023 Beaufort Sea Extreme Wave Studies Assessment

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BEAUFORT SEA EXTREME WAVE STUDIES ASSESSMENT

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TABLE OF CONTENTS

4. Sensitivity and Uncertainty Analysis

5. Design Considerations for Extreme Waves

6. Conclusions

LIST OF TABLES

List of Figures

ACKNOWLEDGEMENTS

SUMMARY

In this study, the two most recently publicly available hindcast studies for the Beaufort Sea have been reviewed. The studies, conducted respectively by Hydrotechnology and Seaconsult, differ markedly in their treatment of the storm windfields and the available fetch length. Consequently, there is a considerable disparity between their estimates of extreme wave heights for deep water conditions, although for shallow water the agreement is more favourable.

A systematic assessment of their respective methodologies indicated factors which would help to undo some of the conservatism in the Seaconsult estimates and warrant a slight increase in the Hydrotechnology results.

A probabilistic extreme wave estimation approach based on joint probability distributions for wind speeds, duration and fetch length has been used as part of a sensitivity analysis to show that the discrepancies in the two sets of published results can be largely explained in terms of the extreme fetch length and severe storm duration used by Seaconsult. The analysis also showed the sensitivity of the estimated wave height to wind speed and duration, a 20% increase in both cases produced increases of 20% and 10% respectively in wave height for all the return periods. The least sensitive parameter was fetch distribution where a 20% increase over the base case fetch length produced only a slight increase (about 3%) in the extreme significant wave height. It should be noted that the fetch length used in the Seaconsult study represents about a 250% increase over the base case, used in the sensitivity analysis.

On the basis of the critical review and the sensitivity analysis, it is concluded that an extreme wave height in the range of 8-9 m is appropriate for deep water locations. The Seaconsult shallow water wave heights show considerable energy losses and it is suggested that their estimate of extreme wave height is slightly on the low side for these conditions. A recommendation is made for an improved description of selected storm windfields using blended measured and derived surface winds as being the most effective means of arriving at a more definitive statement of extreme wave height.

RESUMÉ

Les deux études les plus récentes traitant de la hauteur des crêtes de vagues en Mer de Beaufort sont examinées. Ces études provenant d'une part de Hydrotechnology, et de Seaconsult d'autre part, diffèrent dans leur traitement respectif du profil des vents de tempête et de la distance portante du vent. De ce fait, l'estimation de la hauteur de vagues extrêmes en eaux profondes ne s'accorde pas, bien que pour les eaux peu profondes, les deux études soient concordantes.

Les deux méthodologies furent étudiées en detail, et indiquent certains facteurs qui perm ettent de réduire les estimations conservatives de Seaconsult et qui peuvent guarantir une légère augmentation des résultats de Hydrotechnology.

Une méthode probabiliste d'estimation de vagues extrêmes, basée sur la combinaison des distributions de vitesse du vent, de durée et de distance portante, a été utilisée dans une étude de sensibilité, pour dé montrer que la disparité entre les résultats des deux études, peut s'expliquer principalement par le choix de la distance portante extrême, et par le choix de la durée de tempête de Seaconsult.

L'analyse a montré également que la sensibilité de l'estimation de la hauteur de vague, à une perturbation de 20% soit de la vitesse du vent, soit de la durée du vent, produit un accroissement de la hauteur de vague extrême de 20 et 10%, respectivement.

Par ailleurs, une hausse de 20% de la distance portante du vent ne produit qu'une augmentation de 3% de la hauteur de vague extrême. Il faut noter en outre, que la distance portante utilisée dans l'étude Seaconsult, produit une hausse de 250% dans l'analyse de sensibilité.

La revue critique et l'analyse probabiliste démontrent que la hauteur extrême de vagues en mer profonde est de l'ordre de 8 à 9 m. Les prévisions de Seaconsult pour les eaux peu profondes sont légèrement sous-estimeés à cause de pertes d'énergie considérables. Les auteurs du présent rapport suggèrent une méthode rigoureuse pour estimer la hauteur de vagues extrêmes à l'aide de profils de vents de tempê obtenus à partir de vents mesurés et déduits.

1.0   INTRODUCTION

Over the course of the past 25 years or so, the Beaufort Sea has been the scene of much hydrocarbon exploration activity. As these efforts continue and move closer to a production phase, they must be supported by a constantly improving description of all of the environmental hazards confronting safe operations.   Although ice is generally regarded as posing the greatest threat of disruption to activities, recent experience has shown that wave action is also of considerable importance, affecting not only structural adequacy, but also installation procedures and the selection of operational equipment.   For example, severe storm-induced waves caused the temporary evacuation of the Tarsiut site in July 1982 and eroded a 1-m depth of gravel fill at the base of the caisson. Thus, a sound knowledge of the wave climate in an area is important in ensuring the safe and economic construction and operation of offshore production and exploration facilities.

1.1   PURPOSE OF THIS STUDY

A number of studies have been undertaken during the past 15 years with the object of quantifying the worst sea states in the Beaufort Sea for the purpose of establishing suitable design criteria. There is a wide disparity in the results obtained in these studies and in particular, the values of significant wave height associated with return periods of extreme waves. The disparities result largely from the different data bases and methods used to arrive at extreme values. The purpose of the present assessment is to seek to explain and, if possible, reconcile differences through a comparison of the methods and assessment of the data used.   In addition, shortcomings, weak assumptions, and uncertainties associated with the various methodologies are to be identified and suggestions for improvements made. To meet these objectives, the assessment is broken down into a number of tasks discussed in the following sections.

2.   REVIEW OF EXISTING EXTREME-WAVE STUDY METHODOLOGIES

2.1   INTRODUCTION

Over the past 14 years, six quite extensive hindcast extreme-wave studies have been performed for the Beaufort Sea area (Table 1), the results of which are available as a matter of public record.

TABLE 1

Hindcast extreme-wave studies publicly available

Group performing the hindcast	Year of study	Sponsoring agency
Institute for Storm Research (ISR)	1971	ELF Oil Exploration and Production (Canada) Ltd.
Intersea Research Corporation (IRC)	1974	Imperial Oil Company Ltd.
Dames and Moore	1975	Atmospheric Environment Service, Environment Canada
Brower et al.	1977	U.S. Dept. of Commerce
Hydrotechnology Ltd. (Baird and Hall)	1980	Gulf Canada Resources Inc.
Seaconsult Marine Research Ltd., Danish Hydraulic Institute (DHI), and Meteorological and Environmental Planning Co. Ltd. (MEP) (Hodgins et al.)	1981	Esso Resources Canada Ltd.

In addition to these studies, similar works of a proprietary nature have been carried out by, or for, Dome, Esso, Gulf, among others, including the joint industry Arctic Petroleum Operators Association study APOA 205, "Design Criteria for Arctic Offshore Production Platforms," and APOA 203, "Beaufort Sea Hindcast Study 1970-82." Although the latter study does not address the estimation of

extreme wave height specifically, it does contain the most up-to-date and comprehensive coverage and analysis of the measured wind-fields in the Beaufort region and extends the data base used in the Hydrotechnology study by two more years.

In the six publicly available studies, extreme wave heights were estimated, using a relatively sparse data set of wind records, rather than being extrapolated from an even more limited record of measured wave heights. This practice is fairly common for most offshore locations, for which wave data covering a statistically significant time period may not exist. Hodgins and Dal Santo (1981) did, however, in a study conducted by Seaconsult for Esso, analyse both normal and extreme wave conditions in the Beaufort Sea based on observed sea states. Their major conclusion was that there was no clear preference for one type of probability distribution over another when fitting the measured wave data. They also concluded that the wave data base at their disposal was too short to provide reliable design wave estimates.

In 1983, Seaconsult (Hodgins, 1983) reviewed the publicly available studies listed in Table 1 on behalf of the Marine Environmental Data Service of the Department of Fisheries and Oceans. It is not the intention of the present assessment to repeat this task. It is sufficient to note at this stage that, of the six studies reviewed, all but one used a parametric hindcasting method, the exception being Seaconsult, who chose to use a spectral approach. A pictorial comparison of extreme value distributions of significant wave height for six of the studies is shown in Figure 1, from which it can be seen that the difference that exists between the Seaconsult results and those obtained in the closest parametric model is almost as large as the differences within the group of parametric studies. It is appropriate, therefore, that the present assessment should concentrate upon the differences between the best of the parametric studies and the 1981 Seaconsult study. It is fair to note that in their 1983 review, Seaconsult made a number of recommendations that warrant reducing the extreme values in their earlier study by 30%.

The 1980 Hydrotechnology study (Baird and Hall, 1980) is widely acknowledged to be the best of the publicly-available parametric studies, not only because of the longer data base of wind records available to it at the time that the study was performed, but also the care with which the hindcasting was implemented. The discussion in this section concentrates on describing the methods used in each of the studies, with Seaconsult's 1983 modification of their original hindcast study treated simply as an extension of their earlier effort. More critical comment on the methodologies used is reserved for Chapter 3.

In assesing both studies, it should be emphasized that they differed in their terms of reference, as well as in their means of execution. Both studies are of high technical quality and appear to have been carefully performed. Nevertheless, as with any study, time and budget constraints always make it possible to return to it and find fault. The spirit of what follows is one of seeking to recognize and address potential problems and difficulties to prevent them from being repeated in future studies.
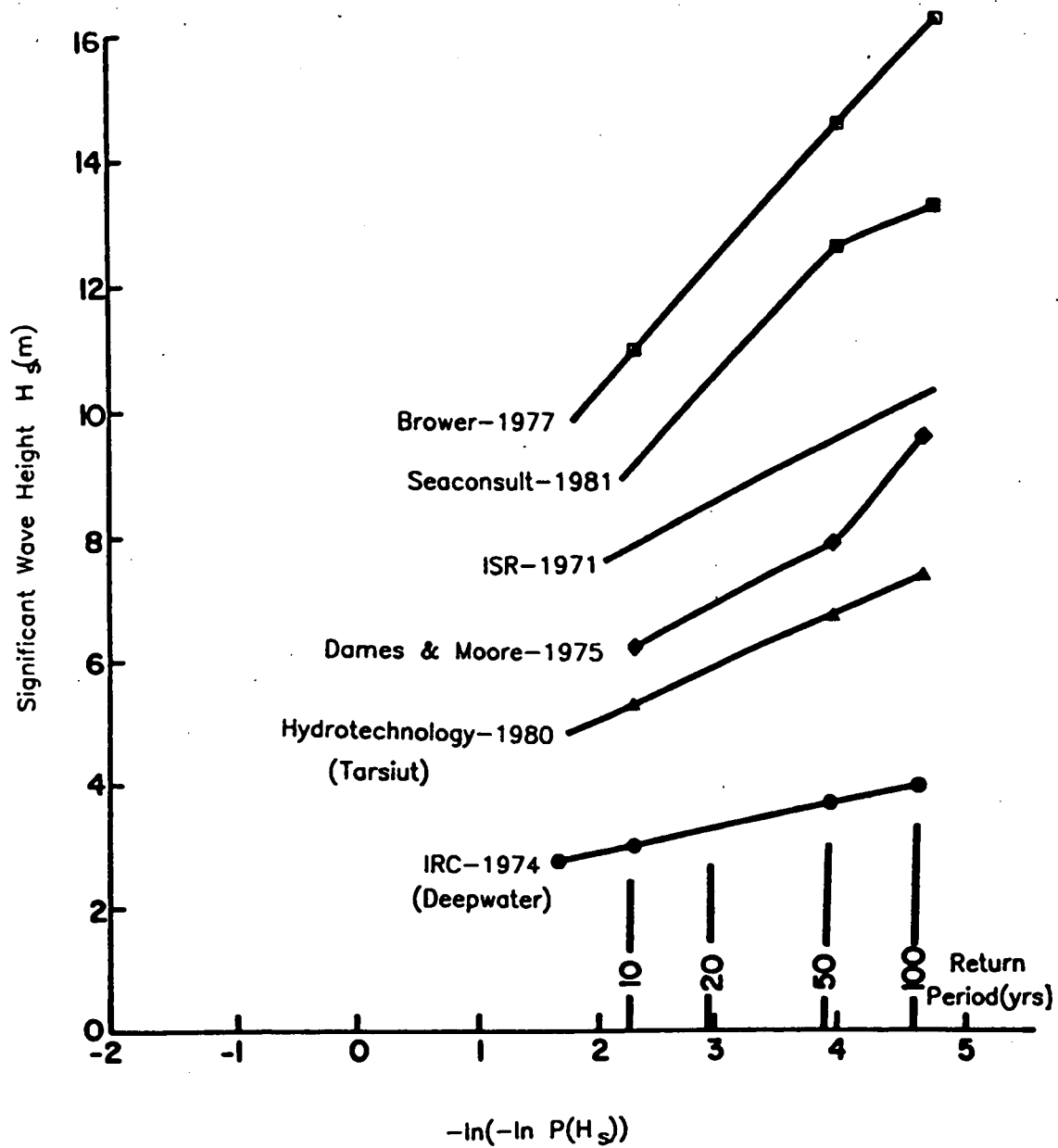
Figure 1.   Comparison of extreme value distribution of significant wave heights
for the Beaufort Sea from various hindcast studies (source: L.R. Muir,
COGLA 1984, Private Communication)

2.2 BASIS FOR COMPARISON

The Hydrotechnology and Seaconsult studies use quite different approaches for estimating extreme wave height, nevertheless, it is felt that some organization of the critique and other pertinent discussions can be maintained by examining five distinct aspects of hindcasting, namely:

- storm/event selection,
- wind-field methodology,
- wave model application,
- verification effort, and
- statistical estimation techniques.

Each of the five aspects noted can be shown to affect directly, by varying amounts, the accuracy of the estimate of extreme wave height. An attempt to quantify these error magnitudes and uncertainties is made later in this report.

2.3 THE HYDROTECHNOLOGY HINDCAST STUDY

Hydrotechnology Ltd. were commissioned by Gulf Canada Resources Inc. in 1980 to develop a wind-wave hindcast procedure to improve the definition of normal wave conditions in the Canadian Beaufort Sea. Although extreme-wave heights are determined for the six locations indicated in Figure 2, the extreme value analysis appears to have been a by-product of the study rather than its principal objective.

2.3.1   Storm/Event selection

Hydrotechnology hindcast the ten open-water seasons of 1970 to 1979 for the six locations (see Figure 2). The annual maximum wave height predicted for each site for each year was selected for inclusion in the analysis.

2.3.2   Wind-Field methodology

To provide reasonable descriptions of the normal and extreme-wave climatic conditions at the six locations specified by Gulf, Hydrotechnology required a minimum of ten years of wave data to be hindcast from reliable estimates of the overwater wind-fields available at hourly intervals throughout the open-water season. They initially considered deriving the overwater wind-field from synoptic charts, but concluded that these charts often failed to describe storm conditions that were evident from contemporaneous wind and wave records for the area. They were also concerned about providing an accurate description of the overwater boundary layer.

BANKS ISLAND

BEAUFORT SEA

CAPE BATHURST

E +

D +

A + B + C +

F +

HERSCHEL ISLAND

TUKTOYAKTUK

~ INUVIK

Site No.	Position	Name
A	69°57'N 136°30'W	Tarsiut
B	70°5'30"N 134°27'W	North Issungnak
C	70°14'N 133°30'W	West Tingmiark
D	70°24'N 135°12'W	Kopanoar
E	70°34'N 130°50'W	Kaglulik
F	69°45'N 139°45'W	Natsek
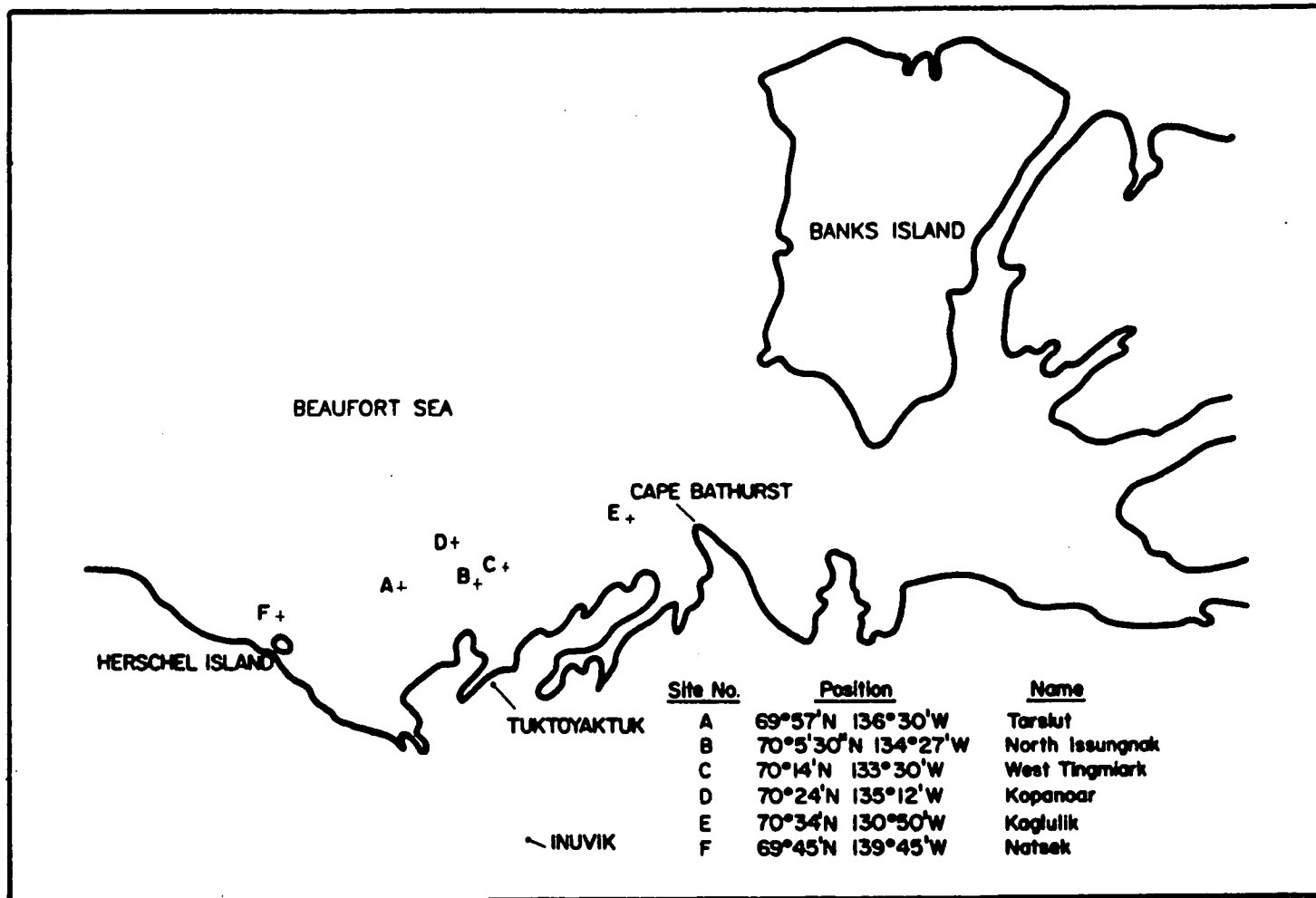
Figure 2   **Hindcast Sites for the Hydrotechnology - 1980 Study**

They chose instead to use the wind speed and direction time histories measured at Tuktoyaktuk airport, using a U2A-type anemometer, recognizing that some of these records were of doubtful quality and that they also contained periods of missing data. Nevertheless, a comparison of sample Tuktoyaktuk data with those measured over the Beaufort Sea at the Kopanoar and Ukalerk drill-ship sites (Figure 3) provided sufficient similarity, they felt, for them to adopt this approach.

They paid considerable attention to developing a suitable set of overland to overwater wind scaling factors, which were then applied to the winds measured at Tuktoyaktuk to obtain spatially homogeneous wind-fields for each hour during open-water conditions. However, they paid no attention to the possible importance of spatial wind-field gradients.

To overcome one of the constraints, that is, the need for a slowly varying wind-field imposed by the use of their particular wave hindcast parametric model, they used a nine-point running average within the data record to smooth the wind directions. There was no corresponding smoothing of the wind velocities incorporated into the wind-field estimates.

2.3.3 Wave model application

The Hydrotechnology wave model essentially used the Bretschneider wave hindcasting equations (Bretschneider, 1973; and given in Coastal Engineering Research Centre, Shore Protection Manual, 1977). The Bretschneider equations are based on dimensionless relationships between significant wave height H, peak period T, wind speed U, fetch F, and duration t. They have the following following form:

$$\frac{gH}{U^2} = 0.283 \ \tanh\left[0.530\left(\frac{gd}{U^2}\right)^{0.75}\right] \tanh\left[\frac{0.0125\left(\frac{gF}{U^2}\right)^{0.42}}{\tanh\left[0.530\left(\frac{gd}{U^2}\right)^{0.75}\right]}\right] \quad (Eq.1)$$

$$\frac{gT}{2\pi U} = 1.20 \ \tanh\left[0.833\left(\frac{gd}{U^2}\right)^{0.375}\right] \tanh\left[\frac{0.077\left(\frac{gF}{U^2}\right)^{0.25}}{\tanh\left[0.833\left(\frac{gd}{U^2}\right)^{0.375}\right]}\right] \quad (Eq.2)$$

and

$$t_{min} = 2 \int_0^{F_{min}} \frac{1}{C_o} \ dx \quad (Eq.3)$$
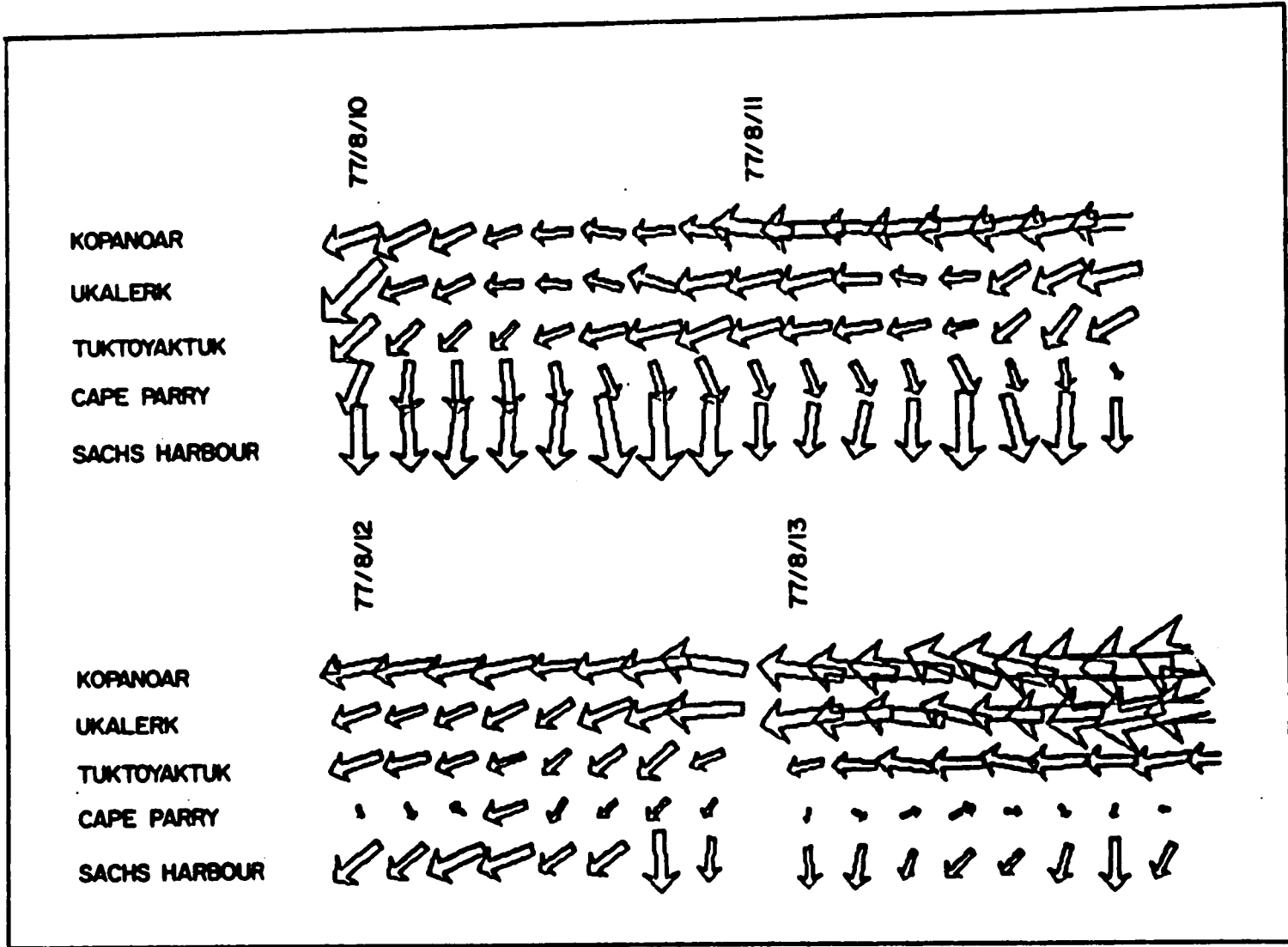
Figure 3.   An example of unmodified wind velocity vectors onshore and offshore (Source: Baird and Hall 1980).

These equations are solved given the wind-speed U, the duration of the wind-speed, t, the average water depth, d, and the fetch length, F, in the direction from which the wind is blowing. The significant wave height, H, and the significant wave period, T, are calculated by using the lesser value of the actual topographical fetch length or the equivalent duration limited fetch.

Strictly speaking the Bretschneider equations are only applicable for winds of constant speed blowing from one direction over a long period of time. In addition, they should be applied only to the type of open-water conditions for which the empirical constants in the equations have been evaluated, which aspect is touched upon in Section 4.4. To overcome the first limitation, Hydrotechnology introduced a modification to the method of applying the Bretschneider equations to permit the effects of changing wind direction and wind speed on the calculation of significant wave heights to be taken into account (Baird 1978; Baird and Glodowski 1978). The modification introduced by Hydrotechnology primarily affects the calculation of wave height with changing wind direction, although changes in wind speed can also be taken into account.

In essence, the procedure followed in the computer-based method was to calculate wave height continuously for each hour in the data period. At any one hour in the sequence of wind data having constant direction, the wave height was determined using the average wind speed during the preceding hour. The calculation was then repeated using the average wind speed over the preceding n hours (where n took the values 1,2,3,...96 hours), or until the record indicated a change in wind direction. The associated duration in each of the calculations was taken to be n hours. The largest value of all the wave heights resulting from these calculations for the hour in question was recorded, along with the associated wave period and the wind direction to represent that hour. The program then stepped forward by one hour and the procedure was repeated. When a change in wind direction was noted in the data set, the wave height estimated for the hour preceding this change was assumed to start decaying. Provided the wind direction then remained constant, new waves were generated in the new wind direction using the averaging procedure described previously. The resulting significant wave height was calculated from the square root of the sum of the squares of the actively generated, and decaying, wave height components. This procedure follows directly from the assumption that each wave is independent, and that the energy in the system is conserved, which is clearly not the case in a growing sea. The empirical equations, however, appear to be robust enough that, despite the physical inconsistency, the hindcast wave-heights produced by the method show good agreement with measured values. The wind direction and wave period recorded for each hour were those associated with this calculated significant wave height. For slowly varying wind directions, the Hydrotechnology model should produce results equivalent to those of the Bretschneider model.

The wave model was run continuously for all ten open-water seasons (1970-79), with the ice limits specified by the position of the average monthly limits of the one-tenth ice cover. Fetch lengths were computed as the actual straight line distances from the hindcast point to the land edge or the limit of the one-tenth ice cover. The position of the ice edge was defined using the "Current Ice Condition Charts" prepared by Ice Forecastng Central of Atmospheric Environment Service (AES). These charts are based on observations made by aircraft and ships in the area, shore ice reports, and

since 1976, satellite imagery (Marko 1975). In most instances, the leading edge of the ice is not very diffuse, though its position is dependent upon wind conditions. A typical ice condition chart is illustrated in Figure 4. The time period during which the ice edge progresses and retreats can vary significantly from year to year. In the ten seasons covered by the Hydrotechnology study, the period of open water varied from a maximum of four months (July - October) in some years, to an essentially no ice-free period in 1974. The maximum extent of open water in the years 1970, 1972, 1974, 1976, and 1978 is illustrated in Figure 5.

It is not immediately obvious from the Hydrotechnology study how shallow water effects, such as refraction or bottom friction, were taken into account. However, they do include a table of refraction and shoaling coefficients, inferring that these were applied to the hindcast results at the shallow sites. The form of the Bretschneider equation also implicitly contains a constant bottom-friction factor of 0.01.

