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# 11-YEAR DEEP-WATER WAVE CLIMATE OF CANADIAN ATLANTIC WATERS

by

H.J.A. Neu

Atlantic Oceanographic Laboratory

Ocean Science and Surveys, Atlantic

Department of Fisheries and Oceans

Bedford Institute of Oceanography

P.O. Box 1006

Dartmouth, Nova Scotia

B2Y 4A2

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## ABSTRACT

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From an 11 year (1970-1980) time series of 12 hourly wave charts for the North Atlantic, long-term annual and monthly wave height distributions were developed for the offshore region of Atlantic Canada. Log-normal distributions of the data provided the average annual largest and the 10 year largest $H_{sig}$ which were 8.7 and 11.7 m off Sable island, 9.0 and 12.3 m for the Grand Banks at the Hibernia oil field and 9.3 and 12.5 m at the entrance of the Labrador Sea, respectively. The monthly largest $H_{sig}$ of the three locations varied from about 7.5 m during the winter to about 4 m during the summer.

The periods ($T_v$) of the largest waves were from 10 to 14 s with 11 s containing the highest concentration of energy. Nearly all the storms came from northwest, west and southwest, that means from the continent and its coastal waters. Many of the seas were therefore young with a number of waves being in the breaking stage.

One outstanding feature of the 11 years data bank was a long term, 6 years quasi-cyclic variation in the wave climate in which the annual wave height of the larger waves varied by 40% through the apparent cycle, an amount greater than the normal seasonal variation.

## RÉSUMÉ

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On a établi des répartitions annuelles et mensuelles à long terme de la hauteur des vagues dans la région de l'Atlantique au large du Canada à partir d'une succession chronologique d'une durée de 11 ans de 12 cartes horaires des vagues dans l'Atlantique Nord. L'application aux données de la loi log-normal a permis d'obtenir les hauteurs annuelles maximales moyennes et maximales pour une période de 10 ans ($H_{sig}$) qui étaient respectivement de 8.7 et 11.7 m au large de l'Ile de Sable, de 9.0 et 12.3 m sur les Grands bancs au champ pétrolifère d'Hibernia et de 9.3 et 12.5 m à l'entrée de la mer du Labrador. Les $H_{sig}$ mensuelles maximales pour chacun des trois emplacements variaient d'environ 7.5 m en hiver à environ 4 m en été.

Les périodes ($T_V$) des plus grosses vagues varient de 10 à 14 s, les périodes de 11 s correspondant aux concentrations maximales d'énergie. Presque toutes les tempêtes provenaient du nord-ouest, de l'ouest et du sud-ouest, c'est-à-dire du continent et ces eaux côtières. Dans un grand nombre des cas la mer n'était, par conséquent, que récemment formée et on comptait plusieur vagues au stade du déferlement.

Une des caractéristiques remarquables que cette succession chronologique de données réparties sur une durée de 11 ans a permis de mettre en evidence est une variation à long terme quasi cyclique de l'état de la mer d'une période de 6 ans pendant laquelle la hauteur des plus grosses vagues variait de 40% selon le moment considéré du cycle apparent, variation supérieure à la variation saisonniére normale.

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## 1. INTRODUCTION

In the late sixties when oil exploration commenced in Canadian waters, the need for a wave climate became apparent. In 1970, the Bedford Institute of Oceanography (BIO) initiated a wave study of the coastal waters and continental shelves of Atlantic Canada (Neu 1971, 1972) and later expanded it to cover the entire North Atlantic (Neu 1976, and Walker 1976, 1977 and 1978).

During the investigation, it was discovered that the level of seastate varied greatly from year to year, however the only clear trend that could be determined from the first three years, i.e., from 1970 to 1972, was that the seastate was increasing annually. Such a variation plays an important role in the extreme value estimates, so the data bank was extended to 1980 inclusive to study the size of the variation. Initially, mainly wave heights were processed and statistically evaluated. The visually observed periods of the larger storm waves are included only for the HIBERNIA region. Other regions will be reported when available.

In the summer of 1981 the Resource Management Branch of the Department of Energy, Mines and Resources, now called the Canada Oil and Gas Lands Administration (COGLA) approached BIO for the development of a wave climate for the Canadian coastal waters, in particular of the HIBERNIA oil field area. This report is in response to this request.

## 2. GENERAL DESCRIPTION

The investigation covers the Scotian Shelf, the Grand Banks of Newfoundland and the Labrador Sea including the adjacent waters (Fig. 1). The Scotian Shelf is open to waves from the central and southern North Atlantic while the Labrador Sea is open more to waves from the northern North Atlantic and from Davis Strait and Baffin Bay. The Grand Banks are exposed to waves from all these directions.

The Canadian continental shelf is the underwater extension of the continental land mass. It is about 200 km wide on the Scotian Shelf, 100 km wide on the coast of Labrador and extends 500 km into the North Atlantic from the southern tip of Newfoundland to the edge of the Grand Banks. The depth of water on the shelf is about 200 m, but is interrupted by basins, channels and gullies which are deeper than 200 m and by shoals and banks which are appreciably shallower than 200 m, at some places less than 75 m. At the shelf break the depths quickly increase to 3000 and 4000 m.


Fig. 1. Canadian Atlantic coast and continental shelf.

## 3. FACTORS AFFECTING SHELF WAVE CLIMATE

### 3.1 Wind and Weather

In Fig. 2, monthly mean sea level pressure and vector mean winds based on 25 years of observations are shown for January, April, July and October (from U.S. Navy Marine Climatic Atlas, 1974). There are noticeable differences in the pressure patterns and in the strength and direction of the wind during the year. These variations are governed by a large system based on the relative strengths and locations of the Icelandic Low and Azores High. During the winter, the influence of the Icelandic Low dominates, but this diminishes during the summer. The related pressure gradients create the predominant westerly wind.

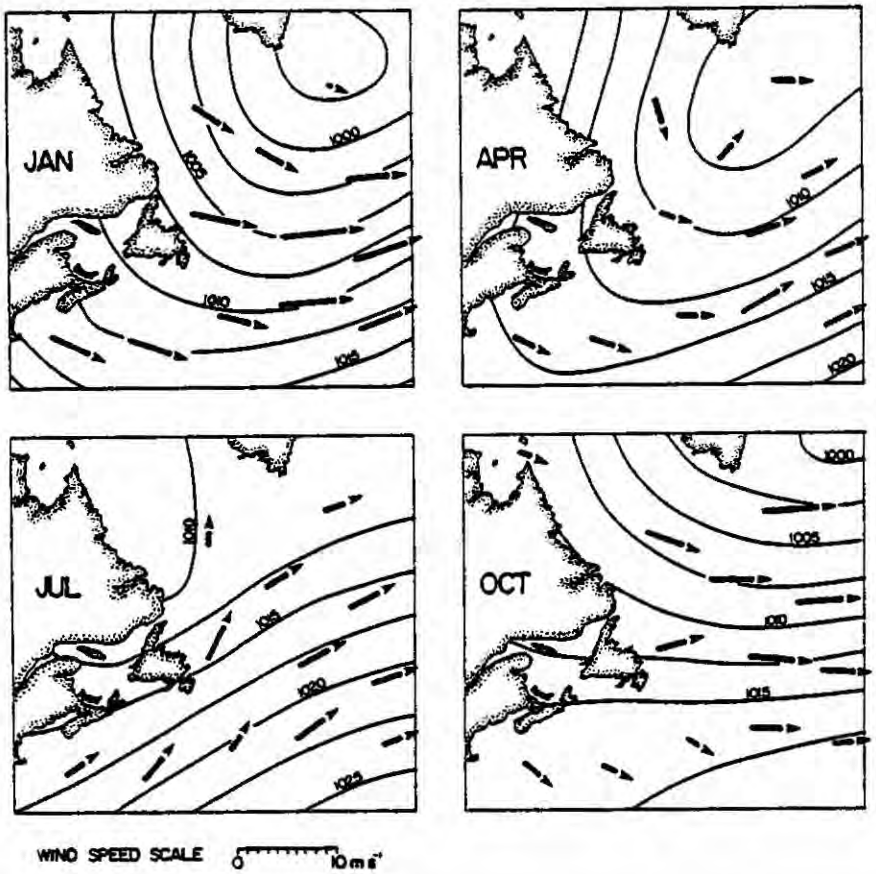



Fig. 2. Monthly mean sea level pressure and vector mean winds; after U.S. Navy Marine Climatic Atlas (1974)

In the winter months, the wind is from northwest and west on the southern Canadian coast and more from the north along the eastern coast. In July, its direction is generally from southwest and its strength is about 40% less than during the winter. These long-term averages are interrupted by large day-to-day fluctuations in the atmospheric pressure and thus in wind strength and direction. This is especially so during the winter months when a strong flow of very cold Canadian continental air encounters the moist warm air over the Atlantic. The resulting great exchange of energy along the edge of this cold front, referred to as the Polar Front, produces frequent storms. As shown by Sovetova (1969) in Fig. 3 for January 1957, these disturbances originate along the North American seaboard, propagate northeastward along the coast and continental shelf and finally head towards Iceland where they are absorbed by the Icelandic Low. The average number of these disturbances, referred to as extratropical cyclones, exceeds 200 during the periods from October to March. Many of these pass over the Scotian Shelf, the Grand Banks and some enter the Labrador Sea.

Other low pressure disturbances occur over the ocean in late summer and early fall, namely hurricanes. These disturbances are of tropical origin and follow characteristic tracks as shown on Fig. 4. The annual occurrence rate is between 3 and 6 but not all of them pass over the Atlantic region of Canada. In 1963 hurricanes No. 2 and 4 and the remnants of No. 1 passed over the HIBERNIA drill area.

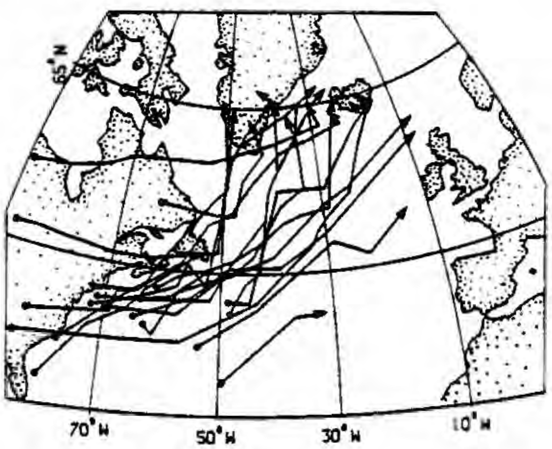



Fig. 3. Trajectories of North Atlantic cyclones for January, 1957, after Sovetova (1969)

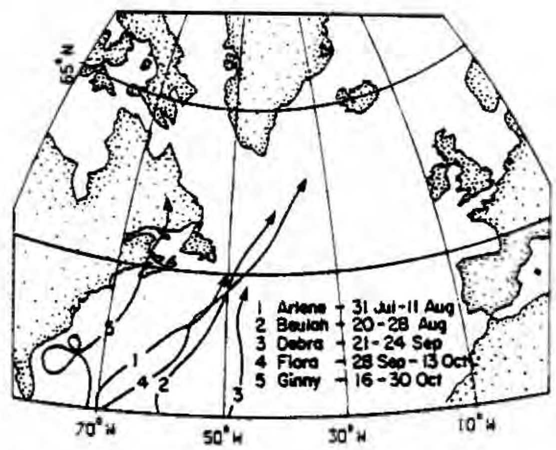



Fig. 4. Hurricane tracks for the 1963 season, after U.S. Navy (1964)

Since the fetch of a typical hurricane system is relatively small compared with a North Atlantic cyclone, its wave generating capacity is not excessive. The most disturbing part of a hurricane is the wind which may be in excess of 180 km/hr resulting in local destruction on water and land.

Generally, the large waves of the Canadian Atlantic Continental Shelf are produced by storms of either extratropical or tropical origin, the former being far more numerous than the latter.

## 3.2 Meteorological Conditions in the 1970's

According to meteorological information, the 1970's was a decade with remarkable weather extremes. In Fig. 5 the results are given of a study by Zishka and Smith (1980) into the interannual variability of the low pressure systems from 1950 to 1977. During this period, in January, the number of storms decreased but so did the mean minimum pressure in the storm centres. Both show great variability with quasi-cyclic variations of 3 and 7 years. Similar changes were found for the other months of the year. If the centre pressure is taken as a measure of the storm intensity - the lower the pressure the more severe is the storm - then the seventies have had fewer but more intense storms over North America and the Atlantic region.

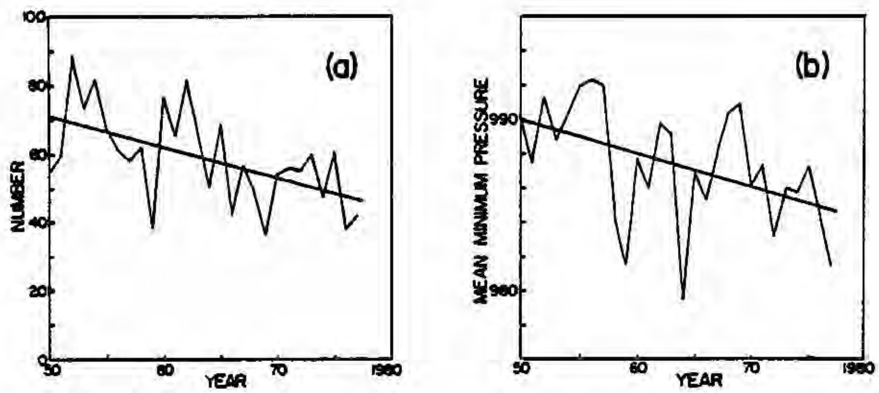



Fig. 5. Yearly variations and corresponding linear regression lines of (a) number and (b) mean minimum pressure (mb) for January cyclones; after Zishka and Smith (1980)

An analysis by Saulesleja and Phillips (1981) of geostrophic winds over the decades ending in 1968 and 1978 respectively indicates a consistent increase in the frequency of occurrences of higher wind speeds in the northern locations. As shown in Fig. 6, where the values for January are plotted, there was little or no change on the Scotian Shelf and the Grand Banks, but near Greenland and in the Labrador Sea, the frequency of higher winds increased during this period by 5% or at the same frequency of occurrence the strength of the higher winds increased by 10 to 15%. This increase seems to continue the trend observed by Rodewald (1968) in the open North Atlantic from 1951 to 1968. Further north toward Hudson Strait, wind activity also increased but at a smaller rate.

