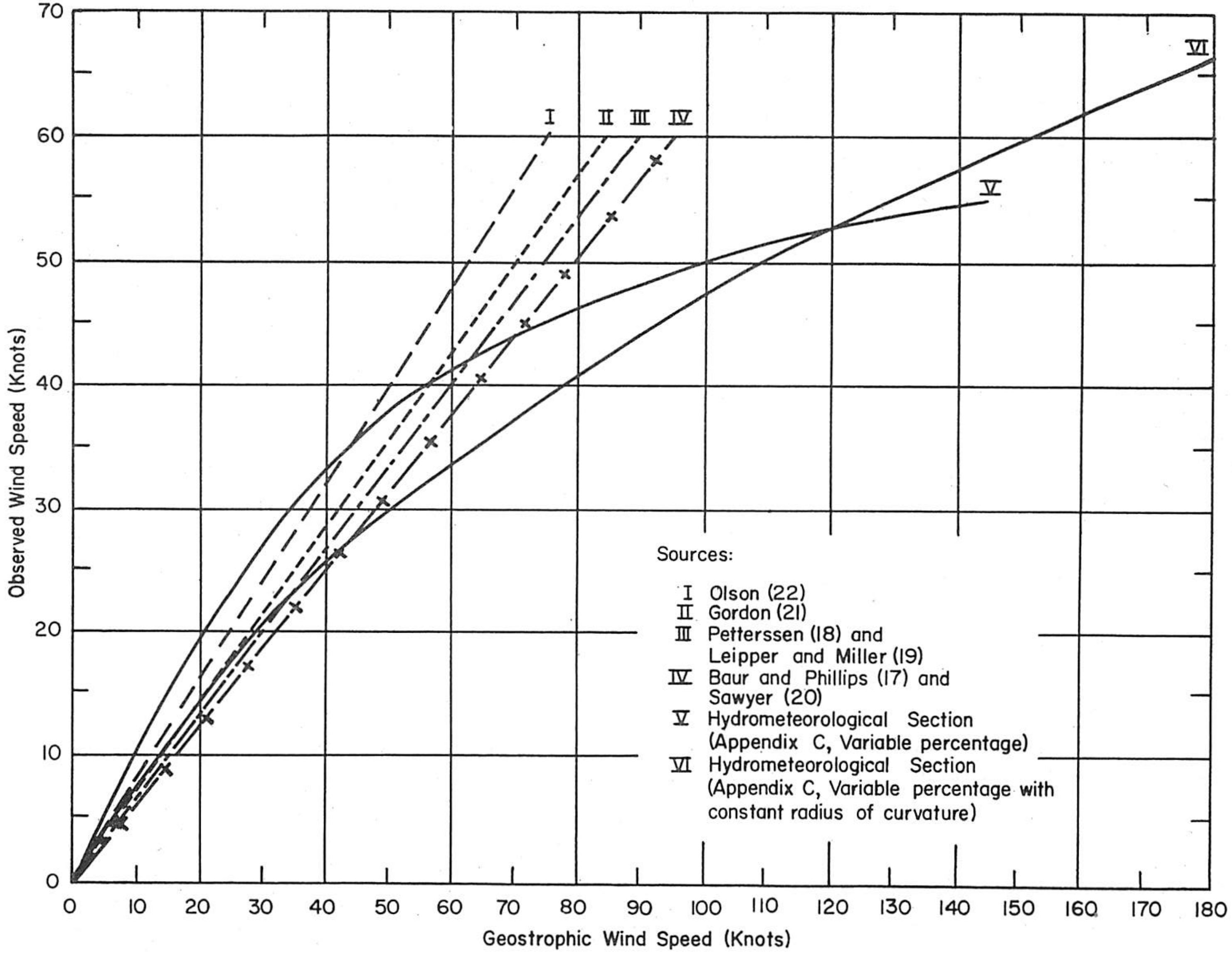

Figure 37. - Nomogram for estimating over-water surface wind speed from geostrophic wind.

Comments. The use of curve V to adjust geographic winds to estimated surface winds has the advantage of simplicity, and the results agree with observations when isobars are not sharply curved, isobaric gradients are not too great, and forward motion of the storm is moderate or slow.