2.3.4   Verification effort

2.3.4.1   Winds

To investigate the reliability of the Tuktoyaktuk winds as an estimate of the overwater wind field at Kopanoar and Ukalerk, the offshore wind data were modified to account for the assumed height of the anemometers (61 m) and the Tuktoyaktuk data were modified to account for overland friction. A 1/7th power law was used to reduce the wind speeds at Kopanoar and Ukalerk to the 10-m reference height at Tuktoyaktuk. No positive justification was given for the use of a 1/7th power law, merely that the other limitations on the quality of the data did not warrant any further improvement. The scaling factors for overwater to overland winds were obtained initially using a procedure developed by AES, whereby specific overwater measurements were compared with contemporaneous overland measurements. The scaling factors quoted in an AES study for the Beaufort Sea (Lalonde and McCulloch 1975) were applied to the Tuktoyaktuk winds and were then compared to the recorded winds at Kopanoar and Ukalerk, which had been adjusted for height. The extent of the data base used in this exercise is illustrated in Table 2. Hydrotechnology claimed that the AES scaling factors produced erroneous results, tending to overestimate the overwater wind speed with the error accentuated for the lower wind speeds. They decided to develop a new set of ratios based on the frequency of occurrence of wind-speed intervals for the data sets at Tuktoyaktuk, Kopanoar, and Ukalerk.

Having first modified the onshore and offshore wind-speed records as described above, they constructed histograms of the data (Figure 6) and used the shape of these to establish a transfer function between the data sets for Tuktoyaktuk and the offshore sites. The goodness of fit between the onshore Tuktoyaktuk and the modified, offshore wind distributions were obtained by visual inspection of the histograms. These histograms are marginal distributions because wind speed and directions are bivariate, although, for this purpose, wind direction appears to have been treated as being constant. A comparison of scaling factors calculated using the AES method and using the transfer function approach is shown in Figure 7. The same information, augmented by work done by Resio and Vincent (1979), is provided in Table 3.
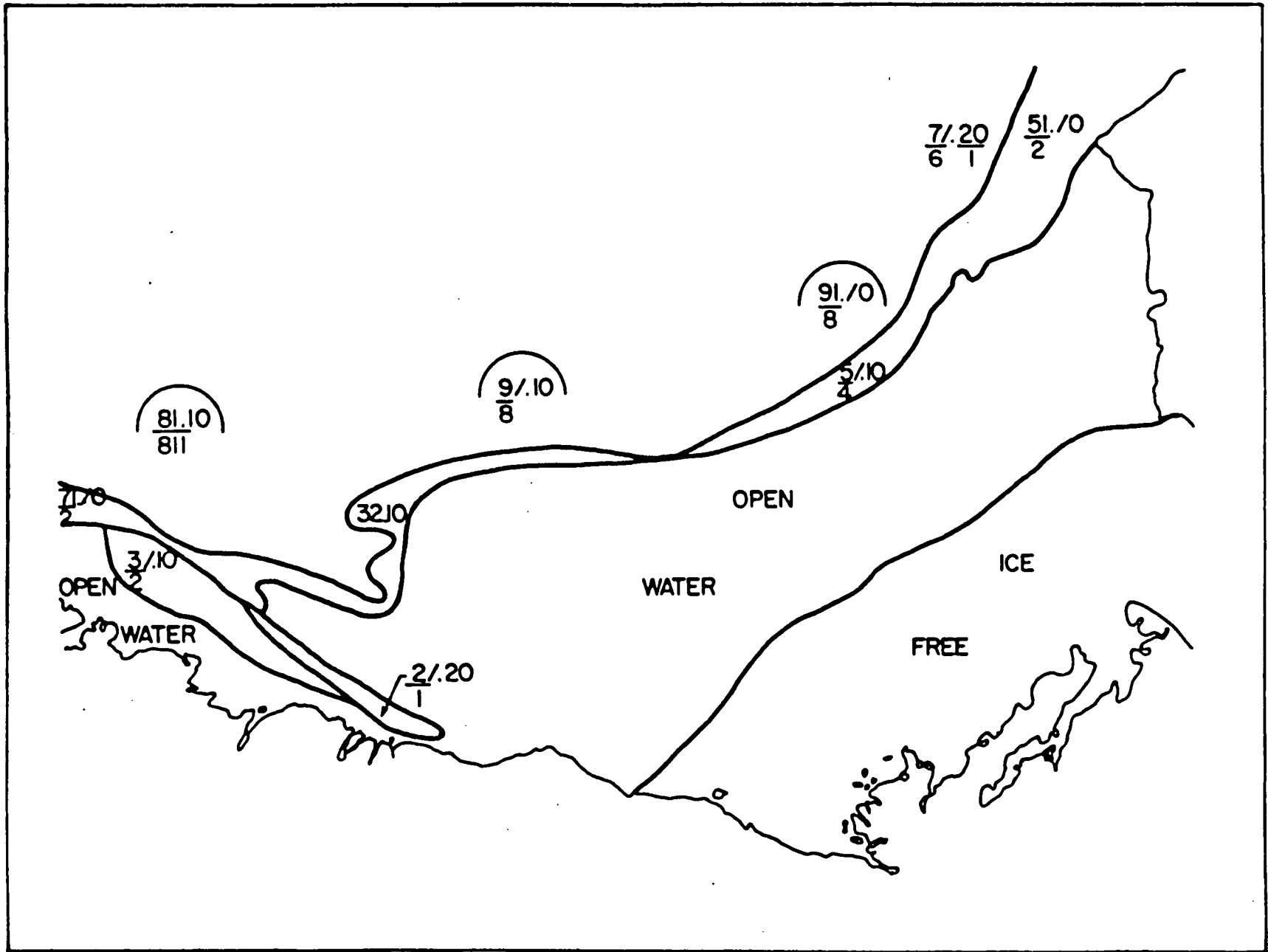
Figure 4. Typical chart of current ice conditions issued by
ice forcecasting central, AES, Ottawa.
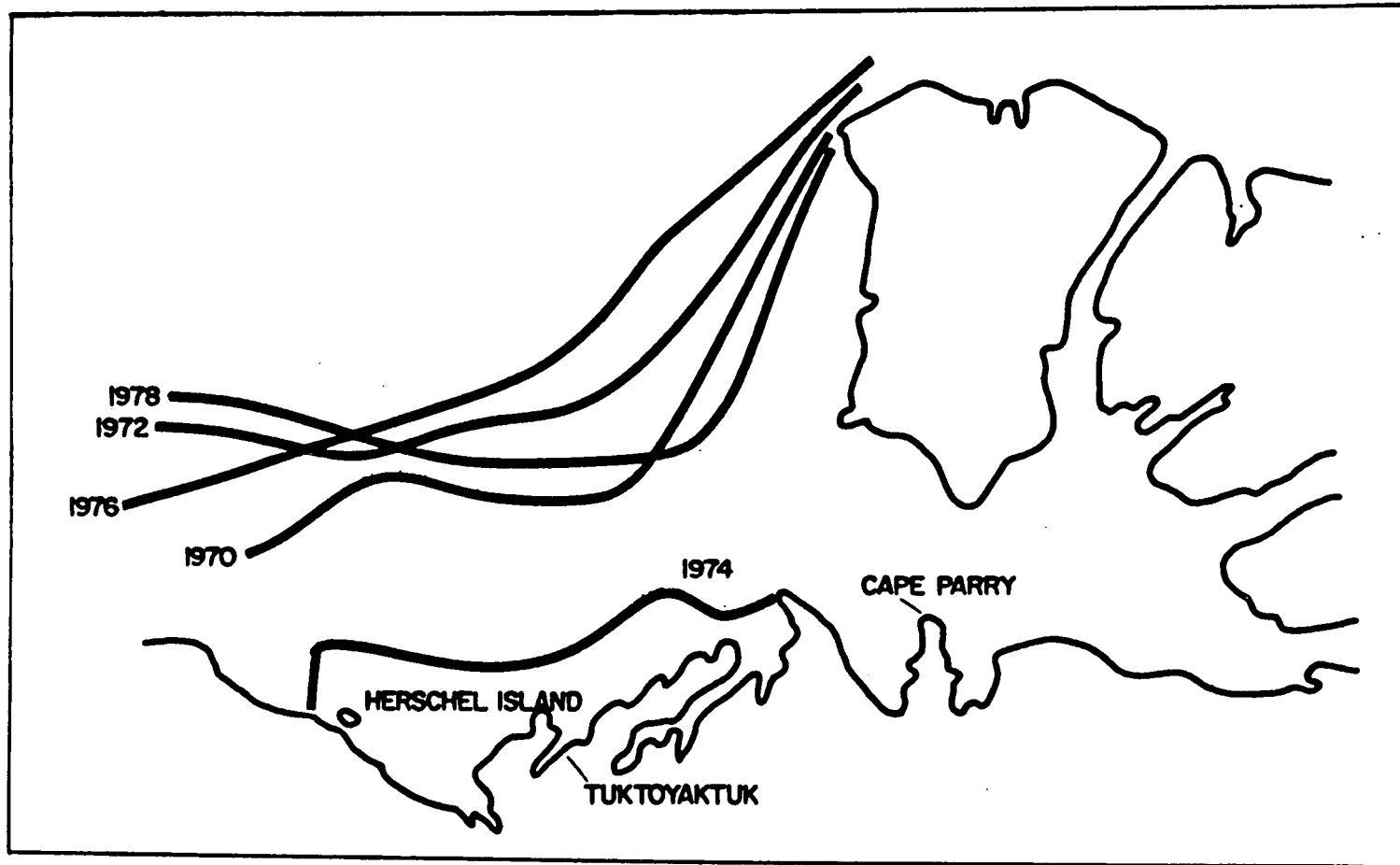
Figure 5. Approximate limits of maximum open water occurring in 1970, 1972, 1974, 1976, and 1978 (Source: Baird and Hall 1980).

TABLE 2

Availability of wind data for wind ratio analysis

| | 1976 | | 1977 | | 1978 | | 1979 | |
	Start	End	Start	End	Start	End	Start	End
Kopanoar	7 August	17 October	19 July	5 October	24 July	16 October	9 August	12 September
							9 October	30 November
Ukalerk			22 July	24 October	7 July	18 October	2 July	9 August
Tuktoyaktuk	1 July	31 October	1 July	31 October	1 July	31 October	1 July	30 November

Source: Modified from Baird and Hall, 1980.
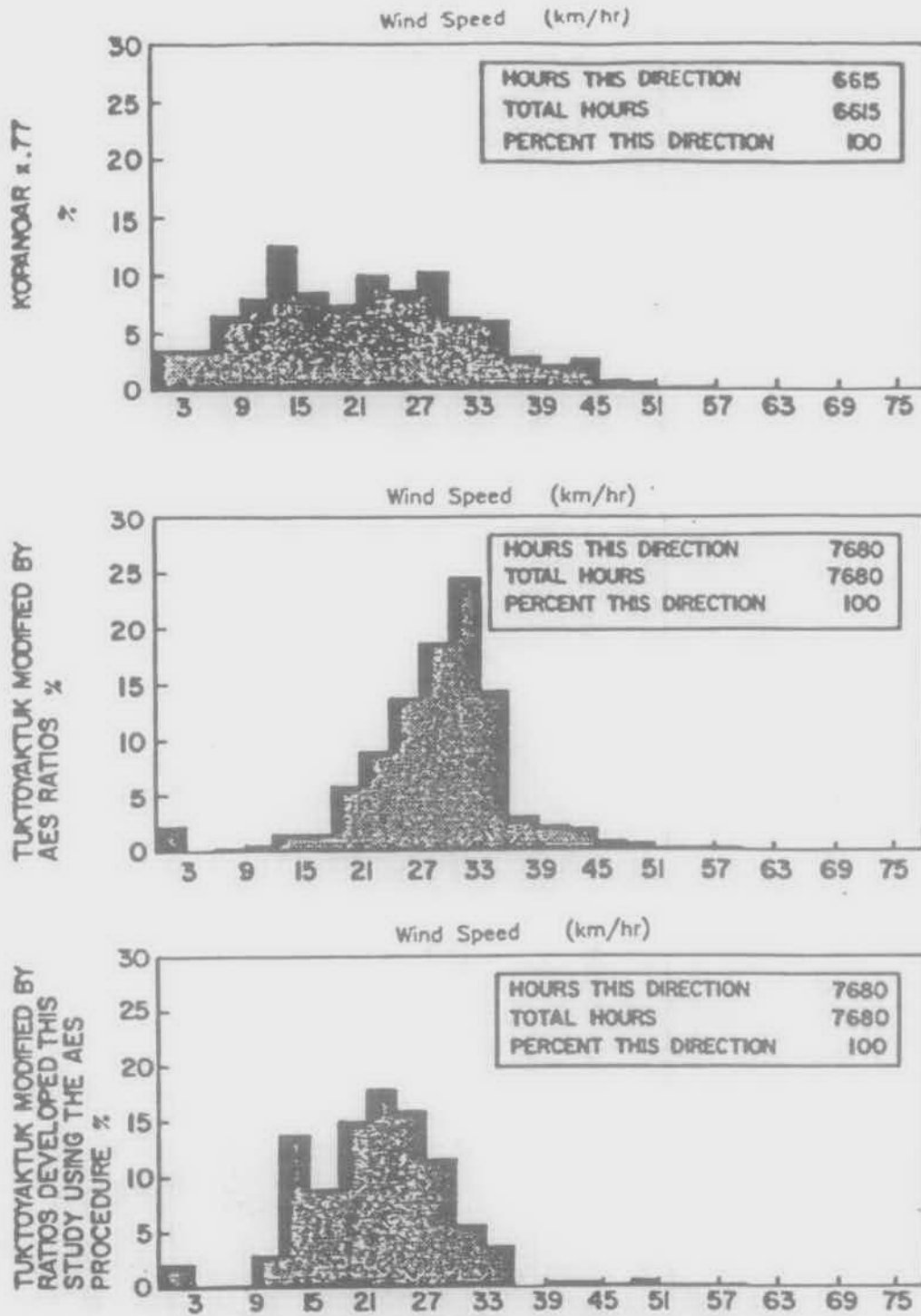
Figure 6.   Marginal distributions for wind speed at Kopanoar, Ukalerk, and Tuktoyaktuk (source: Baird and Hall 1980).
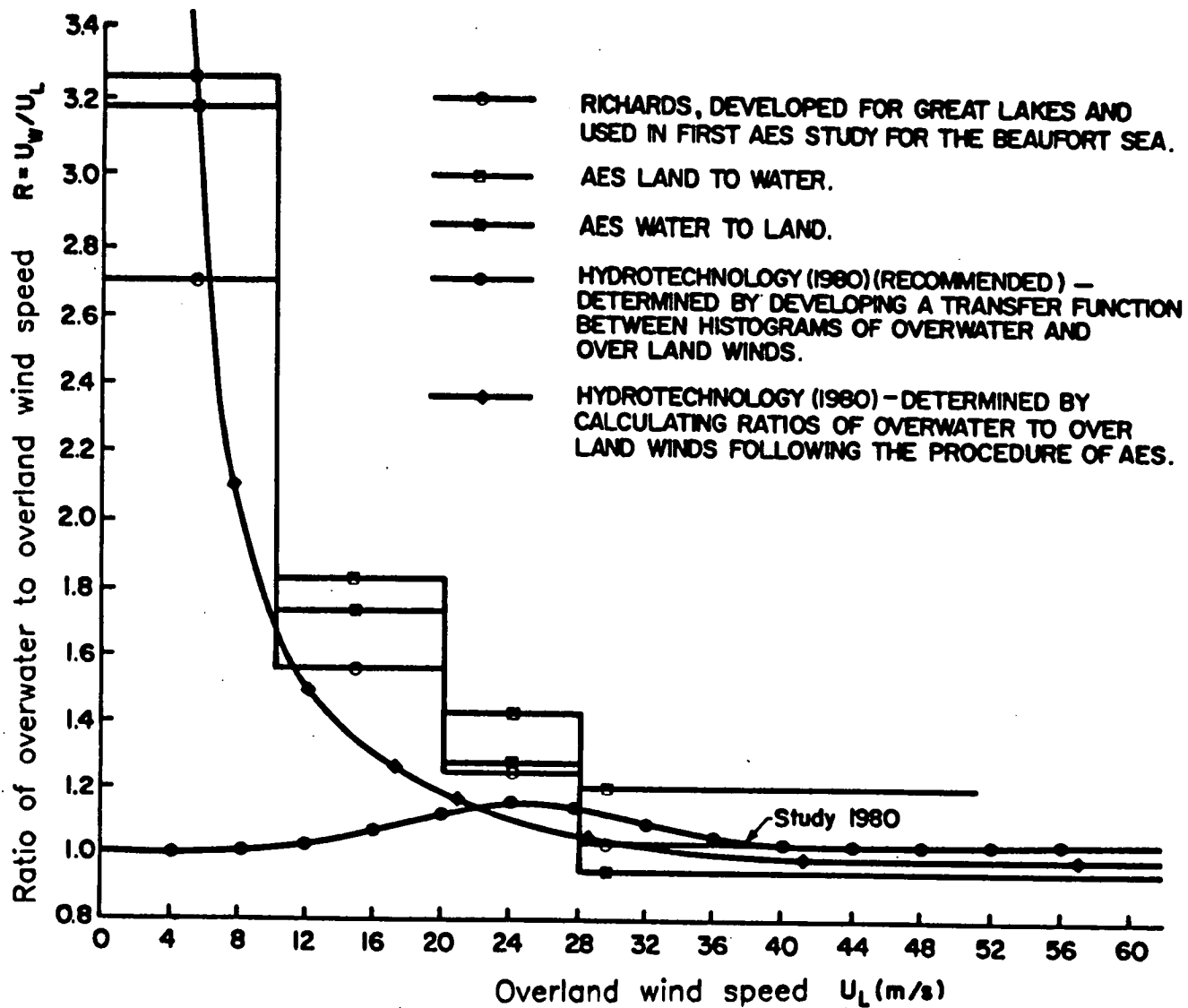
Figure 7.   Comparison of overwater to overland scaling ratios
(Source: Baird and Hall 1980).

TABLE 3

Comparison of overwater to overland wind speed ratio

Study	Wind Speed (km/hr)												
	2	6	10	14	18	22	26	30	34	38	42	46	50
Hydrotechnology (Baird and Hall 1980)	1.00	1.00	1.02	1.07	1.11	1.15	1.13	1.08	1.05	1.04	1.03	1.03	1.03
Resio[1] modified by Baird	1.04	1.11	1.30	1.42	1.45	1.44	1.40	1.36	1.31	1.27	1.24	1.22	1.21
Resio[1]	2.34	2.00	1.80	1.60	1.60	1.50	1.42	1.36	1.31	1.28	1.25	1.23	1.22
Richard 1970[1,3]	2.65	2.65	1.55	1.55	1.26	1.26	1.02	1.02	1.02	1.02	1.02	1.02	1.02
AES 1975[2,3] land to water	3.17	3.17	1.82	1.82	1.42	1.42	1.20	1.20	1.20	1.20	1.20	1.20	1.20
AES 1975[2,3] water to land	3.26	3.26	1.72	1.72	1.28	1.28	0.95	0.95	0.95	0.95	0.95	0.95	0.95

Notes: 1. Great Lakes.
        2. Beaufort Sea.
        3. Average weighted values from studies that consider stability.

Source: after Baird and Hall 1980.

- 16 -
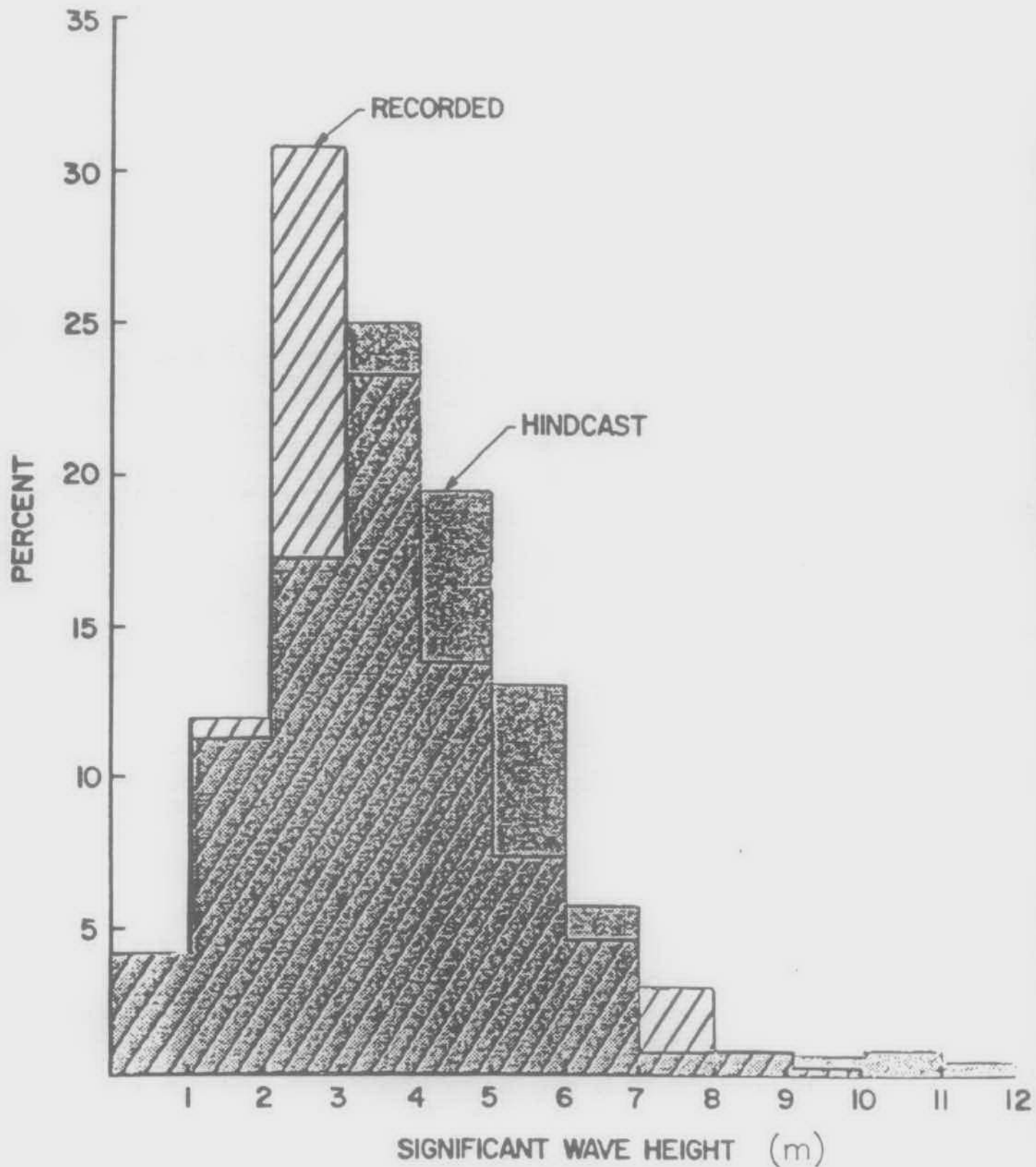
Figure 8.   Comparison of recorded significant wave height and hindcast significant
              wave height at Kopanoar, August and September, 1977 (source: Baird
              and Hall 1980).

No time series comparisons are included in the Hydrotechnology study, nor is there any quantitative discussion of likely errors in the estimation of wind speed and their effects on the estimation of extreme wave heights. Instead, a pictorial representation (see Figure 3) is provided of the velocity vectors averaged over three hours, based on the unmodified winds recorded at Tuktoyaktuk and at several offshore sites for a sample period in August 1977. The Tuktoyaktuk data have been assumed to be representative of the over-water winds at Kopanoar and Ukalerk for a large part of the time, although Hydrotechnology make no claim that the scaling factor remains valid outside of the data base.

2.3.4.2   Waves

Hydrotechnology compared a number of time series of wave heights and periods at selected hindcast points to measurements taken from wave buoys. No quantification of the deviations between the two time series was included in their report, however descriptive comments would indicate that in a large number of cases, "good" agreement has been obtained. It is important to note that the complete hindcast methodology used in the verification comparisons was identical to that used in all production runs; consequently, deviations between measured and hindcast wave conditions can be regarded as characteristic of the actual errors inherent in the production hindcasts.

A further verification was included in the form of comparisons between histograms of measured and hindcast wave heights and wave periods (Figure 8). Although this is very important for verifying the validity of their methodology for operational conditions, it does not, however, provide much information on the validity of the methodology for the purposes of estimating extremes.

2.3.4.3   Statistical estimation techniques

The uncertainty in predicting a future value of wave height results from several causes. For the purposes of statistical analysis, two main areas are identified:

-    shortness of the data record; and
-    scatter in the data.

To estimate the return periods associated with extreme wave heights, Hydrotechnology selected as their sample the highest wave occurring in each of the ten years studied.

The usual technique in analysis of significant wave height extremes is to plot a function of the cumulative distribution, $F(y)$, (or in the case of the Gumbel, double exponential extremal distribution of extremes, $-\ln(-\ln F(y))$, against significant wave height. The cumulative values are estimated from the data. A straight line should result and it is then necessary to estimate the location and scale parameters of α and β, defining the line that is

$$y = \alpha(x - \beta)$$

from the plot. Results obtained by Hydrotechnology for the Tarsiut and Kopanoar sites are shown in Figures 9(a) and (b), respectively; the best-fit line presumably being obtained (because the methodology is not stated) by least squares regression. The use of least squares is not criticized here, however, the authors believe that, as regards confidence intervals, the methodology used by Hydrotechnology is inappropriate for two reasons.

a. It is based on a technique developed by Gumbel (1958, p.214) to compute the distribution of the mth order statistics (x_m) in N observations. No account is taken of the scatter of the obtained data points; in other words, the same standard error is obtained for data points with large and small scatter.

b. The methodology was developed for a value of m approximately equal to (N/2), that is, near the central value.

Under these conditions, an approximate, normal distribution for x_m is found. However, this is not suitable for extrapolation near the ends or outside the data range. Challenor (1979) has presented a method based on maximum likelihood estimators and given standard deviations and confidence intervals for the location and scale parameters. Using the Hydrotechnology data sample with the Challenor methodology results in the graphs shown in Figure 9(c) and (d) for the Tarsiut and Kopanoar locations. These are 90% confidence intervals based on parameter uncertainty. For comparative purposes, the most likely value calculated using the Challenor tables have been included in Table 4. The values of the location and scaling parameters α and β for Tarsiut and Kopanoar were found to be 8.243; 1.6355 and 8.455; 2.108, respectively. Clearly, these results differ from those obtained by Hydrotechnology as would be expected, because the latter have uncertainty in the underlying process.

2.4 SEACONSULT HINDCAST STUDY

The Seaconsult Marine Research Ltd. study (Hodgins et al. 1981) was commissioned by Esso Resources Canada Ltd., with the principal objective of providing an estimate of the upper bounds of wave heights and storm surge levels at ten locations (Figure 10 and Table 5), with return periods of 10, 50, and 100-years. The study was conducted as a joint effort between Seaconsult and the Danish Hydraulic Institute (DHI), who were responsible jointly for the water level hindcasting, and the Meteorological and Environmental Planning Co. Ltd. (MEP), who had responsibility for the meteorological hindcasting.

It should be noted from the introductory paragraph to this section that Esso had commissioned an earlier study on extreme water levels conducted by Intersea Research Corporation (IRC) in 1974. In the intervening period, wind and wave data collected by Esso indicated that the IRC hindcast values seemed low or, more particularly, that the observed return periods for given wind speeds and wave heights were generally less than predicted. These observations placed in doubt the extreme values obtained by IRC for the 50- and 100-year return periods and provided the motivation for a fresh study.

