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THE ANALYSIS AND FORECASTING OF SEA AND SWELL CONDITIONS IN DEEP WATER

by

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ABSTRACT

A description of the principles and practices used in the preparation of wave data analyses and forecasts at the MFWC Halifax is presented. The method makes maximum use of the available reported wave data, and allows one to fill in the areas of inadequate data by using the persistence of waves from an historical sequence of charts, modified according to the classical patterns of development or decay using duration and fetch considerations and the wind field. While computer produced wave forecasts provide useful values, and may be expected to achieve the best results in due course, a combination of the objective and subjective procedures is currently proving more reliable.

ANALYSE ET PRÉVISION DES CONDITIONS DE LA MER ET DE LA HOULE EN EAU PROFONDE

par

M.R. Morgan

RÉSUMÉ

L'auteur présente une description des principes et des pratiques employés au bureau de prévisions météorologiques de Halifax pour la préparation des prévisions et des analyses des données relatives aux vagues. La méthode utilise au maximum les données recueillies sur les vagues et permet de compléter les secteurs où les données sont insuffisantes en se fondant sur la persistance des vagues déterminée d'après une série chronologique de cartes modifiées selon les formes classiques de naissance ou de décroissance des vagues ainsi que sur la durée, la fetch et les régions géographiques de vents dominants. Bien que les prévisions des vagues obtenues par ordinateur soient utiles et qu'il soit éventuellement possible d'obtenir de meilleurs résultats par ce moyen, une combinaison des façons de precéder objectives et subjectives donne d'ordinaire des résultats plus sûrs.

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by

M.R. Morgan

(Manuscript received July 12, 1971)

1. Introduction

The three major hazards which affect operations at sea are, reduced visibility, ice and sea state. Although navigational aids, such as radar, have eliminated many of the problems created by the two former, little can be done to ameliorate the third. Sea waves can contain such enormous amounts of energy being transported at such speed that marine operations are severely restricted and damage to vessels, structures in the ocean and the shoreline, often occur. It is not surprising, therefore, that information regarding sea state conditions has become a prime requirement in marine meteorological support services today.

Information on wave conditions is difficult to obtain and interpret. Merchant vessels report the height, period and direction of the wave trains observed. These reports include the sea wave caused by the local wind field and swell waves which are the decaying waves from distant storms. As there may be more than one visible swell train present, and many more that are imperceptible, it will be appreciated that the state of the sea is usually very complex. It is the combination of several superimposed wave trains, which can only be described accurately in spectral form by a wave recorder. The complete spectral description is, however, too complex to observe and predict for most practical purposes. At present a more simplified approach is in use, describing wind wave and swell trains separately, and referring to descriptive definitions which are in some sense characteristic or representative of prevailing conditions.

2. The Objective

The objective of this paper is to outline the principles and practices used in the preparation of the current MFWC, Halifax, wave data analysis and to demonstrate that these can be extended to produce a useful forecast service.

3. Definitions

a. Wave Height. The vertical distance of a crest above the troughs on either side.

b. Wave Length. The horizontal distance between two successive crests.

c. Wave Period. The interval of time that elapses during the passage of two successive crests past a fixed point.

d. Wave Speed. The apparent rate at which a wave crest advances.

e. Group Velocity. The speed of advance of a group of waves of approximately the same dimensions.

f. Wave Front. The leading edge of an advancing wave train.

g. Fetch. The horizontal length of the generating area in the direction of the wind as determined by any of the following restrictions:

(1) the coastline
(2) meteorological fronts
(3) curvature of the isobars
(4) spreading of the isobars

h. Generating Area. An area in which the wind velocity in the direction of the wave motion is greater than the speed of advance of the waves.

i. Decay Distance. The distance through which waves have run since attaining maximum height in the generating area.

j. Significant Wave. The wave which is representative of the highest third of the waves observed.

k. Maximum Wave. The average of the highest waves observed in a number of wave groups and usually about 1.5 times the significant wave height.

4. Discussion of the Problem

In any portion of the ocean, at any particular time, the surface of the sea will usually appear as a complex, irregular, pattern of crests and troughs due to the presence of a number of waves in various states of development and swells in the process of decay. Sea waves caused by local winds are not simple uniform perturbations because of the wind field variability in direction and speed, both in the lateral and vertical. Swell waves on the other hand are waves of approximately the same dimensions and appear as long crested simple waves. Usually one swell wave is of such dimensions that it obscures all the other swell waves present; the latter are in such an advanced state of decay that they are imperceptible to the naked eye but can readily be recognized in a wave recorder trace. For instance, swell waves have been recorded in the North Atlantic which must have travelled over 6,000 miles such that they could only have been generated in the South Atlantic.

When so many wave trains are passing through the area there will be periods of relatively calm conditions when troughing and cresting of the wave trains balance each other out. On the other hand, there will be occasions when troughs and crests will tend to occur together and result in periods of great turbulence. It is during these periods that the "Significant Wave" is observed. It is important to bear in mind, therefore, that the "Significant Wave" is a theoretical consideration and the resultant of waves in the course of generation, mature waves and decaying waves. The change in the significant wave, after some hours have transpired, is the integration of the changes in the components of the significant wave brought about by the wind field effect during the period.

The complexity of a well-founded forecast can be readily appreciated. It would be an impossible task were it not for the magnitude of the energy and momentum of these waves and the fact that energy is not gained or lost rapidly, due to the density and viscosity of the water surface compared to the adjacent air surface that is imparting the energy required to maintain, or change the shape of, the wave. For example, a wave of 20 feet in height contains approximately 5000 foot-lbs of energy per square foot of surface area and may reach velocities in the order of 40 kts. Clearly such a wave requires an appreciable wind blowing for a considerable time over an extensive fetch, or some extreme condition of wind speed, duration or fetch, to effect its generation and maintenance. Consequently, waves of 20 feet, or more, are the exception rather than the rule; they do not suddenly appear nor do they dissipate quickly once they have been generated. (*See Note 1).

*Note 1: This paper is concerned with wind waves only and these statements do not apply to TSUNAMIS caused by earthquakes.

The importance of the foregoing paragraph cannot be over emphasized for it forms the basic premise upon which the technique described herein is founded, i.e.,

- that where a well developed wave field exists, the short range forecast for this field must be based upon persistence, in the first instance, and the persistence pattern only modified where significant changes in the wind field are forecast.

5. Historical Review

Prior to World War II investigations into the relationship between wind field and sea state had only provided a number of empirical relationships of limited applicability. It was the requirement of the military to be provided with advisory services to assist amphibious landings in Europe and the Pacific which led to detailed studies of the wind/wave relationship and the development of forecast techniques. Under the British Admiralty, Suthons (1) derived nomograms for wave generation and decay based upon observations carried out on Lough Neagh in Ireland and the analysis of sea and swell wave information obtained from a wave recorder located off the coast of southwest England. These nomograms, with minor modification, have been found as reliable as any and are frequently used at MFWC Halifax, Sverdrup and Munk (2) of Scripps Institution of Oceanography produced similar nomograms for U.S. military use and these were modified by Bretschneider (3).

The Bretschneider nomogram is the one most commonly used to-day because of its simplicity and speed of operation. Various researchers have produced refinements to these original papers without causing any significant change as far as the practical forecasting of the significant wave is concerned. The approach is theoretical-physical, but depends heavily on the data available to the researcher for the empirical development of the constants in the equations and nomograms. Fichaud (4) has summarized much of this work in his paper.

The U.S., British and German navies have made progress in techniques for forecasting wave spectra in recent years. Pierson, Neumann and James (5), and Darbyshire and Simpson (6) developed nomograms and procedures to be used in the spectral approach.

Efforts have been made to develop automated wave forecasting techniques. Hubert (7) working at the Fleet Numerical Weather Research Facility, Monterey developed an early operational computer forecast. More recently the U.S. National Weather Service has instituted an automated programme which has been described by Pore and Richardson (8) and (9) making use of the Primitive Equation model wind field. This product has been available on the Canadian Weather Service facsimile system since mid 1970. A similar service has been developed by the British Air Ministry Meteorological Office, described by Zobel and Dixon (10).

These automated products have been found to provide useful guidance in operational meteorological offices, but experience in the U.S.A., U.K., and at MFWC, Halifax, indicates that these products need careful scrutiny, and some hand amendments are required as a general rule. Gross errors have been observed at times. For the present, therefore, the best forecast is being produced with some subjective input by the duty meteorologist.

6. MFWC Halifax Procedure

In the MFWC approach to the wave analysis and forecasting problem no radical departure is made from the concepts laid down by any of the quoted references. It is presumed that the reader's requirement for a theoretical background will be satisfied by a study of a selection of these references. Consequently, this paper will be confined to the use of nomograms, empirical rules and practical procedures at the forecast bench.

The forecast procedure at MFWC developed from a requirement to improve the standard of the analysis product which was suffering from the quality and quantity of the ship reports received. The synoptic reports from ships usually contain a group which describes the sea wave present and one or more groups describing the swell waves. This data is extracted and plotted on a special wave data chart; the plotting model contains the wave direction, period and height. Were there enough reports and if all reports could be considered accurate, then it would be a simple matter to join up all points of the same significant wave height at one metre intervals, bearing in mind the past history of the distribution of high and low sea wave areas. Unfortunately, there are often large areas of the North Atlantic which are devoid of data and there are frequent errors in the observations elsewhere. All reports have to be carefully screened and if the wave field, or wind field, history cannot support the values reported, then the observation has to be checked for incorrect plotting, possible errors in the ship's position, or a communication error. When all data has been accepted, there will often be gaps in the coverage which have to be made good by inserting "dummy" reports. These reports are obtained by examining the wave field history and entering the nomograms for wave development, or decay, using the arguments of duration, fetch and wind data for the area in the last 12 hours. In areas where the wind field remains relatively unchanged the task of inserting "dummy ships" is relatively simple, but in areas where significant changes have occurred the task can be time consuming such that to provide more than two or three "dummy ships", in these areas, is not a practical proposition when working against the clock without computer assistance, For example, some of the forecasts prepared for the support of diving operations at a point in the Chedabucto Bay area, during "Operation Oil: in February - March 1970,took as long as an hour to complete.