Based on all weather factors, Saulesleja and Phillips concluded that the 1970s was a decade of conspicuous climate change in the northwest North Atlantic. Stronger winds and devastating storms, colder winters, summers with either extreme wetness or dryness, and severe ice conditions, have all occurred at times since 1972. The impact of weather was staggering in terms of life, property and lost revenues.

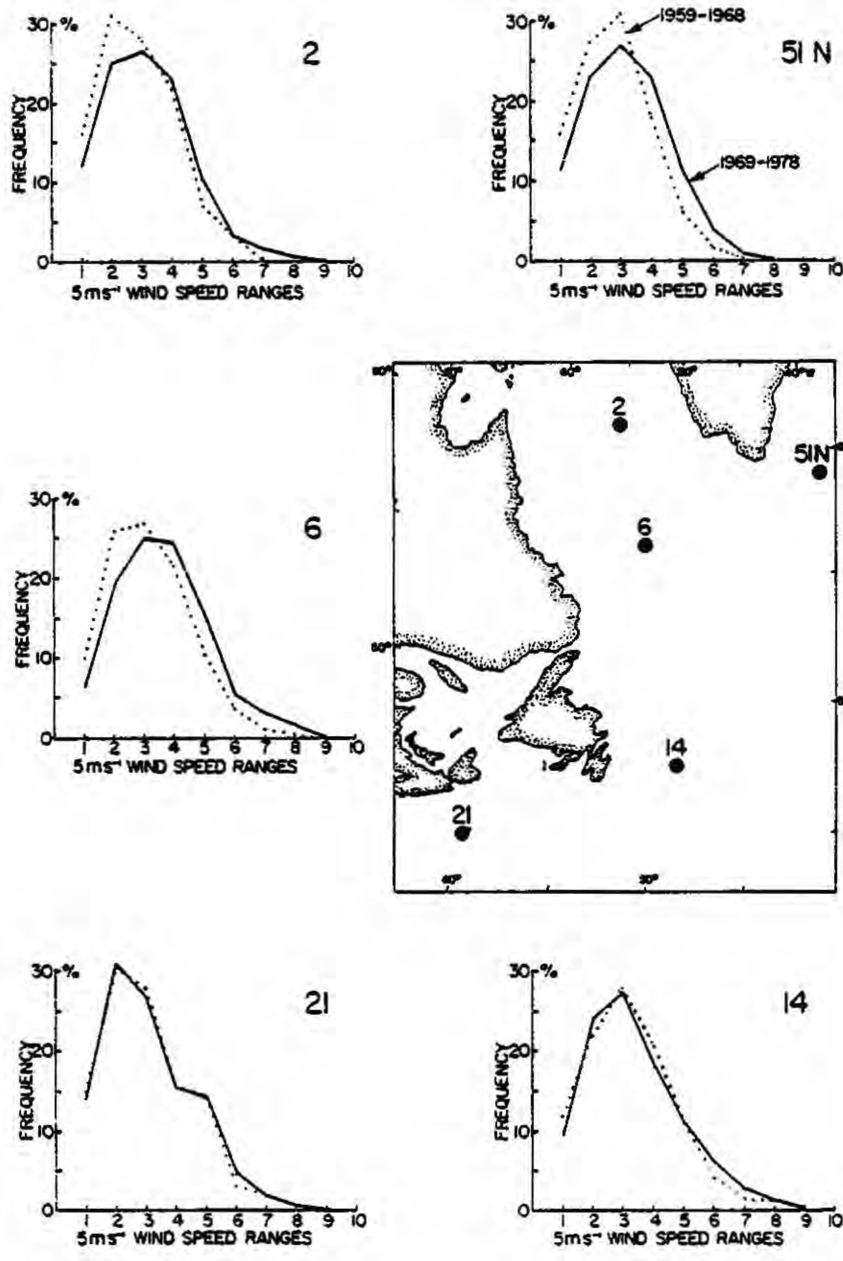



Fig. 6. Decadal geostrophic wind frequency for January; after Saulesleja and Phillips (1981)

The response of the seastate to this weather pattern will be discussed later in conjunction with describing the wave height trends in the 1970s.

### 3.3 Topographical Effects

For the deep ocean and over most of the shelves, waves propagate in 'deep water' conditions. On reaching shallower areas, longer waves experience shoaling and refraction. The most prominent shoals are the Sable Island Bank and the southeast shoal of the Grand Banks. Fig. 7 shows refraction diagrams of 14 s waves approaching Sable Island from the south (a) and the Grand Banks from the southwest and southeast (b); convergence of energy clearly occurs in certain offshore regions. This convergence of energy which increases the wave height locally, is already reported in the observed wave data and need not be considered separately. For the coastal zone, that is the strip of water along the coast in which the depth decreases from about 100 m to only a few metres, refraction and shoaling corrections have to be applied to the incoming deepwater wave data to evaluate the nearshore wave heights.

### 3.4 Ocean Currents

Ocean currents can play a significant role in the modification of wave fields. On the southeastern side of the continent, there are two currents, the Gulf Stream which is located in deep water off the continental shelf moving northeastward and a coastal current on the shelf drifting in the opposite direction. On the northeastern coast of the continent the Labrador Current transports water and winter ice from northern waters southward into the Atlantic. The Gulf stream and the Labrador Current meet and mix on and in the vicinity of the Grand Banks.

It is known that currents affect waves, so these currents will have some influence on the spatial and temporal variability of wave conditions. Most of the modifications, particularly in the long-term, should be inherent in the observed wave data.

### 3.5 Sea Ice

The open ocean on the southeastern Canadian coast is usually free of ice except during the early spring when the Gulf of St. Lawrence exports ice through Cabot Strait onto the Scotian Shelf to form pack ice along the

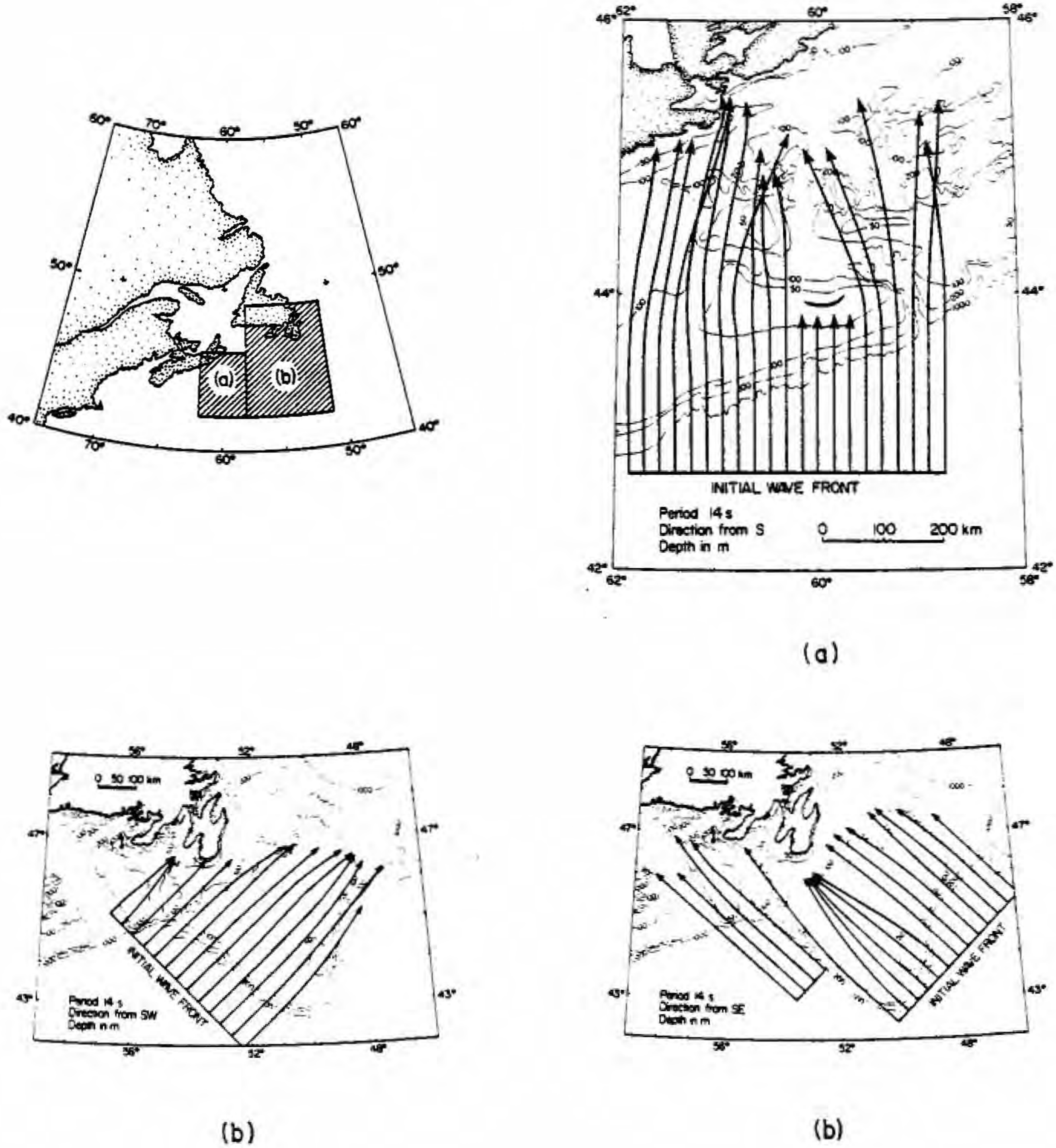



Fig. 7. Wave refraction of 14 s wave on (a) Scotian Shelf and (b) Grand Banks

coast of Cape Breton. On occasion, patches of ice extend as far out as Sable Island. On the northeast coast, ice is present for about half of the year as shown in Fig. 8 (from the U.S. Navy Climatic Atlas of the World, 1974) where the average monthly extent of the ice is given. While the monthly ice fronts represent average conditions, the year-to-year boundaries for each month can vary greatly, as much as 250 km east and westward and 500 km southward at the tip of the ice field. This variability is governed by the action of the wind as well as the air and sea temperature. The ice which is carried from the north by the Labrador Current finally melts on the Grand Banks.

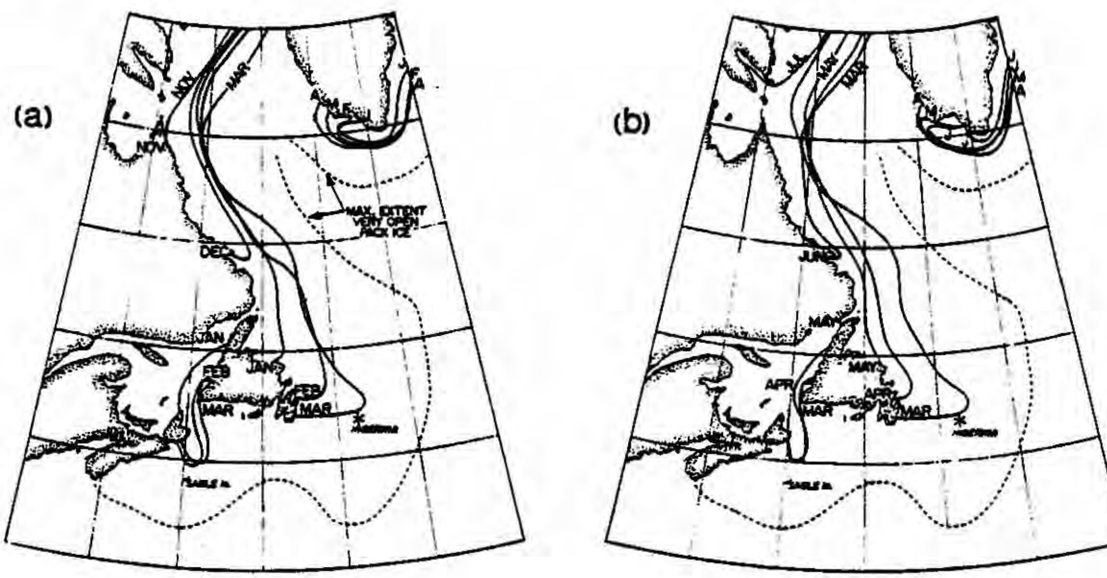



Fig. 8. Limits of open pack ice for (a) advancing and (b) retreating ice seasons; after U.S. Navy Climatic Atlas (1974)

The presence of ice in these waters determines the level of the seastate. Ice coverage interferes with the propagation of incoming waves, the effect increasing with increasing coverage. Longer waves are transmitted underneath the ice until friction and turbulence absorb their energy. The distance of penetration depends on the thickness and firmness of the ice and is seldom more than a few kilometres. Shorter waves are reflected from the ice front and reinforce the height of the incoming waves. This forms a local 'standing' wave system in front of the ice field causing an increase in wave activity which can extend out to as much as a half kilometre from the ice. Sufficient ice coverage can completely prohibit the generation of local waves.

The area most affected is along the coast of Labrador and the east coast of Newfoundland. As shown on Fig. 8, the HIBERNIA oil field is right at the edge of the average March ice front with a high probability of being affected by ice each year. On occasion, the ice can extend beyond this point by as much as 100 km eastward and even further southward.

Wave statistics in this report will reflect the limitations imposed by the average ice cover on regional wave characteristics but will not reflect any of the ice/wave interactions mentioned above. The effect of icebergs can be neglected.

## 4. WAVES

In recent years, a considerable effort was made on behalf of the oil industry to establish a seastate description for various selected points along the coast and over the shelves of Atlantic Canada. One of the major drawbacks of this effort was that each of these investigations was site specific and did not provide a coherent picture of the synoptic large scale environmental conditions. Furthermore, in many cases short-term observations or incomplete time series were used which did not provide a sound basis for long-term predictions.

The aim of this study is to produce a wave climate which describes the seastate with respect to time and space, the time scale being sufficiently small to demonstrate the monthly variation in the seastate, and the spatial scale being sufficiently small to show the continuity of the variability across the northwestern North Atlantic.