- 19 -
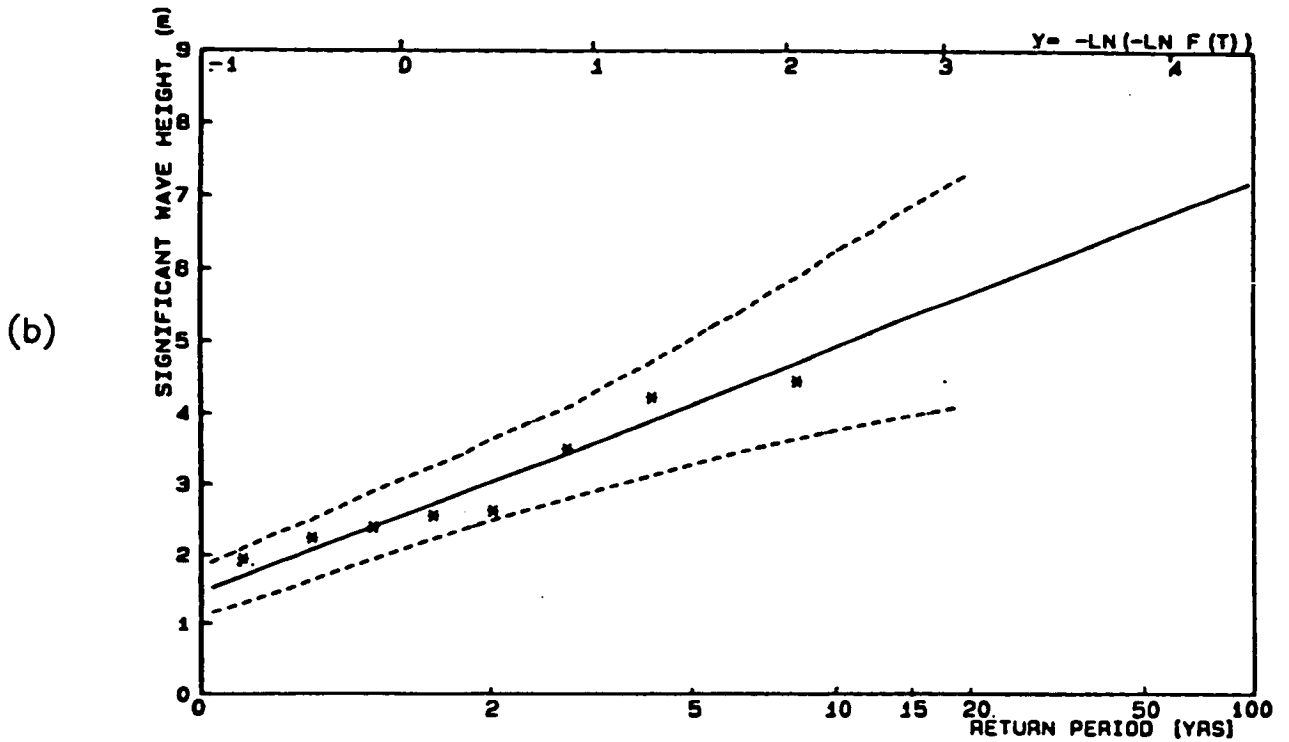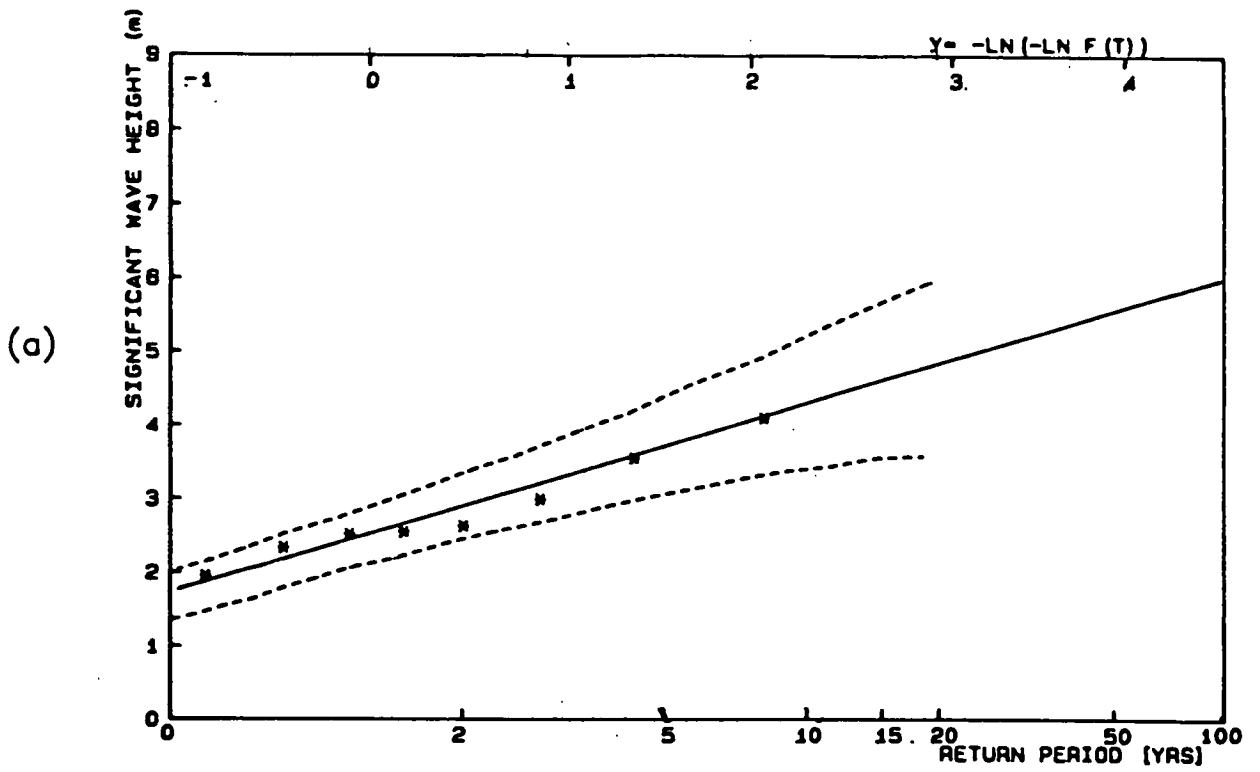
Figure 9 a,b. Extreme value distributions for significant wave height by Hydrotechnology for (a) Tarsiut and (b) Kopanoar (source: Baird and Hall).
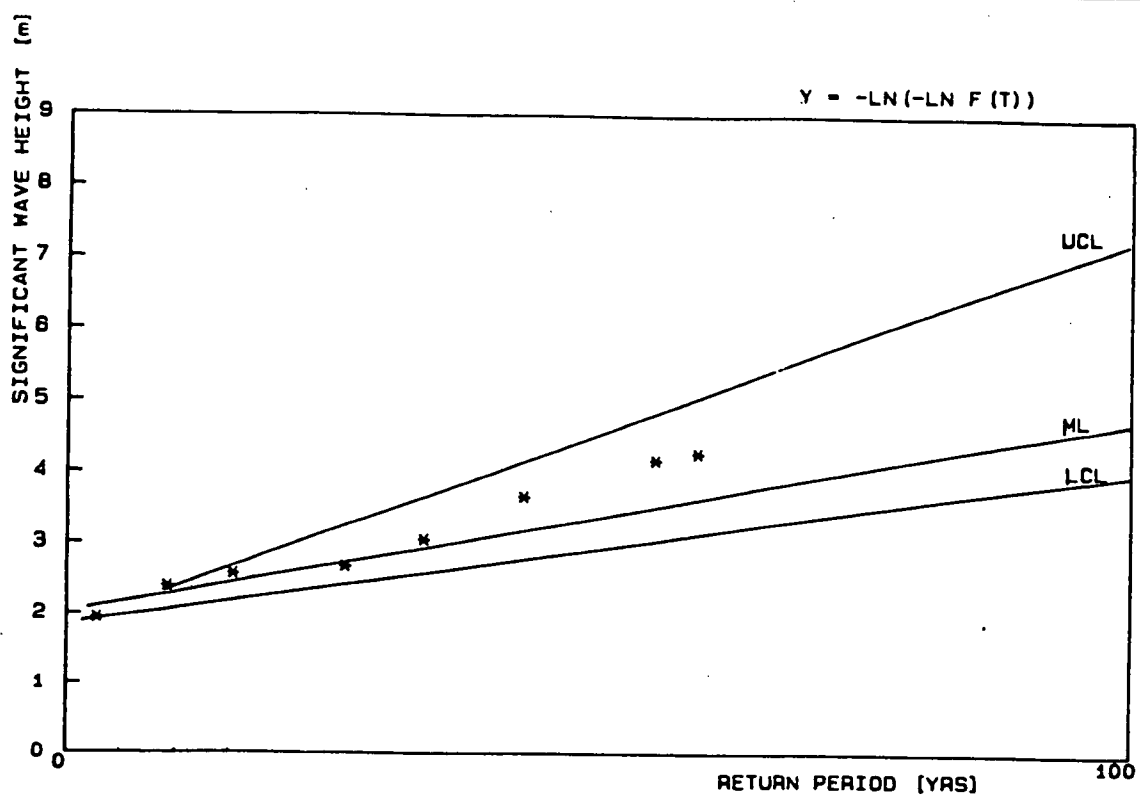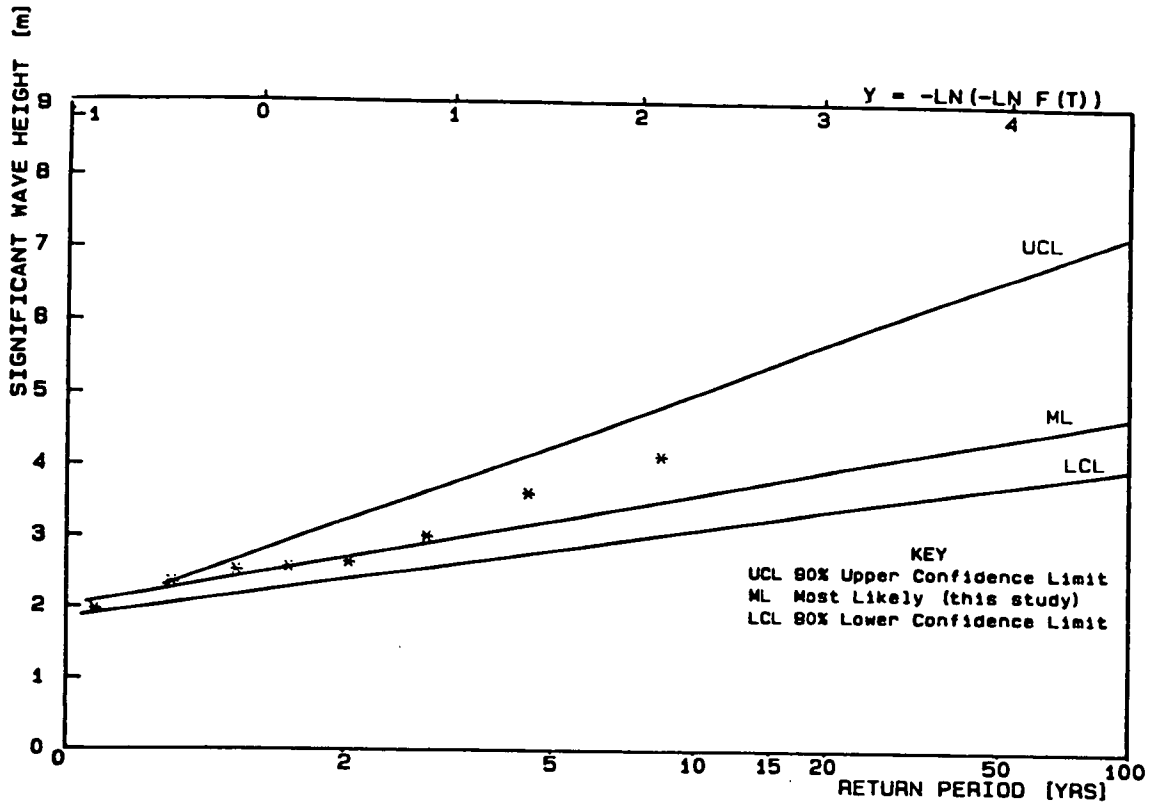
Figure 9 c,d. Extreme value distributions for significant wave height for (c) Tarsiut and (d) Kopanoar (source: this study).

TABLE 4

Summary of extreme wind speed and significant wave height estimates

	Return period (yrs)	Hydrotechnology site (see Figure 2) A	D		Seaconsult site (see Figure 10) 3	7
	10		44	44	45[1]	46[1]
Hourly average	20		49	49		
Wind speed	50		56	56		
(knots)	100		59	59	59	61
Significant wave	10	(4.5)[3]	4.2	4.8	(5.00)[3] 5.5[2]	9.2
height	20	(5.0)	4.8	5.5	(5.60)	
H_s (m)	50	(5.6)	5.7	6.5	(6.35) 5.5	12.8
	100	(6.0)	6.2	7.3	(6.90) 5.5	13.2

1   Source Meteorological and Environmental Planning Ltd. (MEP) (1982).
2   Wave heights were depth-limited for all storms at this site.
3   Wave heights based on Challenor's maximum likelihood estimators (this study).

Sources: Baird and Hall 1980; Hodgins et al. 1981.

ESSO SITES

IRC 1974	Site Number	N. Lat.	W. Long.
A	1	69° 50'	138° 59'
B	2	69° 17'	136° 45'
C	3	69° 52'	134° 30'
D	4	70° 04'	131° 30'
E	5	70° 39'	129° 30'
F	6	71° 00'	132° 00'
G	7	70° 25'	136° 00'
H	8	70° 36'	139° 20'
	9	71° 00'	140° 00'
	10	71° 30'	141° 00'
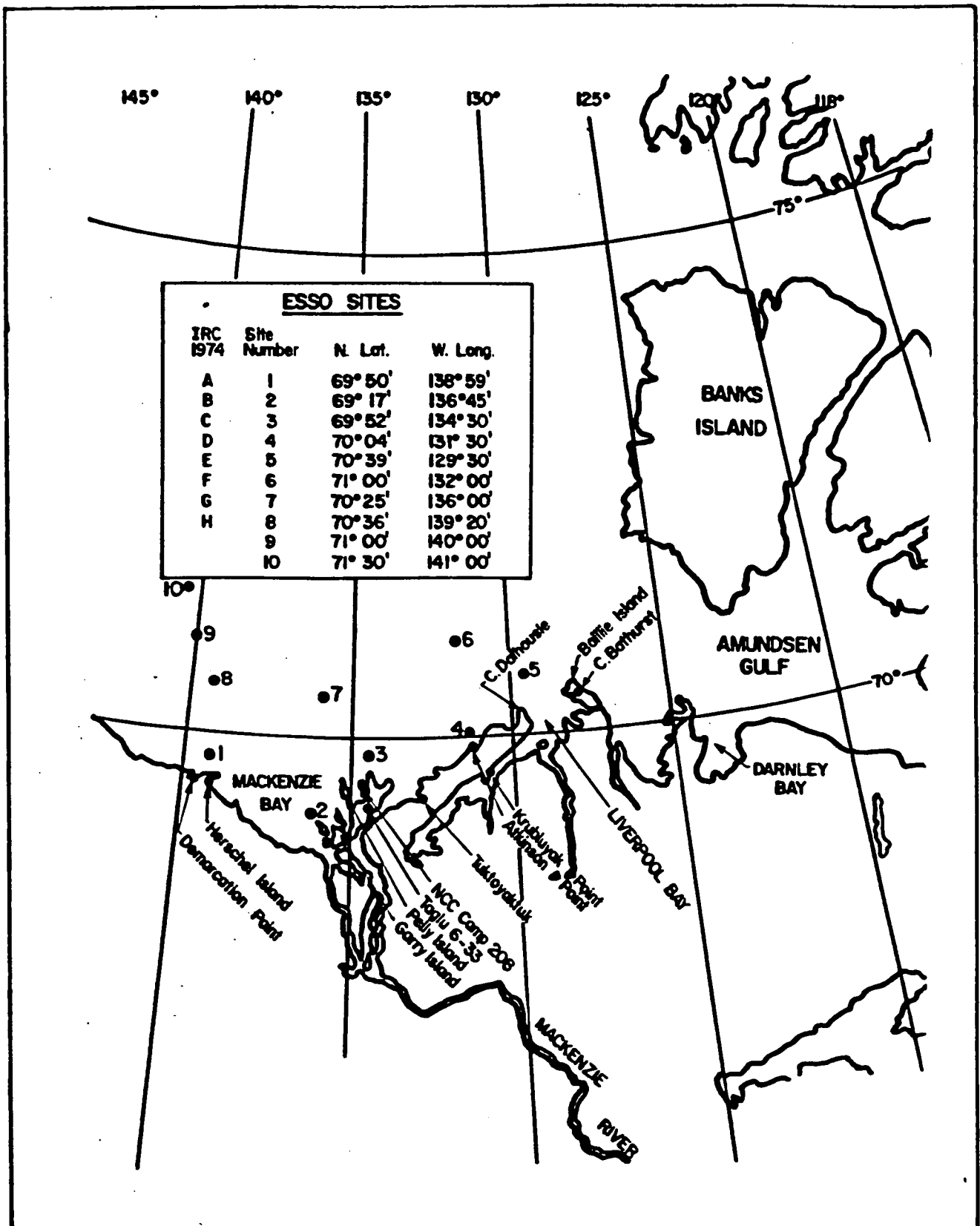
Figure 10. The location of the ten Seaconsult hindcast sites and other names mentioned in text (Source: Hodgins et al. 1981).

- 23 -

TABLE 5

Esso sites used in Seaconsult study

Seaconsult (1981) Site number	IRC (1974) Site number	N. Latitude deg	N. Latitude min	W. Longitude deg	W. Longitude min
1	A	69	50	138	59
2	B	69	17	136	45
3	C	69	52	134	30
4	D	70	04	131	30
5	E	70	39	129	30
6	F	71	00	132	00
7	G	70	25	136	00
8	H	70	36	139	20
9		71	00	140	00
10		71	30	141	00

The wave hindcasting technique selected for the study was fundamentally different from that used in any previous hindcast for the area in that a spectral modelling approach was adopted. This model, developed by the DHI, computed the spatial and temporal variations in the directional wave height spectrum. The technique used was based upon the conservation of wave energy over space and time, and included terms for empirical energy growth and decay. Refraction, shoaling, and wave height decay effects were included within the model.

A second major difference in the Seaconsult approach was the development of an extreme storm hindcast using a prototype storm suitably intensified to provide wind speeds with the required return periods. The wind speeds used in the study were derived from six hourly Canadian Meteorological Centre (CMC) synoptic weather charts for the area for the four months July -October, over the ten-year period 1969-1978.

2.4.1   Storm/Event selection

Seaconsult did not hindcast a fixed number of storms, instead, they reconstructed hypothetical "prototype" storms which were associated with specific recurrence intervals. Thus a 10-year storm was defined as one which would produce the 10-year return wind speed, a 50-year storm for the 50-year return wind speed, and so on. The estimation of the n-year storm was based solely on recurrence intervals, that is to say, wind speed durations and fetch lengths for wave generation were not considered in the selection process. Thus, the n-year wave was postulated to correspond to the n-year storm.

2.4.2   Wind-Field methodology

Meterological and Environmental Planning Ltd. (MEP) were responsible for providing the wind-field descriptions to the Seaconsult hindcast model. A specific review of their methodology can be found later in this section. At this point, it is important to recognize two aspects of the wind-field methodology adopted. First, the methods by which winds for a fixed synoptic time period were estimated from surface pressure observations made at that time; and secondly, the method by which "prototype" storms were estimated for given recurrence intervals.

In the first instance, MEP compiled a data base of mean sea-level pressures over an extended area of the Beaufort Sea, Alaska, Northwest Territories, and northern Alberta using the six hourly CMC synoptic weather charts, which have a 381-km coarse grid, for the ten-year period 1969-78. They then used this pressure information to estimate geostrophic winds, which were subsequently reduced using a planetary, boundary-layer model to produce wind speeds at a 19.5 m reference height. In the actual hindcast study, it was argued, using observed data from the Taglu site (Figure 11, location shown in Figure 10) that the geostrophic winds themselves, and not the reduced wind speeds, provided better agreement with the observations. Consequently, derived geostrophic winds were used in the estimation of wind-speed recurrence intervals.

The extreme wind speed for each of the ten sites of interest was derived by fitting a Gumbel distribution to the ten hindcasted annual maxima (irrespective of wind direction) and by extrapolating the fitted distribution to provide wind speeds having an expectancy of return of 50-years and 100-years. A schematic representation of the relationship between the extrapolated wind speeds and their associated confidence levels is illustrated in Figure 12.

The process by which Seaconsult arrived at the selection of a "prototype" storm appears to be one of default, in an attempt to find a storm with sufficient contemporaneous measured wind and wave data to provide verification. After studying six storms in the period 1970-79 they selected the storm of 26-28 August, 1975 as the prototype. The four synthetic storms used in the hindcast were constructed by intensifying the prototype storm so as to match the desired maximum wind speed associated with return periods of 1, 10, 50, and 100 years. The description of the intensification procedure indicates that the low-pressure system was intensified and broadened, increasing its zone of influence (see Figure 16), which probably has the consequence of characterizing the storms with higher wind speeds by longer durations.

- 25 -
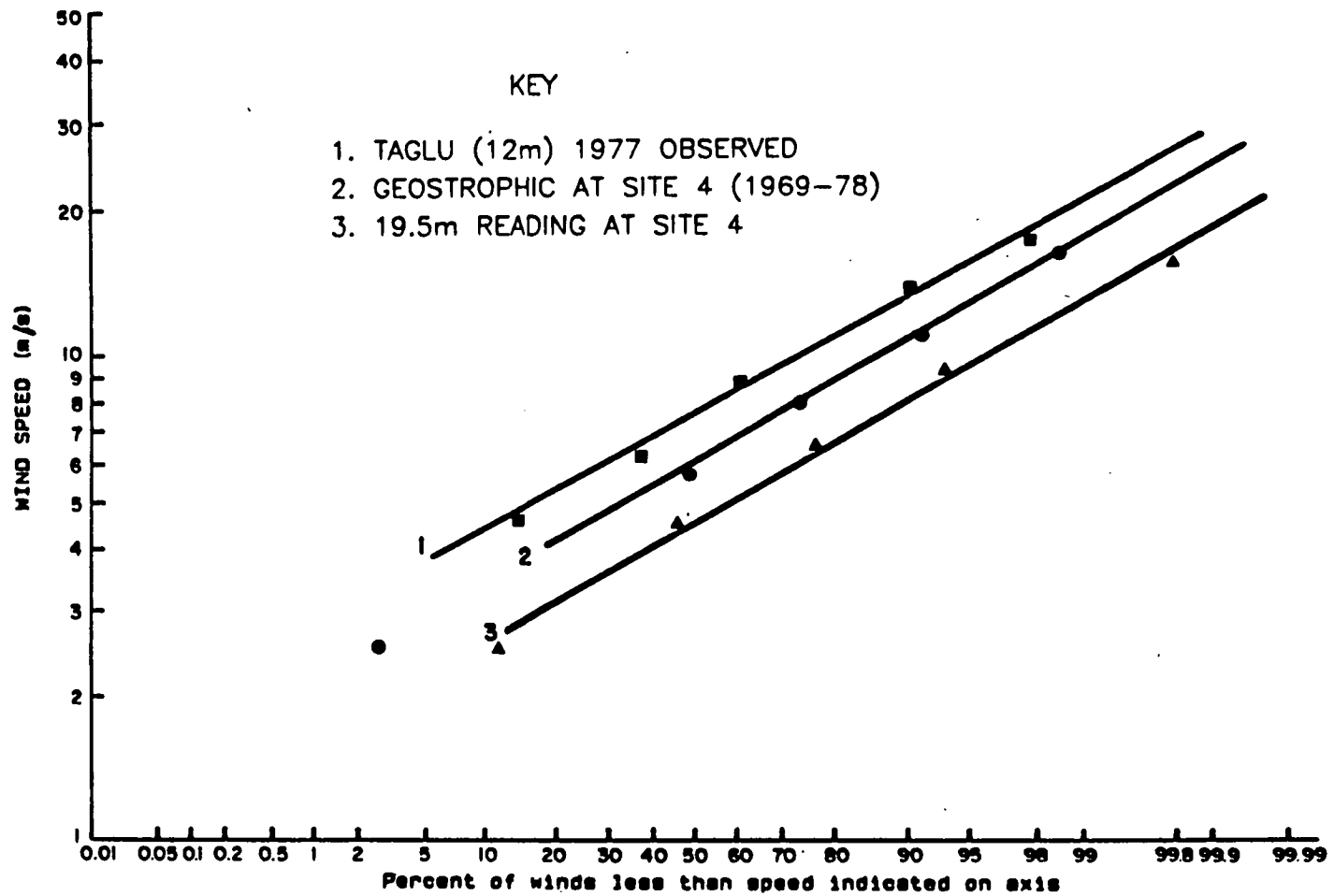
Figure 11. Cumulative frequency of measured and geostrophic wind speeds at the Taglu site (Source: M.E.P. 1982).
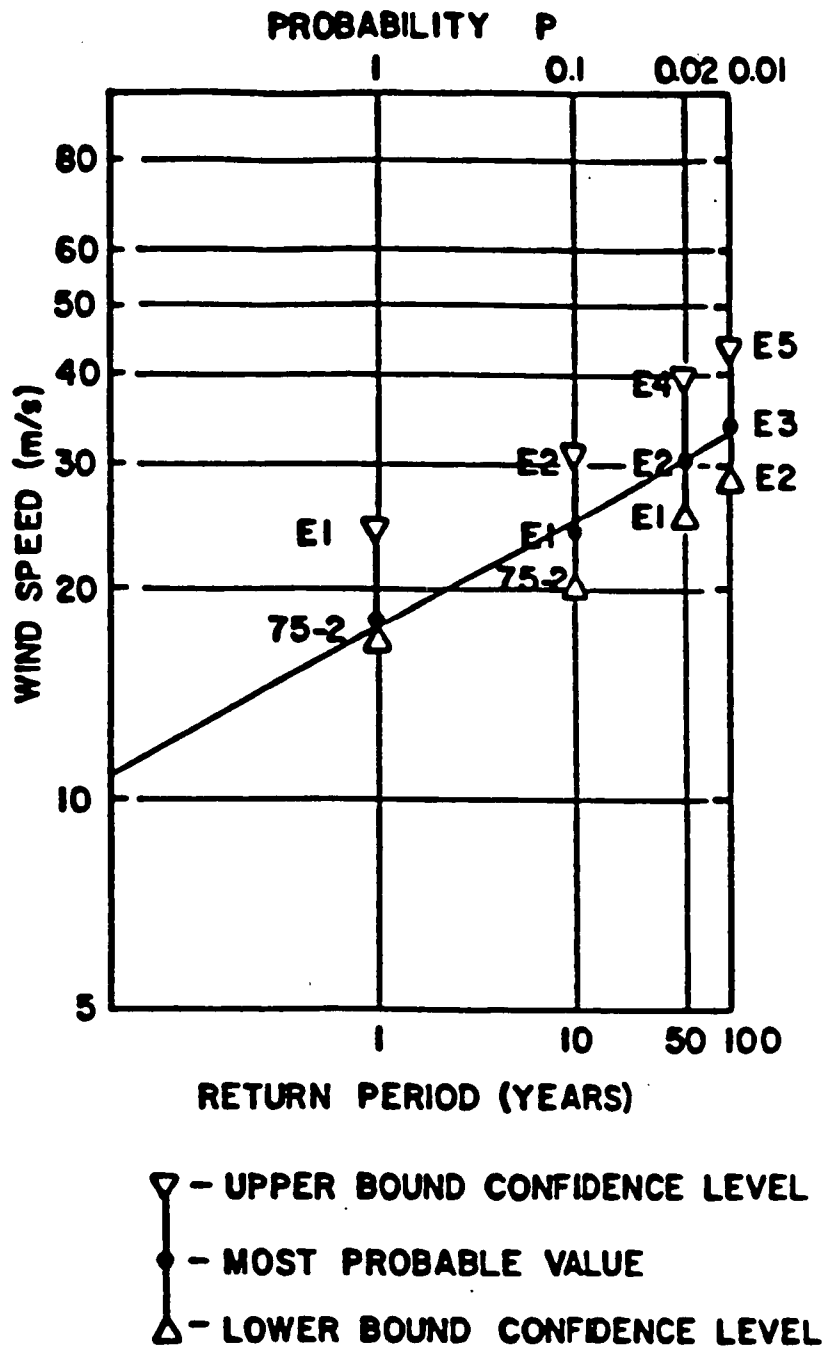
Figure 12. Schematic diagram of the relationship between extrapolated wind speeds and their confidence levels with extreme storms (source: Hodgins et al. 1981).

2.4.3   Wave model application

The wave hindcasting method selected for this study was the System 20 spectral hindcasting approach, developed by the DHI. This model is similar to that published by Inoue (1967) and by Cardone (1969) and has as its primary energy source term a direct atmosphere-to-sea transfer mechanism (Miles (1957) - Phillips (1957)), which allows the spectral form to grow up to the limit of the Pierson-Moskowitz spectrum (Pierson and Moskowitz 1964).