The problem of introducing dummy data was tackled from a different angle about a year ago by constructing a pre-analysis on plexi-glass in order that the analyst would have a preconceived idea of the wave distribution before the actual data was available. When the chart of actual data was superimposed on the pre-analysis, ship reports which were suspect were immediately recognizable and there was intelligent guidance in areas where ship reports were not available. Furthermore, the analysis could be completed in a few minutes as it only necessitated minor amendments to the pre-analysis. The pre-analysis is based on the following premises:

a. the significant wave is rarely going to change radically over the period of 12 hours because of its high energy content relative to the rest of the waves in the wave field, consequently

b. the trend in the significant wave, i. e., its change of speed, height, period and area of coverage, during the past 24 hours is likely to persist for another 12 hours.

c. the extrapolated wave height chart can be modified to incorporate expected changes in the wind field over the extrapolation period.

Hence, by comparing the significant wave charts for H-36, H-24 and H-12 on a light table and establishing the movement of the significant wave centres of high and low waves and the trends in the wave fronts, by simple extrapolation a first approximation of the distribution for Ho can be obtained. The chart will only be in error if the trend in the wind field history changes radically during the period H-12 to Ho. By superimposing the first approximation chart over the surface prog chart for Ho, it becomes apparent immediately where changes in the wind field have taken place which will have caused new waves to be generated or old waves to have been more rapidly built up, or decayed, as the case might be. The dimensions of the new waves can be found quickly by entering the appropriate nomograms (Appendix B) and the chart amended accordingly. The completed chart will retain most of the persistent features and at the same time embrace the modifications due to the wind field during the period H-12 to Ho.

The procedure above may be represented by the flow diagram shown in Figure 1.

7. Examples

Figures 2, 3, 4 and 5 depict simple examples of generating or decaying fields.

The analysis of a chart of the North Atlantic is a much more complicated procedure than any of the examples shown, but the ocean can usually be divided up into a number of sections where the wave trends are quite obvious and extrapolation carried out with reasonable confidence. The sections can then be combined together, making an adjustment for any area where extrapolation of one wave train results in interference with another.

Figures 6, 7 and 8 show a typical sequence of analyzed wave height charts for H-36, H-24 and H-12 with Figures 9 and 10 the pre-analyzed charts for Ho based on persistence and then corrected for wind field changes. The derivation of Figure 9 from the sequence of charts figures 6, 7 and 8 is best seen if these charts are reproduced either on tracing paper or plexi-glass in contrasting colours, and then viewed on a light table. Figure 11 is the completed analysis from the Ho data and it will be seen that it involved only minor modifications to Figure 10.

Note: For ease of reference in this sample sequence, sea height isolines have been drawn at 2m intervals. In practice, intermediate isolines are drawn wherever they contribute significantly to the distribution pattern.

8. A Forecast Chart

A good correlation between the pre-analysis chart and the actual data chart indicates that these procedures can be used for a forecast chart for H + 12. Extrapolation in 12 hour steps can produce extended range forecasts and can be carried out insofar as the forecaster feels confidence in the validity of the wind field prognosis.

Trials have been carried out at MFWC Halifax on the preparation of 12 hour and 24 hour forecasts in this manner and they have compared very favourably with the U.S. computer product. Thirty consecutive forecasts at MFWC were checked against the U.S. computer product for height forecasts at the Ocean Weather Stations in the Western Atlantic and the RMS error was 0.8 metres compared with 1.2 metres for the automated forecast. Zobel and Dixon (10) in the U.K. have also shown that a combination of objective and subjective procedures has produced a better wave forecast than is currently being produced by the British Meteorological Office computer programme.

9. Treatment of Confined Water Such as the Gulf of St. Lawrence

Whereas the foregoing technique is suitable for open ocean areas, it is not so applicable to an area, such as the Gulf of St. Lawrence, because, in a confined area, wave generation and development is fetch limited at an early stage. Only when winds or seas are entering the Cabot Straits, or Straits of Belle Isle, can there be cases of theoretically unlimited fetch. These are not too frequent but are quite significant when they do occur, such that they are included in the MFWC product when appropriate.

For a routine analysis, or forecast, for the Gulf of St. Lawrence, it would be possible to construct a set of nomograms, or templates, for selected wind speeds and durations, which would show the approximate distribution of waves of various heights in the Gulf area. A template could be constructed for 12 hour, 18 hour and 24 hour durations for wind speeds in 10 kt increments. By using three different colours for the durations, only five or six plates would be required for practical purposes. The forecaster could introduce the third parameter of wind direction by orientating the templates base line along the lee shore - the wave height distribution would be read off down wind for the required duration. Some interpolation would be required on the part of the forecaster but it should be possible to forecast wave heights to within $\pm$ 0.5 metres with reasonable confidence. Waves in the Great Lakes could be treated in a similar manner. However, it must be pointed out that waves along the coast and in small bays and inlets are affected by diffraction, refraction and reflection due to headlands, islands and promontary, with the result that wave height nomograms are not applicable close inshore where the depth is less than half a wave length. In such cases techniques for surf forecasting have to be applied.

10. Conclusion

Analyses of wave data and wave forecasts, as defined by the significant wave height distribution, can be prepared routinely by automated programmes, or by simple differential analysis procedures and empirical methods. The latter approach is currently proving somewhat more reliable than the automated product and is not an unacceptably time consuming procedure as far as operational services are concerned.

11. Future Developments

It is considered that forecasts of the significant wave height are not adequate for some operational requirements. There is already a requirement for wave spectra forecasts and the demand will increase in the future. Such forecasts are not feasible on a routine basis without computer assistance.

It would appear, therefore, that the efforts of research workers should be directed towards an automated wave spectra forecast programme, from which a significant wave forecast can be extracted when required, thereby satisfying the operational need for both detailed and coarse advice on sea state.

APPROVED

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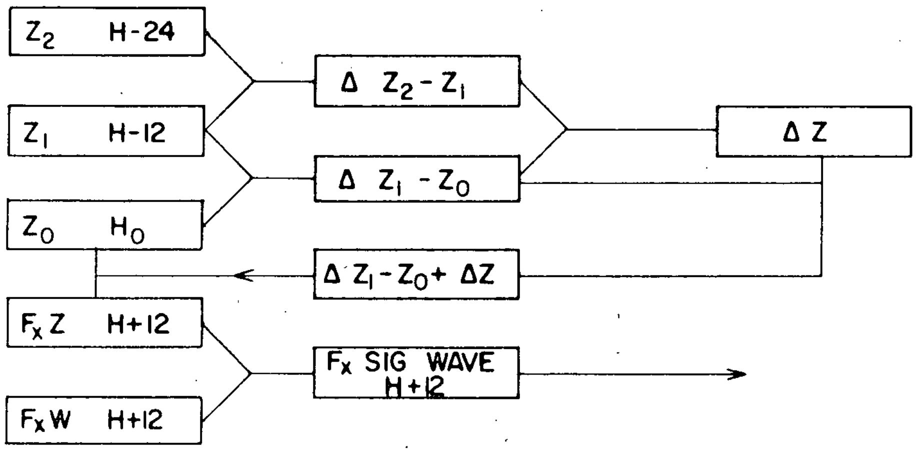


Z_2, Z_1, Z_0 - Historical sequence of significant wave fields

$F_x Z$ - First approximation of next significant wave field, based on extrapolation

$F_x W$ - Wave generation or decay field during the period

F_x Sig Wave - Final significant wave field

Figure 1

Flow Diagram, Representing the Development of the Significant Wave Field from History, and the Generation or Decay Field.

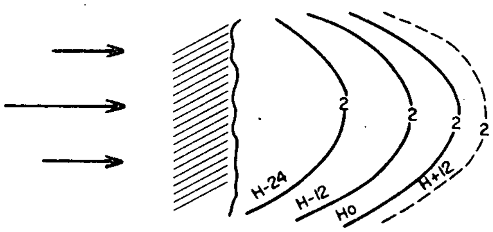


Figure 2

Growing Waves in a Fetch Limited Area.

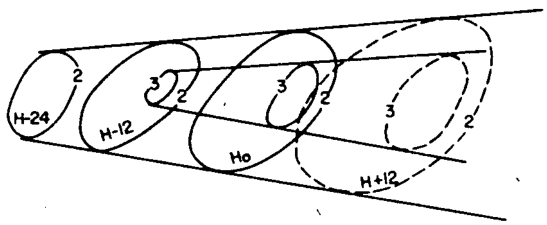


Figure 3

Growing Waves in a Moving Generating Area.

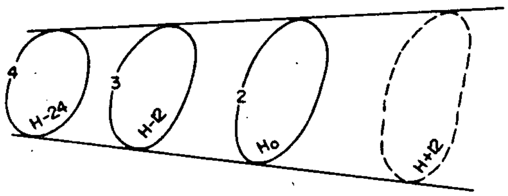


Figure 4

A Decaying Swell Area.