### 4.1 Wave Observation Methods

Information which can be used to develop a practical wave climate can be derived only from three sources: hindcasting from wind observations; direct measurements with wave gauges; and visual observations. Hindcasting of waves particularly over long-term periods such as 10 to 20 years would seem to be the rational method to provide the data, but such a technique suffers from the fact that meteorological observations are frequently inadequate over the open ocean particularly with respect to varying winds and moving fetches. For example, Pierson (1981) noted that for a fully developed sea a 10% error in the wind speed can result in a 21% error in wave height, a 46% error in the area under the spectrum and a spectral peak that is 61% too high.

Direct measurement with gauges does provide the greatest precision, but gauges exposed to the hazards of the open ocean have only short operational lives and are too expensive for a large spatial application. However, they are required for calibration purposes, spectral description and shorter term descriptions of the seastate.

One of the few important quantitative sources of consistent wave data which pertain to deep-water areas are those contained in the METOC set of analysed ship reports. Wave and weather observations from 40 to 100 stations across the North Atlantic, consisting of weather ships, Canadian and U.S. government and navy ships, merchant ships, and oil-drilling platforms, are transmitted every 6 hours to the Meteorological and Oceanographic Centre (METOC) in Halifax where they are reviewed and plotted on wave charts. Information which does not fit in the developing pattern is checked for errors in observing, reporting, or communicating. Guided by synoptic surface pressure charts isopleths are interpolated across any regions sparsely covered by ship observations - such as the northern Labrador Sea. Every twelve hours, 0000Z and 1200Z, synoptic wave charts covering nearly the entire North Atlantic are published, designed primarily for ship routing. The BIO started to collected these charts on January 1, 1970 and now has a continuous data bank of more than 11 years. Example of these charts are shown in Figures 9, 10 and 11.

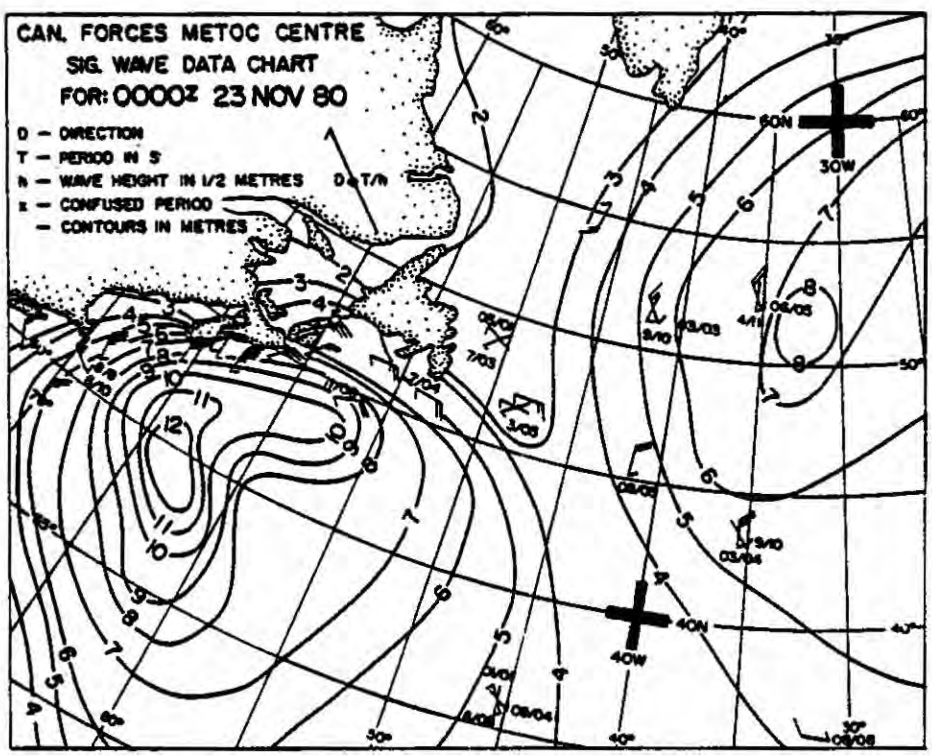



Fig. 9. Wave chart of North Atlantic, 23 November 1980, with the 11 year largest wave height for Scotian Shelf (C4)

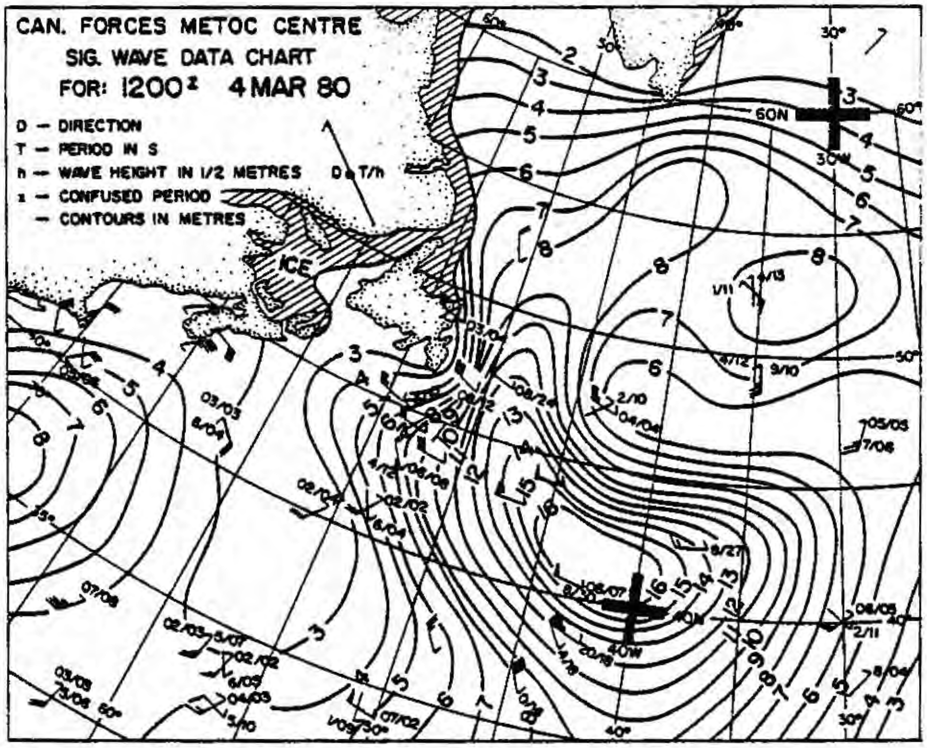



Fig. 10. Wave chart of North Atlantic, 4 March 1980, with the 11 year largest wave height on Grand Banks (D7)

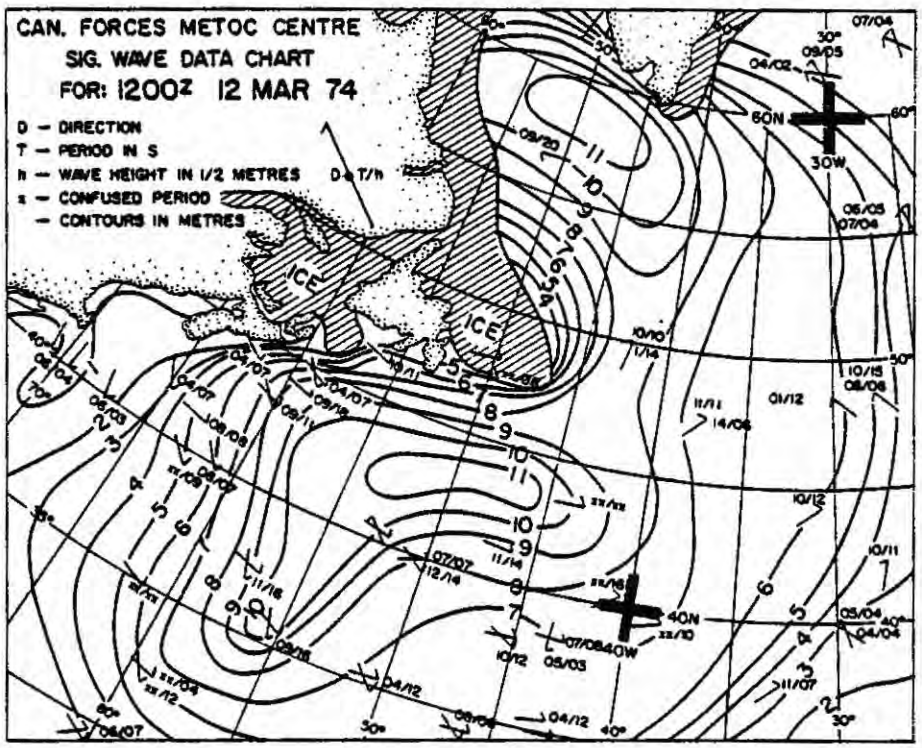



Fig. 11. Wave chart of North Atlantic, 12 March 1974, with the 11 year largest wave height in Labrador Sea (F6)

The high level of quality contol used in the METOC analyses of ship reports, coupled with the maintenance of continuity between subsequent charts and constant cross-referencing with meteorological charts, all serve to support the decision to use these data as the foundation of the B.I.O. wave climate study. By such a technique, fair-weather bias was eliminated from the analyses.

## 4.2 Wave Data

The data given in the charts are wave heights, periods and directions, based mainly on visual estimates. The height given is therefore not the height of an individual wave but more a parameter which expresses the severity of the seastate. The same applies to periods. The question therefore is in which way these properties are related to the standard wave properties.

Regarding the wave height, Wiegel (1964), Ippen (1966) and Jardine (1979) established that the visual observation is practically equal to the significant wave height $H_{sig}$, which is the mean height of the highest one-third waves in a record. Neu (1976) confirmed this with a long-term wave height comparison between a Waverider Buoy and BIO data.

In a storm, the spectrum of wave heights usually appear to be randomly distributed. Longuet-Higgins (1952), by assuming a Rayleigh distribution, related $H_{sig}$ to other key wave heights. For instance, in a storm with $H_{sig}$ of 10 m, this relationship indicates that the average wave height is about 6.5 m; the significant or reference wave height is 10 m; 16 to 17% of all waves or every sixth wave is higher than 10 m; the mean of the highest 10% is between 12.5 and 13 m and the maximum wave height is between 17 and 20 m depending on fetch length and duration of storm.

A similar relationship, but less firmly established, applies to the visually observed period $T_v$. The most common periods in use in the analysis of instrumental wave records are the zero up-crossing period and the period at the peak of the power spectrum. The first is more an average value while the second is the period of the waves with the greatest energy during the recording. As demonstrated by Vandall (1976) and confirmed by Goda (1978), the period of the highest one-third of the waves in a record, $T_{sig}$ is about 0.9 of the peak period $T_p$ and the zero-up crossing period $T_z$ is about 0.75 $T_p$. Even though the visually observed wave height

$H_v$ is practically identical to the significant wave height $H_{sig}$, this is not quite the case for periods. From many comparisons it appears that $T_v$ is about 10% smaller than $T_{sig}$. From these results, the following conversions were chosen:

$$T_{sig} \approx 1.1\ T_v \text{ and}$$

$$T_p \approx 1.2\ T_v$$

In this report, wave periods without subscripts refer only to visually observed periods.

Little difficulty is encountered with the direction of waves. If more than one wave direction was reported, such as of sea and swell, only that of the higher wave was used in the analysis. The direction is given in degrees between true north and the mean direction from which waves are coming.

### 4.3 Seastate Description Methods

Two basic types of wave descriptions are in use today, they are the 'spectral' method and the 'significant wave' method.

In the first case, the data are obtained instrumentally and give a continuous record of the sea surface elevation at a point in the ocean, usually 15 to 20 minutes long. From these data energy spectra are developed which represent the energy distribution over different frequency bands and allow the measurement of wave parameters such as the average wave height, the significant wave height, etc. This approach is presently considered as being more informative and is extensively used in wave research and in the stress design of ships and offshore platforms.

The second type, the significant wave concept, deals with only one representative wave height in a seastate, that is the significant wave. This height is a single parameter which expresses the severity of the seastate at the time of observation. This simplified approach is applied more to the study of the breakwaters, harbour and beach processes where long-term statistics are more relevant.

Both types, however, are compatible if, as suggested by Longuet-Higgins (1952), the wave height distribution does follow the Rayleigh function, from which the common parameters can be determined.

It is obvious that a comprehensive wave climate should incorporate both methods, one complementing and checking the other. Unfortunately synoptic instrumental data are still rare and the only information readily available is that of the METOC charts.

## 4.4 Wave Height and Period Distributions

A distribution function indicates the relative frequency or probability of occurrence of a particular event which, in this case, is wave height or wave period. A number of distributions in use today in wave statistics are the log-normal, Weibull, Gumbel and others. It was found that practically all our data processed for the North Atlantic fitted the log-normal distribution. A chi-square test applied to the wave heights of HIBERNIA showed that the data follow a log-normal distribution with a confidence level of 99%. Wave period distributions also follow this pattern.

Standard statistical tests of significance on the METOC wave data cannot be applied since most of the observations are visual estimates, not wave for wave records.

## 4.5 Long-Term Prediction

In engineering applications, extreme values of wave heights, even though rare, are of prime importance to the designer. 10,50 and 100 year events are common requirements, but observations over these lengths of time normally do not exist. If these long-term occurrences follow the same probability function as the observed data, critical values should be predictable.

In this analysis, the 10 year recurrence heights are obtained from the 11 year data bank. Longer-term data are obtained by extrapolating the distribution fitted to the 11 year data.

In some sets of data, the single largest observation differs from the fitted straight line distribution. This is more likely to occur in the shorter term data sets. In this case the distribution line, being based on the bulk of the data, is assumed to be correct and the apparently anomalous observation must be either a longer or shorter-term value; e.g., a 100 year wave being contained in a 10 year record. The intersection of the straight distribution line with the probability value for the annual occurrence is defined here as the value for a 'normal' year.

## 4.6 Wave Periods of Larger Waves

Long-term wave periods (or wave lengths) follow the same probability distribution as the wave heights, but each being independent of the other. However, they combine to form a complex joint distribution. This was demonstrated by Neu (1976) for the largest annual periods of the western North Atlantic, derived from the log-normal distribution. They varied between 13 and 14 s. Although they were the largest observed periods they were not associated with the highest waves; they were in most cases periods of swell with heights of between 1 and 4 m. The designer, however, is primarily interested in the periods of the higher waves. In this analysis, therefore, only the periods of the highest 1% of waves for the 11 years and of the largest 3% of monthly waves for the 11 years were processed. In the first case, 80 storms of the entire 11 years were represented, regardless of season, while in the second case, this amounted to 20 storms for each month, a storm being defined as one twelve hour event.