The spectral model describes the sea state at any given time in terms of a directional-frequency energy spectrum. This spectrum is described in such a way as to permit the simulation of energy flow into and out of 240 spectral elements; that is, 15 frequency bands and 16 angular intervals. The basic equation used assumes that the wave energy in the spectrum is propagated at the wave group velocity.

Seaconsult chose to define the open-water area as that bounded by the land and the nine-tenths (9/10) ice edge at the maximum extent of open water that had been observed (Brower et al. 1977). This definition placed the ice edge west of Point Barrow, permitting westerly winds to have an effective fetch length in excess of 850 km, that is of comparable order to the scale lengths of the storm. A single ice edge was thus used with all the extreme storms, and the effect of fetch limitation was removed from them by implying that wave growth was essentially duration-limited. However, no attempt was made to verify that such was the case. Because the return periods were based solely on wind fields and the open water conditions have their own probability of occurrence, Seaconsult noted that their return period designations were "slightly conservative."

2.4.4   Verification effort

2.4.4.1   Winds

MEP examined the performance of their modelling procedure by comparing time series of winds for six storms (Table 6) with measured data collected at several of the hindcast locations. No corrections for anemometer height or averaging time were applied in these comparisons.

In general, the results of the comparison were not very good. Specifically all of the storm effects associated with 77-1, 2, and 3 were missed completely, whereas for the others, the modelled winds followed the trend of the measured winds but underestimated the peak values. Some typical results from the comparison can be seen in Figures 13, 14, and 15, which correspond to storm systems 75-1, 75-2 and 77-1, respectively.

Although possible reasons for the discrepancies are given, for example, the effects of small-scale local pressure disturbances missed from the coarse-grid synoptic charts and the inaccurate prediction of the near-surface wind speeds over water,

- 28 -

TABLE 6

Wind-storms used in MEP study

Storm No.	Date	Designation in Seaconsult report
1	1-2 September, 1972	(72-1)
2	9-10 August, 1975	(75-1)
3	26-28 August, 1975	(75-2)a
4	28-29 August, 1975	(77-1)
5	1 September, 1977	(77-2)
6	21-22 September, 1977	(77-3)

a   "Prototype" storm.

there is no discussion of the likely effects of such discrepancies on the wave hindcast. They did, however, undertake an error analysis of their wind modelling procedures, perturbing the grid point pressures to produce a range of wind speeds to enable upper and lower bound estimates to be set for the 50- and 100-year extreme winds. However, as noted later, their statistical treatment of these error bounds is incorrect.

2.4.4.2   Waves

Only one verification event (9-12 August 1975), denoted storm 75-1, is provided in the Seaconsult report. Reasonable agreement between measured and hindcast waves are shown; however, the wind methodology used in the verification is not the same as that used in their production runs. Rather, Seaconsult had concluded that the modelled wind fields were not accurate enough to be used to calibrate the wind-wave model against measured wave data. They chose, instead, to use the measured winds at NCC Camp 208 distributed uniformly over the model grid at each time step for storm 75-1. Hence, the wind estimation method used in the verification run is closer to that used by Hydrotechnology than to that used in the Seaconsult production runs.

Because storm 75-1 was not well represented in the MEP wind verifications, the authors can only conclude that had the MEP wind fields been used in the wave verification, less satisfactory results would have been obtained.
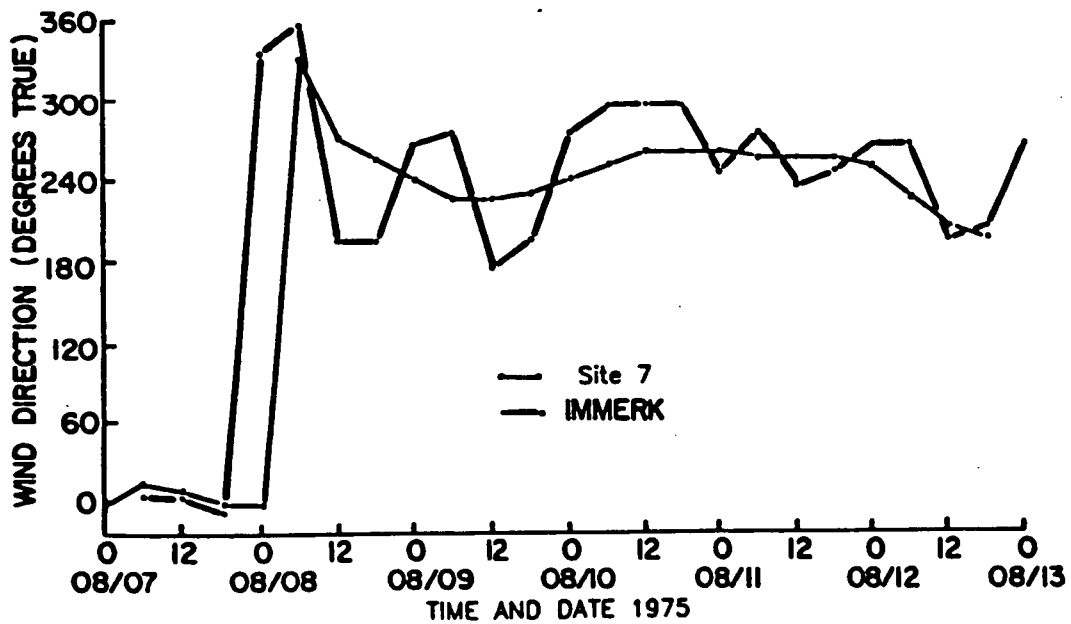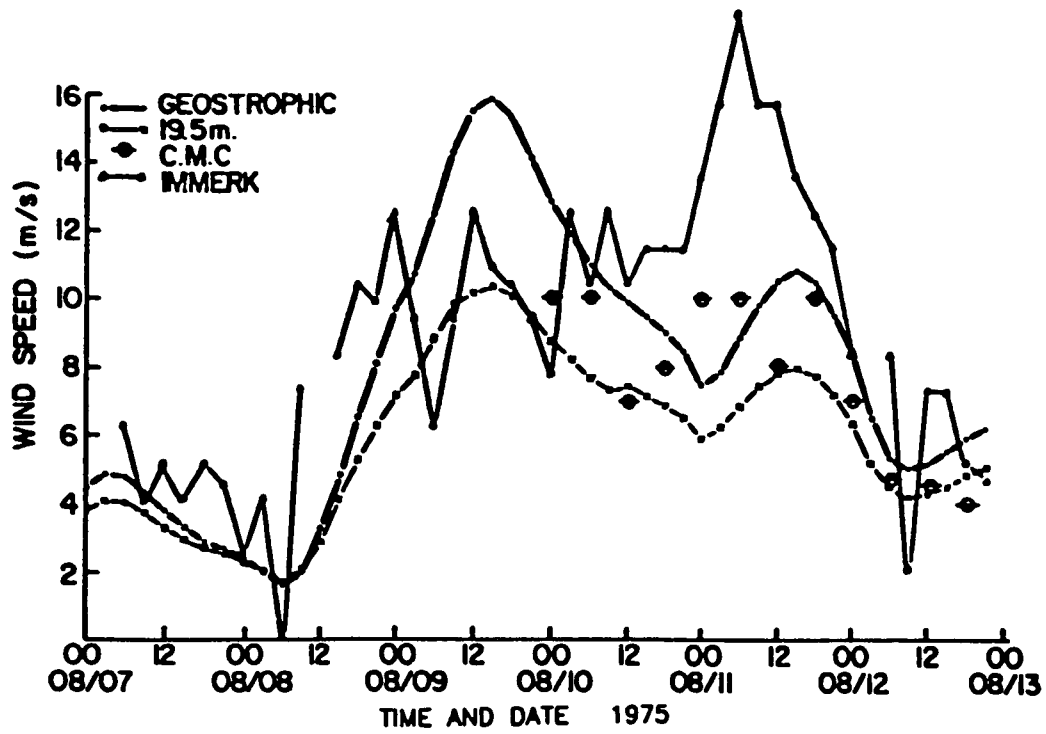
Figure 13   Comparison of Modelled and Measured Winds for Storm 75-1 at Site 7
Taken From the M.E.P. - 1982 Study
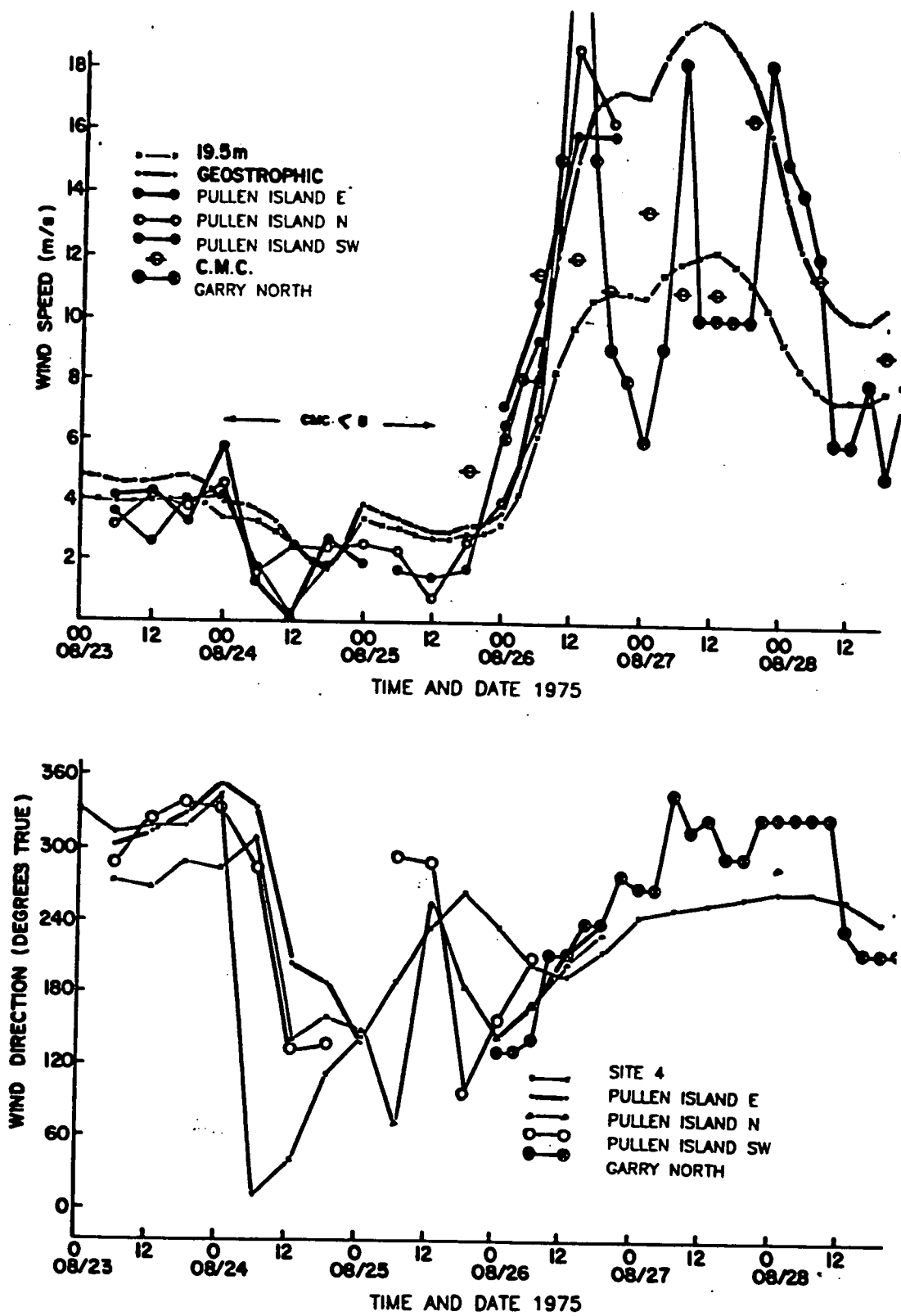
Figure 14. Comparison of modelled and measured wind speed and direction for storm 75-2 at site 4 (source: Hodgins et al. 1981).
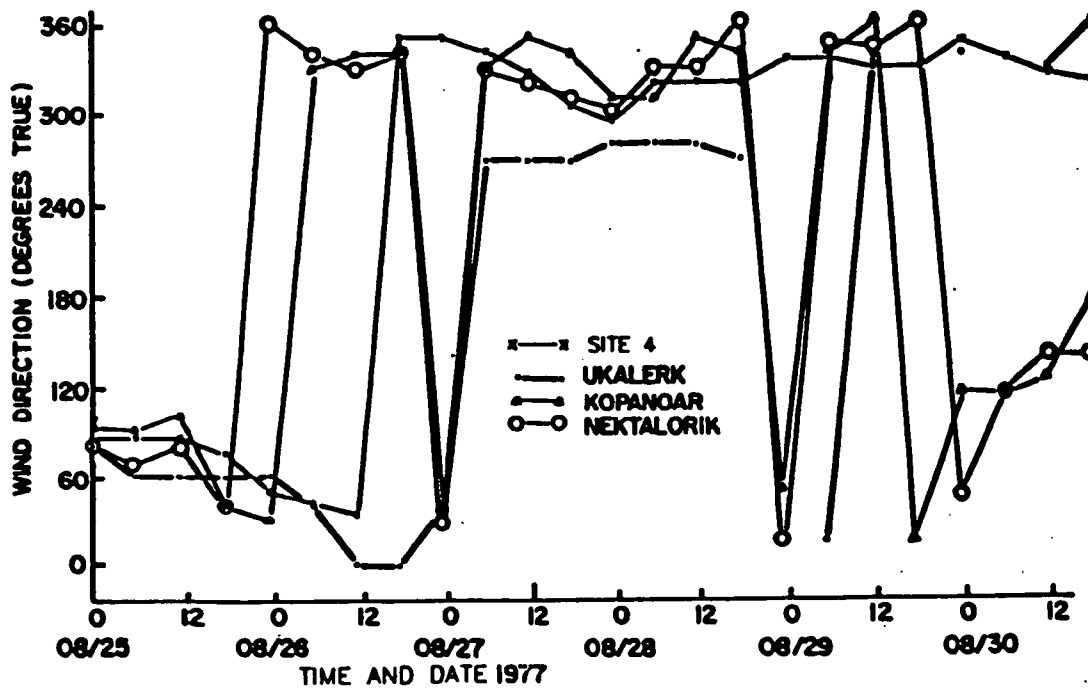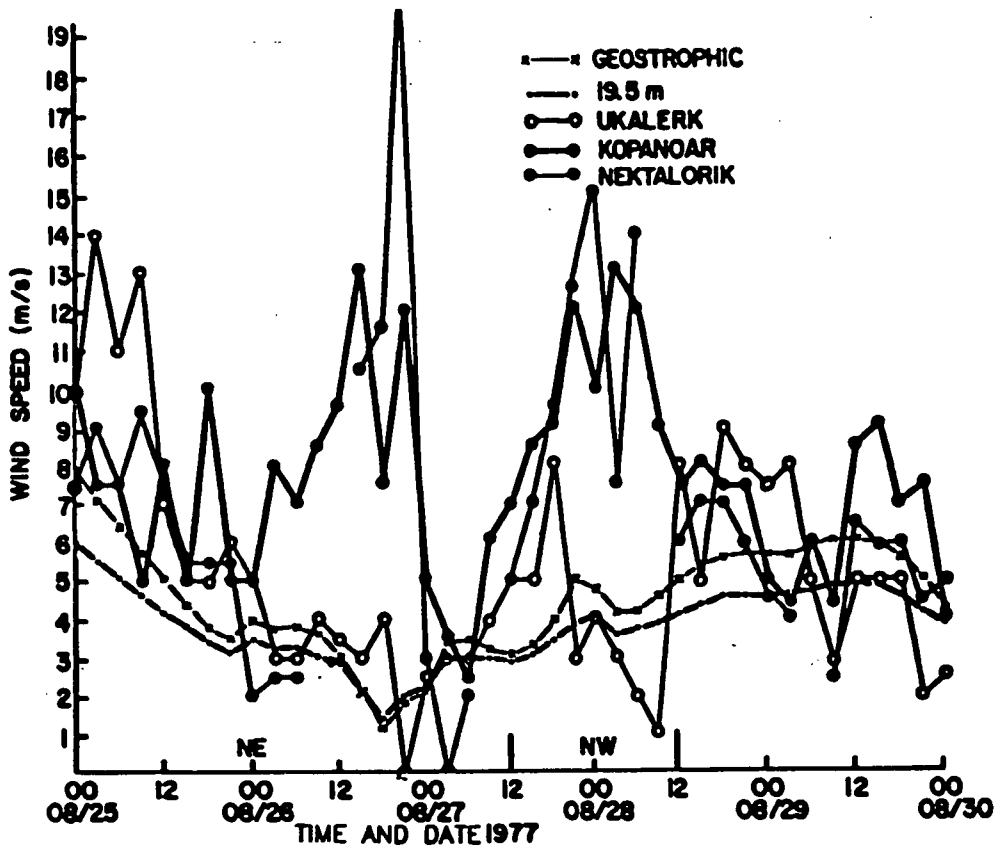
Figure 15 Comparison of modelled and measured wind speed and direction for storm 77-1 at site 4.

Taken From the M.E.P. - 1982 Study

2.4.5 Statistical estimation technique

As pointed out previously, the n-year "prototype" storm was assumed to produce the n-year wave. Confidence intervals of the wave heights were derived somewhat subjectively by selecting additional prototype storms which were taken to represent the confidence bounds on wind speed at each recurrence interval. A summary of the extreme wind speeds and wave heights obtained in this study for two of the sites investigated can be found in Table 4.

2.5 REVIEW OF THE MEP WIND-FIELD STUDY

As outlined in Section 2.4, the wind fields used in the Seaconsult hindcast study were derived by MEP using the six-hourly synoptic weather charts prepared by the CMC over the period 1969-78. Atmospheric stability conditions for the same time period, for the whole region, were based upon radiosonde data at Sachs Harbour and the surface temperatures measured at the nearby meteorological station. To make up for little or no near-surface temperature data offshore, values of 0° and 0.5°C were assumed to apply over ice cover and open water respectively.

The CMC charts for the region cover an extensive area. The MEP model, however, only required the mean sea-level pressures at 72 grid points within this area from which to derive pressure gradients and, hence, geostrophic wind speeds and directions at these grid points and at the ten selected sites noted in Figure 10. In addition to producing ten years of wind-field data, seven storm conditions were analysed separately to provide input to the Seaconsult wave model for verification purposes.

MEP used the Sykes and Hatton (1976) method to derive the geostrophic winds from the pressure grid points. This approach attempts to fit orthogonal polynomials in the horizontal x and y co-ordinate system to the observed station pressures. The coefficients of the ninth-order polynomials used in the fitting procedure have to be evaluated at six-hourly intervals and, to interpolate between these intervals, a fourth-order polynomial in time is used.

The wind speeds at the 19.5-m reference level were derived from the geostrophic winds using a procedure suggested by Agnew and Diehl (1978). To develop a wind profile close to the ground, some estimate must be made of the height of the planetary boundary layer and the surface frictional velocity. These quantities were both related by empirical means to the geostrophic wind speeds and atmospheric stability conditions. The wind direction at the reference level was obtained from the geostrophic wind direction, again using an empirical relationship with the wind speed and atmospheric stability. MEP discussed other possible means of modifying the geostrophic winds, including the use of a fixed reduction factor for both wind speed and rotation, but concluded that the stability-dependent approach of Agnew and Diehl, when used with mean winds of 1-hour duration (or more) produces more representative results.

MEP conducted a sensitivity analysis on their hindcast approach by cataloguing potential sources of error, such as misreading of station pressures and inaccuracies in the fitting procedure relating grid-point pressures to geostrophic wind speeds. The most significant source of error, however, was the coarse space and time resolution of the pressure data. The six-hourly sampling time filters out short-duration effects such as storm peaking, leading to an underestimation of peak wind speeds. The poor spatial resolution prevents locating the centre of sizeable pressure systems accurately while relatively small-scale, though intense disturbances (tentatively designated "Arctic instability lows" by Hodgins 1981), can be missed completely. MEP estimated that if all of the potential sources of error, excluding "missed" storms, were to occur simultaneously, the maximum possible error at any given grid point would be of the order of ±4 millibars (mbar), although this is probably an optimistic assessment. They examined the consequences of such error bounds by analysing an actual pressure pattern perturbing the pressure at each grid point by a random amount in the interval ±4 mbar and calculating the geostrophic winds for the ten design locations. This exercise was repeated 160 times and the maximum increase and decrease of wind speed at each site was determined. The effect at each site was different, with the maximum decrease ranging from 11 to 16%, and the maximum increase ranging from 15 to 29%. For some reason not apparent in their report, MEP chose the average value of 15% to represent the maximum percentage decrease and selected the largest difference, 29%, to be representative of the percentage increase in wind speeds. They noted, however, that the inclusion of small-scale intense storms could effectively double the maximum wind speeds estimated by their model.

A criticism of the MEP work is the use they made of the derived error bounds. These errors are intrinsic in the modelling procedure, lending uncertainty to it. The estimation of extremes in wind data should thus be determined from a single distribution containing these uncertainties, rather than arbitrarily shifting the mode of the original Gumbel distribution to produce distributions of minimum and maximum wind speeds, as defined in the error analysis.

Having associated wind speeds with a given recurrence interval, MEP then operated on each of the seven, defined, storm pressure systems, intensifying the pressure gradients in each until the required wind speeds were achieved. Figure 16 illustrates the consequences of the intensification on a typical storm system. The intensification procedure was confined within a given area at the centre of each storm, although the size of the area could be adjusted to allow the forecaster some subjectivity in modifying the storm event. Beyond this area of influence, uniform increases in pressure were assumed.

As mentioned previously, the verification runs made by MEP did not produce very favourable comparisons with the measured data (see Figures 13, 14, and 15). The inadequacies of the poor time and spatial resolution are quite evident from these figures, because peak wind speeds are underestimated and, in the case of storm 77-1 (see Figure 15), the storm event was missed completely.

ORIGINAL STORM
20 M/SEC
AUGUST 27, 1975   00 00GMT
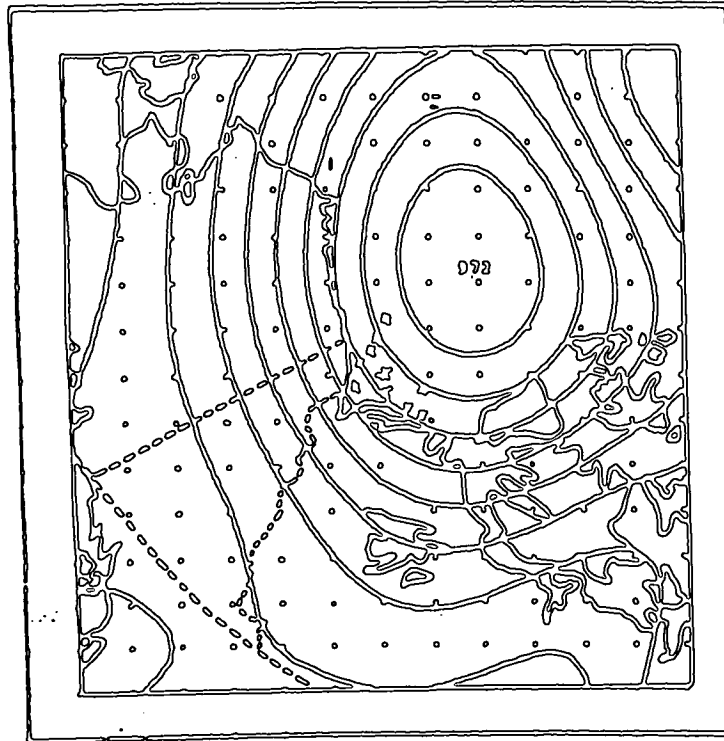
INTENSIFIED STORM
35 M/SEC
AUGUST 27, 1975   00 00GMT

(a)
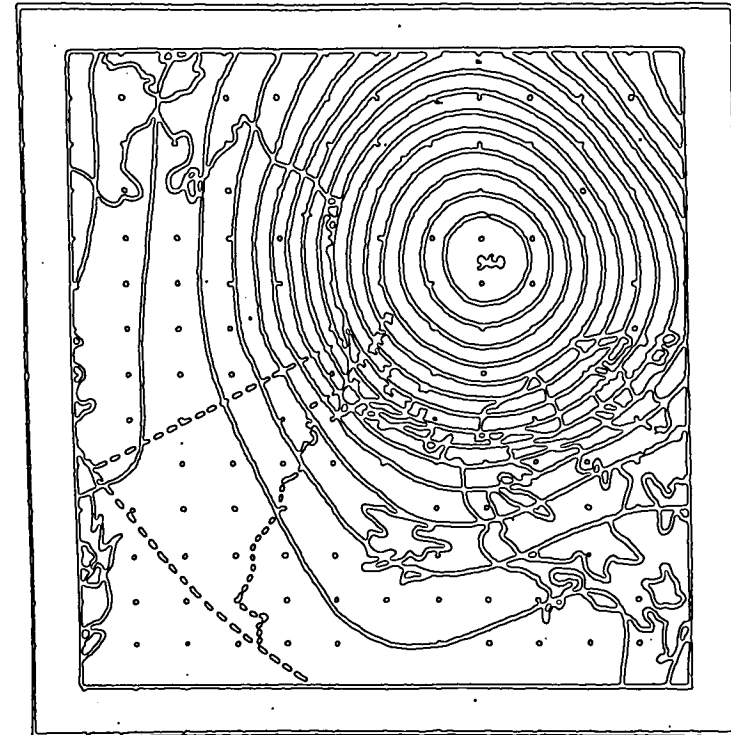
(b)

Figure 16.   An example of a fitted surface pressure analysis for a) an actual
storm; and b) an intensified storm (Source: M.E.P. 1982).

3. CRITIQUE OF THE HYDROTECHNOLOGY AND SEACONSULT METHODOLOGIES

3.1 INTRODUCTION

Because the studies by Hydrotechnology and Seaconsult had quite different terms of reference and approached the problem of estimating extreme wave-height in a fundamentally different manner, discrepancies exist between the results they produced. Referring specifically to the 100-year return period significant wave heights, a commonly used measure for comparing extreme waves, one finds that for water depths less than 30 m, there is reasonably good agreement between the studies. However, in deeper water and at locations which are less than 30 km apart (Kopanoar and Site 7 in the Seaconsult study), Hydrotechnology estimate a significant wave height of 7.3 m whereas Seaconsult's estimate is almost double that at 13.2 m (see Table 4). As a general observation, the extreme wave heights estimated by Seaconsult show a much greater dependence on water depth than do the Hydrotechnology results.

To provide a rational basis for assessing the results of the studies, both in absolute and relative items, a critical assessment of each will be made in this section under the five distinct aspects of hindcasting outlined in the previous section. In addition, a joint probability method for associating return periods with significant wave heights is introduced as a means of suggesting possible improvements to the existing methodologies.

3.2 STORM/EVENT SELECTION

Both studies are based on only ten years of wind records; it is tempting to suppose that this relatively scanty data base could be augmented through the generation of "prototype" storms, the enrichment stemming from the inclusion of the relevant physics describing Arctic storms. However, such a description is beyond the present state of knowledge. In the present circumstance, Seaconsult's usage and means of describing a "prototype" storm in terms of a single scalar variable -- wind speed does not really extend the data base -- it merely makes the consequences of a short data base more difficult to ascertain, and in fact, introduces some additional unknowns into the determination of recurrence intervals.

As a rough rule of thumb, n years of wave measurements at a fixed site can provide a reasonable estimate of wave heights for recurrence intervals up to about 2n-years (Borgman 1975). That is not to say, however, that given a limited set of data such as the ten years of wind records used in both studies, that it cannot be employed usefully in estimating an extreme event with a 100-year return period and ascribing confidence levels to it. The key issue in deciding the extent of the extrapolation is whether the width of the confidence levels are acceptable or not. Clearly, the longer the estimated recurrence interval in comparison with the length of the data record, the greater will be the associated uncertainties.

The construction of an abstract, probabilistic set of storms should follow from a careful, thorough study of storm behaviour. Variations in storm wind fields in both time and space can produce significant variations in the maximum hindcast wave heights. The process of equating a multidimensional, vector wind field with a single, scalar wind speed at a point, however, is equivalent to suppressing important sources of storm-to-storm wind-field variations and, therefore, must be approached with caution.