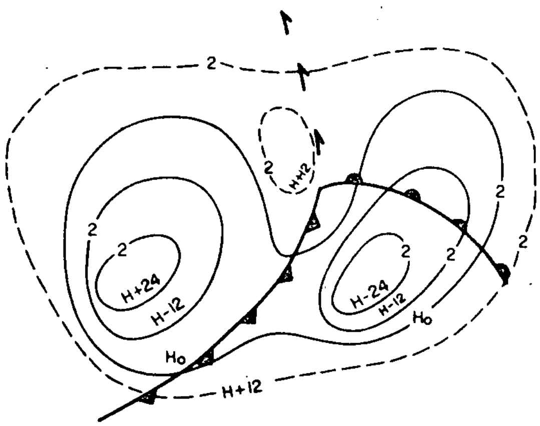


Figure 5

Generation About a Deepening Slow Moving Depression.

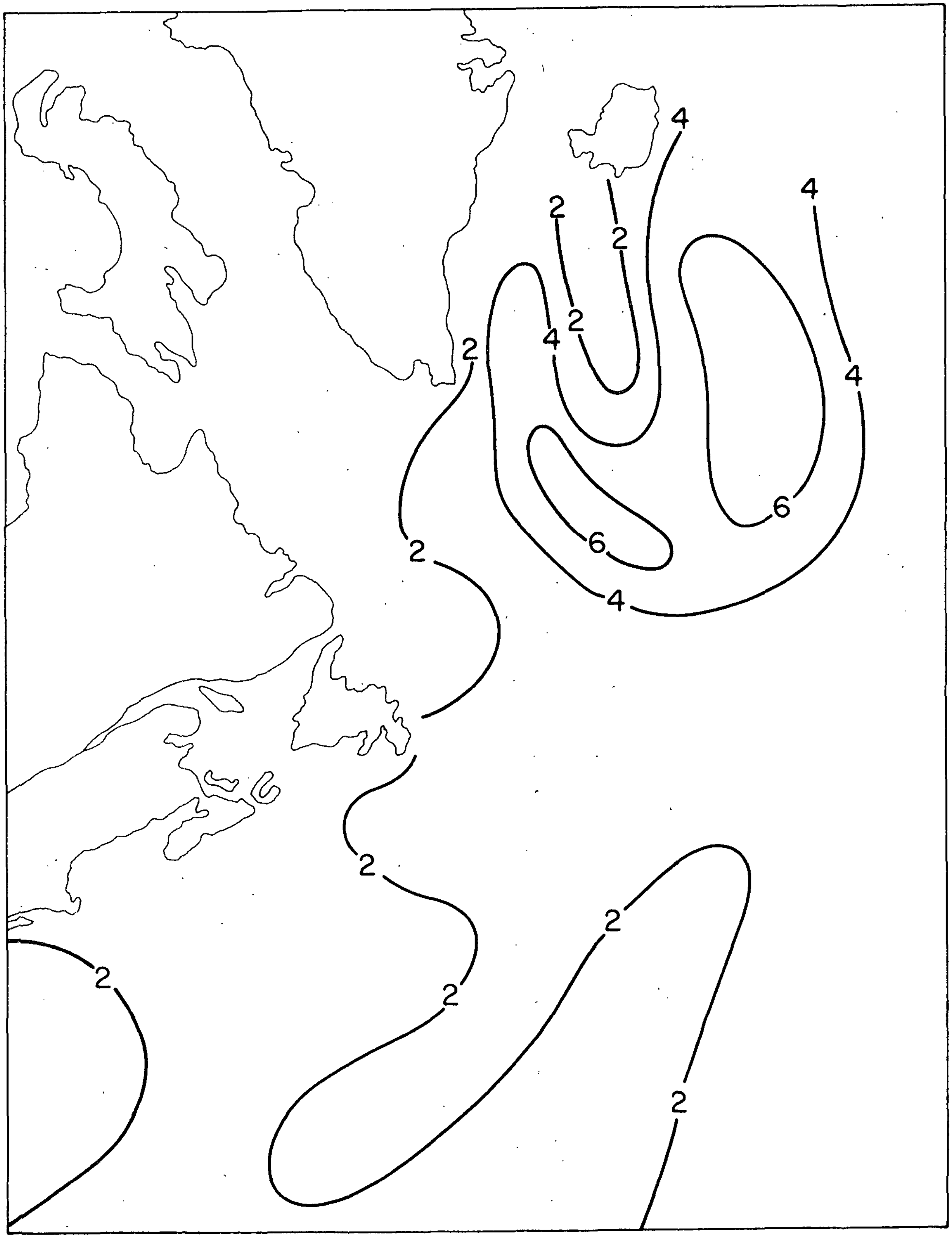


Figure 6

Wave Height Analysis for 0000Z 8 Feb. 1971
Wave Heights in Metres.