The statistical processing of the 11 year wave height data of the western North Atlantic has been completed but, with the exception of important locations like HIBERNIA, the analysis of the periods and the direction of waves is still going on. A more comprehensive report of their distribution in the North Atlantic will follow.

## 4.7 Wave Energy

To obtain a general idea of the seasonal and directional energy distribution off the Canadian Atlantic coast, the relative energy of the wave representing the seastate of the 12 hour reporting period was calculated. Since the periods, which are required to calculate the energies, have only been partly processed, the energies only of HIBERNIA, are presented.

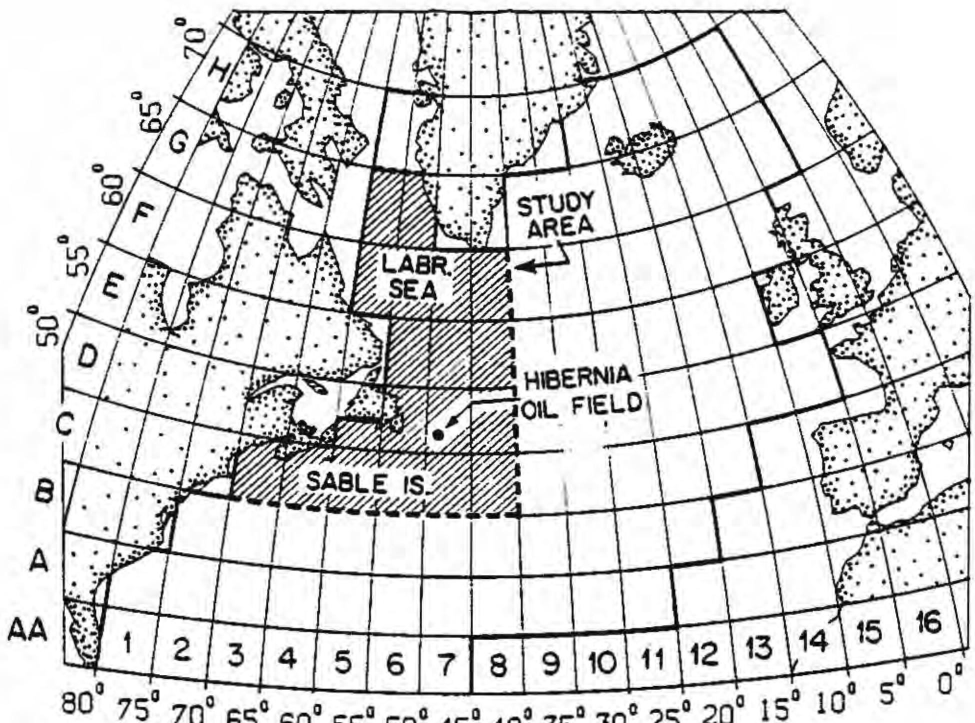
The energy per wave length and per unit width of wave crest is given by:

$$E = 1/8\gamma\ H^2\lambda (\text{m ton/m})$$

where $\gamma$ is the specific weight of seawater (approximately 1.025 ton/m$^3$), and $\lambda$ is the wave length (1.56 $T^2$ (m) in deep water, where T is the wave period in seconds). The energy per metre wave crest and per second therefore, is:

$$E = 0.2\ H^2\ T\ (\text{m ton})$$

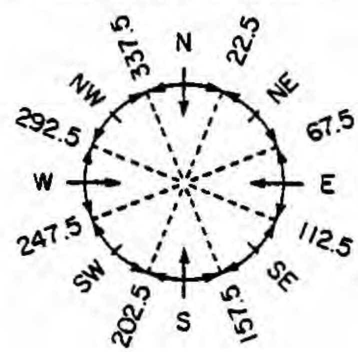
This equation is used here for estimating the relative wave energy.




WAVE HEIGHT

| CODE | HEIGHT(m) |
|---|---|
| 1 | 0.5 — 1.4 |
| 2 | 1.5 — 2.4 |
| 3 | 2.5 — 3.4 |
| 4 | 3.5 — 4.4 |
| 5 | 4.5 — 5.4 |
| 6 | 5.5 — 6.4 |
| 7 | 6.5 — 7.4 |
| 8 | 7.5 — 8.4 |
| 9 | 8.5 — 9.4 |
| 10 | 9.5 — 10.4 |
| etc. | |

8 POINT
DIRECTION SYSTEM




WAVE PERIOD

| CODE | T(S) |
|---|---|
| 5 | 0 — 5 |
| 6 | 5 — 7 |
| 8 | 7 — 9 |
| 10 | 9 — 11 |
| 12 | 11 — 13 |
| 14 | 13 — 15 |
| 16 | 15 — 17 |
| etc. | |

NOTES: Direction - from which waves are coming.
Height - vertical distance from crest to trough.
Period - interval required for successive crests or troughs to pass a fixed point.

Fig. 12. BIO grid system and code of wave properties

4.8 Grid System

The grid system consists of 5° x 5° 'areas' which are identified as in Fig. 12. The map projection differs slightly from Lambert Conformal projection used in our original wave climate. It was chosen to be compatible with the computer program providing coastline and data plotting. The map is centred at 45° west.

The region covered in the study extends from Davis Strait to 40° north and from the Canadian coastline to 40° west. The key points of the investigation are Sable Island, the HIBERNIA oil field and the Labrador Sea.

At the centre of each 5° x 5° degree area, for every 12 hours, the wave height, wave period and wave direction were determined from the METOC wave charts. The total number of representative waves for each block is 8036, forming a uninterrupted time series of 11 years from January 1, 1970 to December 31, 1980.

5. RESULTS

The data are presented both graphically and pictorially. This is the only practical way to condense for instance, the more than one hundred thousand data points of the wave heights for the largest seastate.

5.1 11 Year (1970-1980) Wave Height Distribution

Following the technique described in 4.4, the 12 hourly significant wave heights of the 11 year time series are plotted in Fig. 13 on log-normal probability scales. Each distribution line is based on 8036 observations. On the right side of the graphs the respective recurrence intervals in terms of years are given. With the exception of a few high values, the data fit straight line log-normal distributions extremely well. Once established, the straight line is the basis for further analyses and comparisons.

The 1 year wave height of this distribution does not relate to a particular year, but to the 'normal' year as determined by the 11 year distribution. The same applies to the other return periods up to a maximum of 11 years. From there on, the distribution lines are linearly extrapolated for long-term prediction as shown in Fig. 13. For instance, at HIBERNIA (D7), the normal 1 year and 10 year wave heights are 9.0 and 12.3 m and the predicted 50 and 100 year heights are 14.6 and 15.6 m respectively.

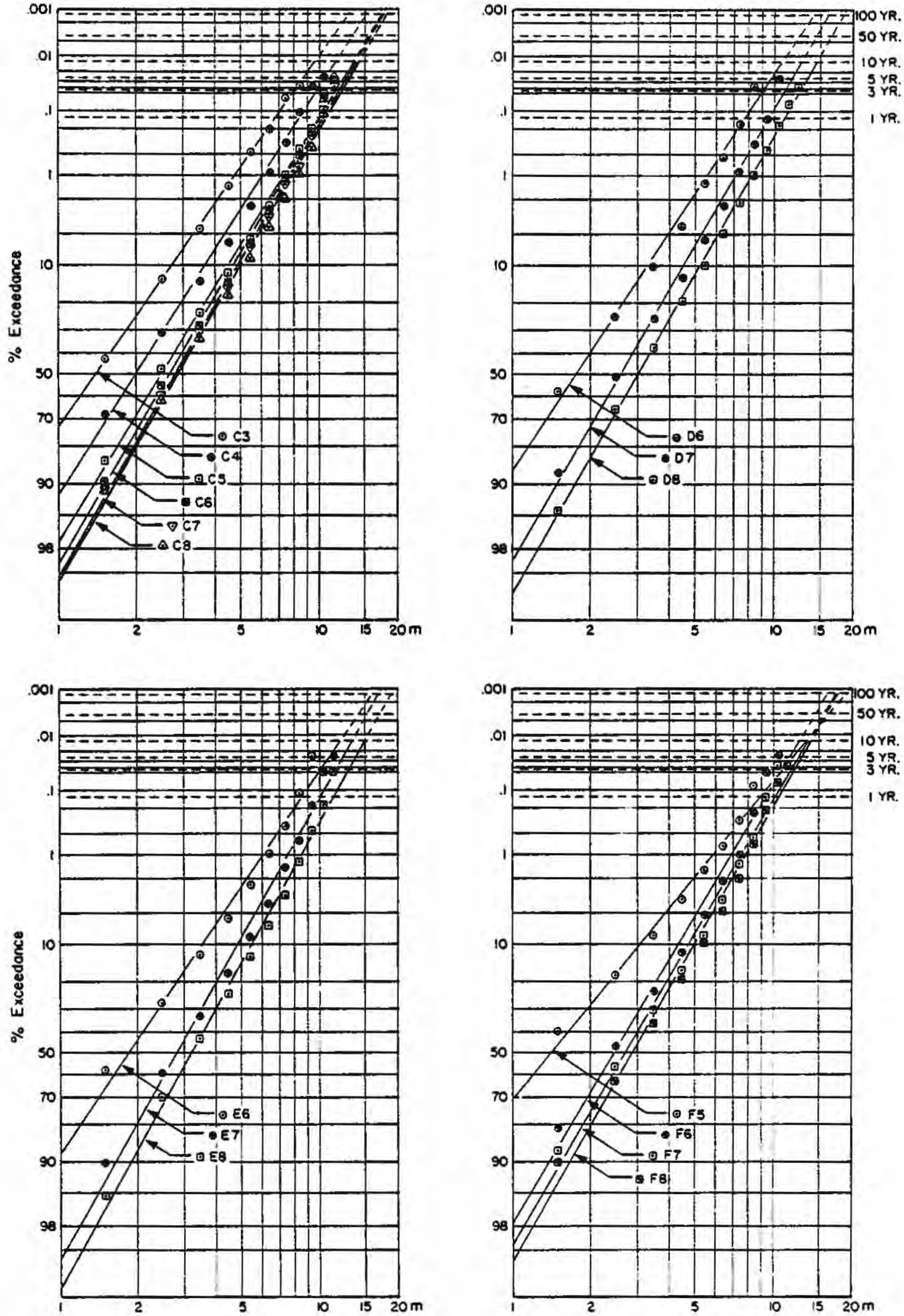



Fig. 13. 11 year (1970-1980) wave height exceedance diagrams and long-term predictions

The four groups of distribution lines show the progressive increase in wave heights from west to east. As already reported by Neu (1976), the widest spacing between the distribution lines (eg. C3, C4 and C5) and therefore the greatest increase in wave height is in the first 800 to 1000 km from the shore. From there on the wave height increases relatively slowly. This indicates that west of this point the seastate is more in the developing stage while to the east, the seas approach the fully developed condition. Thus, with the exception of the region southeast of the Grand Banks, the seastate in Canadian waters is primarily in the developing stage with a considerable amount of wave breaking.

As mentioned, ice affects the coast of Labrador and the east coast of Newfoundland in late winter and spring. This can particularly be noticed in F5 where the slope of the distribution line differs distinctly from that of F6, the neighbouring block which is free of ice. The fault in the distribution becomes particularly conspicuous in the long-term prediction which would provide higher values for the near shore region than for the offshore region, which is inconsistent with the predominant westerly wind. A monthly analysis which is done later and deals only with ice free months helps to clarify this problem.

## 5.2 Spatial Distribution of Large Waves

Based on the 11 year wave height distribution of the 18 grid areas, the spatial distribution of the largest $H_{sig}$ of a normal year and of a 10 year period are shown on Fig. 14 and on Fig. 15 respectively. In both cases, the lines of equal wave height were parallel to the coast, enclosing Newfoundland and the Grand Banks. The spacing between the lines is smaller in the near-shore zone than in the offshore region, indicating that the shelves reduce the longer waves presumably through breaking, or conversely, indicating the growth of waves being generated by offshore winds. At the Labrador coast ice interferes with waves, and large waves can occur in the coastal area only during the summer and early part of winter when it is ice free.

The seastate increases generally from west to east and from south to north but differs only slightly between the three specified locations. The largest $H_{sig}$ of a normal year and of a 10 year period are 8.7, 9.0 and 9.3 m, and 11.7, 12.3 and 12.5 m for Sable Island, HIBERNIA and the Labrador Sea respectively.