In a probabilistic sense, a scalar random quantity, such as wave height, can be produced by a large range of storm wind fields (for example: very high wind speeds with short durations or with short fetches, or lower wind speeds with longer durations or fetches). By the same token the inverse problem, that of reconstructing a storm field from a single parameter (wind speed), as attempted by Seaconsult, is ill-posed. In a formal sense, if one were to attempt to derive a parametric-abstract set of storms to hindcast, all the possible sources of variation in the wind fields and fetches would have to be considered to obtain a joint probability estimate of all of these parameters. This has been done in joint probability method studies of hurricane surge levels (Myers 1954), where the probability space consists of five parameters. The storm wind fields in the Beaufort Sea are more complex than a tropical storm and would be much more difficult to describe with parameters; nevertheless it is worth consideration.

If the wind field, which is spatially and temporally varying, and the open-water area were specified completely for one storm by some vector of parameters x, then the hindcast method could be expressed as a function H(x), for the maximum, significant wave height generated by that storm.

The probabilistic description of storms should include their arrival rate and the joint probability distribution of the parameters describing the spatial and temporal distribution of the wind field within a random storm, $fx(\underset{\sim}{x})$. Ideally, the parameters used to describe a storm should be sufficient to specify completely the spatial and temporal variations in the wind field throughout its history. The vector of parameters for one storm might include the wind speed, the duration of the storm, and the scale of the spatial variations in the wind field. Of course, a complete description would require a large number of parameters, so some subjectivity must be introduced to make the procedure tractable.

Like the wind field, the extent of open water during a storm is probabilistic. Ideally, its description should include the correlation between the area of open water and the wind field in the form of a joint probability distribution. If the vector of parameters used to describe a storm, X, is expanded to include the parameters to describe the open-water area, then $f_X(\underset{\sim}{x})$ is the joint probability distribution of the wind field and open-water area through one random storm.

Assuming that the wave height, H, can be calculated from $\underset{\sim}{x}$ using the relationship $H = (\underset{\sim}{x})$, and its inverse can be obtained from $\underset{\sim}{x} = H^{-1}(h)$ then the probability of the calculated significant wave height exceeding a specified height, h, in a given storm is given by:

$$Pr(H > h) = \int_{H^{-1}(h)}^{\infty} f_X(x) \, dx$$

<div align="right">(Eq.4)</div>

If the average frequency per unit time, or the arrival rate, is denoted λ, the expected number of storms, n(h), with a significant wave height greater than h in a unit of time is given by,

$$n = \lambda \int_{H^{-1}(h)}^{\infty} f_X(x) \, dx$$

<div align="right">(Eq.5)</div>

Thus the expected time period between storms which exceed h, or the return period denoted R(h) is given by 1/n, or:

$$R(h) = 1/n$$

<div align="right">(Eq.6)</div>

That is to say, the return period associated with a given wave height is the inverse of the product of the frequency of storms, and the probability that the maximum wave height in one random storm would exceed that height. The probability that the maximum wave height in one random storm would exceed a given height is the sum of the probabilities of occurrence of all combinations of wind-field and open-water area parameters, which would generate wave heights in excess of that value. This procedure is used in the next section, when the sensitivity analyses are performed.

If n years of waves are hindcast at a site, then the resulting data set, if the hindcast is accurate, is roughly equivalent to n years of measurements at that site. These hindcasts should provide, inherent in their results, all of the nonlinear interactions among different wind fields and fetches that are suppressed in the simplistic single parameter "prototype" storm methodology, as applied in the Seaconsult report. This methodology appears to be more direct, given our present knowledge of storms in the Beaufort sea.

It is difficult to quantify the error of extreme wave height magnitudes resulting from overly short record lengths, except under restrictive assumptions (independent storms, homogeneous population, etc.). Resio (1978) addressed some of the complicating factors from both long- and short-term climatic fluctuations and concluded that the more important influences on extreme wave heights were related to short-term (5-10 years) fluctuations. Based on this, a sample length of at least 20 years should produce a reasonably stable estimate, in a climatic though not necessarily a statistical sense, of longer term recurrence intervals.

3.3 WIND-FIELD METHODOLOGY

Neither the Hydrotechnology nor Seaconsult studies appeared to address the problem of wind-field specification in a manner commensurate with its importance to wave hindcasting: without accurate wind estimates, it is impossible to obtain accurate wave estimates. This deficiency does not mean that the accuracy of the wave model need be no greater than that to which the wind speeds are estimated, for such reasoning would only lead to a compounding of the error by contributing additional bias and random errors to those already present in the wind-field estimates. In neither of the studies were the wind speeds from observation stations reduced to specific reference heights and fixed averaging periods.

As Seaconsult recognized, the grid spacing of 381 km used in their study is too large for the adequate resolution of important wind-field features in the Beaufort Sea. Fitting higher-order polynomials to these grid-point pressures does not really contribute a better resolution. In fact, it probably tends to smooth out spatial and temporal variations in the wind fields. As mentioned previously, characterizing a storm in terms of a single parameter, peak wind speed, has the effect of shaping all spatial and temporal variations in the storm into the mould of the one prototype storm.

Wind speeds and pressures have been available from Barter Island, Tuktoyaktuk, Cape Parry, and Sachs Harbour for over 20 years. The average distance between these sites is only about 250 km. Much better resolution is inherent in this wind data, given proper overland-to-overwater conversion factors, than in those produced in the MEP study. These wind observations and more localized synoptic charts, such as those produced by the Beaufort Weather Office of AES, could form the basis of a thorough methodology which would blend a kinematic analysis into winds derived from geostrophic-level analyses. This proposal is discussed again in Section 6, under recommendations on improvements to the wind-field data.

The hindcast model used in the Hydrotechnology study imposed a restriction of using only spatially uniform wind fields, in addition no account was taken of the low ice concentrations within the open-water area. Uncertainties also were associated with the use of measured wind data from only one location (Tuktoyaktuk) to be representative of the winds over the Beaufort Sea.

As discussed by Resio and Vincent (1977), there are reasonable theoretical foundations for the estimation of overwater-to-overland wind scaling factors. Physical effects such as atmospheric stability, relative heights of anemometers, direction of wind, and general roughness scales surrounding the land station can affect the ratio of overwater-to-overland wind speeds. With the exception of anemometer height, Hydrotechnology did not address these factors in their study. Wind events tend to have particular correlations between wind directions and stabilities, so it is possible that ratios derived from histograms might be misleading. It should be noted that a number of these concerns have been addressed within the proprietary APOA study 203, the general findings of which are discussed later in Section 4.2.2.2.

It is important to note that the momentum transfer into the waves is expected to be a function of wind stress, not wind speed; consequently stability effects can become important to the specification of wave growth. Fortunately, the atmospheric stability conditions for westerlies follow a consistent pattern, as similar storm sectors are involved. The errors inherent in the wind-field estimates are probably the largest potential source of error in the hindcast wave heights at sites with water depths greater than 40 m.

3.4 WAVE MODEL APPLICATION

It is difficult for a parametric wave model to represent the various types of propagation and sheltering effects found in coastal areas. In addition, there are difficulties in defining fetch lengths and in dealing with changing wind directions. A spectral model, however, should be able to account for these effects in a more accurate manner.

The basic Bretschneider parametric model used by Hydrotechnology has been shown to produce a different wave growth with fetch than the Joint North Sea Wave Project (JONSWAP) 'type' of wave growth which is commonly used (see Section 4.2.3). There is also some deviation between their duration rates of growth. These differences can be accounted for by the use of a different exponent in the Bretschneider fetch relationship, that is:

$$\bar{H} \sim \bar{X}^{0.42}$$

as opposed to:

$$\bar{H} \sim \bar{X}^{0.5}$$

in the JONSWAP formulation. Here, H, the non-dimensional wave height, is defined as

$$\bar{H} = \frac{gH_s}{u^2}$$

and g is the gravitational constant, H_s is the significant wave height, and u is the wind velocity. X is determined as

$$\bar{X} = \frac{gx}{u^2}$$

where x is the fetch length.

The DHI spectral model also has been shown to be incapable of producing fetch-limited wave growth equivalent to those observed (Resio 1981), though in this case, it

is because of neglect in the model formulation of the non-linear growth terms for wave-to-wave interaction.

Neither of the studies examined the effects of partial ice cover on wave growth and decay. However, this aspect may not be critical when considering the estimation of extreme wave height, since extreme waves can be generated only in fairly ice-free conditions. When the ice edge and significant partial ice cover are near a site, large waves are not generated. On the other hand, Resio[1] has stated that in proprietary hindcasts of more than 40 storms in the Alaskan Beaufort and Chukchi Seas, there was not a single case in the observed wave data where large areas of partial ice cover influenced the wave conditions significantly. In fact, in all of the hindcasts, with one exception, the waves were duration limited, not fetch limited. This condition may or may not be the case in the Canadian Beaufort Sea; however, it should not be assumed to be of importance unless shown to be.

Since the time that Hydrotechnology and Seaconsult completed their studies, a new theory for wave transformations in shallow water has developed. Large sets of measured data now exist, which support the existence of a self-similar spectral shape in water of any depth, during high wind conditions (high steepness waves) (Bouws et al. 1985). Resio (1982) published an outline of the theory and consequences of this phenomenon for waves on a sloping bottom. One of the fundamental differences is an increase in the wave period of the spectral peak for a given wave height, which might explain some of the consistent discrepancies between Hydrotechnology's predicted periods and the measured wave periods.

3.5   VERIFICATION EFFORT

A thorough verification effort is a prerequisite to placing confidence in hindcast results. It has a twofold purpose, first to demonstrate the validation of each of the steps which make up the hindcast methodology, and secondly to obtain quantitative estimates of the errors inherent in the approach taken. Neither the Hydrotechnology nor the Seaconsult studies achieved these goals. Even a cursory review of their comparison of modelled and measured winds would indicate that neither methodology was verified successfully. The same conclusion can be drawn for the verification of the wave-modelling techniques, although in this circumstance the scarcity of appropriate measured data inhibited the verification effort.

Ideally, in terms of verifying the combined model performance for extremes, comparisons should be made between hindcast, maximum wave heights and measured, maximum wave heights for a substantial number of events. If, in specific cases, subscale influences degrade the comparisons, this needs to be regarded as a contribution to the error, at least for the type of storm in which this degradation is significant (the polar instability lows). Once the types and magnitudes of wind and wave errors for different storms are understood, they need to be quantified appropriately. Following this step, the effects of random error and overall bias on estimates of the extremes both need to be quantified.

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[1]   D.T. Resio, O.C.T.I. Ltd., 1985, personal communication.

3.6 STATISTICAL ESTIMATION TECHNIQUES

In the circumstances of a limited data base, both studies applied reasonable methodologies to determine extreme wave heights, however, the parameters to which they were applied warrants closer investigation. Extreme wave heights can only be generated during strong wind storms. Therefore, it is appropriate to treat the extreme wave-height generation problem as being made up of discrete events, such as is the case with earthquakes and ice invasions. In practice, environmental characteristics, such as wind speed or wave height, can be treated as random quantities given a storm event. The extremes can subsequently be derived as the maximum of a random number of random quantities. The associated techniques are well established (Lawless 1978; Carter and Challenor 1981). It is also important to examine whether all of the extreme wave-producing storms are of a homogeneous storm type or if they are of differing types which require subgrouping before performing the analysis of extremes (Muir and El Shaarawi 1986). A step forward would be to establish a set of criteria for a critical storm definition, such as strength and duration of the wind and the extent of the open-water area. The definition of what constitutes a critical storm, however, is of less importance than ensuring that all storms which could generate high waves are included within the definition.

4. SENSITIVITY AND UNCERTAINTY ANALYSIS

4.1 INTRODUCTION

As described in the preceding sections, there are four principal factors governing the hindcast estimation of extreme wave height in deep water, namely:

- the temporal and spatial description of the wind field (defining duration, wind speed, and directionality);

- the definition of the open-water area (defining the effective fetch length);

- the hindcast procedure adopted; and

- the method of associating a return period with a wave height.

In the discussion that follows, an attempt is made to identify and, where possible, to quantify, the effects on extreme wave-height estimation of the various simplifications and assumptions inherent in the methodologies adopted in the two studies which have been reviewed. To assist this process, a number of areas of uncertainty and sources of possible errors have been compiled for both studies. These are shown in pictorial representations of the information flow path for each of the two different approaches that were followed (Figures 17 and 18). For consistency, the assessment of model sensitivity and uncertainty is made for each of the five aspects of hindcasting discussed in the previous section.

The general purpose of an uncertainty analysis is to have the relevant random quantities, such as wind speed or wave height, reflect not only their own inherent random behaviour, but in addition, the unpredictability of other associated parameters or assumptions. For example, the onshore one-hour wind speed, X, observable at a given location, is clearly a random quantity with a probability density function (pdf), $f_X(x)$, that can be determined from previous data. However, the instrumentation used to measure values of the wind speed might not be perfect or may systematically overestimate the "true" wind speed. Therefore, given a value of $X = x$, there exists another "uncertainty" regarding the actual wind speed, X'; this is expressed by a conditional pdf of the form $f_{X'|X}(x'|x)$.

The "total" uncertainty regarding X' is consequently expressed by the pdf $f_{X'}(x')$, which results from the following compound:

$$f_{X'}(x') = \int_x f_X(x)\, f_{X'}(x'|x)\, dx$$

(Eq.7)

POTENTIAL SOURCES OF ERROR

ICE EDGE
VARIABILITY

WIND DIRECTION

METHOD OF MEASUREMENT

SAMPLING TIME

STABILITY EFFECTS

DIRECTIONALITY

OVERLAND/OVERWATER
CONVERSION

HEIGHT CORRECTION

SHALLOW WATER EFFECTS

WAVE-WAVE INTERACTION

FETCH

DURATION

MEASURED
ONSHORE
WINDS

TRANSFER
FUNCTION

DERIVED
OFFSHORE
WINDS

WIND
SPEED

WATER
DEPTH

BRETSCHNEIDER
3 PARAMETER
WAVE MODEL

LARGEST ANNUAL H

H is Wave Height

ANALYSIS OF EXTREMES
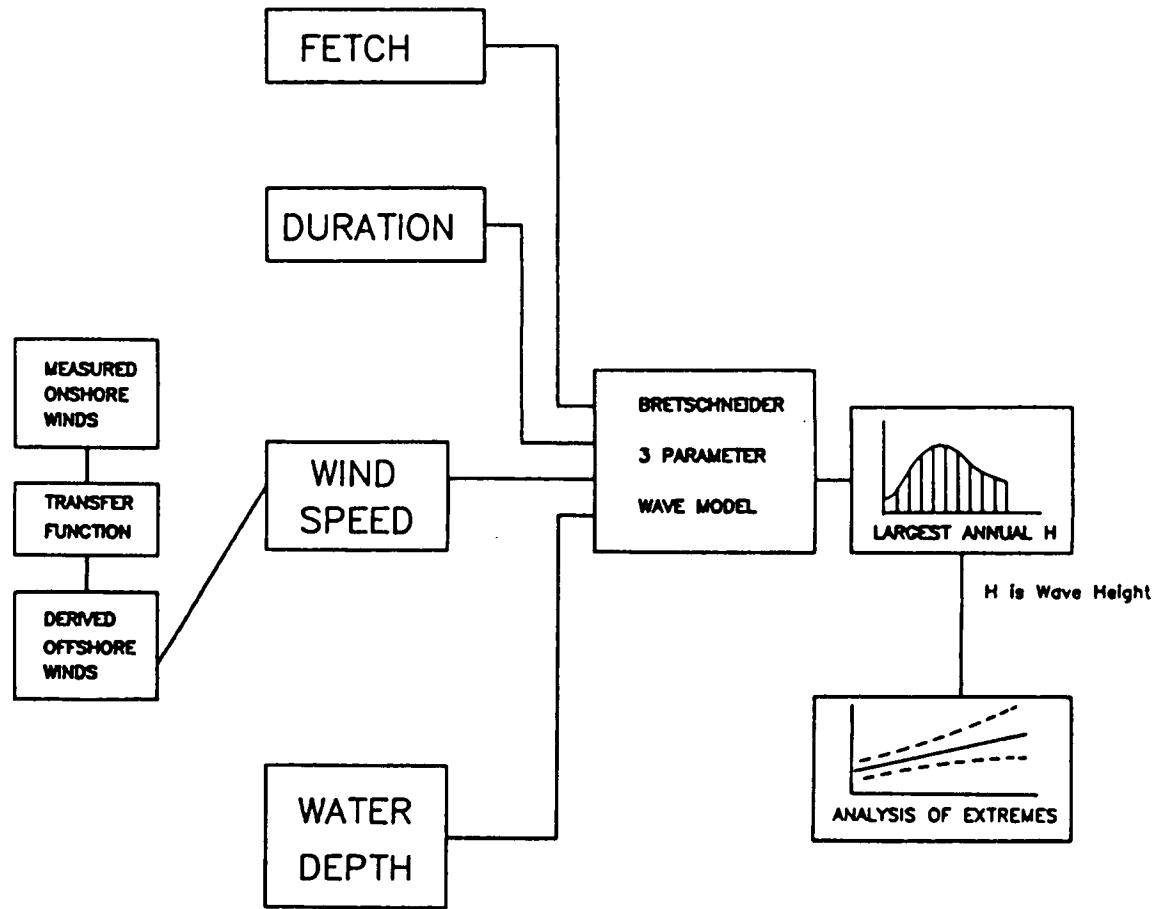
Figure 17. Information flow chart for estimating extreme wave heights using a significant wave height model.

POTENTIAL
SOURCES
OF ERROR

POSITION OF ICE EDGE

WAVE-WAVE INTERACTION

PRESSURE
MEASUREMENT
GRID SIZE
CHART PREPARATION
(INTERPOLATION
AND SMOOTHING)
MISSED STORMS
REDUCTION FACTORS
(eg STABILITY)

WIND
DIRECTIONALITY

INDEPENDENT
TREATMENT
OF ERRORS

LENGTH OF
DATA BASE

UNIQUENESS
OF EVENT

FETCH

C.M.C. 6 Hrly
PRESSURE
CHARTS

TEN ANNUAL MAX WINDSPEEDS

ANALYSIS OF EXTREMES
WINDSPEED RETURN PERIOD

50- and 100-Year
RETURN WIND SPEED

SPECTRAL
WAVE
MODEL

Hs,Te for 50 & 100
YR RETURN PERIODS

PROTOTYPE
STORM
SYSTEM

STORM
INTENSIFICATION
(DURATION)

PROTOTYPE STORM
SELECTION

WATER
DEPTH
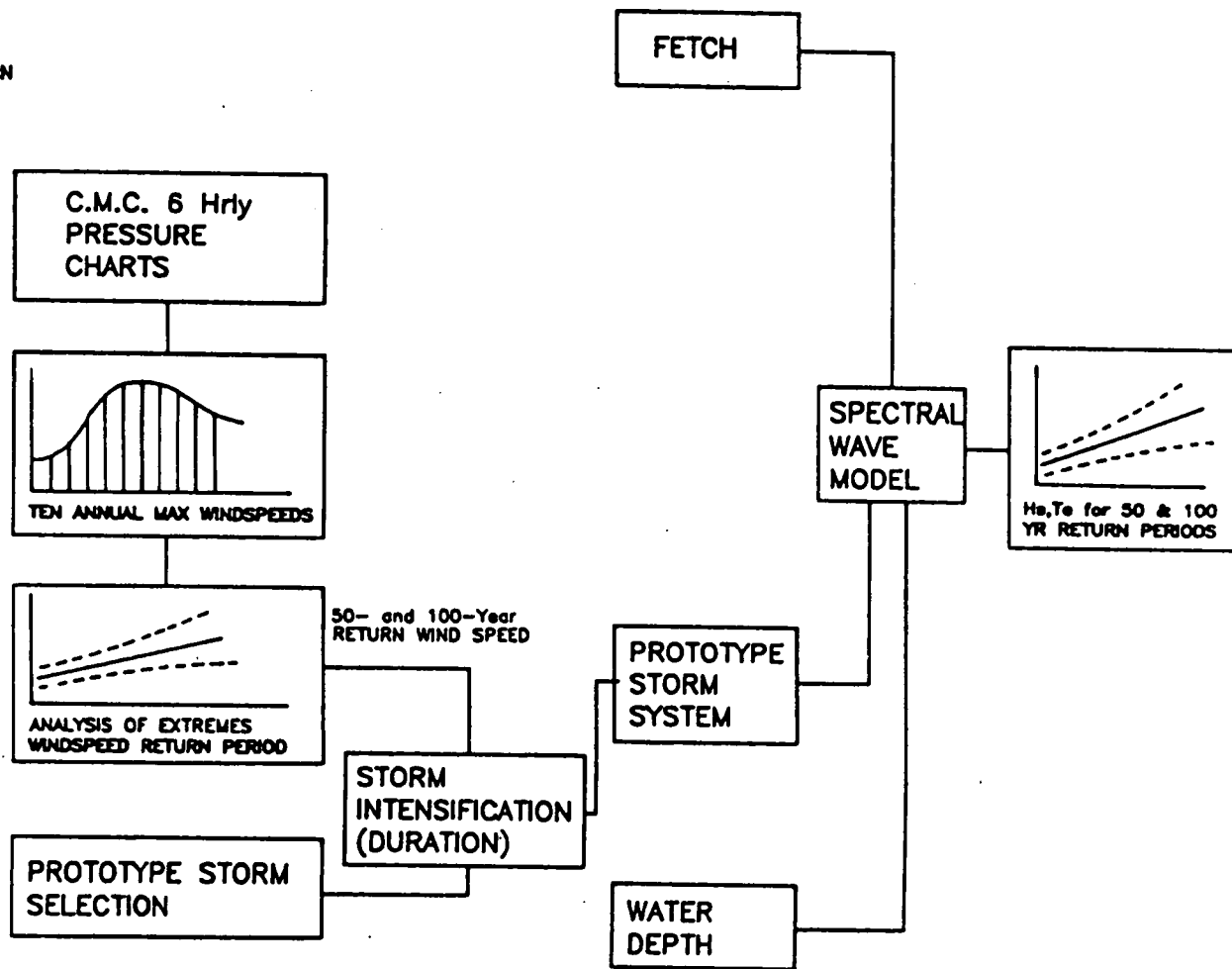
Figure 18. Information flow chart for estimating extreme wave heights using
a spectral wave model.

- 45 -

In the present discussion, the conditional distributions of the type $fX' | X$ will not be given explicitly, but in most cases the variability of X', given the "range" or "error bound", X, will be indicated.

A number of computational exercises have been performed using the parametric wind storm-extreme wave prediction method outlined in Section 3.2 and described in more detail in Section 4.4, to test the sensitivity of the extreme wave height estimates to variations in the input parameters. The results of the exercise are presented and discussed at the end of this section.

4.2 UNCERTAINTIES AND POTENTIAL ERRORS ASSOCIATED WITH THE PARAMETRIC MODEL

The various components which make up the modified Bretschneider parametric, significant wave model used by Hydrotechnology are depicted on the information flow chart (see Figure 17). The four principal elements involved in producing a significant wave height are seen to be wind speed and direction, duration, fetch length, and water depth. Each of these elements contain either measured or derived data products with which there are associated measures of uncertainty. For example, measured data may be corrupted by erratic sampling procedures or poorly calibrated equipment, while derived data may have been obtained from an inadequate theoretical model. It is not always possible to determine the exact probability distributions of the random quantities introduced into the modelling process, however, some measure of confidence in the end results can be obtained given a subjective assessment of the margins within which the random quantities are likely to vary.

4.2.1 Event selection

When attempting to define return periods for extreme wave heights at an offshore location, without having access to in situ wave height measurements, the only data base with a sufficiently long run is the meteorological record. Fortunately for the southern Beaufort area, wind-speeds have been measured every six hours by AES at Tuktoyaktuk airport and other coastal locations, on a regular basis for at least 14 years. During the course of this study, the authors were directed to another significant source of measured wind data, at AES Station No. 2203910 located at the Distant Early Warning (D.E.W.) line station some 3 km northeast of Tuktoyaktuk airport. The six-hourly U2A anemometer records at this site date back to early 1960s. The winds blowing in the area exhibit quite distinct directional patterns, the two most frequent being winds from the north towards the west, and from the southeast towards the northeast.

Harper and Penland (1982) have presented directional wind distributions for the area (Figure 19) based on the AES measurements taken at Tuktoyaktuk and a number of other coastal stations over different time periods. For example, at Tuktoyaktuk, the data used covered the period 1975-80, at Komaluk, 1975-80, and at Shingle Point, 1974-79. It can be seen from Figure 19 and 20 that the stronger winds, that is those greater than 40 km/hr (22 knots), are predominantly westerly or northwesterly in direction. The directional wind data, in percentage terms, described by the various pie charts shown in Figures 19 and 20 can be interpreted using the radial scales shown alongside each figure.

Figure 19   Directional Distribution of Winds at Stations Along the Beaufort Sea Coast.
-Harper and Penland, 1982

Figure 20.   Directional distribution of summer winds for offshore locations
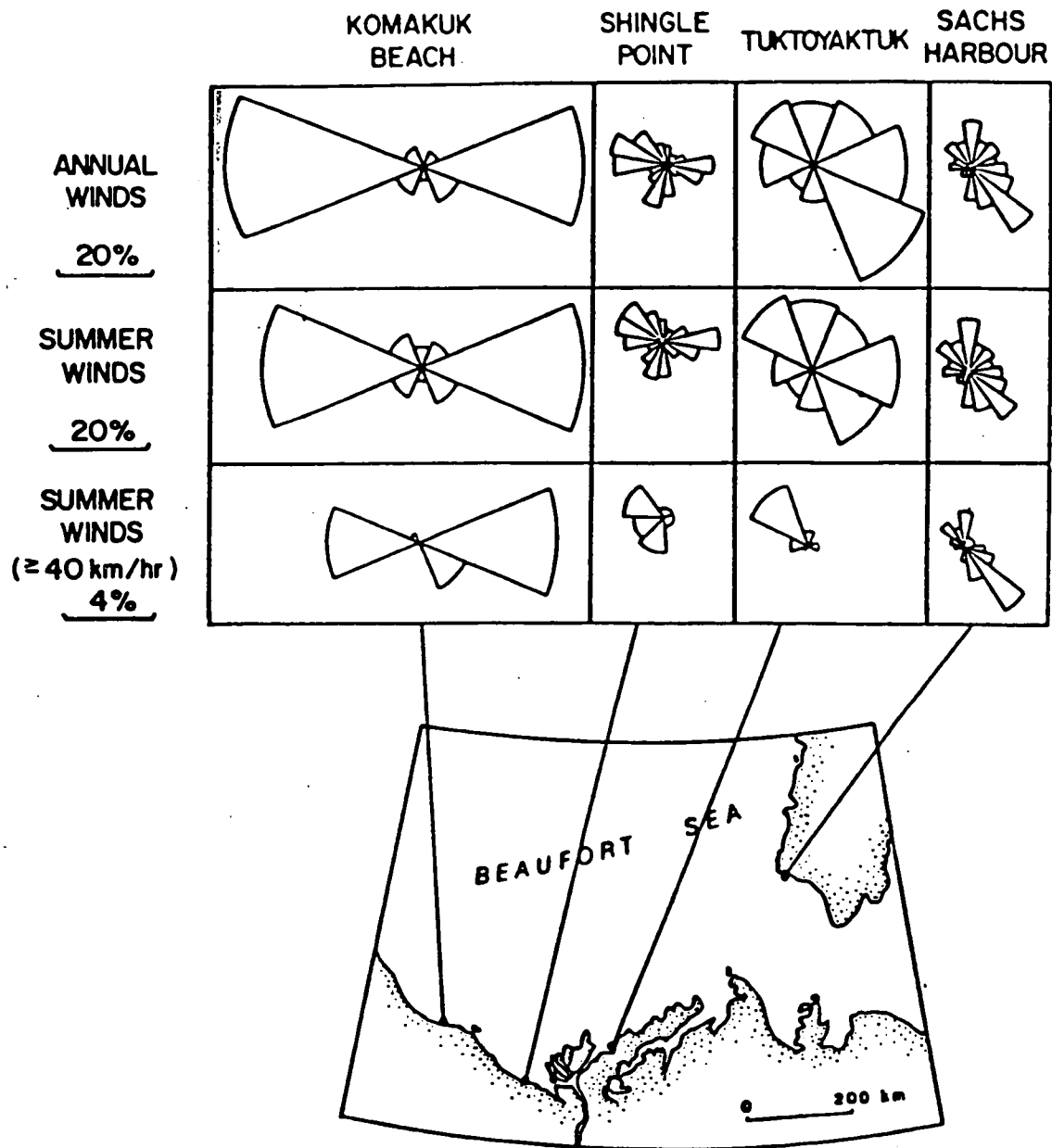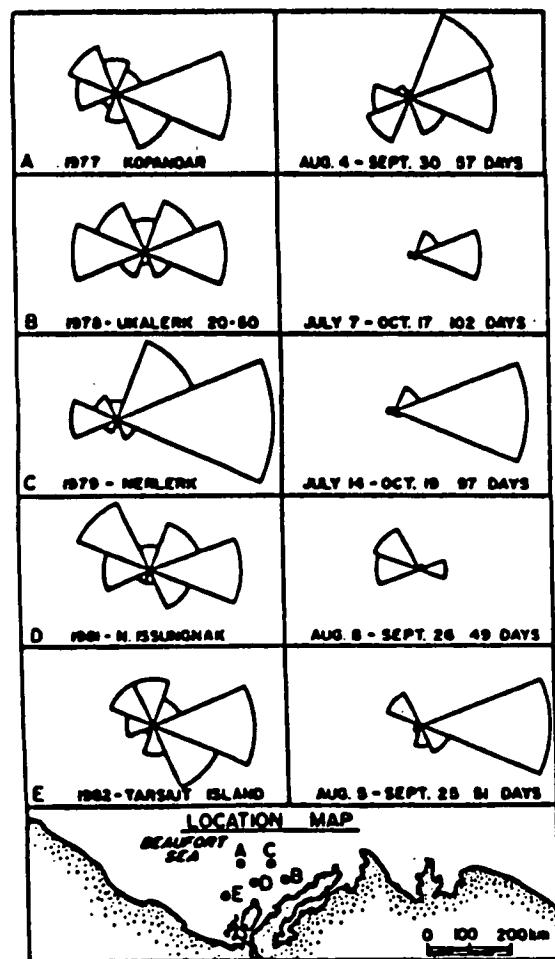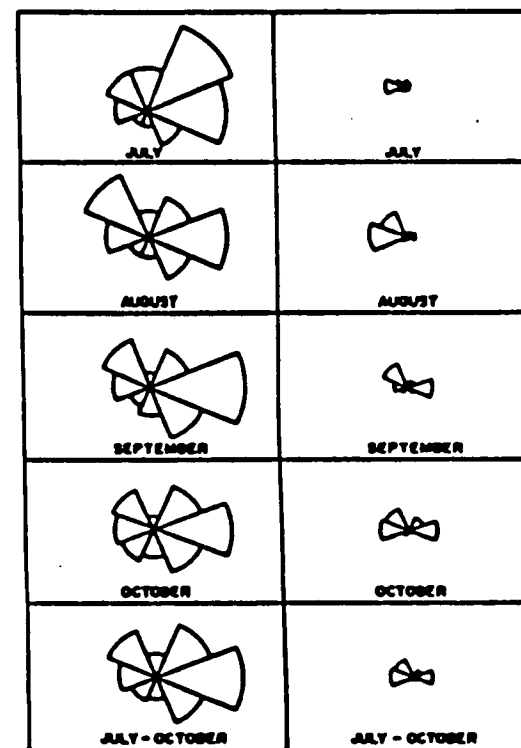in the Canadian Beaufort Sea (Source: Fissel and Birch 1984).