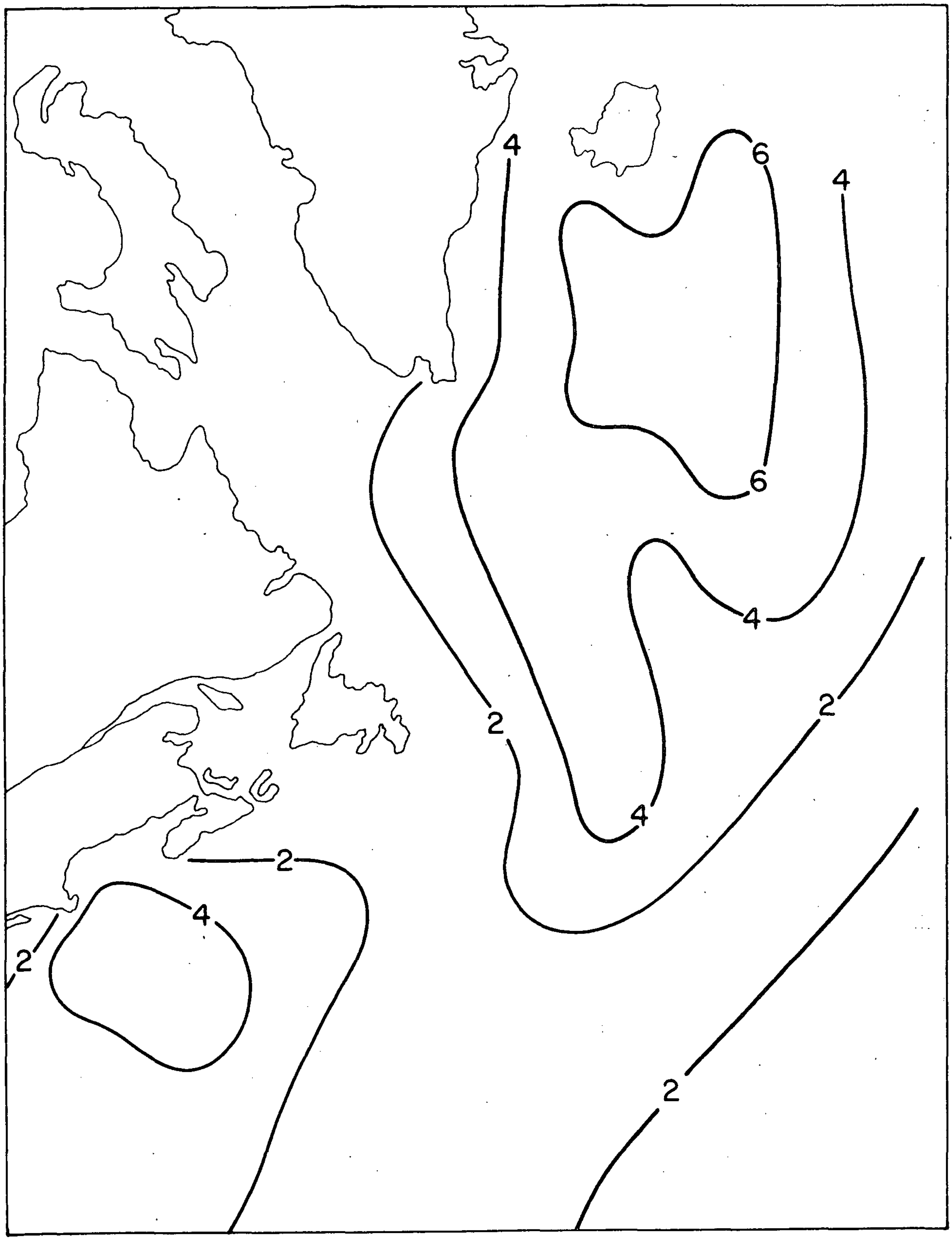


Figure 7

Wave Height Analysis for 1200Z 8 Feb. 1971
Wave Heights in Metres

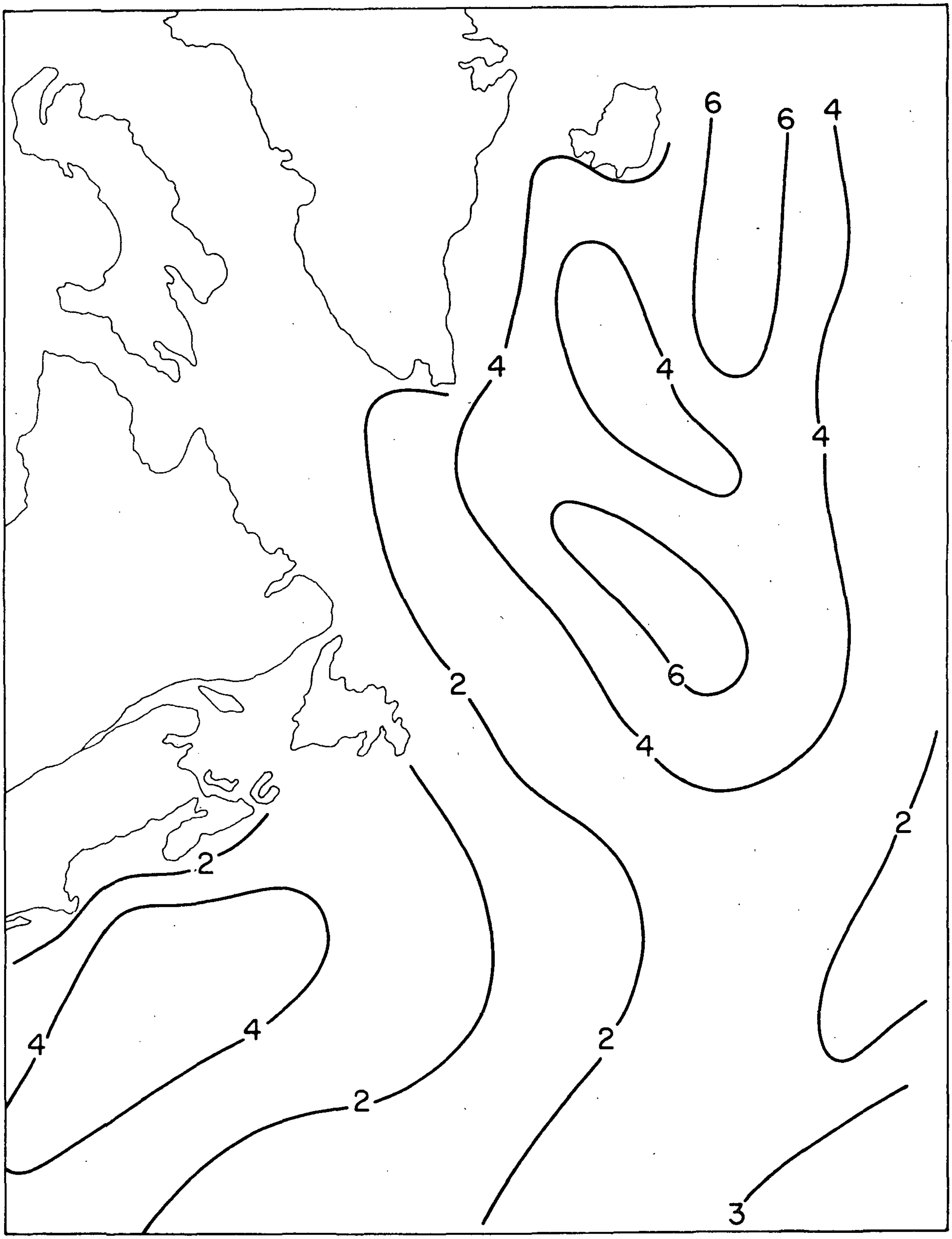


Figure 8

Wave Height Analysis for 0000Z 9 Feb. 1971
Wave Heights in Metres.