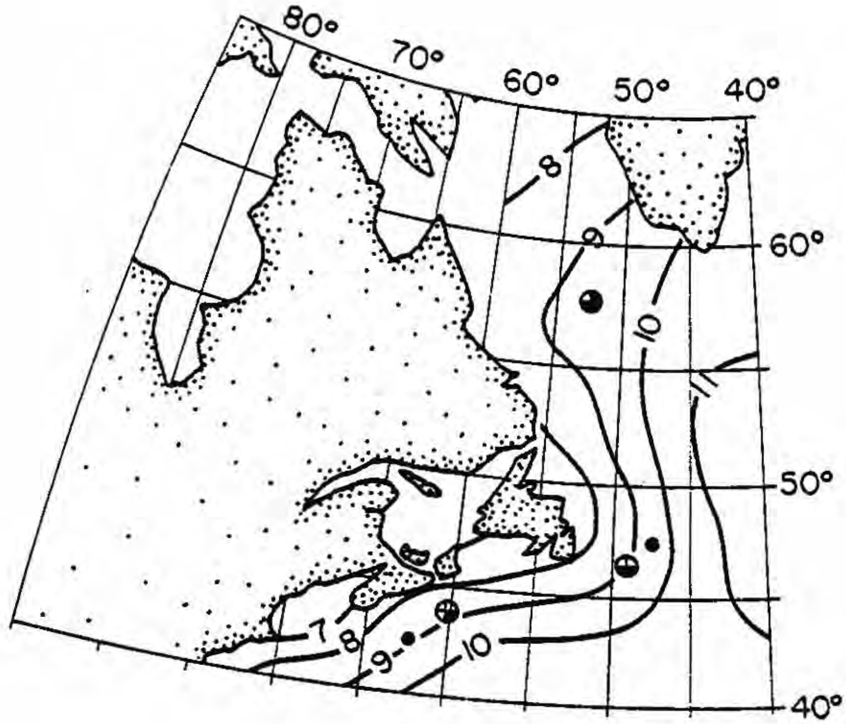



Fig. 14. Largest $H_{sig}$ for normal year

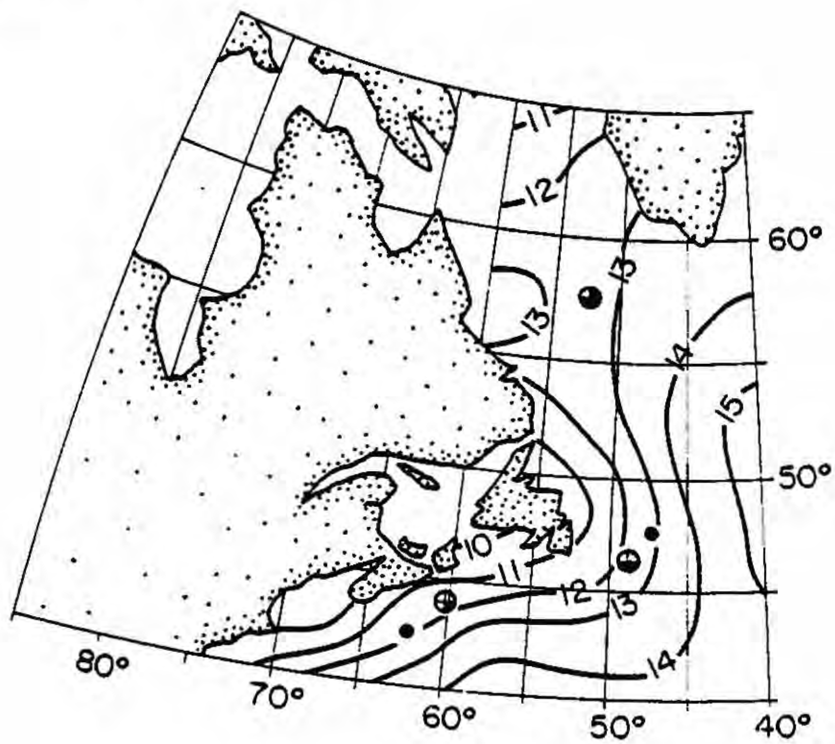



Fig. 15. 10-year largest $H_{sig}$ based on 11 years data (1970-1980)

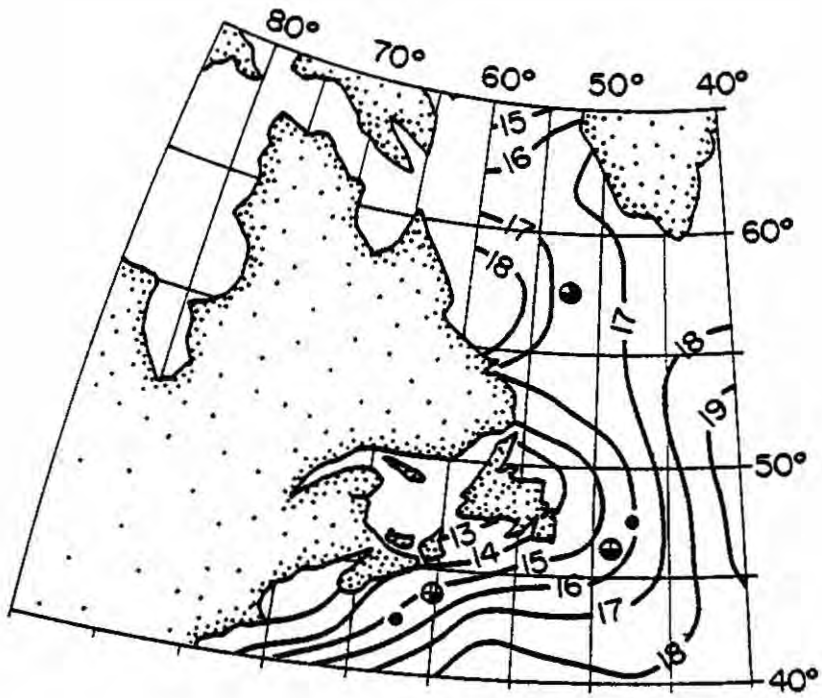



Fig. 16. Predicted largest 100-year $H_{sig}$

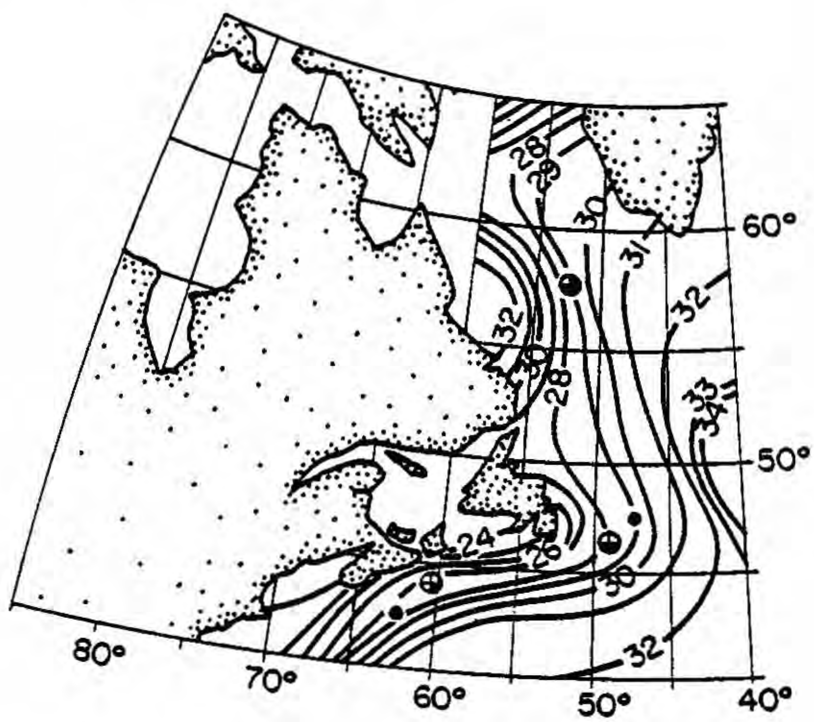



Fig. 17. Predicted 100-year $H_{max}$

As mentioned, in engineering practice, the 100 year design wave concept is applied and for this investigation the log-normal probability distribution is used. In Fig. 16 the 100 year $H_{sig}$ and in Fig. 17 the 100 year $H_{max}$ values are plotted, the latter obtained by multiplying $H_{sig}$ by a relating factor of 1.8. On this basis, the design wave for offshore structures in the Canadian Atlantic waters should be about 30 m.

The largest wave ($H_{sig}$) recorded on the METOC wave charts during the 11 years for each of the three locations are given in Figures 9, 10 and 11. On the Scotian Shelf where Sable Island is located, a wave with a height of 11 m was noted at the centre of C4 on November 23, 1980. This wave was part of a wave field which moved by further south with a wave height of 12 m at its centre. The largest wave at HIBERNIA occurred on March 4, 1980. As shown on Fig. 10, it was located on the outskirts of a wave field which passed by 500 km to the south with a reported wave height of 16 m. If the centre of this wave field had passed over HIBERNIA, the 100 year wave condition would have been approached. During the sinking of the OCEAN RANGER the centre of a wave field of 12 m ($H_{sig}$) passed less than 100 km from the platform; this was an event with a return period of 10 years. In the Labrador Sea, the largest wave encountered was on March 12, 1974 (Fig. 11) with wave heights in excess of 12.0 m. In this case the peak of the wave field nearly reached F6, the grid area in the centre of Labrador Sea.

The three wave charts, although demonstrating the maximum observed wave height in the three key locations, depict a relatively common feature during extreme events off the East Coast: namely, a very intense generation of waves within a very narrow wave field that rapidly traverses the area.

## 5.3 Long-Term Variability of Seastate

Individual annual wave height distributions vary noticeably from year to year as shown for C4 from 1970 to 1972 in Fig. 18. A decreasing slope of the distribution lines indicates an increase in wave activity and the opposite a decrease. Taking the annual largest $H_{sig}$ as an indicator for the level of wave activity the variation of the seastate at the three locations and the spatial distribution of these values for the 11 years are given in Figures 19 and 20 respectively. The year showing the highest wave activity was 1978.

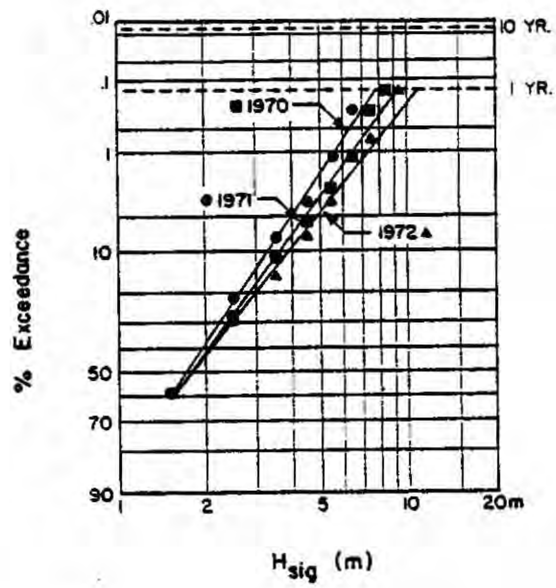



Fig. 18. Annual wave height distributions for C4 from 1970 to 1972

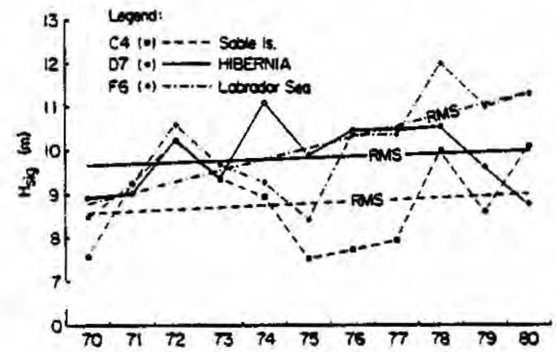



Fig. 19. Variability of annual largest $H_{sig}$

As can be seen, there are strong fluctuations in which the wave height varied by more than 40%. These quasi-cyclic fluctuations appear to have periods of three and six years and possibly longer. From these results, it is obvious that shorter data banks can be biased by year to year fluctuations and produce widely different long-term predictions. Therefore regardless of the theory applied, long-term prediction must be based on the longest possible time series, preferably in excess of 10 years.

In Fig. 19, the RMS lines through the data of each of the three locations give an indication of the still longer-term trend in wave activity. On the Scotian Shelf (C4) and Grand Banks (D7), the increase in seastate over the 11 years was very slight but in the Labrador Sea its growth was quite large, energy-wise by 50%. This agrees with Saulesleja and Phillips (1981), who found from meteorological data that the winds in the Labrador Sea increased from the sixties to the seventies (Fig. 6), while to the south the wind, and thus the wave activity, hardly changed during this period. An additional conclusion that the number of storms declined as their severity increased was not confirmed by our results. As shown in Fig. 21, the number of storms producing waves exceeding 8 m increased during the 11 years in the Labrador Sea, particularly in the second half of

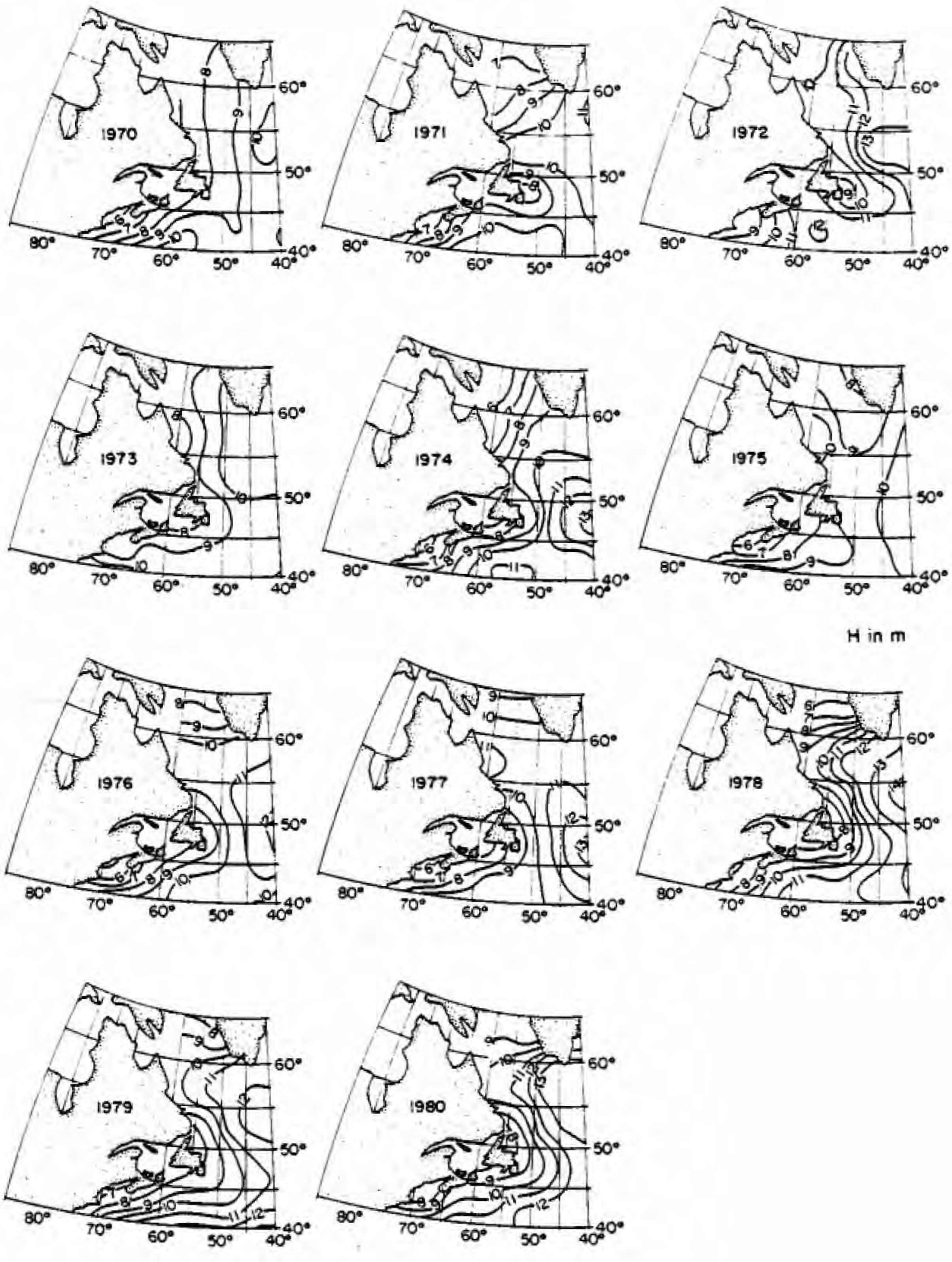



Fig. 20. Annual largest $H_{sig}$ from 1970 to 1980

the seventies. Therefore, both the meteorological and wave climate data show that the long-term seastate activity in the Canadian waters during the last 11 years has not changed, except in the Labrador sea where a significant increase has occurred over an area extending into the northern North Atlantic.