An examination of the maximum of the hourly wind record at Tuktoyaktuk for the period 1970-80 confirmed this finding. Figure 21 shows that while monthly, mean wind speeds remain almost constant throughout the year, the strength of the westerly and northwesterly winds increases in the autumn and winter months. It is worth noting, however, that the annual reports from the Beaufort Weather Office indicated that the storm pattern which occurred most frequently during the 1982, 1983, and 1984 drilling season was associated with a trough of low pressure aligned west-northwest to east-southeast across central or northern Alaska, causing winds from an easterly direction to dominate the Canadian Beaufort area. In general though, the separate analyses gave support to the Hydrotechnology finding that the highest wind speeds at several offshore locations were associated with predominantly westerly-northwesterly winds. The wind data base at Tuktoyaktuk showed a good degree of consistency when used to establish directionality associated with high wind speeds over lengthy periods of time. This conclusion is also supported in the more detailed APOA Study 203.

4.2.2   Uncertainties associated with wind field data

The offshore wind-field record is required as input to the parametric model. In the case of the parametric model, this record either did not exist for a number of sites or covered only a short period of time, so that it had to be derived from the onshore wind data. As can be seen from Figure 17, this required a number of procedural steps, each having a measure of uncertainty. Without a doubt, the most crucial step in the modelling process involved the determination of the transfer function(s) required to relate the offshore and onshore winds. Before this relationship could be established, however, the wind-speed records at the onshore reference station (Tuktoyaktuk) and at several offshore reference sites had to be obtained. Therefore, to maintain the chronology, we first examine the means of collecting onshore and offshore wind data and their potential sources of error.

Both the Fissel and Birch (1984) and Danard and Gray (1984) examinations of the Beaufort Sea wind data formed part of studies whose principle objective was not the development of hindcast wave heights. In contrast, the 1983 APOA Study 203 on Beaufort Sea wave hindcasting was a concerted effort to produce hourly wave climate data for direct use in the design and operation of exploratory drilling activities in the area. The study contains a thorough compilation of measured onshore and offshore winds in the region, with careful checking of the location, type of instrument, recording height, and extent of coverage for at least 44 sites. It was not intended that all of these data be used in the updating of the Hydrotechnology hindcast, but they do provide a valuable source of information.

Considerable effort was expended during the APOA Study 203 to repair the gaps in the U2A anemometer measurements taken at Tuktoyaktuk airport and to verify that the overwater wind field in the Beaufort Sea was essentially uniform and that it could be represented (with suitable modification) by the onshore wind data recorded at Tuktoyaktuk. This latter task involved a detailed study of the transformation of the recorded overland winds into overwater wind speeds. To do this, transfer functions were developed for two situations, first for those instances where long periods, that is one to two months, of recorded overwater wind data were available and secondly, for
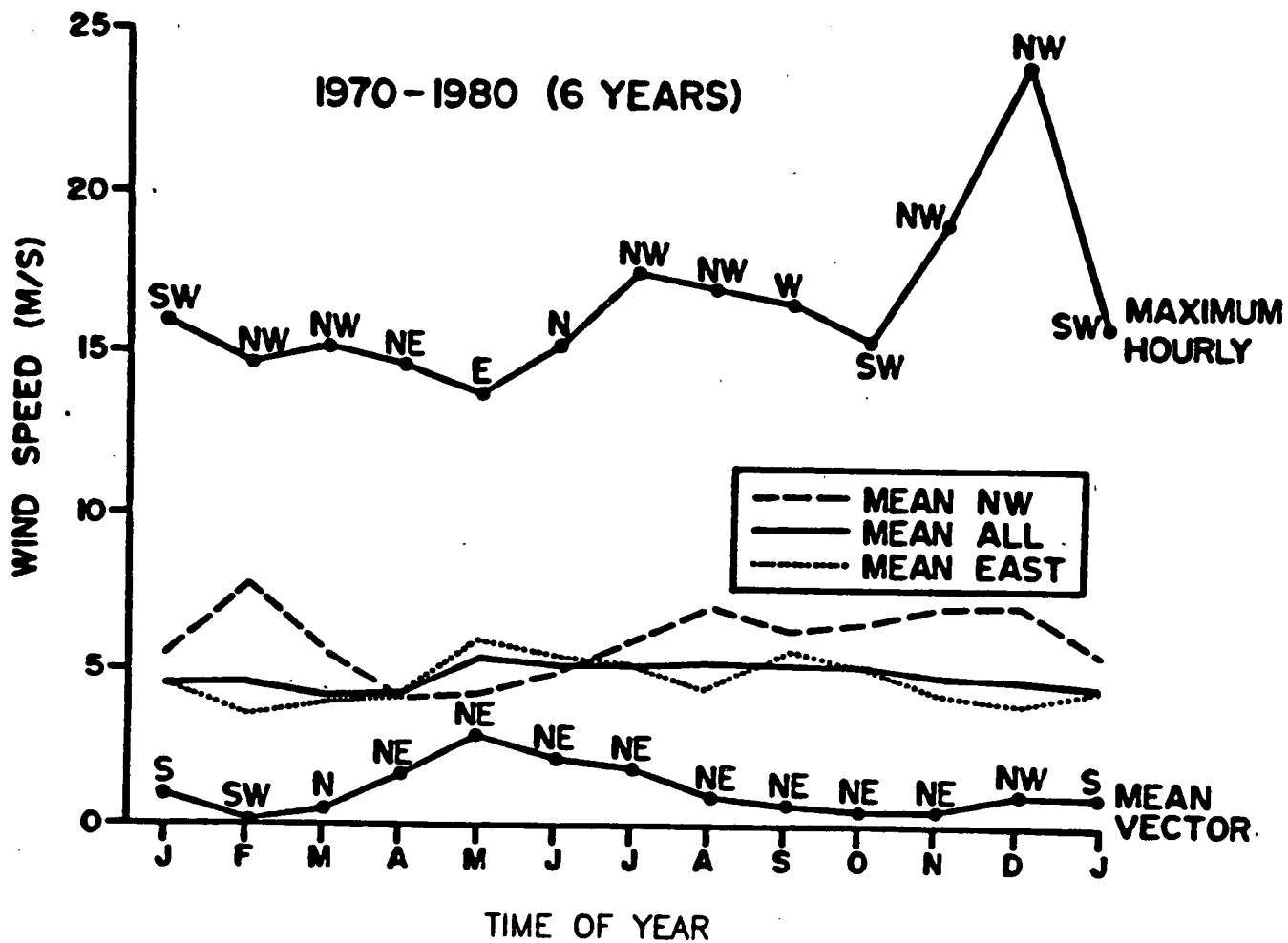
Figure 21.   Seasonal variations in wind-speed statistics for Tuktoyaktuk (source: Fissel and Birch 1984).

those storm conditions, when recorded winds in excess of 54 km/hr persisted for at least six hours (AES category 2 storm) and for which contemporaneous offshore winds were available.

For the first category, some 23 transfer functions covering different time periods were established between Tuktoyaktuk and 13 offshore sites. An additional 26 functions were developed for the category 2 storm periods at the 13 sites. From all 49 transfer functions, two generic types emerged: one having an exponential type of form similar to that shown in Figure 7, and the other indicating a constancy over the observed speed range. Both shapes were found during storm conditions and over the longer time intervals. The individual transfer functions differ from one another within the same generic group, indicating that no single transfer function is generally applicable for all locations, all years, or all times of year.

The procedure used to derived the transfer function was considerably more detailed than that used in the Hydrotechnology study, although it ignored direction and the preparation of wind frequency distributions (histograms) for each data set. The transfer functions were assumed to belong to a family of curves given by the expression:

$$S.F. = d + aV^b * exp(cV)$$

where S.F. is the overland/overwater scaling factor and V is the overland wind speed. The value of the transfer function at the highest observed wind-speed interval on land was calculated simply as the ratio of the highest wind speeds in the onshore and offshore files.

The values of the coefficients a, b, c, and d were determined in an iterative procedure which involved the uniformly random selection of values for a and b within specific ranges and the calculation of the value of c from an expression which implicitly related the ratio of the highest recorded values of wind speed on land and at the offshore location, to the highest recorded wind speed in the onshore record. The maxima of the resulting equation was calculated and if it exceeded 2.5 the four parameters were reselected, otherwise a detailed goodness of fit procedure was initiated. This step involved calculating a weighting function for each interval of wind speed in the onshore record before comparing the onshore and offshore histograms. The comparison of these histograms was performed numerically by calculating a "figure of merit" whose basis was such as to give equal weight to the fit at higher wind velocities and to the intervals with the greatest frequency of occurrence.

An extensive examination within APOA Study 203 of the data sets used to develop the transfer functions did not yield any explanation as to the reason for the two generic types, or the variations within each type, other than to suggest that it was in some manner related to the iterative fitting procedure, the goodness of fit procedure, and to the individual characteristics of the various synoptic systems or of the storm tracks.

A significant finding of the study was that of the 49 transfer functions generated, all but 14 indicated that at the higher wind speeds, that is greater than 30 to 40 km/hr, the recorded onshore winds could be as much as 20% higher than those recorded offshore. This result is at variance with all the previous studies; it was suggested in the APOA Study 203 that the physical explanation for this result might lie in the hypothesis that the surface friction factor may be related to the age of the waves and that it is only after the sea state has ceased to increase that the surface friction factor decreases to the low value. It was then suggested that it is probable that the offshore friction factor fluctuates around the value which is characteristic of the flat, low terrain surrounding Tuktoyaktuk airport, and that during the growth stage of a storm the friction factor offshore is greater than it is on land.

4.2.2.1   Method of recording wind data

Whereas the offshore wind records have been collected by drillships on location, the onshore data collection has been the responsibility of the Atmospheric Environment Service. AES makes use of two quite different types of anemometer to record wind speed. First, the U2A is a purely mechanical device consisting of three cups which, when rotated, turn a shaft at a rate directly proportional to the wind speed. The shaft is connected through gearing to an anemograph, a 24-hour, step-recording instrument which integrates wind speed over each whole hour. Secondly, the 45B is also comprised of three cups, but they drive a small direct-current generator, whose output can be calibrated to produce a continuous read-out of wind speed. Thus, whereas the hourly wind record reported by the mechanical device reflects the total distance covered by the anemometer in the preceding hour, the readings from the electrical, analogue device represent the average speed during a one-minute interval, and are obtained from a visual estimate of a strip chart taken on the hour. In gusty conditions, the observations of the wind speeds produced by the electrical anemometer are extended to cover a three-to four-minute period to be more representative of the hourly mean. Subjective judgment is used when taking readings, however, it is assumed that a trained observer will maintain a consistent level of accuracy. Jandali (1985) studied the relationships between four commonly used indicators of time-averaged wind speeds at two coastal stations on the Queen Charlotte Islands. The comparison was made between

-    one-minute wind speeds averaged on the hour;
-    maximum one-minute average wind speed during the hour;
-    peak gust recorded during the hour; and
-    mean hourly wind speeds.

At both coastal locations, a U2A type of recording anemometer was used, and Jandali used the most stable of the speed indicators, the hourly mean, as the reference speed. He found that over the course of 4369 and 3654 valid hourly records for the two locations, the maximum one-minute wind speed was an average 37% greater than the hourly mean -- somewhat higher than generally quoted in the literature. Whereas this result could well be representative of conditions along the north coast of British Columbia, it would be unwise to suppose that it is directly applicable to the U2A observations made at Tuktoyaktuk. According to Baird and Hall, no definitive studies have been undertaken to compare the data recorded with the two types of

anemometer. Businger et al. (1971), however, noted that the response of a typical three-cup anemometer to a fluctuating horizontal wind field is nonlinear. The device also responds nonlinearly to vertical wind components and these characteristics tend to lead to overspeeding, resulting in indicated wind speeds that are greater than the actual horizontal wind speed. Although quantitative estimates of inaccuracy are rare, Businger et al. referred to a comparative wind tunnel and atmospheric test conducted by Izumi and Barad (1970) using sonic and three-cup anemometers. The sonic anemometer is an inherently linear and accurate device. Izumi and Barad found that their mean wind speeds using this instrument were correct to within 1%. By comparison, the three-cup anemometer readings were consistently 10% higher for all stability conditions.

At Tuktoyaktuk, the anemometers are positioned on an exposed tower at a reference height of 10 m, as recommended by the World Meteorological Organization. They are inspected and calibrated annually by AES personnel, the calibration procedure in the case of the electrical device taking the form of applying a battery pack of known current and voltage so as to drive the anemometer at a particular rotational speed corresponding to a given wind speed. The accuracy of the anemometer is considered to lie within ± 1 m/s for wind speeds up to 15 m/s, and within ± 1.5 m/s for wind speeds in excess of 30 m/s.

The accurate measurement of offshore winds at drilling sites is complicated by the fact that drillships are quite unsuited to the task of functioning as observation platforms. Often the air flow around the superstructure and derrick is so disturbed that anemometer readings are distorted and inconsistent. In addition, it is usual practice to moor the drillship at a fixed heading for considerable periods of time, with the result that the anemometer can be sheltered from the wind, causing a bias in the recorded wind speeds and durations. Usually two anemometers are fitted to the vessel at different heights. The lower instrument is generally located near the bridge (about 25 m above mean water level), with the other instrument positioned at the top of the derrick (in the range of 55-80 m above mean water level). One difficulty associated with the analysis of offshore wind records is that the readings often do not indicate which of the anemometers have been read. It is generally assumed to be the uppermost one, but if this assumption was consistently incorrect then the recorded winds could be underestimated by up to 13% (based on a simple power scaling of the assumed elevations of the anemometers).

4.2.2.2   Overland/Overwater wind-speed ratios

As mentioned previously, a prerequisite for the estimation of extreme wave height using the parametric model is an extensive meteorological data base. Because there was a paucity of offshore wind measurements for the locations of interest, recourse had to be made to the available observations at coastal stations. It was noted earlier that Richards et al. (1966) showed that the overland/overwater ratio of wind speed varied with the wind speed and also depended upon atmospheric stability, the fetch, and the assumed difference in roughness of the land and water surfaces.

The Richards et al. results indicated overwater/overland wind-speed ratios to be in the range of 0.7 to 3.0, the lower values being associated with higher wind speeds and conditions of atmospheric stability (see Figure 7). It should be recalled that Baird and Hall (1978) were quite critical of these ratios, claiming that they overestimated the wind speed over water for the lower range of wind speeds. Using their statistical approach of comparing histograms of modified wind speeds for the onshore and for several offshore locations, they produced a different speed ratio characteristic. Their values had the much narrower range of 1.0 to 1.15, with the highest values associated with moderate wind speeds (7-8 m/s).

As part of one of the early hindcast studies (Dames and Moore 1975), Berry et al. (1975) used a factor of 1.22 to relate the wind speeds at Tuktoyaktuk to those offshore. This value was calculated from a power law developed by McKay (1966) to describe the relationship between surface winds at offshore and onshore locations at a standard 10 m reference height. It has the form,

$$\frac{V_o}{V_L} = (\frac{Z}{10})^N$$

(Eq.8)

where V_o/V_L is the ratio of the wind speeds at the offshore and the onshore sites, and Z is the height at which surface topography effects are assumed to be negligible, and N depends upon the difference in the surface roughness of land and water surfaces. The underlying assumption in the development of the equation was that deep, turbulent mixing of the air occurs. In the case of lighter winds this assumption is not the case, hence, the equation is only applicable for use with higher wind speeds. There is, thus, a difference of 22% in the correction factors used by Hydrotechnology and Berry et al. when considering the wind speeds conducive to the generation of large wave heights.

Quite recently Arctic Sciences Ltd. (Fissel and Birch 1984) conducted a study on sediment transport in the Beaufort Sea. As part of this work they performed several regression analyses on simultaneous wind measurements taken at a number of offshore drilling locations and from the U2A recording anemometers at the Tuktoyaktuk DEW line station, which is some 3 km to the northeast of the airport measurement site. The offshore data sets used were Kopanoar, 4 August - 30 September 1977; Nektoralik, 31 July - 13 October 1977; Nerlerk, 14 July - 19 October 1979; Issungnak, 8 August - 27 September 1981; and Tarsiut, 5 August - 25 September 1982.

All of the offshore wind data were converted to a 10-m reference height and conditions of neutral atmospheric stability was assumed. As pointed out in the previous section, these data were subject to measurement errors, sheltering effects, variations in atmospheric stability, etc. The hourly wind speed records from the drillships were subsampled at six-hourly intervals to make them contemporaneous with the Tuktoyaktuk data set. Correlation analyses, however, indicated that the latter data consistently led the offshore data by about six hours, with the exception of Nerlerk for which a best fit was reported to have been obtained by lagging the

Tuktoyaktuk data by 12 hours. With the exception of Nerlerk, all of the regression analyses were performed by using the Tuktoyaktuk data lagged by one record length (six hours).

The regression analyses performed on the Kopanoar data were somewhat more extensive than for the other locations; a sampling of their scatter plots is shown in Figure 22. All of the data in the Kopanoar set were used to produce these plots with no distinction made for speed, fetch, or atmospheric stability. The dominant winds were found to be aligned east-west and the results of the regression analysis indicated that the east-west wind component measured offshore was 19% higher than that measured at Tuktoyaktuk. The water-to-land wind-speed ratio for the Kopanoar location was found to be in good agreement, with a least squares fit of 0.98 at zero intercept. Fissel and Birch concluded that given the Tuktoyaktuk wind direction, the offshore wind direction could be deduced to within better than ± 40°. They repeated their analysis of the Kopanoar data, first excluding all wind speeds less than 4 m/s and secondly excluding those wind speeds less than 8 m/s. As expected, the correlation for wind speed improved markedly, as can be seen in Table 7. The difference in the wind directions also improved to within ±10°.

Table 7

**The water-to-land wind ratio for sample wind records measured
at the Kopanoar locations, with Tuktoyaktuk winds given for all wind speeds, and
wind-speed classes exceeding 4 and 8 m/s.**

	Wind Speed Classes		
Water/Land Ratio	All records	> 4 m/s	> 8 m/s
Speed	1.29	1.34	1.47
E-W component	1.19	1.20	1.32

Source: Fissel and Birch (1984).

Similar regression analyses were performed on the data for the other four sites, the Tuktoyaktuk record being lagged by 6 or 12 hours to obtain the best fit to the offshore wind records. Table 8 summarizes the results of the analyses performed.
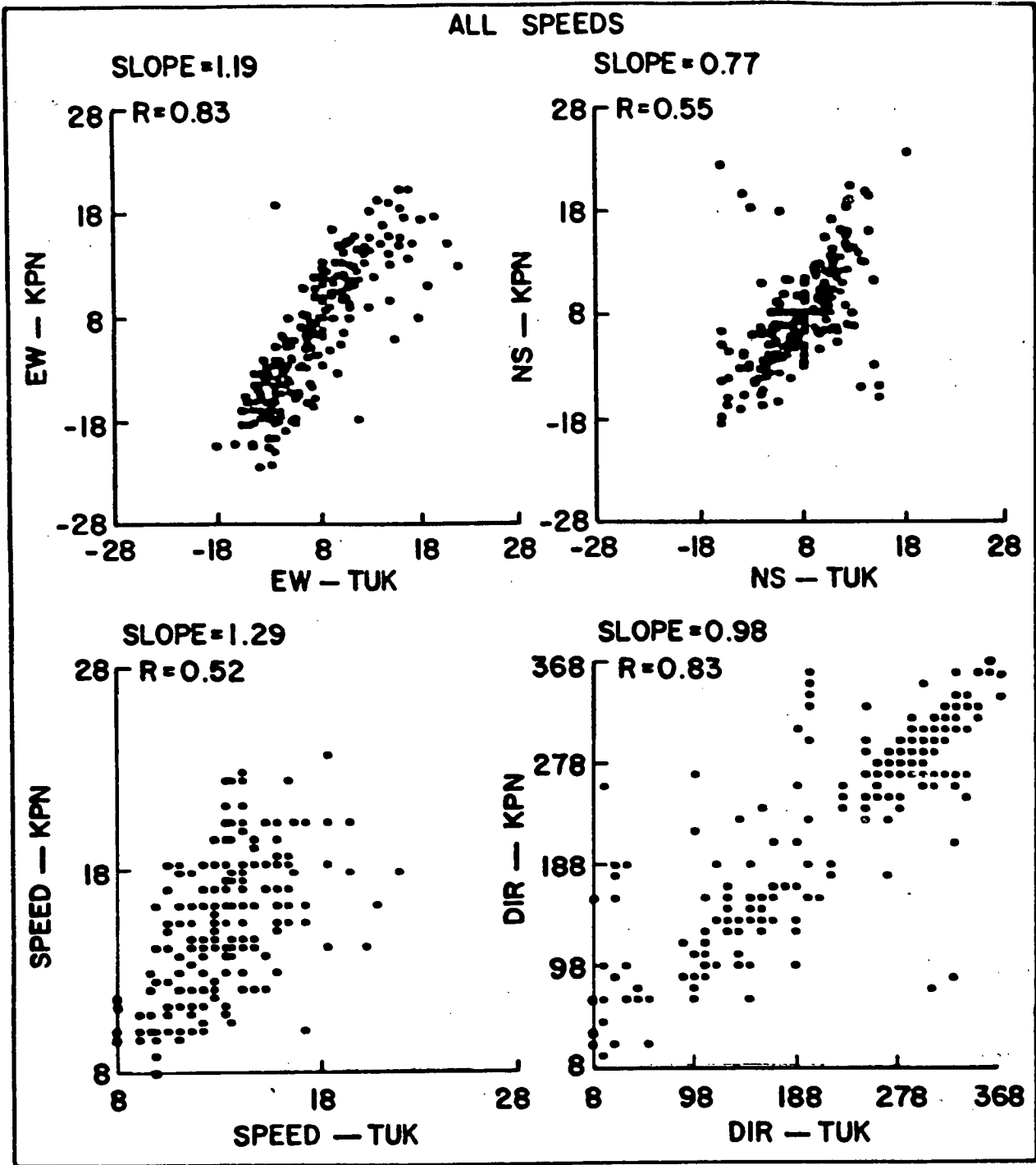
Figure 22.   Scatter plots for offshore winds as measured at Kopanoar (KPN) and Tuktoyaktuk (TUK) for the period 4 August - 30 September 1977. Regression fits have been contained through zero (source: Fissel and Birch 1984).

Table 8

Summary of wind ratio regression analyses for all wind-speed classes, based on comparisons of data from five offshore sites with Tuktoyaktuk winds

Site	Time period		Ratio	Lag time (hrs)
Kopanoar	4 Aug.-30 Sept. 1977	Speed	1.29	6
		E-W	1.19	
Nektoralik	31 July-13 Oct. 1977	Speed	1.26	6
		E-W	1.19	
Nerlerk	14 July-19 Oct. 1979	Speed	1.23	12
		E-W	1.19	
Issungnak	8 Aug.-27 Sept. 1981	Speed	1.04	6
		E-W	1.03	
Tarsiut	5 Aug.-25 Sept. 1982	Speed	1.27	6
		E-W	1.20	

Source: Fissel and Birch (1984).

The Issungnak result is anomalous, although Fissel and Birch could find no satisfactory explanation for it, nor could they explain the lead time of the Tuktoyaktuk data. The results obtained from the other sites indicated that the offshore winds are generally 20 to 30% higher than those measured onshore at Tuktoyaktuk. When the data analysis was confined to wind speeds greater than 8 m/s, the water-to-land wind-speed ratio for the four sites lay in the range 1.33 to 1.55.

A useful finding was the variation in the water-to-land speed ratios for different locations. Although the differences were small, they indicate that using the same ratio for all locations, as was the case in the Hydrotechnology study, could introduce an error in the order of ± 3% in the wind-speed record. A similar analysis to that performed by Fissel and Birch was undertaken by Danard and Gray (1984). They compared wind data measured at eight offshore drilling locations in the summer of 1982 to the Tuktoyaktuk wind data, measured at the airport using a 45B anemometer. No height correction was made to the measured offshore winds, although Danard[1]

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[1] M. Danard, Atmospheric Dynamics Corp. 1985, personal communication.

claimed that any error from this source would be counterbalanced by a correction for atmospheric stability conditions. The data analysis was confined to those Tuktoyaktuk wind speeds in excess of 5.5 m/s (20 km/hr) having a direction from 253° through north to 073°. The average water-to-land speed ratio for this data set was stated to be 1.18, with little directional difference noted.

In summary, it appears from the various studies conducted that, after taking account of the various anomalies, sampling periods, and data restrictions, the land-based wind record could underestimate the offshore record by as much as $\pm 20\%$ and that the variability in wind directions is better than $\pm 40^{\circ}$.

4.2.2.3   Wind profiles over water

In the previous section, it was noted that in converting the offshore wind data to a 10-m reference height, Arctic Sciences assumed conditions of neutral atmospheric stability. That is to say, no account was taken of the vertical temperature gradient over the water or of the wind stress. Similarly, Hydrotechnology, it will be recalled, used a 1/7th-power scaling law to account for the vertical wind profile, commenting that although it was not representative of all conditions, further refinement was unwarranted in view of other limitations in the data. Nevertheless it represents a potential source of error and one which is amenable to quantification.

Smith (1981) has reviewed a number of empirical formulae governing wind and temperature profiles over water, and used these to tabulate factors for adjusting measured winds in the range of 2-50 m/s at heights of between 1 m and 60 m to a standard 10-m reference height. The range of air-sea temperature differences covered is $\pm 20^{\circ}$C. The suggested adjustment is, in addition to correction factors, to account for errors in wind measurement or flow distortion as outlined in section 4.4.1. Smith's algorithm takes into account the effects of surface roughness as a function of wind speed and the variation of wind and temperature profiles as recommended by Dyer (1974). The effect of waves on the wind profile is not included in his formulation, because it is assumed to be quite small. An example of the tabular output from his computer program is shown in Figure 23.