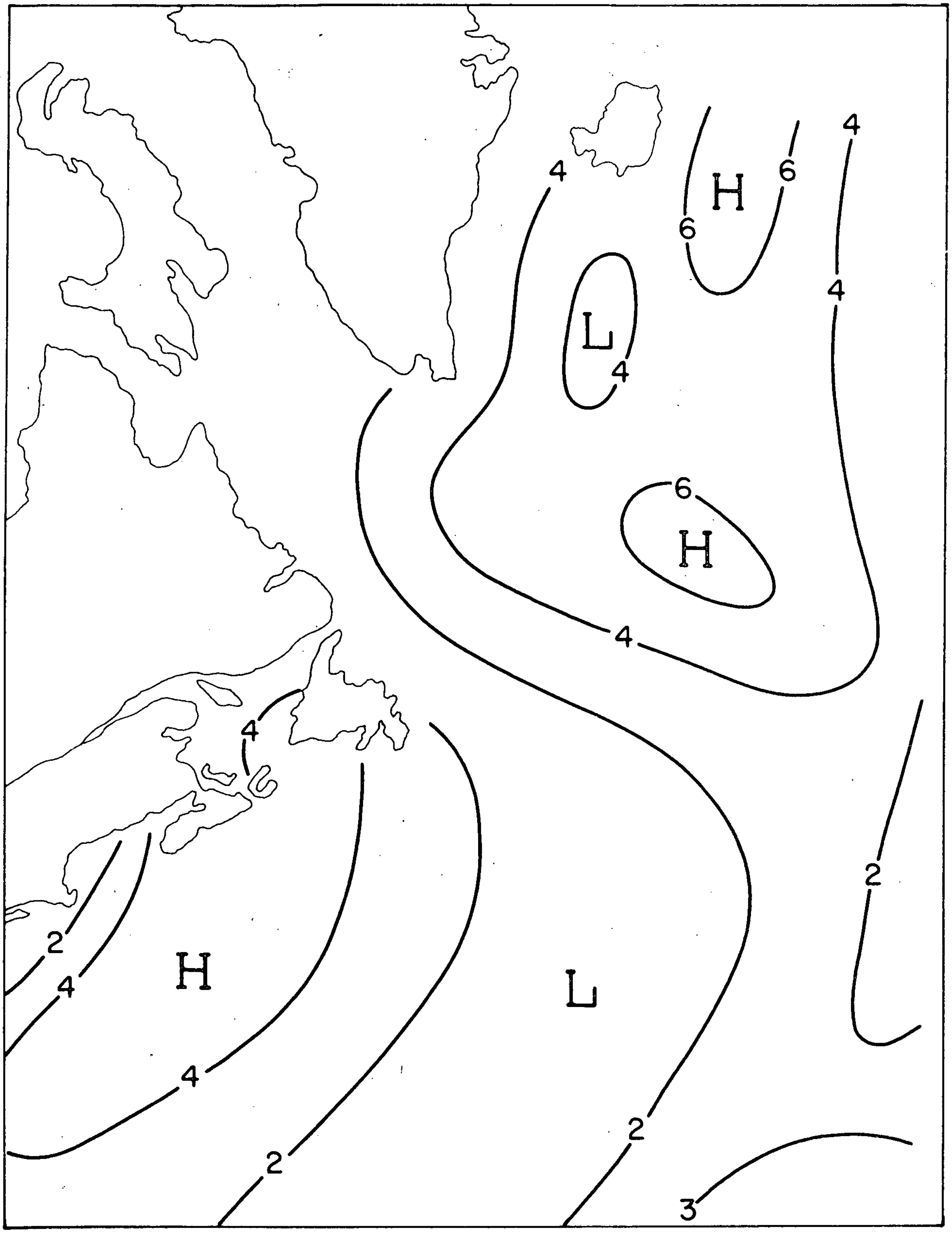


Figure 9

Wave Height Forecast Chart for 1200Z 9 Feb. 1971

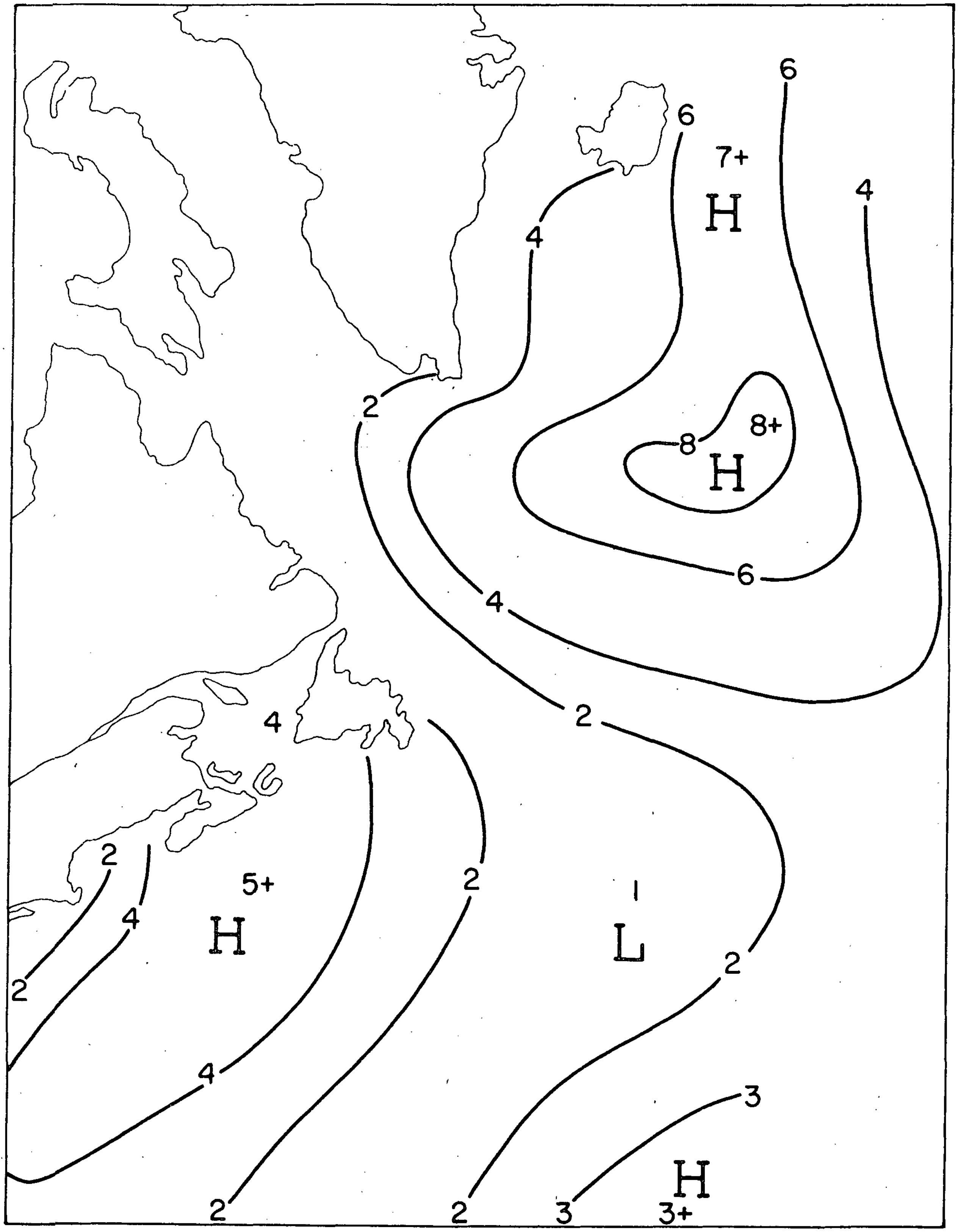
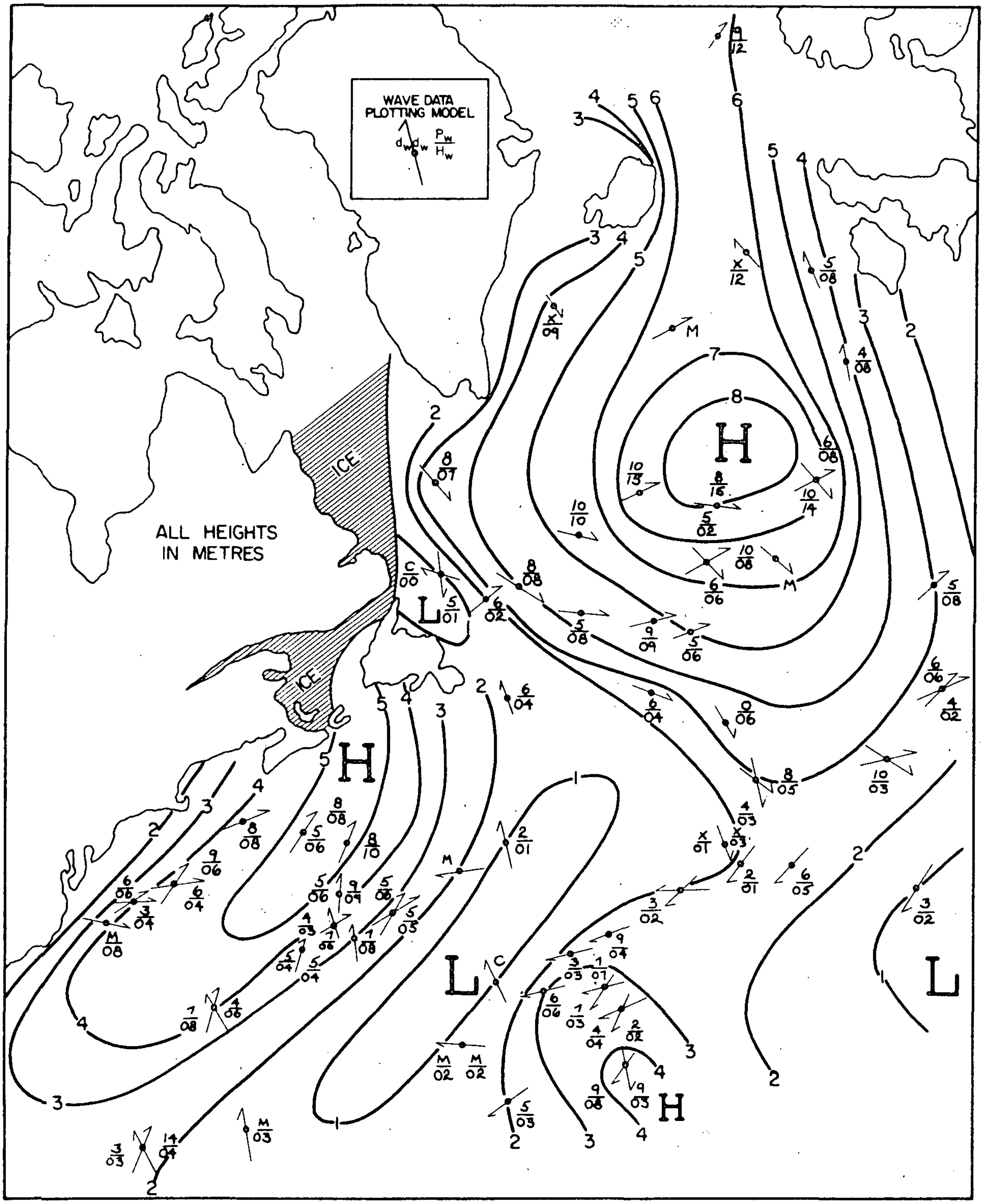


Figure 10

Wave Height Forecast Chart for 1200Z 9 Feb. 1971
Based on History, and Corrected for Wind Field.
Wave Heights in Metres.



Wave Height Analysis for 1200Z 9 Feb. 1971
Based on History, Corrected for Wind Field,
and Including Observed Wave Data.
Wave Heights in Metres.

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APPENDIX A

Formulae and Empirical Relationships in Wave Forecasting

1. Wave Speed

The speed of waves of relatively small height compared to wave length is given by:

$$C = \sqrt{\frac{gL}{2\pi} \tanh \frac{2\pi d}{L}}$$

where C is wave speed in knots, L the wave length in feet, d is the depth and g the acceleration due to gravity. For very deep water $\frac{d}{L}$ is large and the formula may be reduced to:

$$C = \sqrt{\frac{gL}{2\pi}} \quad \text{or} \quad C = 1.3 \sqrt{L}$$

In relatively shallow water $\frac{d}{L}$ is small and $\tanh \frac{2\pi d}{L}$ approaches $\frac{2\pi d}{L}$

$$C = \sqrt{gd}$$

Generally waves, in depths greater than one half the wave length, will have the characteristics of deep water waves. Waves in depths of less than 1/25th the wave length will have shallow water characteristics. Therefore, the speed of deep water waves is dependent upon wave length whereas the speed of shallow water waves is dependent upon depth.

2. Group Velocity

$$V_G = \frac{V_w}{2}$$

The group velocity, or the speed at which a wave train travels out of the deep water generation area, is half the speed of the individual waves which comprise the group. This is because the wave energy is made up of two equal components - potential and kinetic energy. The potential energy advances with the wave front, as it moves out of the generating area, but the kinetic energy remains behind.

3. Wave Speed, Length and Period

$$C = \frac{L}{P}$$

Each wave advances one wave length during each period P. Wave length and period are connected by the relationship:

$$L = \frac{gp^2}{2\pi}$$

Where C is in knots, L in feet and P in secs, the following relationships apply:

$$C = 3.03P$$
$$L = 5.1P^2$$
$$P = 0.44\sqrt{L}$$
$$C = 1.34\sqrt{L}$$

4. Equivalent Simple Wave

When two or more wave trains are passing through an area the energy per unit area is the sum of the energies of the separate components. It is useful to describe the equivalent simple wave as the wave which would have the same energy per unit area as the waves actually present. This wave would have the height $\sqrt{H_1^2 + H_2^2 + \ldots H_4^2}$ and its velocity is that of the greatest component. Its length and period are appropriate to this speed.

5. Rate of Supply of Energy to Waves

The rate of supply of energy from the wind to sea waves is determined by:

a. the density of the air

b. the square of the relative velocity of the wind over the wave crests $(W - C)^2$

c. the square of the wave steepness $(H/L)^2$

d. the wave speed C

When (W-C) is positive the waves are continuing to build, and when negative the waves are decaying. The rate of supply of energy can be shown to be:

$$1/2\ kr\ (\frac{H}{L})^2\ (W-C)^2 C$$

where k is a constant.

6. Relation Between Average, Significant and Maximum Waves

There is no complete agreement upon these relationships particularly between the significant and maximum waves. Using the significant wave Hs as a base, there seems to be fair agreement between researchers that the average wave is about 0.6 - 0.7 Hs. The maximum wave relationships vary from 1.35 Hs Pierson, Neumann and James (5), 1.4 Hs Suthons (1), 1.6 Hs Darbyshire and Draper (11) to 1.9 Hs USNWS. It is believed that this variability is due to the fact that the maximum wave cannot be clearly defined, the longer records are kept the higher the value Hmax will be. For practical purposes, it is suggested that the maximum wave will be about 1.5 times the significant wave but that there is always the possibility of a phenomenal wave of twice Hs occurring in isolated instances.

APPENDIX B

Simple Procedures in Practical Wave Forecasting

1. To forecast the waves at any grid point in the forecast field, it is necessary to attempt the problem in three stages:

   a. to assess effects of the wind field on the old wave field during the forecast period;

   b. to calculate the new waves generated by the wind field;

   c. to combine the results of a and b into a simple equivalent wave.

For these steps it is necessary tó examine the wave field history and the forecast wind field in duration, fetch and speed.