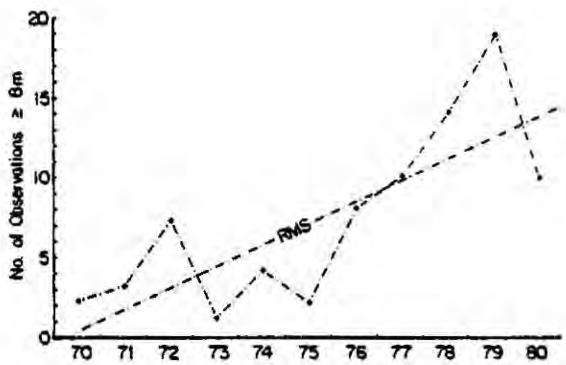



Fig. 21. Number of storms in Labrador Sea with $H_{sig} \geq 8$ m.

## 5.4 Percentage Exceedance of Given Wave Heights

Waves of lower heights than the extreme values also play an important role in the everyday operations at a drill site. For instance, the knowledge of down-time due to wave action, or the number of days when the transfer of loads from supply vessels to the platform cannot be performed, are necessary operational information.

For this purpose, percentage exceedances were developed for significant wave heights exceeding 1.5 m, 3 m, 6 m and 9 m, based on the 11 year data bank. Fig. 22, shows that conditions do not change greatly along the Canadian coast. 60 to 80% of the time, waves are higher than 1.5 m and 10 to 30% they exceed 3 m. Also for higher waves, the distribution is quite uniform, being less than 2.5% for 6 m and between 0 and 0.25% for 9 m. For instance, for a normal year, at HIBERNIA oil field, the integrated time for a seastate exceeding 9 m significant wave height (this includes waves up to a height of 16 m) is about three quarters of a day. Under more unusual conditions, such as occurred to the OCEAN RANGER on February 15, 1982 at the HIBERNIA oil field, cyclones can stall and provide extended periods of high seastate. On this occasion, in a single storm, 11 to 12 m wave heights were exceeded for a full day.

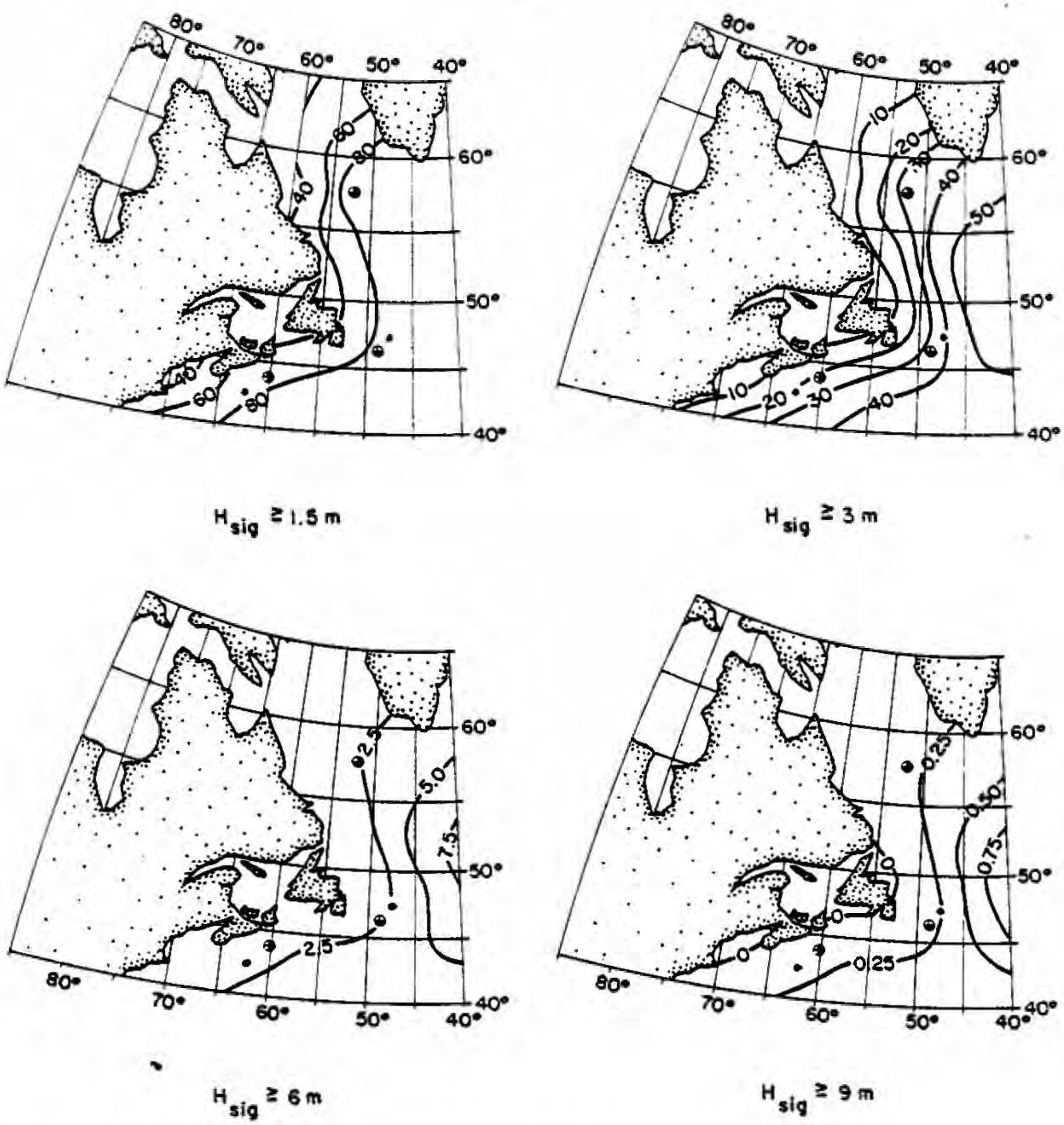



Fig. 22. Annual percentage exceedance for given wave heights

## 5.5 Monthly Seastate

Also required for navigation and oil exploration are monthly and seasonal descriptions of the seastate. Based on the 11 years of data, the monthly log-normal distributions for D7 (HIBERNIA) are plotted in groups of three in Fig. 23. The slope and the location of the distribution lines identify the seasons to which they belong from the viewpoint of wave activity. The months from October to March inclusive represent the winter storm

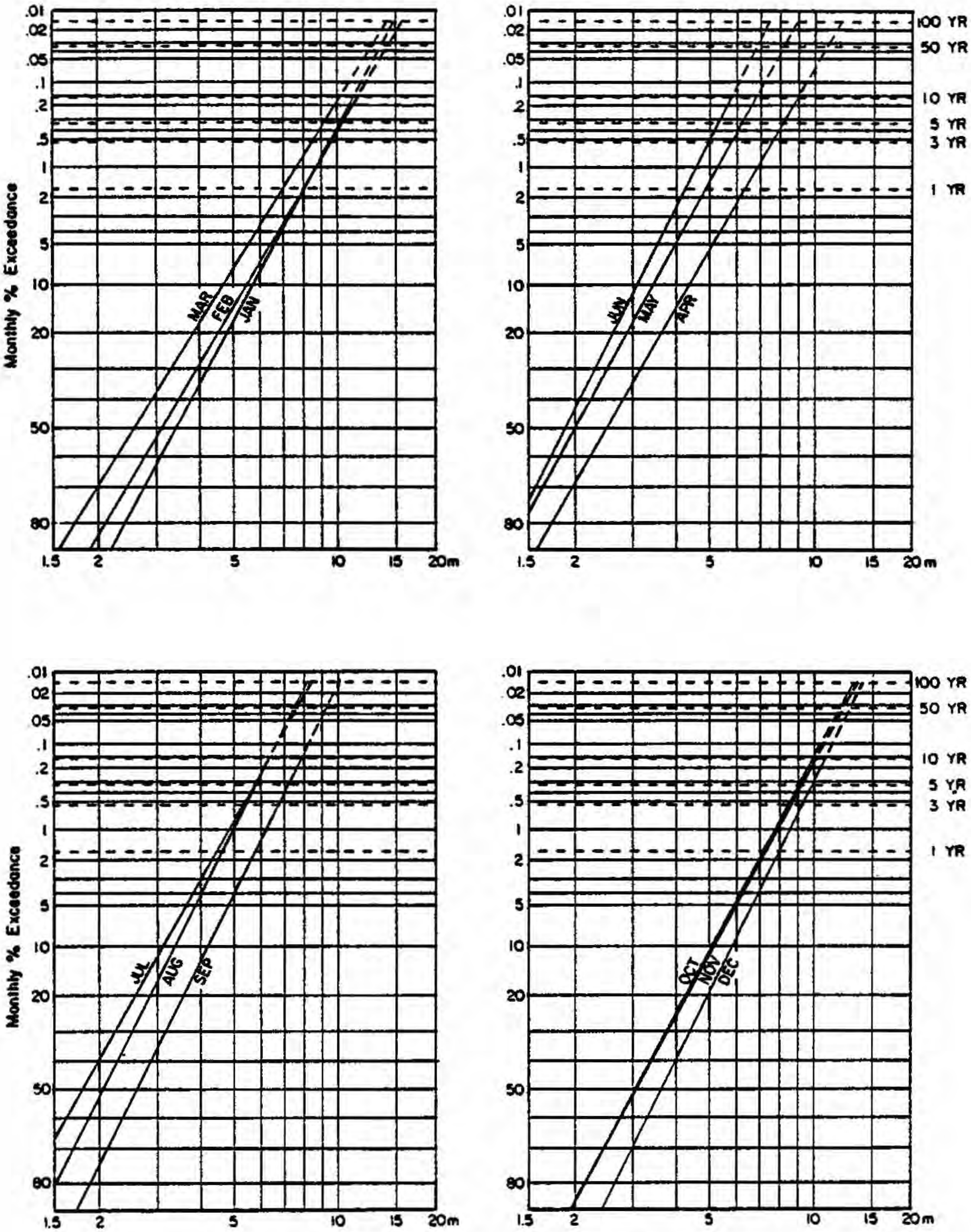



Fig. 23. Monthly wave height exceedance diagrams for D7 (HIBERNIA) based on 11 year data (1970, 1980)

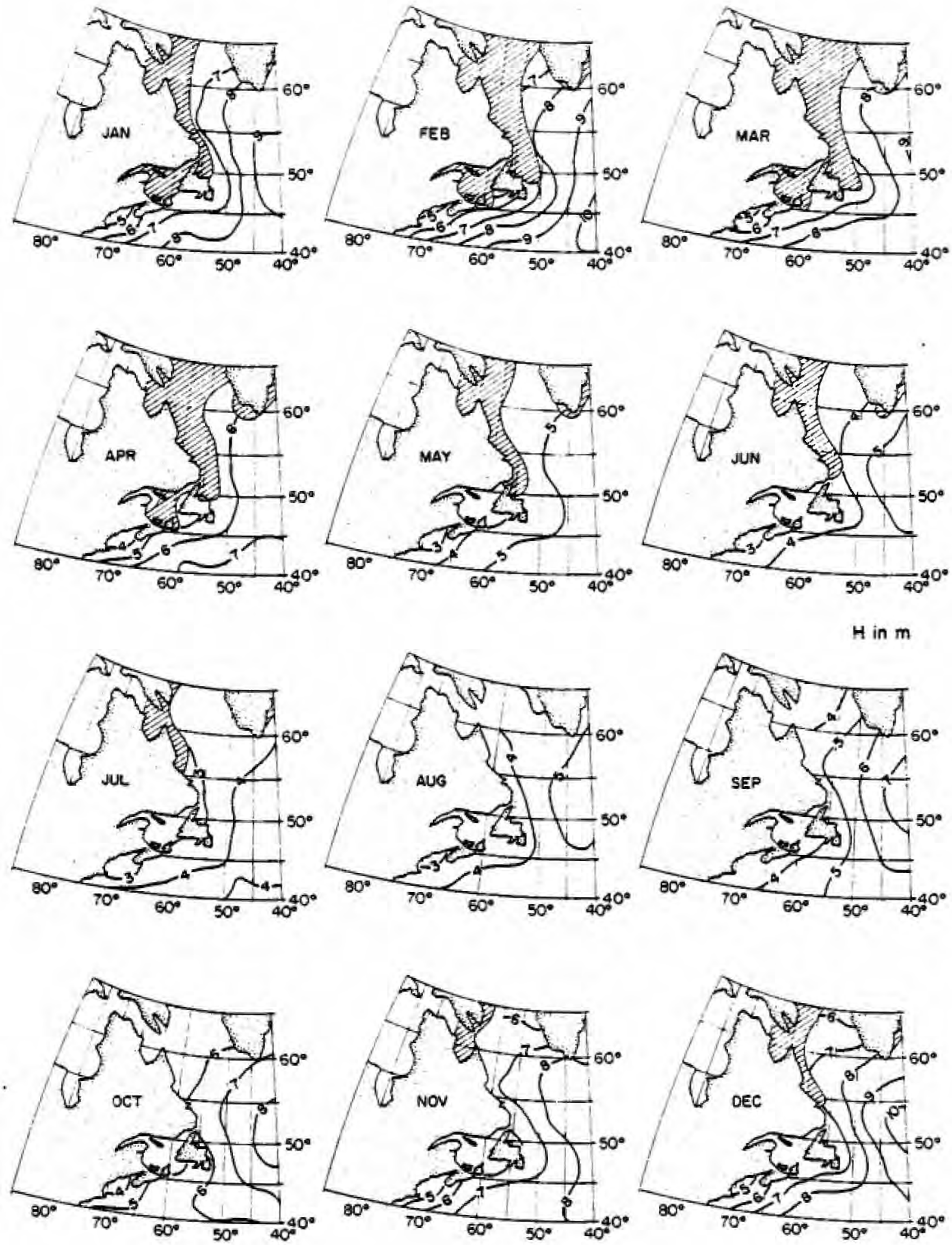



Fig. 24. Spatial distribution of monthly largest $H_{sig}$ for normal year

season, June and July and part of August the summer season and the remaining months the transitional seasons. Since monthly distributions are only based on one-twelfth of the 11 years of observations, their reliability may therefore be less than those which are based on the entire data set. This should be kept in mind when making long-term predictions to 50 and 100 year values.