Using bulk water-surface and air temperatures of 0° and $+5^{\circ}$ C, respectively for the Beaufort area for the month of September, taken from the Beaufort Weather Office (1984) report, it can be seen that the correction factor that should be applied to a wind speed of 30 m/s measured at a height of 60 m is 0.81. A straightforward 1/7th-power scaling would indicate a conversion factor of 0.77 but the wind speed and air-water temperature difference varies considerably over the data-collection period, so that the 5% difference between the 0.77-power scaling factor and the 0.81 obtained from Smith's tables cannot be applied universally. However, it is indicative of the possible error from this source.

TABLE 16

WIND CORRECTION FACTOR 60.0 TO 10.0 M

Figure 23. Factors for adjustment of wind speed over water to a 10-m reference height (Source: Dyer 1974).

4.2.3　Sources of error in the wave modelling

It is important to note that since the completion of the Hydrotechnology 1980 study, the Coastal Engineering Research Centre (CERC) of the U.S. Army Corps of Engineers have revised the original Bretschneider hindcasting equations. These revisions have been based on a detailed review and analysis of the data used in the preparation of the original empirical equations and results, obtained from JONSWAP (Hasselmann et al. 1973). The revised equations were used in the APOA Study 205 for wave hindcasting, and are included implicitly in the methodology of the sensitivity analysis performed in the present study.

Hindcasting deep water waves using the Bretschneider, significant wave height model is quite a straightforward process. The waves are assumed to generate and propagate along a line towards the site for which the hindcast value is sought. It is necessary to define the length of this line (the fetch), and to provide a description of the wind speeds and durations. In wave hindcasting, the duration is the length of time the wind blows in essentially the same direction over the fetch. As was noted earlier, it is difficult for a parametric model to represent the various types of sheltering and propagation effects that are present in coastal areas. The changing wind patterns and the complex geometry of the coastal edge make it difficult to estimate fetch lengths and duration times accurately. The errors introduced to the modelling process from these sources, however, are unknown.

In the Beaufort Sea, the fetch lengths are also affected by the position of the polar pack ice and fetches of great length in comparison to their width are quite common. This effect inhibits energy transfer from the winds into the waves, with the result that the wave heights generated under such circumstances are lower than would be expected in less-restricted waters. The width effect is not considered in the Hydrotechnology parametric model, although the absolute effect of its omission is unknown.

4.2.3.1　Ice edge variability

The wave climate in the Beaufort Sea is highly variable and is frequently limited by the short fetches over open water. The effective fetch lengths can vary markedly according to the changes in the position of the pack ice edge. In some years, such as 1974, the ice edge remained within 100 km of the shoreline and as a consequence the wave climate was mild. At the other extreme, Brower et al. (1977) identified one occasion when the ice edge retreated northwards over the entire length of the Beaufort Sea, from Banks Island to a point just west of Point Barrow. Under these circumstances, westerly winds would have a fetch length of about 850 km. According to the Canadian Ice Atlas (Markham 1981), movements of the ice edge of the order of 50-100 km over a 2- to 3-week period are quite common, which raises the question of the suitability of using mean monthly averages of the ice edge position with wind events of a much shorter time scale. The variability of the position of the ice edge, therefore, introduces an uncertainty into the wave-modelling process, although Hydrotechnology (after a number of trial hindcasts) concluded that the difference in hindcast waves obtained using limits defined by the one-tenth to nine-tenths ice cover was insignificant.

4.2.3.2   Shallow water effects

To account for the energy loss encountered as waves which have been generated in deep water propagate into shallower water, Hydrotechnology used the form of the Bretschneider equations which implicitly contain a constant bottom friction factor of 0.01. This formulation is used frequently by coastal engineers and is the basis for the published charts contained in the CERC Shore Protection Manual for estimating wave heights in shallow water. It is well known, though, that the friction factor is highly sensitive to the type of material on the sea bed, and the Shore Protection Manual states that the choice of an appropriate friction factor is a matter of judgment. A literature search failed to find any published data for bottom friction factors obtained specifically for the Beaufort Sea. This topic is addressed in more detail when uncertainties associated with the spectral wave approach are discussed.

4.2.4   ERRORS ASSOCIATED WITH VERIFICATION

It is difficult to obtain suitable measured values of significant wave height with which to compare the contemporaneous hindcast results. The wave buoy data used by Hydrotechnology often was incomplete, and when obtained under severe storm conditions, displayed large variations in the recorded wave heights; these prevented a representative comparison with the hindcast results. Wave directionality was not recorded so that no comparisons can be made with the wave direction inferred from the wind record. Such a lack of verification of the model's capability of representing storm conditions must have an influence on the confidence limits of the extreme value estimates. As Hydrotechnology used the same hindcast methodology in both their verification and production runs, any deviations between measured and hindcast wave conditions are characteristic of the actual errors contained in the production hindcasts.

Hydrotechnology's difficulty with verification resulted largely from the extent and quality of the measured wave data. Since 1980 a considerable quantity of the measured data has been collected, some of which was used to verify the improved hindcast models used in the APOA Study 203, which was identical to that used in the sensitivity analysis in the present study (see section 4.4).

4.2.5   SUMMARY OF UNCERTAINTIES ASSOCIATED WITH THE PARAMETRIC WAVE MODEL

The potential sources of error described above are listed in Table 9, the uncertainty associated with the magnitude of each potential error is ranked high, medium, or low, and an estimate of the variation of the random quantity involved is included where possible.

Table 9

Sources of error and associated levels
of uncertainty in the parametric wave model approach

Error source	Level of uncertainty	Variability (%)
Measurement of onshore winds	Low	± 6
Measurement of offshore winds	Medium	0-13
Stability effects	Low	± 5
Water/land speed ratio	Medium	0-20
Wind directionality	Low	±10
Wind duration	Medium	-
Fetch width	High	-
Ice edge variability	Low	-
Shallow water effects	High	-

4.3 UNCERTAINTIES AND POTENTIAL ERRORS ASSOCIATED WITH THE SPECTRAL WAVE MODEL

In comparison to the parametric or significant wave model, the spectral wave approach is considerably more complex, although that in itself does not make it more prone to errors. The various components contributing to the spectral wave model are illustrated in the information flow chart shown in Figure 18. The crucial elements are the selection of the prototype storm, the derivation of the surface winds from the synoptic pressure charts, and the energy transfer mechanism within the waves, particularly for shallow water conditions.

4.3.1 Event Selection

The selection of a unique storm event from which to develop return periods is significant in this approach from a statistical viewpoint. Seaconsult identified two classes of storms in the wind records: storms that enter the Beaufort Sea area from the north-northwest with trajectories across the polar pack, and storms moving from west to east. Their prototype storm was of the latter category. They do, however, note that in terms of hindcasting severe waves, both types of storms should be

considered. Their estimation of the 100-year storm was based solely on the consideration of wind speed recurrence intervals, with no consideration given to wind speed durations or fetch length. It is highly improbable that a single scalar quantity (wind speed) could provide an adequate means of characterizing a prototype storm event statistically, so there must be a high level of uncertainty associated with the selection process.

4.3.2   Sources of error in establishing the windfield

The CMC coarse grid of surface pressures was the primary data source used by MEP Ltd. to derive the two-dimensional, storm-based wind field for use in the spectral wave model. These data are prepared from a numerical, weather prediction model for North America and provide an accurate description of large-scale systems in the Beaufort area but allow small-scale systems to go undetected (Hodgins 1983). At present, considerable effort is being expended on the study of meso-scale storms, particularly in relation to their generation and advection. The U.S. has an ongoing project of the National Weather Service entitled "GALE," and Canada has the Canadian Atlantic Storms Project (CASP).

The type of small-scale disturbance of interest in the Beaufort area may, however, be much more akin to the "polar instability lows" that occur in the southern Norwegian Sea and in the northern North Sea. Since 1971 the Norwegian Hydrodynamics Laboratory has identified 71 incidents of polar lows, which have affected the Norwegian coast and which have resulted in wind forces from gale to hurricane strength. These features have a limited horizontal extent, about 150-300 km, so that it is difficult to follow their tracks across the ocean by means of conventional meteorological observation. Consequently, they frequently reach the coastline unpredicted. (The polar depressions can be identified on satellite photo imagery, as helically shaped clouds.) The cyclonic polar lows bear some resemblance to the much larger tropical cyclone or hurricane. They differ from the more common frontal systems not only in size, but also in that they generally lack a pronounced frontal structure. The mechanism for their generation is not understood completely, although useful discussions of their formation and energetics may be found in Okland (1977), and Rasmussen (1979).

The low-pressure phenomenon develops in areas where the temperature differential between air and water reaches 20-25°C, for example near an ice edge and close to temperature fronts. The large temperature differential leads to plentiful evaporation and warm, moist air is transported into the lowest air strata, yielding an important source of energy for the development of the rapidly forming system. In the Norwegian Sea the low has been characterized by a wind increase up to hurricane force within half an hour. The polar low superimposes itself on the large-scale atmospheric circulation patterns and generally has been noted to move in the direction of the large scale flow. On the right side of the centre of the depression (when viewed in the direction of propagation), the cyclonic and large-scale motions are reinforced and it is in this region that the highest wind speeds are observed.

It has been noted (Rabbe 1975; Tryggestad et al. 1983) that as the region of maximum wind speed passes, the wind changes direction quickly. The low may travel with a speed that equals the group velocity of the largest waves; in such circumstances, high waves are generated and the increase in the wave height at a specific location can be fairly rapid. Wave observations made from the Ocean Weather Station AMI at Tromsoflaket, 71°30' N; 19°00' E, indicate that the quick veering in wind direction results in very confused sea states. The Tromsoflaket location was the scene of what, as far as wind speed is concerned, may be an extreme example of a polar low. On 18 June 1980 a polar low struck the drillship Treasure Seeker. Initially the wind speed was recorded as 25 knots from the northeast. Air pressure fell rapidly and the wind speed (as measured at the top of the derrick) increased to 90 knots over the course of half an hour. This wind speed persisted for about four hours, though it changed direction from southwest to north during the event, so that the resulting sea state was not too high. After five hours the wind calmed to about 10 knots. During the period February 1978 to February 1981 the OWS AMI recorded details of ten polar lows at various locations in the northern North Sea and the Barents Sea. Given the absence of measured data on meso-scale disturbances in the Beaufort region, the AMI data records might prove to be a useful starting point in characterizing these phenomena.

Returning to the MEP study, reviewed early in section 2.5, the company conducted a sensitivity analysis of their modelling procedure, cataloguing a number of potential sources of error. This discussion is amplified in the following subsections.

4.3.2.1 Pressure measurements

An accurate measurement of grid station pressures and their subsequent reduction to mean level pressure is essential to the preparation of accurate weather mapping. MEP identified pressure measurement as the least significant source of error ascribing to it a maximum value of 0.2 mbar. The Beaufort Weather Office report (AES 1984), however, notes that misreadings of between 0.5 and 1.0 mbar are not uncommon in reports from drillships. It is expected, though, that noticeable pressure discrepancies of the latter type would be detected and not used in the determination of grid point pressures.

4.3.2.2 Development of grid point pressures

Mean sea level pressure is analysed after each six-hourly interval at CMC, and the pressures are stored for all 381-km grid points. In general, the level of error contained in the computer analyses of these grid point pressures is in the order of 0.2 mbar. The probability of larger errors increases for regions of sparse data reports, such as the Beaufort Sea, where the position and central pressures of systems often are difficult to assess. In such circumstances, the error in the grid point pressures over a localized area could be about ±4 mbar, which is sufficient to cause a significant change in the derived wind speeds for the region affected.

The error associated with interpolating or smoothing the grid point pressures on the finer 190.5-km grid scale is relatively small, and in a number of test cases performed by MEP, amounted to less than 1 mbar, which for a typical pressure pattern corresponds to an error of 1 m/s in the geostrophic wind speed. MEP stated that the most important errors arising from the grid point analyses are the combined effects of these spatial errors and time resolution inadequacies which are introduced as a result of the 6-hour sampling rate. It is possible that short-duration events are filtered, which could lead to the peak values of storms being missed.

As mentioned in the preceding section, there are occasions when relatively small, but highly intense, storm systems exist in the area. These systems, defined by Hodgins as "Arctic instability lows" have the capability of generating severe sea states, yet they often escape detection on the synoptic weather charts and are only evidenced by recorded wind data. According to MEP, these "missed" storms could cause wind speeds several times greater than those deduced from an unduly large grid point pressure pattern.

4.3.2.3   Deriving surface winds from synoptic charts

Wind is the gravitational response to density differences in the atmosphere that are represented on synoptic charts by differences in atmospheric pressure. Once the air flow is in motion, its direction relative to the land surface is determined by the combined influence of the Coriolis effect, centrifugal force, and frictional effects. The Coriolis effect (caused by the earth's rotation) causes the air mass to move in a curvilinear fashion, this motion being opposed by the centrifugal and frictional forces. The effect of friction is most pronounced near the surface, and is almost negligible at altitudes above 800 m. At this altitude, the resultant wind flow direction is found to be almost perpendicular to the isobars that represent levels of equal atmospheric pressure. This air flow is referred to as the geostrophic wind, and is probably the most commonly used first step in the computation of surface winds.

Several correction factors must be applied to the geostrophic wind to arrive at realistic values of the surface wind. In each case, there is the possibility of introducing errors. These correction factors take account of:

-    surface roughness or frictional effects;
-    atmospheric stability;
-    curvature of the isobars in the vicinity of well-developed lows (or highs); and
-    isallobaric (rate of change of pressure) effects.

Invariably surface frictional effects cause the measured wind speed to be somewhat lower than the geostrophic wind speed. As noted earlier in this section, the more unstable the air mass, the closer the real wind speed approaches the geostrophic speed.

The Beaufort Sea is well known as an area for cyclogenesis. The synoptic charts, therefore, usually contain some quite sharply curved isobars in the vicinity of well-developed lows (or highs). When the isobars are curved, in a cyclonic fashion around a low or anticyclonically around a high, an additional centrifugal force must be taken

into account to achieve balanced flow. The development of the balanced flow equation obtained by equating the centrifugal Coriolis and pressure gradient forces can be found in most textbooks on numerical weather prediction (see, for example, Petterssen 1956). For anticyclonic flow the resulting quadratic equation has the form:

$$V_{grad} = V_g - \frac{V_g^2}{fR}$$

(Eq.9)

or

$$V_{grad} = \frac{fR}{2} \{(1 + \frac{4V_g}{fR})^{0.5} - 1\}$$

(Eq.10)

where: V_g =   geostrophic wind speed (m/s)
V_{grad} =   gradient wind (m/s)
f   =   Coriolis parameter $= 2\Omega\sin\phi$
R   =   radius of curvature (m) which is positive in cyclonic conditions and negative in anticyclonic conditions
Ω =   speed of rotation of the earth $= 0.7292 \times 10^{-4}$ rad/sec
ϕ =   latitude (deg.).

Equation 10 provides a good approximation to the true wind above the planetary boundary layer, where the isobars do not sharply converge or diverge and the pressure gradients are not changing rapidly with time. It is seen from Equation 10 that the geostrophic wind is an overestimate of the balanced wind near a low and an underestimate near a high.

In anticyclonic conditions, it is possible, theoretically, for conditions of V_g and R to be found that would create an imaginary solution. Clearly, the limiting case is reached when the gradient wind equals twice the geostrophic wind speed. It should also be noted that as R diminishes, the value of the geostrophic wind must decrease. This condition requires that the pressure gradient must decrease towards the centre of a high. The results of applying Equation 10 to modify the geostrophic component can be seen in Tables 10 and 11.

TABLE 10

Effect of cyclonic curvature at latitude 70° N on geostrophic wind speeds

Radius of isobar (deg.)	Geostrophic wind V_g, (knots)										
	15	20	25	30	35	40	45	50	55	60	70
1	11	14	16	18	21	23	25	26	28	30	33
2	12	16	19	22	25	27	30	32	35	37	41
3	13	17	20	24	27	30	33	36	38	41	46
4	13	17	21	25	28	32	35	38	41	44	49
5	14	18	22	26	29	33	36	39	43	46	52
6	14	18	22	26	30	34	37	41	44	47	54
7	14	18	23	27	31	34	38	42	45	49	55
8	14	19	23	27	31	35	39	42	46	50	57

TABLE 11

Effect of anticyclonic curvature at latitude 70° N on geostrophic wind speeds

Radius of isobar (deg.)	Geostrophic wind V_g, (knots)										
	15	20	25	30	35	40	45	50	55	60	70
1	14										
2	13	23									
3	11	19	30	43							
4	11	18	25	36	58						
5	11	18	24	32	42	57	73				
6	11	17	23	30	38	48	61	88			
7	11	16	22	29	36	45	54	66	84		
8	11	16	22	28	35	43	51	60	72	87	117

Thus it can be seen that in the vicinity of a storm centre the actual wind speeds can differ from the geostrophic wind speeds over the range of 15 to 100%. This difference should be reflected in the wind-wave model developed from a synoptic chart. The blanks in the table for anticyclonic curvature occur for high speeds associated with small radii. In other words, balanced flow is not possible with strong winds flowing around a high with sharply curved isobars.

4.3.2.4 Isallobaric contribution to the wind

Isallobars are imaginary lines joining places of equal change of atmospheric pressure within a defined period of time, usually 3 hours. They are defined by lines along which the local pressure variation, p, with time, t, is constant (isopleths). The equation of these lines may be written

$$\frac{\partial p}{\partial t} = b(x,y) = \text{constant}$$

(Eq.11)

In practice, the isallobars are separated by a 1-mbar pressure difference over the 3-hour time period. The isallobaric wind component is at right angles to the isallobars and is directed out of a rising centre into a falling centre, see Figure 24.
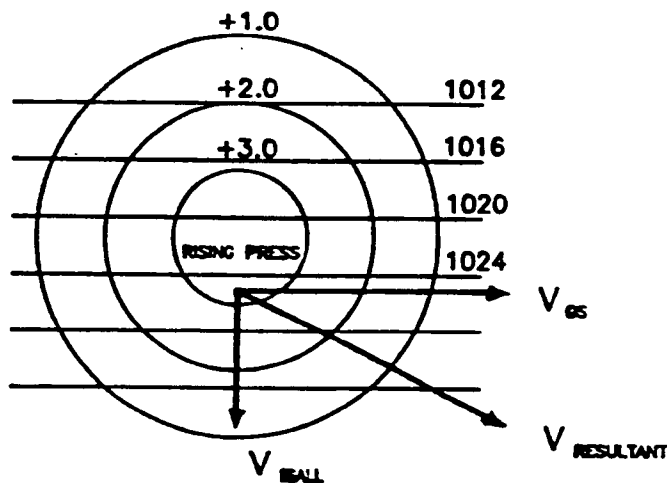
Figure 24.   Isallobaric wind component.

The modification of the actual wind velocity required to take account of the isallobaric component is given in Petterssen (1956) as,

$$\vec{V} = \vec{V}_g - \frac{\alpha}{f^2} \frac{\partial^2 p}{\partial n \partial t} \qquad (Eq.12)$$

where α equals $1/\rho$ and ρ is the air density.

The magnitude but not direction of the geostrophic wind, V_{gs}, can be written as

$$|V_{gs}| = -\frac{\alpha}{f} \frac{\partial p}{\partial n} \qquad (Eq.13)$$

which is similar in form to the isallobaric component, suggesting that it could be measured using a geostrophic wind scale. In that case, the isallobaric speed, V_i, is

$$|V_i| = \frac{1}{4f} V_m \qquad (Eq.14)$$

where V_m is the wind value as measured on an isopleth chart using a geostrophic wind scale. Note that the factor of four in the denominator reflects the fact that isallobars are usually drawn at 1-mbar intervals.

A further modification to the formula is required to ensure that the Coriolis factor and the isallobaric gradient are in consistent time units, thus

$$|V_i| = \frac{1}{4 \times 2 \times 7 \cdot 292 \times 10^{-5} \sin\phi \times 3 \times 3600} V_m . \qquad (Eq.15)$$

At 70°N the modulus of the isallobaric wind component is given by

$$|V_i| = 0.168 V_m .$$

A typical value for V_m at this latitude is 30 knots, indicating that the vector addition to or subtraction from the wind speed should be about 5 knots.

4.3.2.5   Adjustment Factors for Height

To determine the wind speed at a reference height of 19.5 m, MEP used a planetary boundary layer model developed by Agnew and Diehl (1978), specifically to predict surface winds in the Beaufort Sea area. Their atmospheric stability conditions were derived from radiosonde data collected at Sachs Harbour. However, this may not

be representative because Sachs Harbour is situated frequently on the cold air side of an Arctic low. It is probable that data from Inuvik or Barter Island would have been more accurate and would be worth investigation. Another useful comparison would be to use Smith's adjustment factors as outlined in subsection 4.2.2.3 to establish if there were significant differences in the adjusted wind speeds.

4.3.3 Sources of error in spectral wave modelling

The variability of the position of the ice edge (as discussed in subsection 4.2.3.1) affects the values of fetch which could be used in this model. Seaconsult chose to fix the ice edge at its extreme position, which removed any fetch limitations and effectively limited the duration for wave growth. A later study by Hodgins and Harry (1982) took account of the influence of seasonal ice distributions on the extreme wave height and concluded that a 30% reduction in the values reported in the original study was warranted.

The intensity and duration of the storm record also are quite important elements because the basic equation contains an energy source term whose strength is determined by the wind speed and direction, allowing the energy spectrum to grow until a fully developed Pierson-Moskowitz spectrum is achieved. In the 1981 Seaconsult study, the intensification process was carried out until the peak storm winds matched the required recurrent wind speed. Two possible sources of error are the assumptions that the storm movement is constant, and that deepening the low pressure system also will cause it to broaden.

The rate of decay of wave height in shallow and intermediate water depths is treated empirically in the wave model, the wave energies for the different water depths being scaled so as to be in agreement with the Bretschneider method. However, the rapid dissipation in the wave energy from deep to shallow water observed in the Seaconsult results cannot be explained in terms of bottom friction and percolation effects alone. It is suggested that there is a missing energy sink term in the spectral formulation which should be combined with the refraction and shoaling terms to account for the energy loss. Resio and Vincent (1982) identified such a term, associating it with the energy change required to adjust the spectral shape from one water depth to another. Justification for the inclusion of such a term in the DHI model is found in the large body of measured wave data now available, which supports the existence of similar spectral shapes in water of any depth (Cardone and Ross 1978).

4.3.4 Potential errors in the hindcast model verification

A single verification event was used to establish the accuracy of the 1981 Seaconsult hindcast model, in which the source of the wind-field data used was quite different from the derived wind fields used in their production runs. In fact, quite poor agreement was achieved when the winds modelled by MEP were compared with

measured values, the differences were frequently about 30%: because these derived winds were used in the production hindcasts they represent a significant source of error.

The wave model had, according to the Seaconsult study, been verified independently by DHI using North Sea data and errors of ± 0.6 m in significant wave height were found. This value represents about ±10% of the peak wave height measured in the trial. No references to the verification studies, however, were quoted.

4.3.5 Summary of uncertainties associated with the spectral wave approach

A list of the potential sources of error in the spectral wave approach and in their associated measure of uncertainty can be found in Table 12. It is difficult to make precise estimations of the magnitude of the potential variations of the uncertainty, but, where possible, on the basis of this critique, an indication has been included in the table.

TABLE 12

Sources of error and associated levels of uncertainty in the spectral wave model

Source of error	Level of uncertainty	Variability (%)
Prototype storm selection	High	
Pressure measurements	Low	5-10
Grid point pressures [a]	Medium	± 15-20
Missed storms	High	
Cyclonic curvature effects	Low	2-5
Isallobaric effects	Low	2-5
Storm intensification	High	
Vertical wind profile	Low	5-10
Shallow water	Medium	
Use of unverified wind fields	High	

[a] For Beaufort area.

4.4 SENSITIVITY ANALYSIS

Having established a number of potential sources of error in the two hindcast approaches, it is important to try to quantify their expected effect on the estimation of extreme wave height. The present study included a sensitivity analysis using the wind storm and wave hindcast parametric model developed by Canadian Marine Drilling Ltd. (Canmar) for use in the APOA study 205 (1984). The wind data base used in the model was identical to that in the APOA Study 203 (1983), which is essentially the Hydrotechnology data augmented by a further two years of records. The wave hindcast equations used in the model were the revised Bretschneider equations contained in the CERC's Coastal Engineering Technical Notes CETN I5, I6, and I7 (1981) given as follows:

$$\frac{gH}{u^2} = 0.283 \ \tanh \ \left(0.530 \ \left(\frac{gd}{u^2}\right)^{.75}\right) \ \tanh \left[\frac{0.00565\left(\frac{gF}{u^2}\right)^{0.5}}{\tanh \ \left(0.530\left(\frac{gd}{u^2}\right)^{.75}\right)}\right];$$

(Eq.16)

$$\frac{gT}{u} = 7.54 \ \tanh \ \left(0.833\left(\frac{gd}{u^2}\right)^{.375}\right) \ \tanh \left[\frac{0.0379 \ \left(\frac{gF}{u^2}\right)^{0.5}}{\tanh \ \left(0.833\left(\frac{gd}{u^2}\right)^{.375}\right)}\right]; \ \text{and}$$

(Eq.17)

$$\frac{gt}{u} = 5.37 \ \times \ 10^2 \ \left(\frac{gT}{u}\right)^{.375}$$

(Eq.18)

These were applied in the model in a similar fashion to that described in the Hydrotechnology approach. The hindcast model was used in conjunction with a wind storm parametric model and statistical distributions of storms, and fetch lengths, to produce a distribution of peak significant wave heights in one random wind storm. Using the methodology described in subsection 3.2, the distribution of peak significant wave heights in the random storm was transformed to enable the prediction of distribution of peak significant wave heights in one year. This latter distribution was used to establish return periods for various peak significant wave heights.

The nub of the methodology is thus the characterization of a wind storm and the development of storm statistics, as the statistical description of fetch lengths had been obtained from the available monthly AES ice charts. Canmar had analysed the wind data of storms for the 12-year period 1970-82, by searching out wind speeds in excess of 40 km/hr with peak wind speeds exceeding 50 km/hr. The 40 km/hr threshold speed enabled storm durations to be ascertained; with the exception of tolerating short lulls (of less than two hours), the storms were deemed to end when the wind speed dropped below 40 km/hr. Storms with a duration of less than one hour were ignored when compiling the statistics. Canmar's subsequent study of the storm analysis data showed that within the 12 years of records (13 drilling seasons), there were nine storms exhibiting wind speeds greater than 55 km/hr, all emanating from the northwest. Two populations were discernable in those storms having peak wind speeds in the range 50-55 km/hr, storms from the northwest and from the northeast. The northeasterly storms were rejected from the storm population set, because such storms in the region move the ice edge closer to the shore, hence reducing fetch.

The wind storms were characterized by a simple bilinear symmetrical shape defined in terms of the peak, mean, and threshold wind speeds, and the storm duration. The peak wind speed was assumed to be reached at the halfway point of the storm duration, while the wind speed was assumed to build up linearly from the threshold speed at the start of the storm until the mean wind speed was reached. The time at which this speed was reached was selected so that the area under the measured wind-speed history equalled the product of the mean wind speed and the storm duration. The left-hand flank of the idealized wind-speed history was completed by assuming a linear increase in speed until peak value was reached. Statistics of storm duration and peak and mean wind speeds were compiled in the form of probability of exceedance tables. Checks on storm duration and fetch established that these were independent of wind speeds.

To derive the distribution of peak significant wave height in a single random storm, sets of peak wind speeds, average wind speeds, wind durations, and fetches were selected which had equally spaced probabilities of exceedance and the peak significant wave heights were calculated for all combinations of the parameters. The validity of the model was checked by testing whether the proposed method would yield height estimates close to those obtained in the Seaconsult and Hydrotechnology studies. Using the same fetch and storm durations as Seaconsult and a distribution of extreme wind speeds similar to those used in both the Seaconsult and Hydrotechnology studies, the 25-year and 100-year return-period wave heights were estimated to be 11.0 and 12.8 m respectively, which is quite close to the predictions made by Seaconsult for deep-water locations. However, when the distributions of fetch and duration based on the observed wind records over ten years were used as input, the 25- and 100-year return-period wave heights were found to be 6.3 and 7.7 m, respectively, which are similar to estimates from the Hydrotechnology study for deep-water locations. Both of these comparative exercises provided the necessary confidence in the adequacy of the model to perform the sensitivity analyses. They emphasized that the assumptions of one extreme fetch and one extreme duration are inappropriate when estimating the return periods of extreme wave heights. In addition, they support the view that most of the discrepancies in the results produced in the two studies can be explained by the use of the extreme fetch and duration assumed by Seaconsult.