2. Estimation of Fetch

In a relatively straight isobaric pattern the fetch will terminate somewhere upwind at a coastline, or at some area where the spreading of the isobars results in little contribution to the energy supply in the generating area. Fetch areas frequently terminate at a front where the wind field can change direction by more than 30° in the frontal zone. For curved isobar patterns, the fetch is taken as the distance upwind to where the wind backs or veers more than 30° from that at the datum point.

3. Estimation of Mean Wind Speed

In the British Admiralty nomograms (1) for wave generation and decay, gradient wind speed is used but in Bretschneider (3) surface wind is the argument. If no surface ship reports are available it is necessary to apply stability factors and curvature corrections to the geostrophic wind. Stability factors vary between 0. 55 for very stable conditions to 0.9 for very unstable air. Curvature factors used are 0.85 - 0.95 for cyclonic curvature and 1.05 - 1.15 for anti-cyclonic curvature, depending on the degree of stability, or instability, respectively.

When the wind changes by not more than 15 knots during the forecast period the mean wind speed is obtained by calculating the "equivalent steady wind"

$$W = \frac{W_1 + 2W_2}{3}$$

Where W_1 is the wind at the beginning of the fetch or blow and W_2 the wind at the end.

Where the variation in the wind speed is large the forecast period must be divided into intervals during which a steady equivalent wind can be applied.

4. Duration

In the ideal case, the duration is the time between the instantaneous onset of a steady wind and the time of the forecast. For all practical purposes some approximations have to be made such as those in the foregoing paragraph. If the variation in the wind field is large the duration is obtained by:

a. finding the wave height appropriate to the initial wind speed and duration;

b. finding the time it would take the second wind to generate a wave of this height;

c. adding this time to the time the second wind actually blows and obtaining the equivalent duration.

5. Use of Nomograms for Wave Generation

Two methods of computing wave generation are available, using either the British Naval Weather Service nomogram by Suthons (1) or those by Bretschneider (3).

Nomograms by Suthons

a. Enter Figure 12 with the gradient wind as the abscissa and move up the ordinate until the curve for appropriate duration or fetch is reached. The lower of the two values is taken (i.e., a wave will either be fetch limited or duration limited) and then the ordinate values of wave speed, wave length and period can be read from the scales at the left.

b. Enter Figure 13 or 14 (depending whether in step a, the wave was duration or fetch limited), with gradient wind speed, and move up the ordinate to the duration(or fetch) curve and read off the wave height on the left hand side.

Nomogram by Bretschneider

Enter Figure 15 with estimated surface wind along the ordinate, the abscissa is fetch and the diagonals are duration isolines. Moving from the left laterally along the wind speed ordinate, the operator will intersect either the fetch line, or duration line, whichever occurs first. At this point the wave height and period can be read off from the appropriate curves.

6. Decay of Waves

Waves leaving a generating area run mainly in the direction of the wind but usually spread 10-15° on either side of the mean wind direction. The energy of the spreading waves is small compared with the main body of the waves and they decay rapidly. In the case of the main body of waves, as soon as the wind field decreases to the extent that the waves are moving faster than the wind velocity, energy is lost from the waves to the atmosphere. The height of the wave decreases, the period and wave length increases, The forecast problem is to determine the extent of the changes in these parameters at the end of the decay distance, or time interval. The relationship between the parameters involved is shown diagrammatically in Figure 16. The turbulence set up by the wind is responsible for the length, speed and period of the waves. This applies just as much in the decay area as in the generating area. Hence C_1 L_1 and P_1 in Figure 16 are dependent upon the decay distance X and the wind velocity W in the decay area but irrespective of the wind direction. The latter does, however, affect the height of the wave. The loss of energy due to the component of W, in the direction of the Wave, (W_1) always being less than the wave speed in the decay area, results in a decrease in height.

a. To determine the Speed, Wave Length and Period at end of Decay Distance:

(1) Enter Figure 12 with wind speed W in the decay area and the original wave speed C_o and obtain the corresponding fetch. Add F + X to obtain the equivalent fetch.

(2) Enter Figure 12 again with fetch F + X and wind speed W and read off the speed C_1, wave length L_1, and period P_1 of the waves at the end of the decay distance.

b. To obtain the height:

(1) Estimate the component of the wind speed W in the direction of the waves, i. e., W_1 and find the ratio W_1/C_m where C_m is the mean wave speed over the decay distance. (considered to be negative when the component wind is blowing against the waves);

(2) Compute X/L i. e., ratio of the decay distance and the mean wave length;

(3) Enter the nomogram in Figure 17 with these two arguments and obtain H_1/H_o, the ratio of the height of the wave at the end of the decay distance to that at the beginning.

(4) Multiply H_o by this ratio and obtain H_1.

c. Calculation of Travel Time:

As the wave front moves with half the velocity of the individual waves, the time required for a swell wave to reach the end of the decay distance will be:

$$T = \frac{2X}{C}$$

where X is the decay distance and C the mean speed of the waves, this is usually written as

$$T = \frac{4X}{C_1 + C_0}$$

where C_0 and C_1 are the wave speeds at the beginning and end of the decay distance as obtained from nomograms.

7. Notes

(1) As the energy of the swell wave dissipates the height of the wave increases but the wave period and length increase. The shorter and lower waves decay rapidly leaving behind the highest and longest waves with the result that the complex sea condition leaving the generating area eventually decays to a long low simple wave. As the wave length of this wave increases so does its speed with the result that the waves from a slow moving deep system can arrive at the observer's station many hours ahead of the actual storm. Before the days of satellites and air reconnaissance this phenomenon was used in tropical storm forecasting.

(2) A useful rule of thumb found by Suthons (1) can be used in rough estimations of wave decay

- where the resultant wind field in the decay area, in the direction of the swell, is near zero, the swell wave will lose approximately 1/3 of its height over a decay distance, in nautical miles, numerically equal to its wave length in feet.

  i.e., a wave of 24 feet with a wave length of 600 feet would decay to 16 feet over a distance of 600 miles.

APPENDIX C

U.S. National Weather Service Automated Wave Forecasts

The USNWS automated product now available on Canadian Weather-fax System is based upon the procedures developed at the Fleet Numerical Weather Research Facility, Monterey, Hubert (6).

The 1000 mb PE wind field forecasts are used for calculating the dimensions of the significant waves for all ocean grid points on the NWS octagonal grid. The duration of the generating wind at time T is determined by hindcasting in six hour intervals up to a maximum of 18 hours or until a wind shift of 22^{o} is reached, whichever is the earlier. Each wind step is weighted; the most recent winds being given the greatest weight.

Fetch limitations are introduced by searching upwind two grid lengths for land or ice. If the fetch is found to be limited in one grid length, the wave height is reduced to 70% and, if within two grid lengths, 90%.

The print out of effective wind, significant wave height, period and direction is made for 12 hour steps up to H + 48.

Swell calculations involve such distances that each grid point has to be given a map factor to determine the map projection distance for swell travel. Swell waves are based on the wind wave forecasts but a minimum travel time of 15 hours from the generating area is considered necessary for a wave to be treated as a swell wave in the programme; i.e., only wind waves T-24 to T-72 hours are used. Starting with the wind wave at T-72 each wind wave having a greater height than five feet is accepted and the swell travel and decay calculated for H+24, H+36 and H+48. Once the swell travel has been calculated a search is made along the wave fetch and if land or ice is found within one grid length the wave is discarded.

Since a grid point may be hit by many swells, only the greatest swell is retained at the affected point.

It is of interest to note that whereas in most techniques, stability factors and curvature factors are used to obtain the wind speed to enter the nomograms, the USNWS automated programme uses the PE 1000 mb wind without a correction. According to Pore (8) a study of the relationship between the PE wind and actual wind, observed by the Ocean Station Vessels, showed no cause for applying any correction to the former for stability. Obviously this divergence, in the views of marine meteorologists, regarding stability factors needs further investigation.

The combined sea wave chart is constructed by taking the square root of the sum of the squares of the heights of the wind and swell waves at the grid points. Output charts are prepared for wind wave, swell wave and combined sea wave for H + 24 and H + 36.