The largest $H_{sig}$ for a normal year, derived from the monthly distributions of all the 'areas' are shown in Fig. 24. As can be seen, in the Canadian waters, there are significant spatial and large seasonal variations. Like the annual data, the lines of equal wave heights are parallel to the coast, the waves being lower along the coast than offshore. The largest seastate occurs during the winter with wave heights in excess of 8 m east of the Grand Banks. The lowest seastate is during the summer with heights of less than 3 m in the Gulf of Maine at the entrance to the Bay of Fundy.

Also shown is the monthly average spread of the sea ice. Most of the Canadian waters are ice free as mentioned in section 3.5, except along the coast of Labrador where ice free conditions occur only from August to November. Wave heights in this area are therefore affected by ice. Otherwise the ocean seastate appears to prevail right up to the edge of the ice field.

The normal year largest monthly $H_{sig}$ for the Scotian Shelf (C4), the Grand Banks (D7) and the Labrador Sea (F6) are given in Fig. 25. In the summer their heights are between 3.5 m and 4.5 m and in the winter between 7 to 8 m. The lowest wave heights are on the Scotian Shelf (C4) and are about 1 m less than over the Grand Banks and in the Labrador Sea. There was an exception in the Labrador Sea for July when the wave height dropped to the same level as on the Scotian Shelf. The height for the Labrador Sea was greater than for the Grand Banks in March and November.

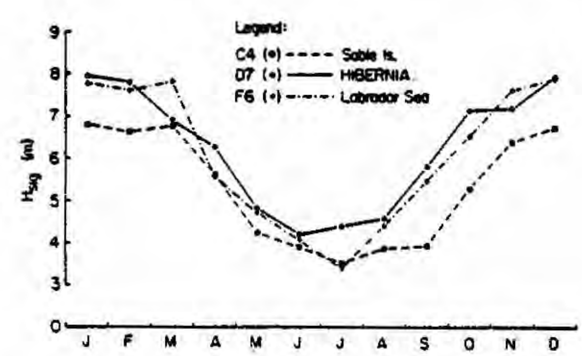



Fig. 25. Monthly largest $H_{sig}$ for normal year

## 5.6 11 Year Wave Statistics D7 (HIBERNIA)

Wave statistics are most usefully presented in the form of scatter diagrams. They contain graphically and numerically all the height, period, direction and occurrence information for a complete analysis. While directional data are of great importance in the design and operation of structures in the ocean, they will not be presented in this report. Some example of directional scatter diagrams are given by Neu (1976).

In the present analysis, periods and directions are not yet generally analysed and are not included here, but one manual analysis has provided a non-directional scatter diagram for HIBERNIA (Fig. 26). On the vertical axis are plotted $H_{sig}$, on the horizontal axis the visual periods $T_v$ and at the intersection of the parameters the number of occurrences is given. As can be seen, the bulk of the waves of the 8036 observation are in the 2 to 4 m height range and 6 to 8 s period range. Larger waves, in excess of 8 m, have periods from 8 to 14 s only. The period ($T_v$) with the largest concentration of wave energy is close to 11 s. The respective significant period $T_{sig}$, and peak period $T_p$ are about 12.1 and 13.2 s.

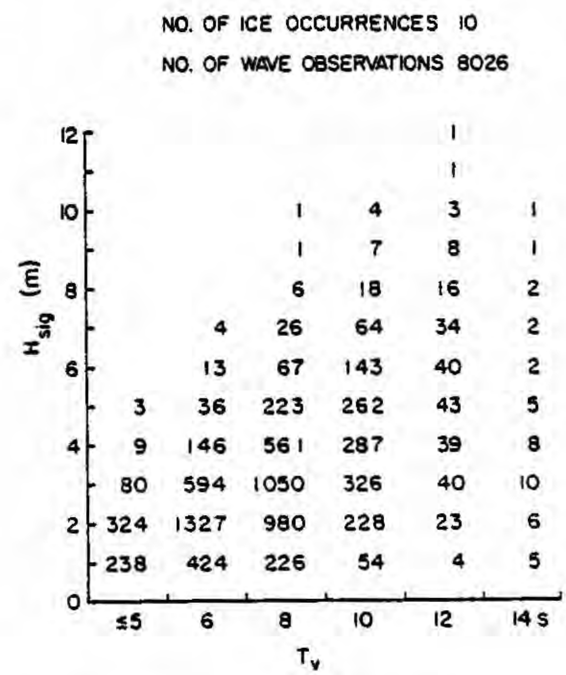



Fig. 26. 11 year (1970-1980) wave statistics (scatter-diagram) for D7 (HIBERNIA).

A number of studies can be performed on these statistics, such as the state of wave breaking at the site. Theoretically, waves break when their steepness (height over length) exceeds 1 over 7. In practice, with the exception of standing waves in front of walls, or composite waves, the maximum slope seldom exceeds 1 over 10. In Fig. 26, the envelope or upper limit of wave heights in the scatter diagram provides for each period group the wave height at which the waves become instable and break. Since 16% of all waves are larger than $H_{sig}$ (see Section 4.2), a considerable part of the wave with periods of 6 and 8 s and respective heights of 7 and 9 m are in the breaking range. Since many of the waves in these waters are in this period class, it can be concluded that the seastate for a number of storms is affected by a considerable amount of wave breaking.

## 5.7 Wave Periods and Directions of Storms at D7 (HIBERNIA)

Although visually observed periods follow a log-normal distribution as do the visually observed wave heights, the two plots of percentage exceedance values do not correlate and any joint distribution would be too complex to be attempted here. However, for navigation and offshore operations, the periods of storm waves are of primary interest. So, the periods of the highest 1% of the waves of the 8036 observations at the HIBERNIA site (D7) were chosen as being representative of the storm conditions, that is some 80 storms with $H_{sig}$ exceeding 7 m. Their wave periods ($T_V$), in 2 sec intervals, and their % occurrences are given for the 8 directions in Fig. 27.

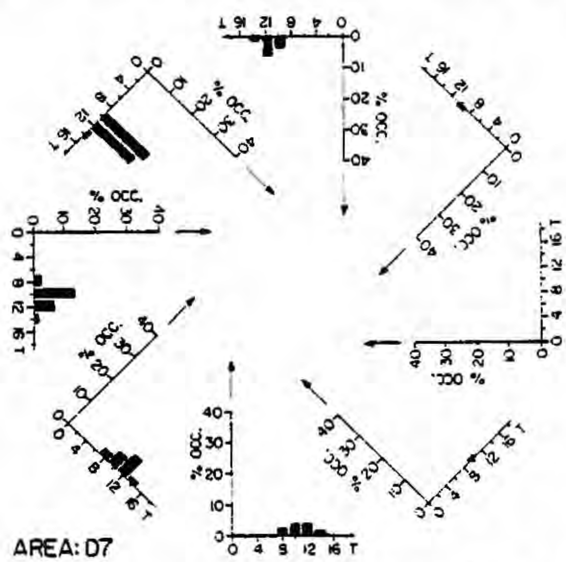



Fig. 27. Directional period ($T_V$) distribution of the 80 largest storms during the 11 years

As can be seen, nearly 40% of the 80 storms had waves coming from northwest, or the waters of the northeastern Newfoundland Shelf. Their periods ($T_V$) were in the 10 and 12 s range, indicating that the waves were generated by winds over some distance, probably from along the coast of Labrador. About 25% of the waves were from the west that means from the Scotian Shelf and about 16% and 13% from the southwest and south respectively, that is from the offshore region of the U.S. and the Sargasso Sea. A significant portion from the west and southwest was therefore in the longer period ranges centering on 12 and 14 s, that is, when converted into $T_{sig}$, 13.2 and 15.5 s and into $T_p$, 15.5 and 16.8 s. These waves are primarily generated by North Atlantic cyclones with relatively large fetches. It is of interest to note that hardly any waves came from the east, that is from the open ocean, during these biggest storms of the 11 years.

Another analysis was made to show the monthly variability in the distribution of periods and directions. For this purpose, the top 3% of the largest waves per month of the 11 years data were used. This means that the 20 largest storms for a month were chosen from the eleven sets of records for that month. Wave heights of the winter storms are about twice those of the summer storms; 8 m in the winter compared with 4.5 m in the summer due to higher and longer lasting wind speeds. The results for the 12 months of the year are presented in Figures 28a and 28 b. In the first three months of the year, waves came primarily from northwest, west and southwest with a few from the south, the largest occurrence in each month progressively shifting from northwest to southwest. In the following two months, April and May, which are transitional months, the directions were not clearly defined. In June and July, the summer months, waves came from the westerly section with more than 50% from the southwest in July. This trend changed in August and September to northwest again until by October 85% of all the storm waves came from northwest. In the last two months of the year waves seem to be arriving from nearly all directions but with a general preference between north, northwest, west, southwest and south. Between 5 and 10% only was contributed from the east.

From the results of the two analyses, it can be concluded that the prime direction of the larger storm waves is from northwest with declining frequencies in the following order: west, southwest, south and north. The

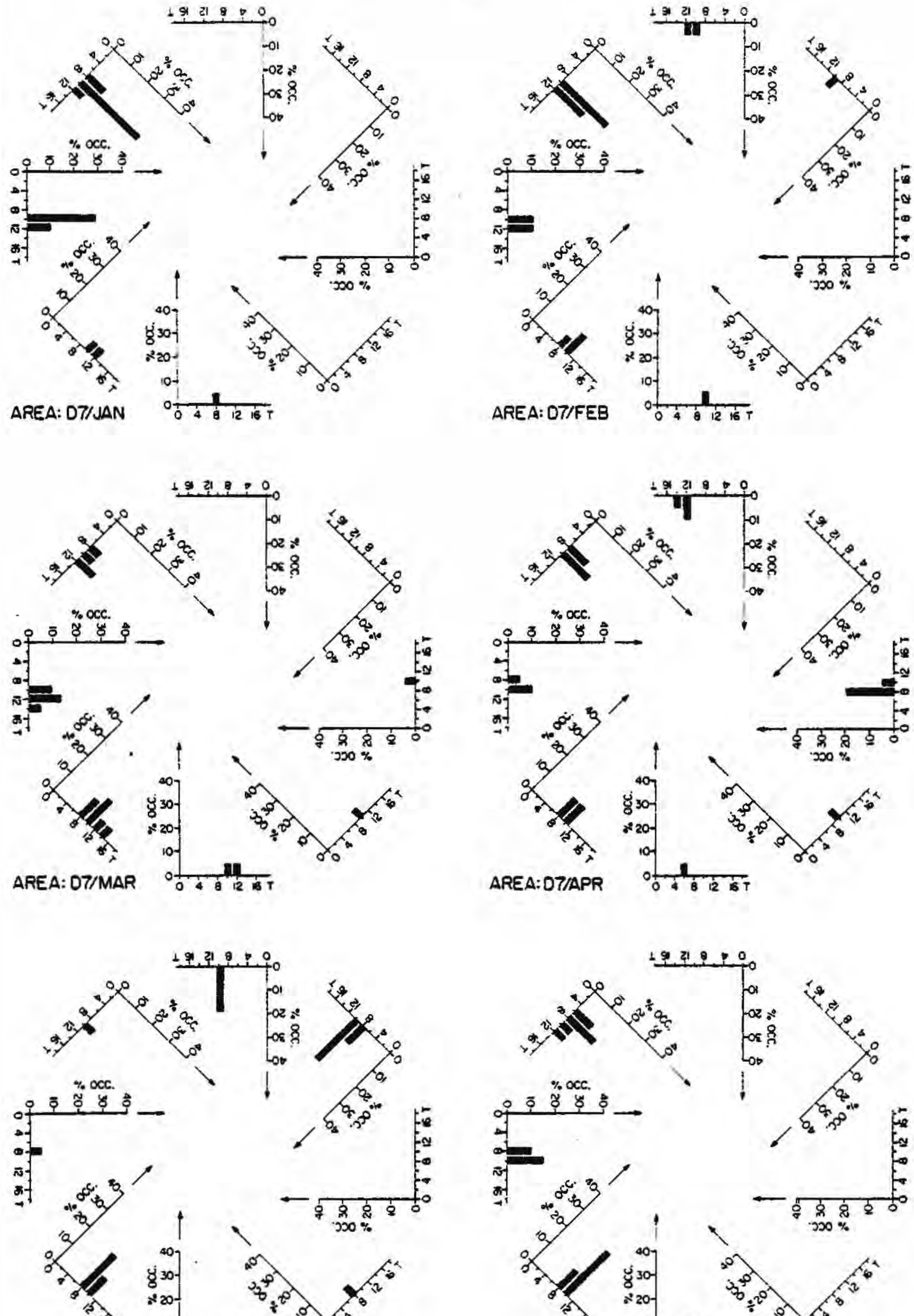



Fig. 28a. Directional period ($T_V$) distribution of the 20 largest storms each month during the 11 years; January to June