Equilibrium Wind Approach to Synthesizing Surface Wind Fields

Introduction. The equilibrium wind, as defined by Myers and Malkin /24/, is essentially the gradient wind adjusted to include the effects of friction and the forward speed of the storm.

Theoretical basis. In a polar coordinate system, the equilibrium wind equations in component form are:

$$\frac{1}{\rho}\frac{\partial p}{\partial r}\sin\beta + \frac{1}{\rho r}\frac{\partial p}{\partial \theta}\cos\beta - K_t V^2 = 0 \qquad \text{(C-4)}$$

$$\frac{1}{\rho}\frac{\partial p}{\partial r}\cos\beta - \frac{1}{\rho r}\frac{\partial p}{\partial \theta}\sin\beta - fV - \frac{V^2}{r}\cos\beta - K_n V^2 + \frac{VV_s}{r}\sin\theta = 0 \qquad \text{(C-5)}$$

Where:

p = sea level pressure

β = deflection angle, positive when inward toward lower pressure

V = wind speed

V_s = forward speed of storm center

r = distance from storm center to point where V is computed, and

θ = angle between direction of storm movement and radial direction, r, measured clockwise

The other symbols have been previously defined.

The individual terms of the equations represent the following:

(1) the first and second terms of both equations represent the pressure gradients,

(2) $K_t V^2$ and $K_n V^2$ are the terms for frictional acceleration,

(3) fV is the Coriolis acceleration, and

(4) $\frac{V^2}{r}\cos\beta$ and $\frac{VV_s}{r}\sin\theta$ are the centrifugal acceleration terms.

Frictional coefficients. The frictional coefficients used in constructing equilibrium wind fields used in this report were $K_t = 0.005$ n. mi.$^{-1}$

and $K_n = 0.004$ n. mi.$^{-1}$. These coefficients were initially determined while reconstructing the wind fields of several hurricanes. Test computations were made using assumed values of surface friction and the computed winds were compared with actual observations until coefficients were obtained which caused the computed and observed winds to vary by no more than a few knots.

The same coefficients were used to synthesize the isovel patterns of the April 1956 northeaster. These coefficients, although initially derived for hurricanes, showed good agreement with both available observations and the isovel patterns synthesized by Graham and Hudson /25/, by a different method. Further application of the friction coefficients to the March 1962 northeaster indicated good agreement between computed and observed winds. Therefore, it seemed satisfactory to assume that K_t and K_n are nearly constant from storm to storm and in northeasters have the above values.

Comments. The equilibrium wind technique has the advantage of being easier to handle computationally than the trajectory method, but does not account for accelerations due to changing pressure patterns and makes an assumption (although a reasonable one) regarding the radius of curvature of the trajectory of the air parcel. Both methods make the same basic assumption regarding friction.

In comparison with the methods using a percentage of the geostrophic wind, this technique takes into account:

1) the storm motion V_s;
2) the variation in the radius of curvature of the wind trajectory in different parts of the storm and different storms. Friction is introduced in a different manner.

Combination of Geostrophic Wind Technique and Equilibrium Wind Computations

These last two methods were combined so as to take advantage of the simplicity of one and the refinement of the effects of curvature of the wind trajectory of the other. From equations (C-4) and C-5) equilibrium winds were computed for a variety of storm radii, r, and pressure gradients, $\frac{\partial p}{\partial r}$, with the simplifying assumption that the storm is stationary ($V_s=0$) and circular ($\partial p/\partial \theta=0$).

Curves were constructed of the resulting equilibrium wind vs. geostrophic wind at various radii. The curve for r = 300 n. mi. most nearly fit the wind conversion curve from method II, curve V of figure 37, and is shown as curve VI. 300 n. mi. also approximates the radius from storm center of the axis of maximum winds of the northeasters.

Comments. In preparing the Standard Project Northeaster isovels and in computing other wind fields described, equilibrium winds were computed at a basic grid of points from equations (C-4) and (C-5) with an electronic computer. Supplementary values were computed in critical areas by reference to curve VI.

Both curve V and curve VI provide fairly good approximations of the surface wind in regions where isobars are not sharply curved, isobaric gradients are not extreme, and storm motion is moderate or slow.

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