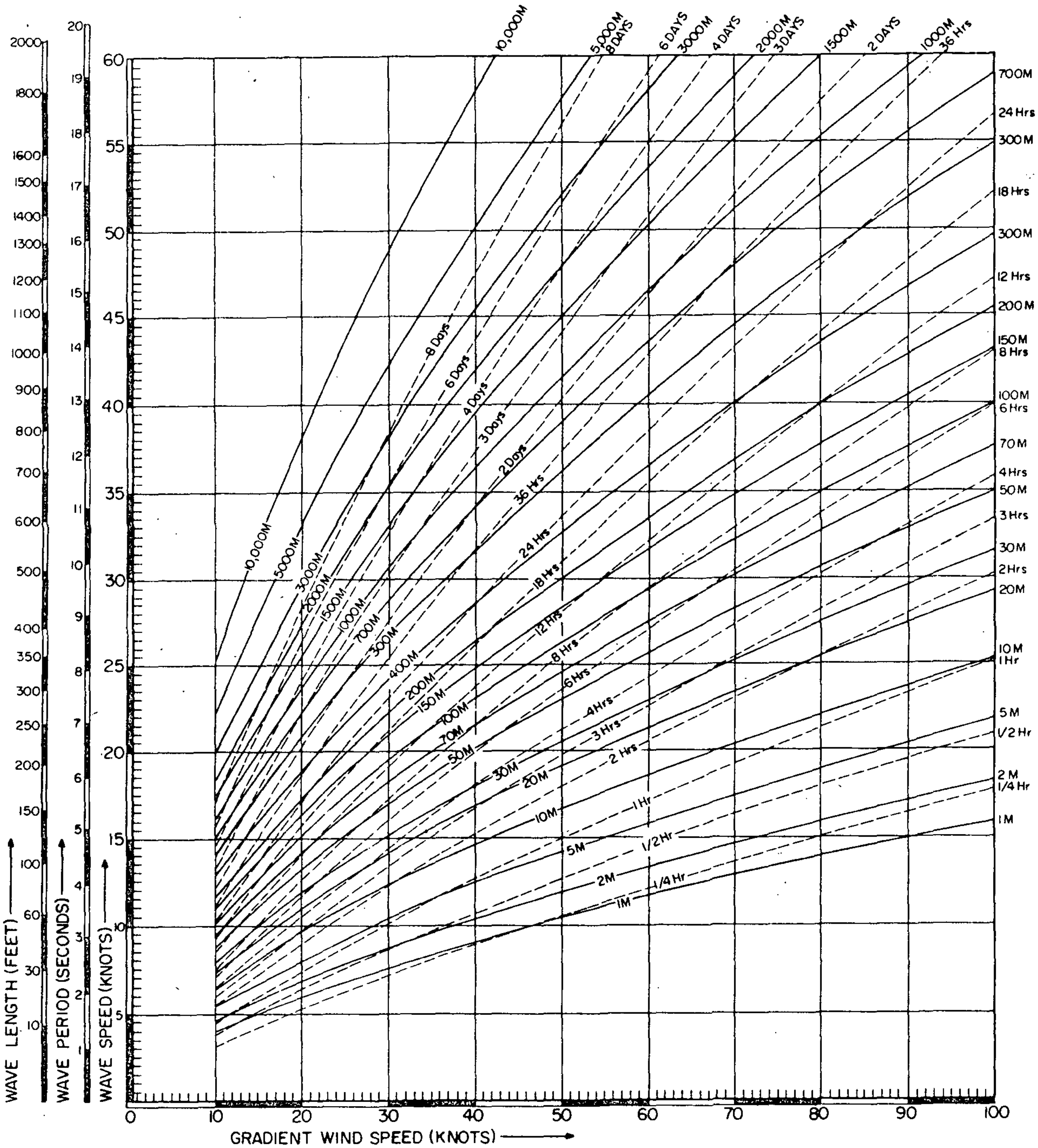

Figure 12

Suthons Nomogram for Wave Length, Period and Speed.

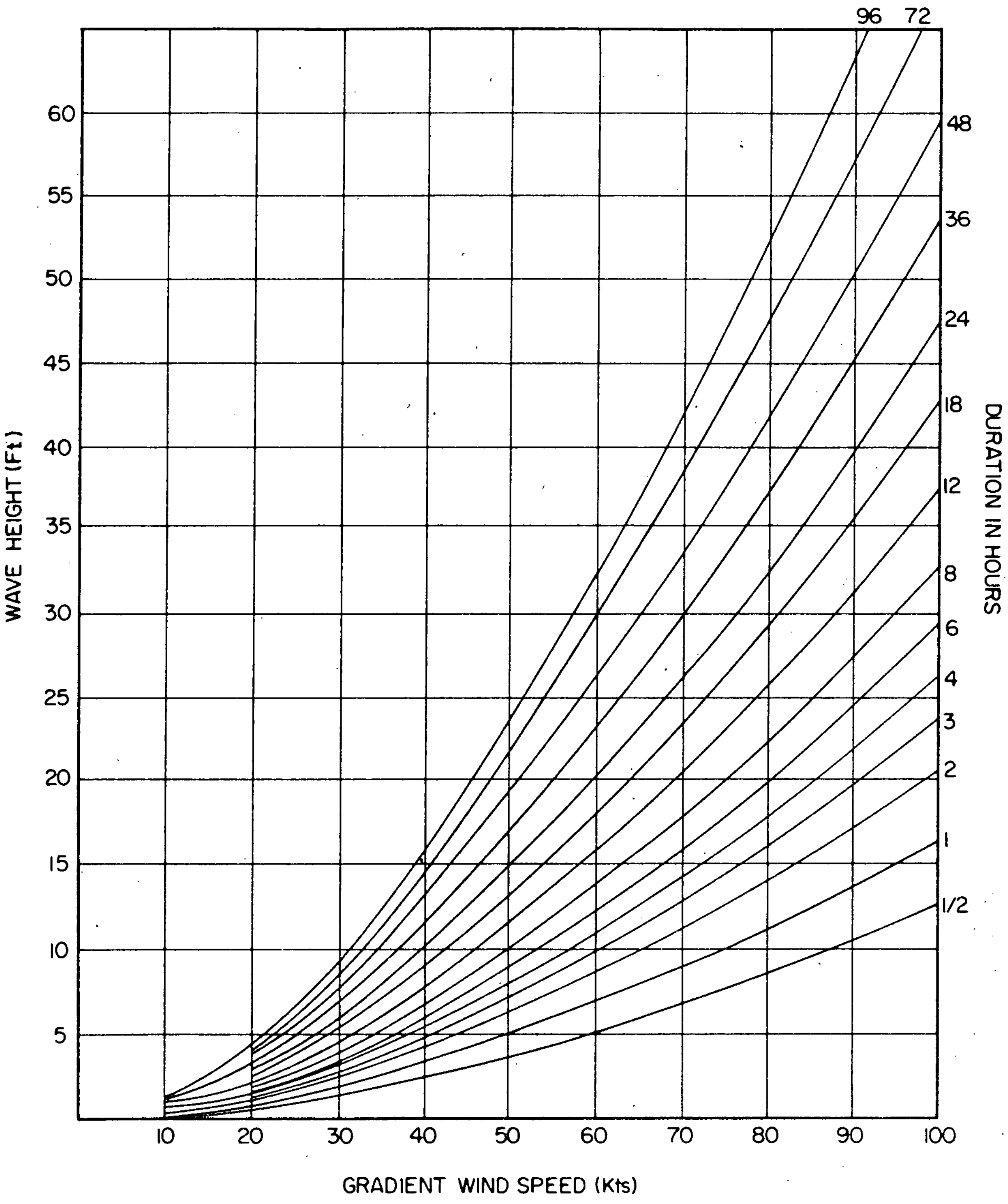

Figure 13

Suthons Nomogram for Wave Height
When Waves are Duration Limited.

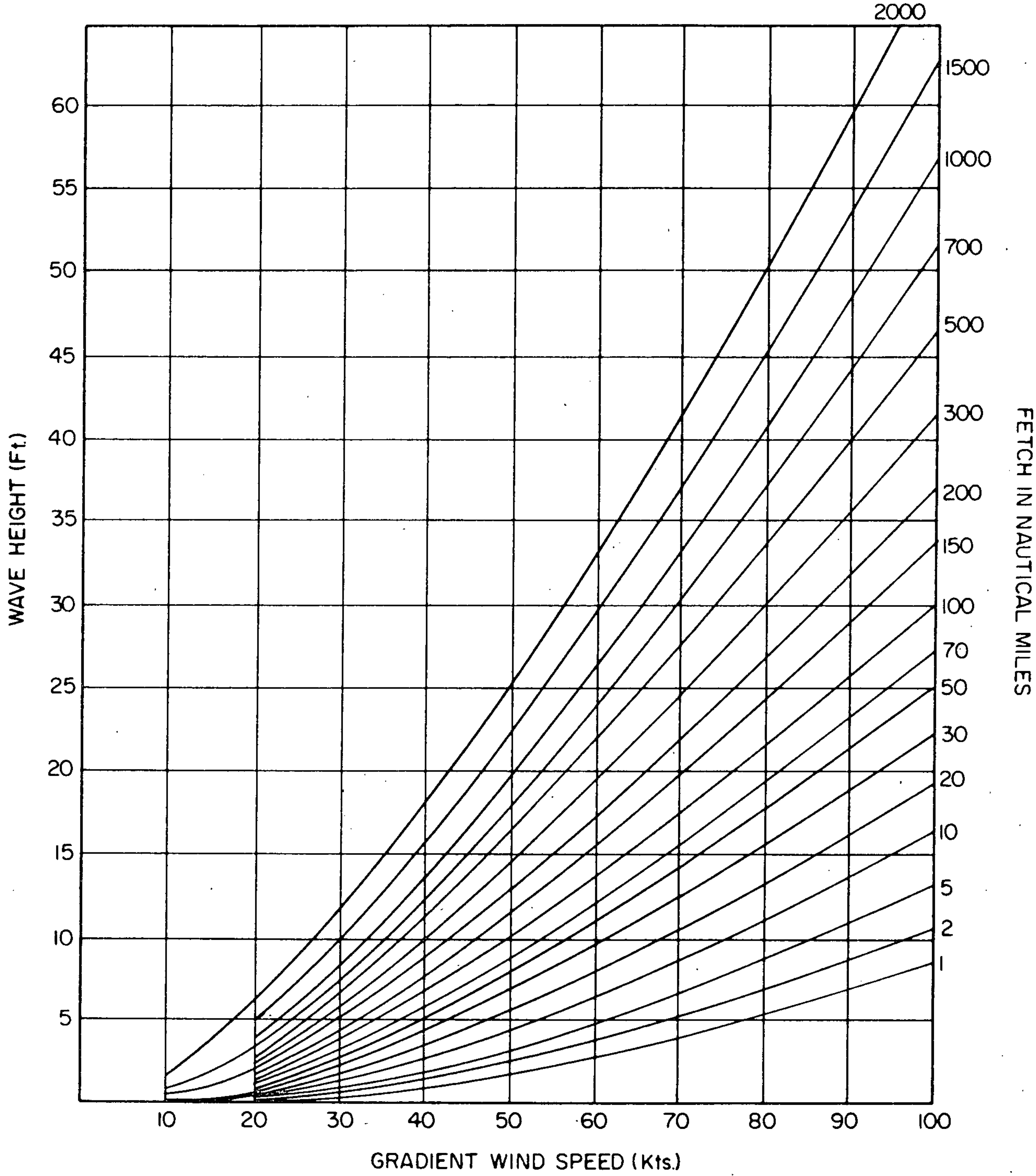

Figure 14

Suthons Nomogram for Wave Height
When Waves are Fetch Limited.