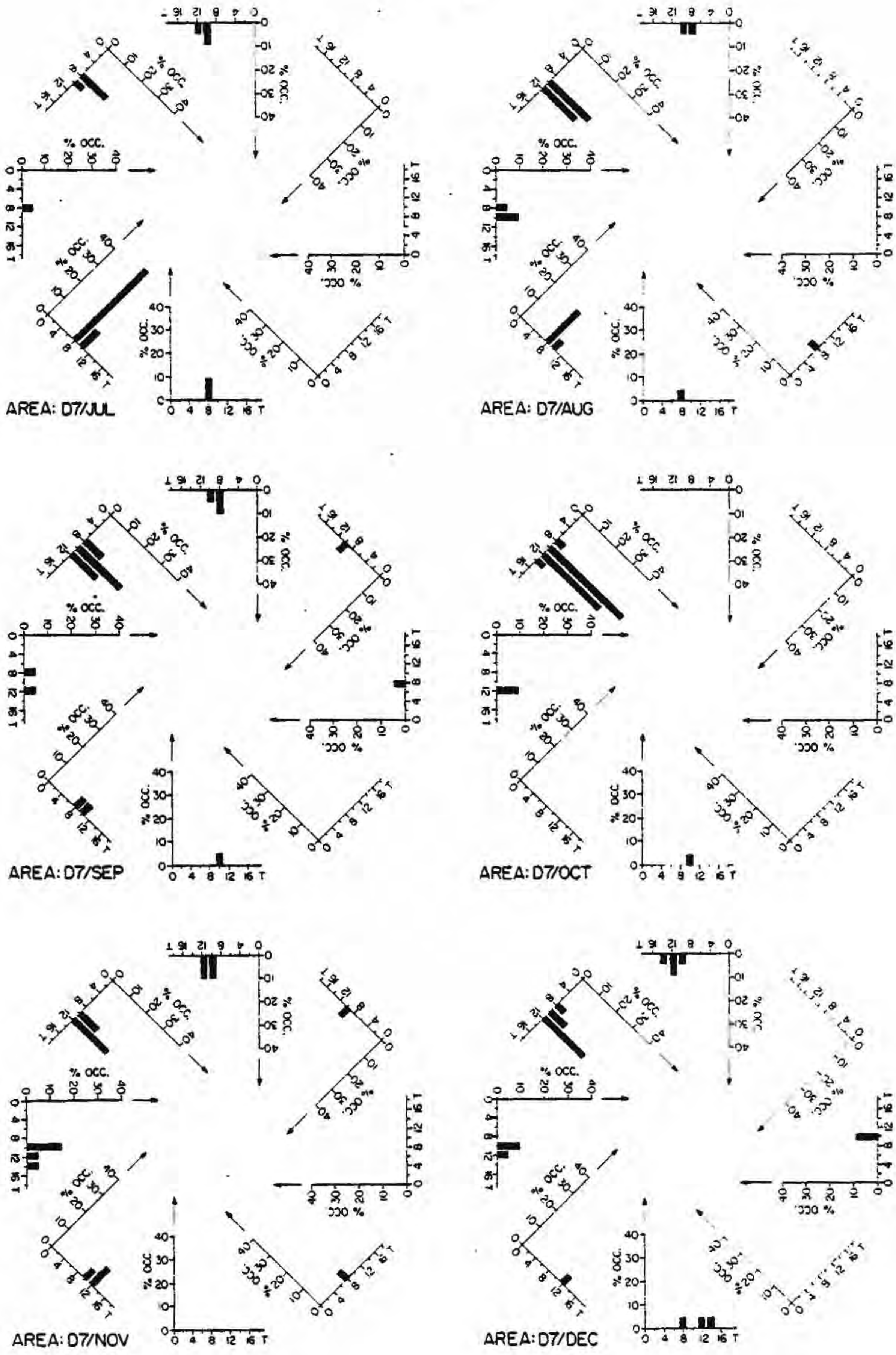



Fig. 28b. Directional period ($T_v$) distribution of the 20 largest storms each month during the 11 years; July to December

periods of the waves from the southwest are about 1 to 2 s longer than those from the northwest. The monthly frequencies and direction vary greatly but the prime direction is also from the northwest to southwest sector.

## 5.8 Directional Wave Energies at D7 (HIBERNIA)

Since wave energy is basically the product of the square of the wave height and the period, it provides a useful expression of the joint factors in seastate activity, particularly so when directions are also included. For this purpose directional energy spectra were developed for D7 (HIBERNIA) for every second month. In this case, all the wave observations are utilized, not just the waves of larger storms, and the energy level calculated from $H_{sig}$ and $T_V$.

As shown in Fig. 29, in January, a major part of the energy, about 30%, came from northwest while smaller portions came from west, southwest and also from southeast. In March, May and July the energies declined to summer conditions but were more from southwest than from the other directions, while in September and November, energies were increasing to winter conditions. As can be seen, there is great similarity with the period distribution in Figures 28a and 28b, particularly in their direction.

## 6. CONCLUSION

According to recent estimates, probably one quarter of the world's oil lies beneath the continental shelf areas of the world. In Canada, gas and oil explorations are carried out on nearly all its shelves, including the Arctic. In the southern waters, waves present the greatest problem, while in the North ice is the prime concern. For the waters south of 60°N, a wave climate was therefore developed to clearly describe the seastate of the region in a practical and useful way. The study is based on an 11 year time series, that is on continuous observations from January 1, 1970 to December 31, 1980. The wave information derives from 12 hourly wave charts of the METOC Centre which are based primarily on visual observations for routine ship weather reports, but in recent years, particularly in Canadian waters, instrumental measurements from oil and gas exploration platforms are also included. Representative parameters, particularly germane to long-term and large-scale variations were developed which characterize the conditions. The study relates only to deep-water waves.

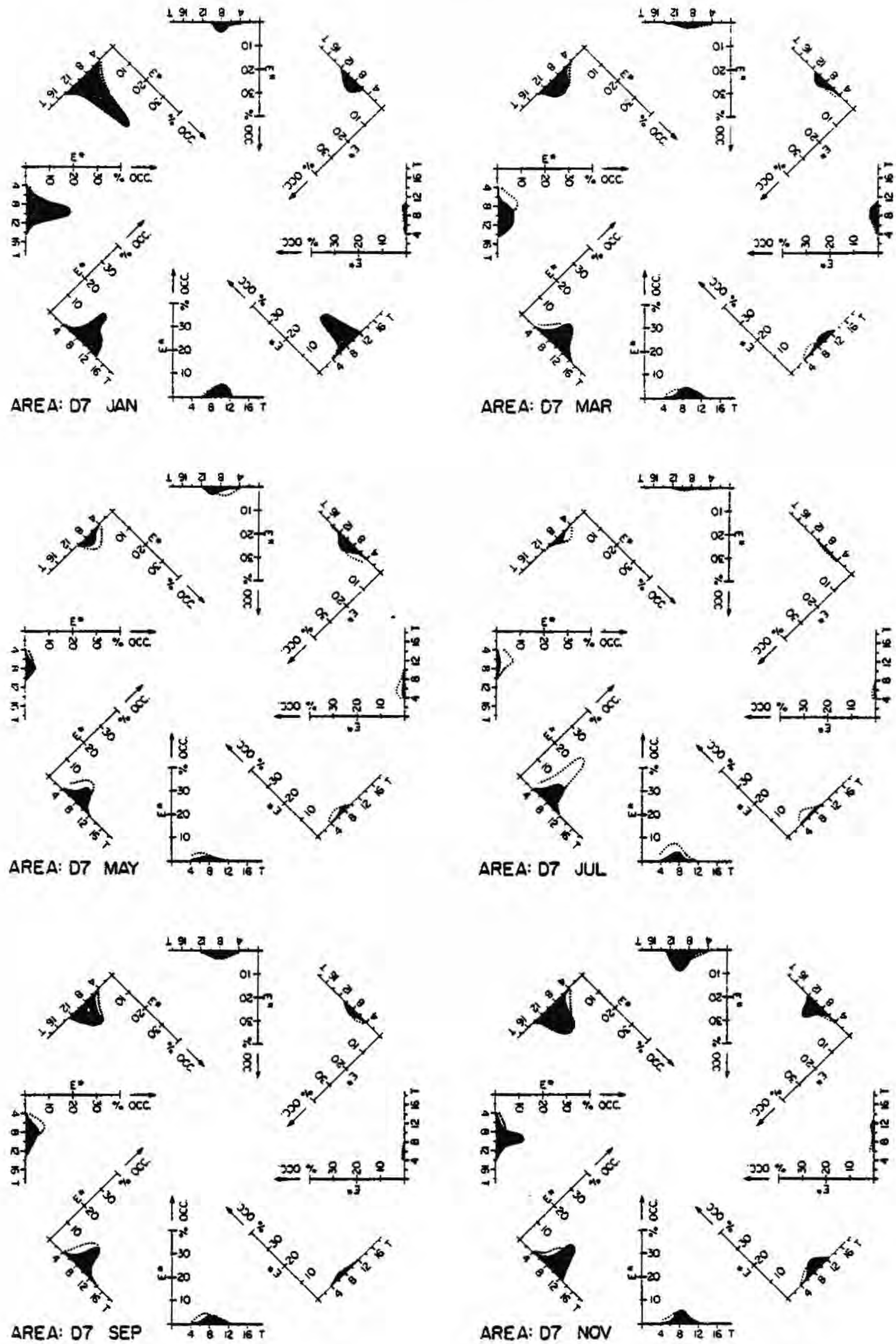



Fig. 29. Monthly directional energy spectra for D7 (HIBERNIA) based on 11 years data

Since waves are the obvious result of winds, long-term links between them were discussed. In the southern part of the Canadian waters, the Grand Banks included, both wind and waves did not show any appreciable change during the seventies; however, in the Labrador Sea and south of Greenland significant increases occurred in both during this period.

In the northwestern North Atlantic, waves are generated primarily by the prevailing westerly winds, which are in the winter more from the northwest and in the summer more from the southwest, as well as by the North Atlantic cyclones which form during the winter on the continental polar front and propagate along the coast of North America toward Iceland. During a winter season there may be as many as 250 of these disturbances. Many of them pass through Canadian waters. In late summer and autumn, a few tropical cyclones may follow the same route.

Wave statistics were obtained by fitting the observed wave data to a log-normal distribution, which in a compatibility test for HIBERNIA data showed a confidence level of 99%. This statistical distribution, which was used in all our previous analyses, was therefore retained to represent the 11 years data and for long-term prediction. From these, spatial and temporal wave charts were developed.

The results indicate that the seastate increases only slightly from near the U.S.A. border to the Grand Banks and from there to the Labrador Sea it remains practically constant, while seaward the seastate grows across the continental shelf by 1.5 to 2.2 m. For Sable Island and the centre of C4, for HIBERNIA and the centre of D7, and for the Labrador Sea, the normal annual and 10 year $H_{sig}$ with the respective extreme wave heights ($H_{max}$) obtained by conservatively multiplying $H_{sig}$ with a factor of 1.8, are given in Table 1.

The monthly largest $H_{sig}$ of a normal year varies for the three locations from about 7.5 m during the winter to about 4 m during the summer.

Wave periods and directions have only been processed for HIBERNIA and of these only the waves of the largest storms were analysed in their frequencies and directions. Waves with $H_{sig} \geq 8$ m had periods ($T_v$) not smaller than 8 s, but of the 11 largest waves of the 11 years with $H_{sig}$

TABLE 1

LARGEST ANNUAL (NORMAL YEAR), 10 YEAR AND PREDICTED 50 AND 100 YEARS $H_{sig}$ AND $H_{max}$

| LOCATION | 1 Year | | 10 Year | | Predicted 50 Year | | Predicted 100 Year | |
|---|---|---|---|---|---|---|---|---|
| | $H_{sig}$ | $H_{max}$ | $H_{sig}$ | $H_{max}$ | $H_{sig}$ | $H_{max}$ | $H_{sig}$ | $H_{max}$ |
| Sable Island | 8.7 | 15.7 | 11.7 | 21.0 | 14.2 | 25.6 | 15.3 | 27.6 |
| C4 | 8.5 | 15.3 | 11.6 | 20.9 | 14.1 | 25.4 | 15.2 | 27.4 |
| HIBERNIA | 9.0 | 16.2 | 12.3 | 22.2 | 14.6 | 26.3 | 15.6 | 28.1 |
| D7 | 9.5 | 17.1 | 12.7 | 22.8 | 15.1 | 27.2 | 16.1 | 29.0 |
| Labrador Sea-F6 | 9.3 | 16.8 | 12.5 | 22.5 | 14.9 | 26.8 | 16.0 | 28.9 |

exceeding 10 m, one had a period $T_v$ of 14 s ($T_{sig}$ = 15.5 s and $T_p$ = 17.0 s), five had a $T_v$ of 12 s ($T_{sig}$ = 13.2 s and $T_p$ = 14.5 s), four had a $T_v$ of 10 s ($T_{sig}$ = 11 s and $T_p$ = 12 s)), and the remaining one had a $T_v$ of 8 s ($T_{sig}$ = 8.8 s and $T_p$ = 9.6 s). During the latter seastate with $H_{sig}$ of 8 m and $T_v$ of 8 s, some of the highest waves, those exceeding 14 to 16 m, start to break. The rate of breaking increases with shorter periods and decreasing wave heights. The reason for the relatively large amount of breaking lies in the westerly winds and storms which generate relatively young seas with steep waves in the Canadian waters. The impact of this excessive breaking on structures and operations in the ocean must be investigated individually.

Climatological effects are not the same from year to year and neither are the wave activities. One of the most outstanding features of the 11 year data bank are long-term 3 and 6 year quasi-cyclic variations in the wave climate in which the height of the larger waves varied by about 40%; that is, larger than during the regular normal cycle between winter and summer. From this it is obvious that long-term extreme value prediction and related ocean climatic studies must be based on data banks of at least 6 years, preferably 12 years or more as even longer cycles are possible. Predictions based on shorter time spans may differ greatly.

## 7. ACKNOWLEDGEMENT

The person contributing most to the success of the project was R.E. Walker who read and processed millions of wave data, developed and applied the required computer programs and prepared the greater part of graphs for this report. I am also grateful to F. Jordan who supplied the meteorological and ice data and helped to prepare the report and to P.E. Vandall, Jr., J.R. Wilson and J.A. Elliott for reviewing it.

Finally, acknowledgement is given to the Canadian Forces METOC Centre which provided the data in the form of wave charts. Without this information, the investigation would not have been possible.

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