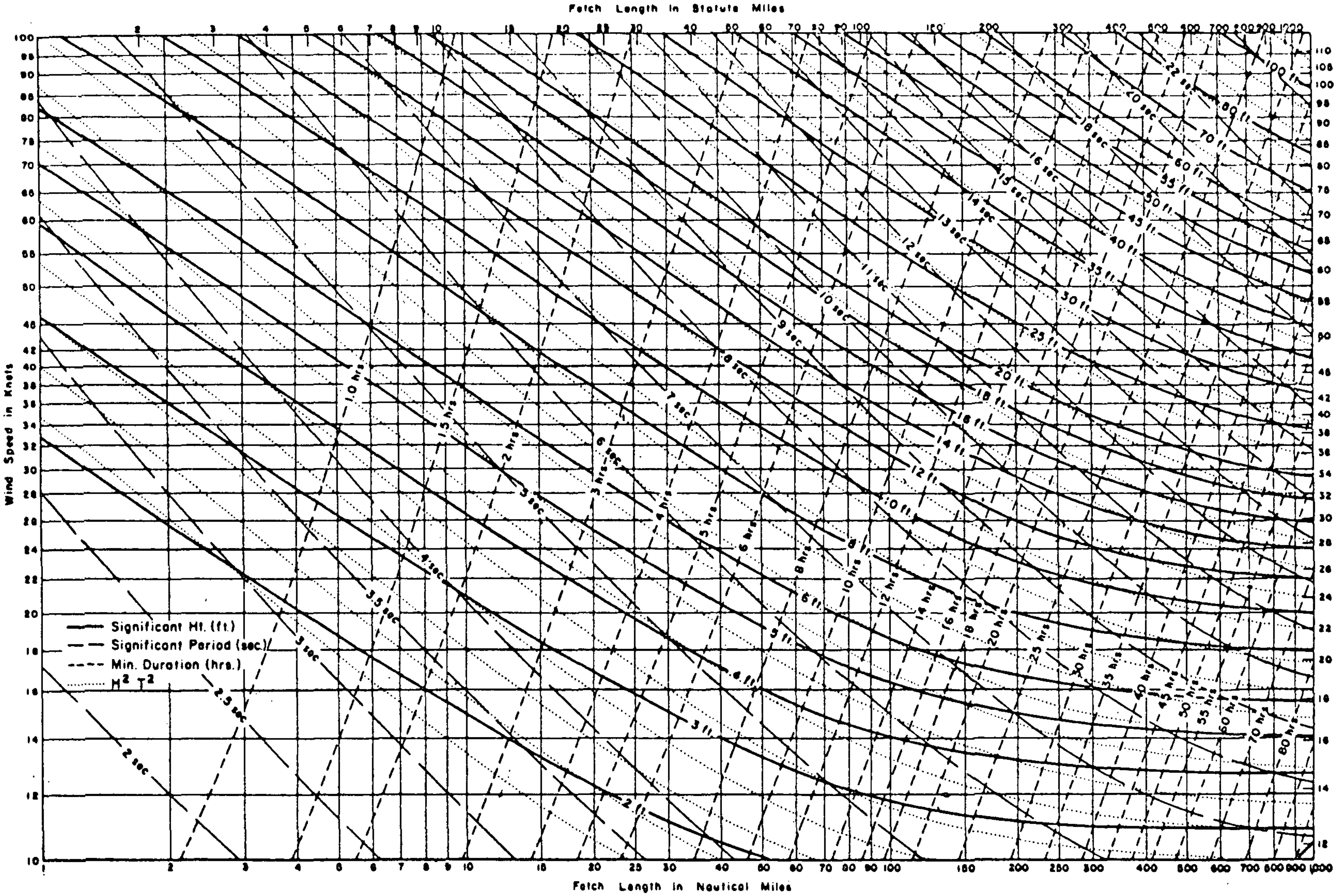

Figure 15

Bretschneider's Nomogram for Wave Height and Period.
From U.S. Army Coastal Engineering Research Centre
Shore Protection Planning and Design
Technical Report No. 4, 1966.

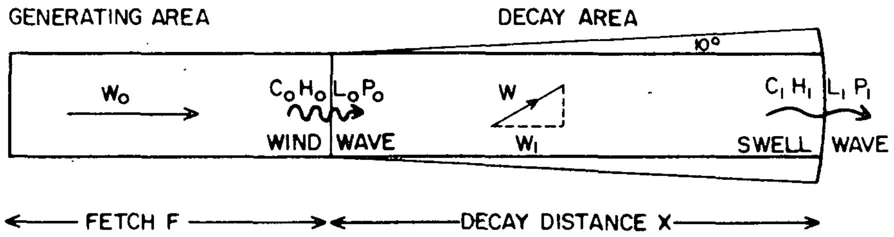

Figure 16

Diagrammetic Relationship of The Wind and Wave Parameters at the end of the Generating Area and After Decay.

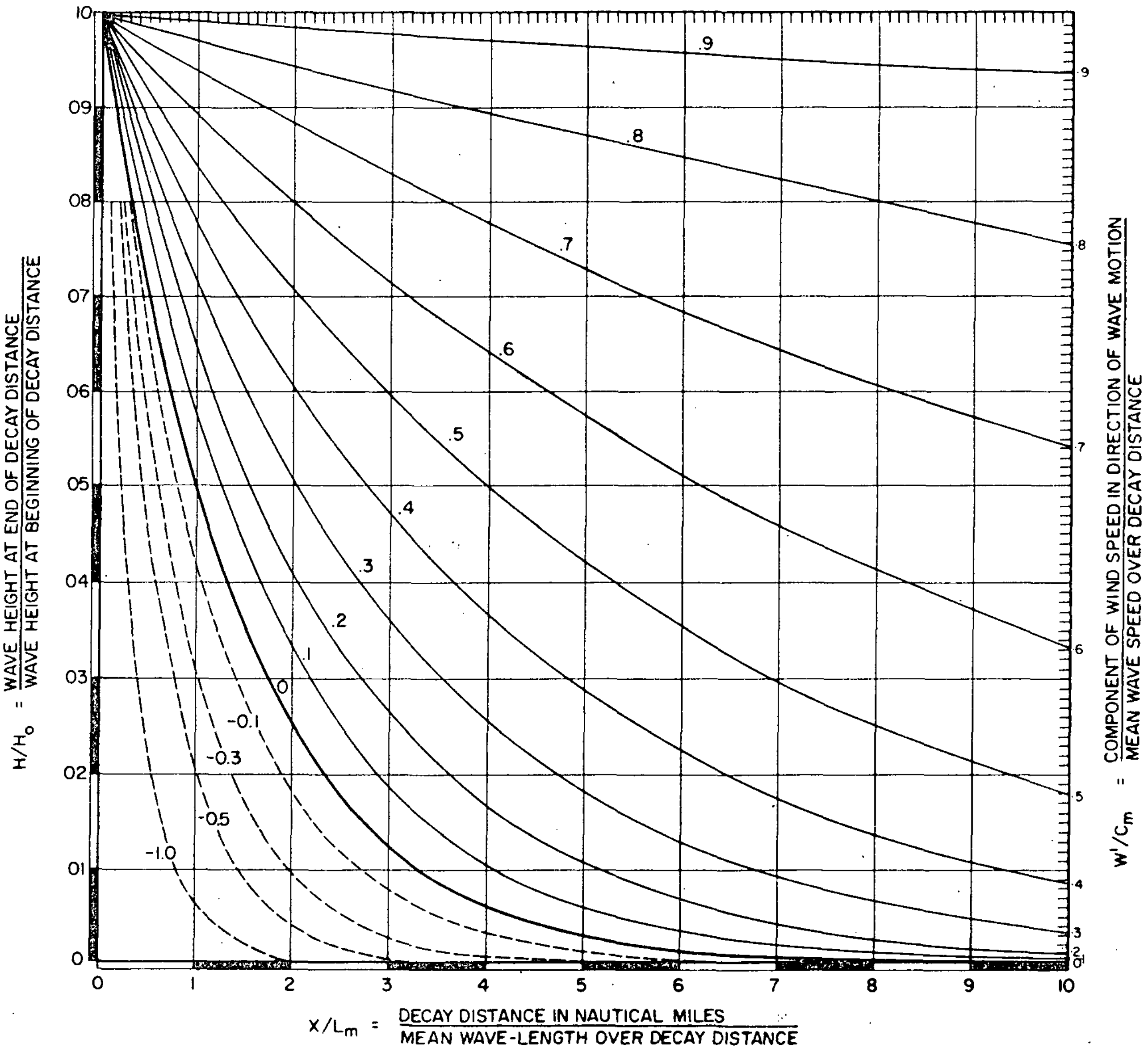

Figure 17

Suthons Nomogram for Wave Height After Decay.