On the basis of the results from more recent analyses of the onshore and offshore wind-speed transfer function (Fissel and Birch 1984; Danard and Gray 1984; Hsu, 1984), it was decided to test the sensitivity of the estimated wave height relative to the base case of a 20% increase in wind speeds used by Hydrotechnology. This exercise resulted in about a 20% increase in wave heights for all the return periods compared. Further, a 20% increase in the storm durations over the base case resulted in an increase of about 10% in the estimated wave heights. The percentage increases chosen were incorporated into the model by scaling the distributions by the appropriate amount. Interestingly, a 20% increase in the fetch distribution produced only a slight increase (3%) in the extreme wave heights, indicating that the storms most likely to cause an extreme wave are duration-limited, rather than fetch-limited or fully developed.

5.0   DESIGN CONSIDERATIONS FOR EXTREME WAVES

5.1   TYPE OF STRUCTURE

Sea ice is the environmental parameter that governs substructures design for production in the Beaufort Sea. Designated ice loads and ice/structure interaction require that structures be of the gravity type, where the island weight (in non-cohesive soils) and base contact area (in cohesive soils) ensure horizontal resistance to the expected ice load. Within this limitation, there are three basic classes of substructures: artificial islands, berm-supported structural units, and structural units supported by the sea-bed, which are shown schematically in Figure 25.

The choice of substructure type is site specific and is defined by water depth, crude oil transportation system or oil storage requirements, and development time available, as discussed in detail by Houston (1983) and by Weeks and Weller (1984). It is considered that in water depths less than about 20 m, economic considerations would dictate an artificial island with a pipeline to shore. In water depths greater than about 20 m, structural units could have an economic advantage. Caisson depth and berm or no-berm considerations would be dictated by water depth, structural cost versus berm cost, and a requirement for internal storage of crude oil as compared to pipeline transport of oil to the shore.

The application of wave design criteria and the significance of the choice of the design wave will be discussed as it is relevant to each type of structure. To date only exploration structures have been installed in the Beaufort Sea and design criteria of these structures were much less stringent than for production structures. However, a review of the application of design waves to exploration structures is included, as the exploration structures provide "scale models" of production structures. Sea states used to estimate downtime and operational restrictions are not considered in this report, because they do not relate to extreme waves.

5.2   DESIGN CONDITIONS

5.2.1   Exploration Structures

The bottom-founded and fill type of exploration structures, of which more than 30 have been constructed since 1976, have a design life of one year and are intended for winter drilling only. For the most part, these exploration structures have been constructed during the three to four months of open water to allow drilling during
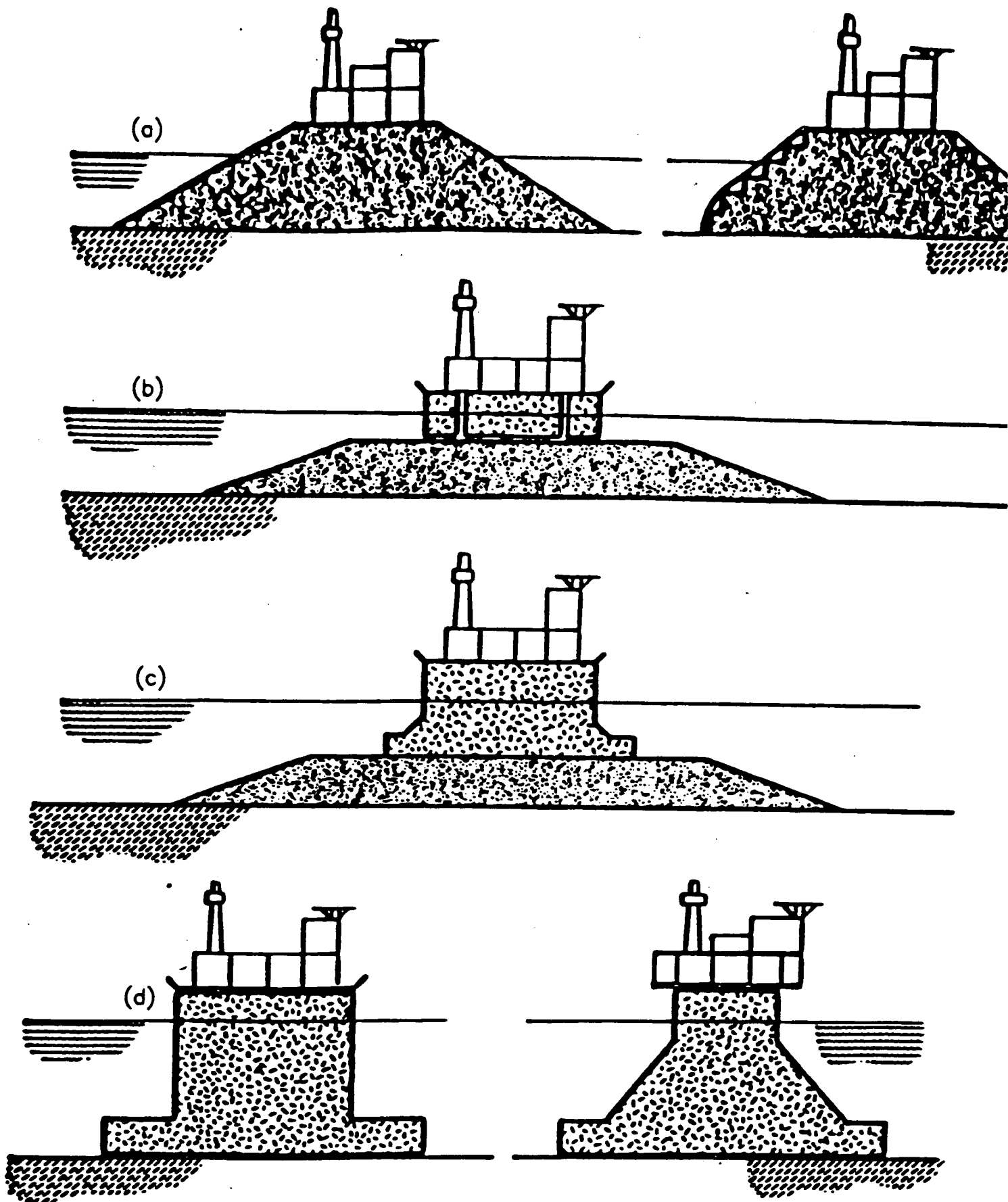
Figure 25.   Basic classes of substructure for production facilities:
(a) artifical islands, (b) berm-supported multi-unit structures, (c)
berm-supported single units, and (d) sea-bed supported single units.

the following winter and, hence, are designed to withstand a wave environment only during construction. One exception to this was Tarsiut Island, which was designed for two years of operation and which survived two complete open-water seasons before it was disassembled. A distinction must be made between the design of the structural unit, such as a caisson, and the design of the installed unit, that is, the caisson and berm combination. If the installation will be exposed at a site for only a year, a low return period would apply for the design criteria. However, because the caisson may function as a mobile offshore unit, it is appropriate to consider larger return periods when establishing its design criteria.

All designs of exploration structures have reflected not only normal design criteria for expected environmental and operating loads, but also an alert and evacuation plan. The purpose of this plan is to pre-establish the operating response to forecasted environmental conditions. For example, if a 12-hour forecast of wave height exceeds a critical value, then initial precautionary steps are taken to ensure safety and to minimize the likelihood of environmental pollution. If the 6-hour forecast value still exceeds the critical condition, then further action is taken, such as the evacuation of non-essential personnel. Ultimately, upon the forecast of the critical wave height within a prescribed minimum response time, the drilling hole is secured and the facility is evacuated. Such a plan assures safety of life and minimal pollution risk during storm events occurring within the low return period of the design, which for many parameters could be as low as ten years. Such a low return period would not be appropriate for production structures; however, given appropriate design return periods, the same strategy would apply.

Components of exploration island design which require wave design criteria as input, include wave forces, wave overtopping and spray, erosion, and slope protection.

5.2.1.1   Structural units

Generally, wave forces are not a critical factor in the design of structural units or caissons because ice forces govern. For example, when considering the structural design of existing Beaufort Sea exploration structures, the wave forces used comprised less than 25% of the design forces. However, the calculation of wave forces is still required, it simply means that their effect on the total cost of the structural unit is negligible. During the design of exploration structures, wave forces have been calculated to determine uplift forces on overhanging components, to design wave deflectors, and to ensure stability during construction.

Wave overtopping is an important consideration. However, experiences at caisson islands have demonstrated that if the island height is safe against ice rubble pile-up, it will be more than adequate to ensure that no green water overtops it. This generality may not apply to deep structural units where the caisson extends deeper than about 10 m, but spray overtopping during extreme events at caisson islands is not critical to exploration island design. Unlike Canadian east coast offshore platforms,

structures in the Beaufort area do not have to contend with the possibility of high-impact loading from wave-driven sea ice and pieces of icebergs, because high sea states have invariably occurred at times of the year when open water conditions have prevailed.

Erosion and toe protection is an important element of design, and it is the design consideration that is most sensitive to wave criteria. The criterion for which toe protection has been designed is to ensure that no serious structural undermining occurs during operation. All toe protection design to date has been sacrificial, in the sense that there is no design requirement for stable toe protection. However, a design consideration is that the erosion should not be serious enough to undermine the structure.

The cost of exploration structures composed of structural units, either on the sea bed or on a berm, is, therefore, only moderately affected by wave design criteria. It is estimated that less than 5% of the capital cost of an exploration structural unit is governed by wave design criteria.

5.2.1.2   Artificial islands

Wave design criteria are more important to the design of artificial exploration islands than they are to the design of structural units, because they dictate both the island elevation and the requirements for sacrificial overfill or slope protection.

Artificial islands are more suited to shallower water depths, and it is possible that the extreme wave used in the design may well break, in other words, it could be depth restricted. Parameters defining wave breaking are wave steepness and beach slope, however, for a first approximation on natural, gentle slopes, waves may be assumed to break in water depths of 1.3 times the wave height. For erosion considerations, the critical design criteria are often the storm frequency and duration, rather than the extreme wave condition. Similarly, when considering overtopping (since the extreme wave will have broken well offshore on the fill slopes or even on the natural sea bed), the island height will be dictated by wave conditions resulting in maximum run-up, which may be less than the extreme wave height. The sensitivity of fill volumes to island height is discussed in detail in the Swan Wooster (1982) contribution to the Environmental Input Statement Study of Production Structures for the Beaufort Sea oilfield development.

5.2.2   Production structures

The major differences (relevant to design sea states) between a substructure designed for production and one designed for exploration are:

- increased return period (up to 100-years) of design criteria;
- increased design life time to about 25 years;
- year-round operation; and
- increased topside area requirements, unless facility stacking is used.

Sensitivity of the design of the substructure to the selected design wave climate is summarized as follows.

5.2.2.1   Deep structural units

If the production structure is to be associated with the transport of crude oil by tankers, it must provide adequate internal storage volume for the oil and adequate available water depth for tanker draft. Both these restrictions require a structural unit depth of 20 to 30 m (assuming about 200-m diameter). A structure of this depth, whether on a berm or on the natural sea bed, does not pose difficult design problems to ensure protection against undermining, and the higher design 100-year storm estimated by the 1981 Seaconsult study could be selected for design with no cost penalty. As discussed previously, topside elevation and loads would be dictated by sea ice parameters. Therefore, for this type of structure, selection of the extreme wave is not critical to design.

5.2.2.2   Shallow structural units

If the production structure is provided with a pipeline for crude transport to shore or to a separate storage site, then the structural unit can be much shallower, perhaps resting on a much larger berm than in the case of the deep structural unit. The design balance between berm elevation and structural depth will be defined by cost comparison, timing, and operating restrictions. It is considered by the major operating groups in the Beaufort Sea that the structural unit's depth will be between 10 and 20 m.

Application of the design wave to this type of structure will dictate toe protection requirements and berm fill stability. The major cost of toe protection is due to marine transportation and floating construction equipment, and total weight is, therefore, a sensitive parameter. It is likely that toe protection would be in the form of an articulated concrete mat or quarried shot-rock. A range of design wave heights of 5-8 m would require mat weight in the order of $1800-2700 \text{ km/m}^2$, indicating about a 30% increase in cost. Rock toe protection would probably be mobile, being designed for say a five-year climate with anticipated maintenance costs. It is necessary to ensure that there is no structural damage during a 100-year storm, and the design must, therefore, accommodate the governing criteria (i.e., a single 100-year storm or average storms over the anticipated maintenance period).

Both of these erosion protection schemes are subject to damage by sea ice rubble and therefore, could require maintenance because of displacement by ice. A distinction must be made between erosion at the toe of the structure and at berm slopes. The previous discussion relates to toe protection, but the erosion of berm sand by the design storm will not be significant and is not overly sensitive to the anticipated range of design sea states.

5.2.2.3   Artificial islands

Artificial islands with pipeline transport of crude oil to shore is the favoured alternative in water depths shallower than 10 m, and may be economic in depths up to 20 m. In water depths between 10 and 20 m, the extreme design wave may not be depth-restricted, hence, extreme value analysis will dictate the slope of the island and, hence, volumes of fill required. Figure 26 shows the dependence of breaking wave height on water depth.

The island slopes may be sacrificial sand, sacrificial rock, or they may be armoured by stable rock or protective coatings. The sizing of stable armour is a function of the design extreme sea and is highly sensitive to the design wave height. A sacrificial sand or sacrificial rock option will be more sensitive to the frequency of seas in excess of the critical sea for armour stability. It would be reasonable to allow transport of sacrificial fill annually and to overfill so as to require maintenance about every five years. The design seas would, therefore, be five-year extremes and would relate to the volume of material lost over a five-year period, rather than to one extreme event. As previously discussed, it is important to assume total stability after a 100-year storm event; however, most sediment transport rates are governed by the "background transport" rather than by transport during a single extreme event.

5.3   WAVE CRITERIA ACCURACY

The required accuracy of design wave criteria is dependent upon design and cost sensitivity and upon the accuracy of the design techniques for which the input criteria are to be used. It makes little sense to increase confidence in the design wave height unless the input of that increased confidence is passed on to the design in some way. As discussed previously, artificial islands are more sensitive to design waves than are structural units, however, in many cases they will be located in water depths where the design wave will be depth-restricted.

Erosion rate is dependent upon wave direction and spreading as well as height and period, and is more a function of operational sea states than of extremes. The most important requirement for extreme wave criteria is in determining the wave run-
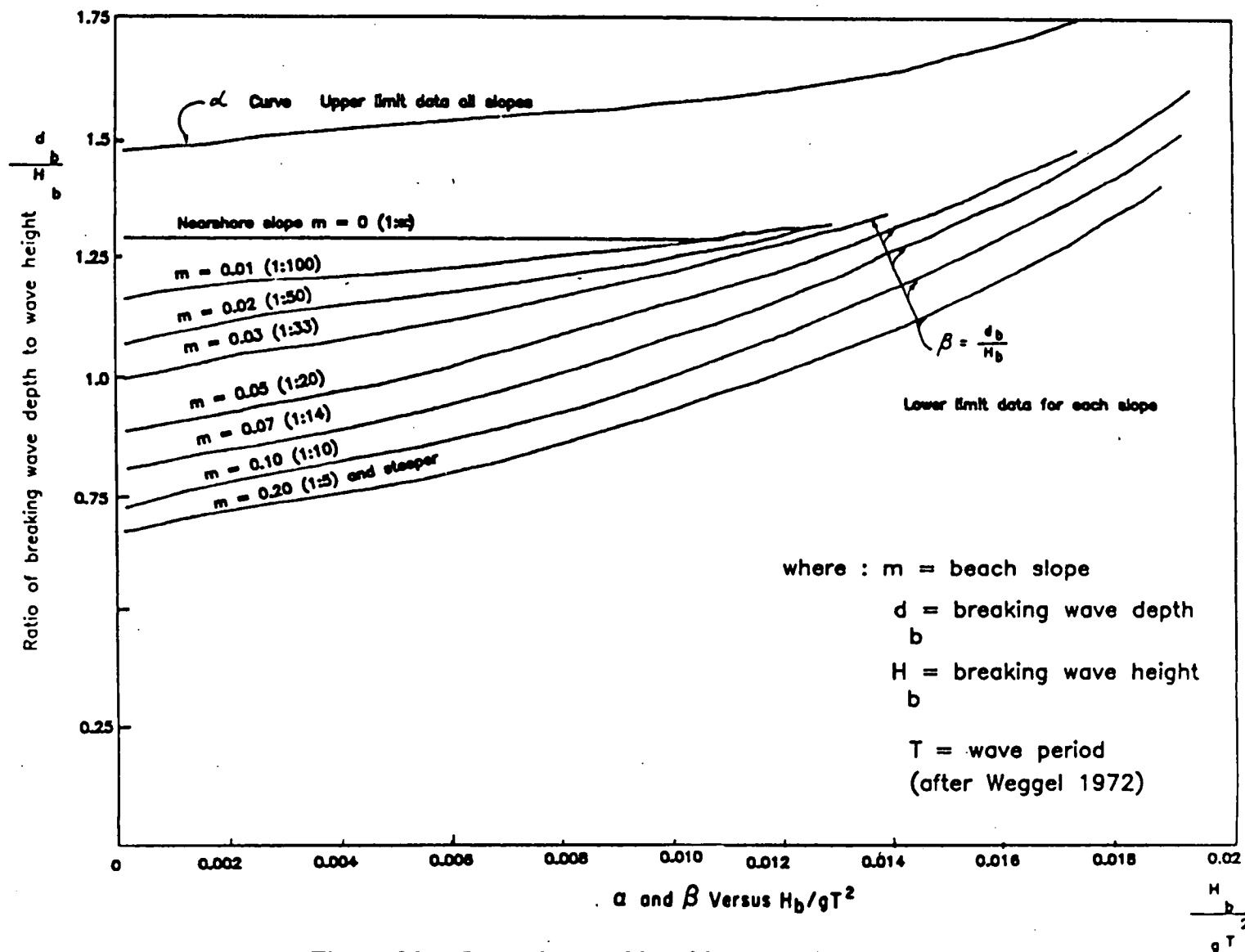
Figure 26. Dependence of breaking wave height on water depth (Source: Weggel 1972).

up on artificial islands. The trend towards using sacrificial slope protection, however, means that the consequences of extreme waves will not be as serious as they would be for a sacrificial sand island. It is contended, therefore, that the design of elements for production structures in the Beaufort Sea which require the input of an extreme wave can generally use a conservative value without incurring cost penalty.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

A review was undertaken of the 1980 Hydrotechnology and 1981 Seaconsult hindcast wave studies, with a view to reconciling the differences which existed between their respective estimates of extreme wave height. The most conservative of the studies was that conducted by Seaconsult, in which a prototype storm was used to derive the wind fields for input to a spectral wave model. Their methodology has been examined closely, and a number of factors have been identified which could make their deep-water results less conservative.

The Hydrotechnology approach used offshore wind speeds (derived from measured onshore wind records) as input to a parametric wave model. Again, a number of factors were identified which were likely to have important effects on the values of the estimated wave heights. On the basis of this review, it is concluded that neither study adequately addressed the problem of defining the offshore wind fields accurately.

The variability of sea-ice conditions and the effect of this ice on fetch were treated quite differently in the two studies. Seaconsult adopted an extreme approach, which effectively removed fetch from the hindcast model. The Hydrotechnology study chose to define the position of the ice edge in terms of its monthly mean position. With the relatively fast movement in the ice edge over time periods shorter than a month, it is concluded that the fetch lengths used in this model were usually underestimated. The major reasons for the disparity in the two sets of results are contained in these issues of fetch and the description of the windfield.

Although the use of measured onshore wind records at Tuktoyaktuk as a basis for deriving offshore winds is intrinsically sound, there is a major difficulty in the determination of suitable water/land speed ratios. Hydrotechnology (Baird and Hall 1980) used a ratio that varied from 1.0 to 1.15 for the wind speeds of interest. A comparison of these ratios with those used in the APOA Study 203 and with other published studies show quite marked differences. Both Danard and Gray (1982) and Fissel and Birch (1984) produced scaling factors which were on average 20% higher than the Hydrotechnology values over the wind-speed range of interest. (These factors are comparable to those quoted by Hsu (1984) for more general geographical application.)

It is important to note that these latter studies did not use the same data base as Hydrotechnology, either in extent, onshore location, type of instrument, or reference height. These reservations, however, do not apply to the APOA Study 203's data base, in which for wind speeds between 35 and 75 km/hr, the discrepancy in the scaling

factor varies linearly from 0 to 25% over the range of wind speeds concerned; significantly, the Hydrotechnology modified wind speeds are the higher of the two. In addition to identifying anomalies in the scaling factors, the comparison showed that it is inappropriate to use the same scaling factor distribution at different offshore locations. Although the differences involved, 3-4%, are small, they should not be ignored. It is important that the question of height adjustment in the overwater profiles is investigated further. The 1/7th-power scaling factor used by Baird and Hall is used more appropriately when the vertical wind component is weak, but this is not the case under Arctic storm conditions. It is recommended that effort be expended to establish the scaling factors for use in the region more accurately. The Hydrotechnology ratios were obtained using a comparison of histograms of the measured data at Tuktoyaktuk, with data measured at two offshore locations. It is unfortunate that they did not compare a time series of these records, because it would have lent more credence to their results.

A further indication that the Hydrotechnology results are on the low side, particularly for storm conditions, is found in their limited verification of wave heights. It appears from a series of histograms comparing hindcast with measured wave heights, for extended periods during four drilling seasons, that the model describes operational wave height conditions adequately. However, a number of time series plots in the report indicate that the agreement is not as good for storm conditions, the tendency being for the hindcast values to be lower than those measured. It is concluded, therefore, that the Hydrotechnology extreme wave height estimates are too low for deep-water conditions.

The Seaconsult study incorporated a number of interesting features, in particular, the concept of a prototype design storm the intensity of which could be adjusted so as to provide wind speeds commensurate with those speeds with a specified return period. The initial pressure field for the prototype storm was generated numerically from the large-scale, 381-km CMC pressure grid. The numerical procedure involved did not take account of either isallobaric or cyclonic curvature effects to correct the geostrophic wind speeds. It was noted in subsections 4.3.2.3 and 4.3.2.4 that these effects can be quite sizeable for rapidly changing wind fields in a frontal system. Their combined effect diminishes as the geostrophic wind is adjusted to a reference height and usually would have only a marginal effect on the derived surface wind speeds. However, it will be recalled that MEP chose to use the unadjusted geostrophic winds rather than the surface wind speeds in their verification and subsequent production runs.

A further, and more serious, deficiency in the Seaconsult derived wind fields was their inability to reflect the effect of severe storms both spatially and temporally. This deficiency was due primarily to the large grid size and the relatively long (6-hour) sampling times which combined to smooth the peaks in the storm wind fields. As a consequence, in several verification trials, the time series comparisons of measured and derived wind speeds showed that some storm events were missed completely while

the effect of others were diminished. As a result, the prototype storm contained an overestimate of the duration of those strong winds that contributed directly to the generation of severe sea states. The concept of defining a design storm is a useful one, however, in our opinion it is inappropriate to scale a complex storm system on the basis of a single variable -- the wind speed corresponding to the required return period. Instead, we suggest that a set of criteria, such as strength and duration of the wind, the amount of upper atmosphere support, a prescribed direction of storm movement, be used to categorize storms of the most likely type to generate large waves.

Seaconsult's decision to use the extreme ice edge position effectively removed the influence of fetch from their estimates of wave height. In a subsequent proprietary study (Hodgins and Harry 1982), in which the influence of the seasonal distributions on the extreme wave was considered, Hodgins (1983) reports that a reduction of about 30% in their earlier wave height estimates was warranted. Thus they consider a significant wave height in the range of 8-9 m associated with a 100-year return period to be appropriate for deep-water conditions. In the shallow-water conditions, it was apparent in their original study that their wave model incurred quite sizeable energy losses. This appeared to be a consequence of scaling the wave energies to be in agreement with the Bretschneider (1973) Shore Protection Manual method. As a general conclusion, the 1981 Seaconsult extreme wave values are considered to be too high in deep water conditions and too low in shallow water conditions.

A number of sensitivity analyses were performed as part of this study, using a simple extreme wave height prediction method which takes account of the joint probability distributions for wind speeds, duration, and fetch lengths. The validity of the approach was tested by running separate comparisons with the Seaconsult and Hydrotechnology results. The distribution of extreme wind speeds used in the model are similar to those contained in both studies. Using the appropriate assumptions relating to fetch and duration, the model closely reproduced the results quoted by Seaconsult and Hydrotechnology. The sensitivity of the model to variations in wind speed, storm duration, and fetch length was assessed. In three separate analyses, the wind speeds, durations, and fetch distributions were increased by 20% above the base case. The estimated wave heights were found to be most sensitive to the variation in wind speed: the 20% increase producing a 20% increase in wave height over all return periods. The effect of the 20% increase in the storm duration was to increase wave heights by 10%. The least sensitive parameter was fetch distribution, with the increase in fetch producing only a slight increase in the extreme wave height. As a consequence, we conclude that the extreme wave heights are associated with duration-limited rather than fetch-limited storms. Applying the wind speed sensitivity to the Hydrotechnology results, and assuming that the wind speeds used in their study are 10% lower than they should be, their estimate of extreme wave height would be upwardly adjusted to about 8 m at the Kopanoar site.

It appears, therefore, that, with the suggested downward adjustment of the Seaconsult estimates and a moderate change to the Hydrotechnology results to account for an underestimation of wind speeds, an extreme wave height in the range of 8-9 m is appropriate for deep-water conditions in the area. In the much shallower water conditions, that is less than 12 m, the waves may be depth-limited, in which case there is little point in using analysis of extremes, because the wave height will be determined by the wave breaking-limited height. This circumstance would not be true of the large body of water existing between the 12-m and deep-water locations where it would be appropriate to take proper account of shallow water adjustments.

6.2 RECOMMENDATIONS

6.2.1 IMPROVEMENTS TO THE WINDFIELD DATA

From the sensitivity analysis performed in this report and from the critique of the Seaconsult and Hydrotechnology studies, it is clear that an accurate definition of the offshore wind field is the most significant contribution that can be made to improving confidence in the estimate of extreme wave heights. The authors recommend, therefore, that a careful reconstruction of the wind fields from all available data sources be undertaken, for the largest 20 or so storms over the past 15 years which have storm tracks in a predominantly west-northwesterly direction over the open water of the Beaufort Sea. There should be sufficient information in these wind fields to enable good-quality estimates to be made of the wind stress, wind speed, and direction obtained for averaged hourly intervals at a fixed reference height. This effort will require a careful blending of kinematic analyses and derived wind conditions.

Hodgins (1983) has made a significant start in this direction by identifying two classes of severe storm systems for the area. The first of these classes reach the Beaufort Sea area from the north-northwest after moving across the polar pack ice. Wilson (1971) provided a very interesting description of one such storm which occurred on 13-15 September 1970 and which involved a loss of life (as a result of a storm tide) and considerable damage to property. The event produced three separate, hurricane-strength conditions in quick succession. The deepening of the storm appears to have resulted from the heating of very cold air as it passed over a considerable area of open water.

The second class of storm identified by Hodgins is similar to Pattern 2, Figure 27 (a) of the storm classifications, made by the Beaufort Weather Office. The storm centers on a trough moving approximately east-west off the Alaskan Coast.
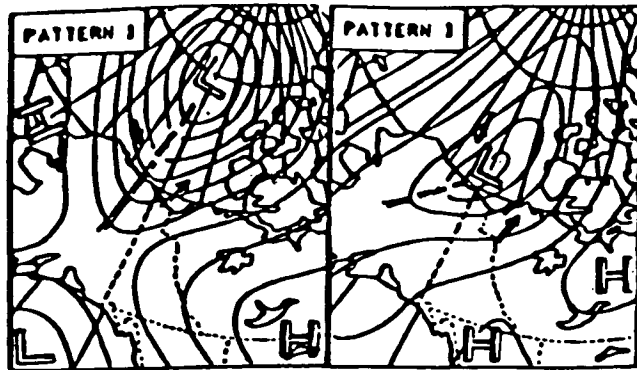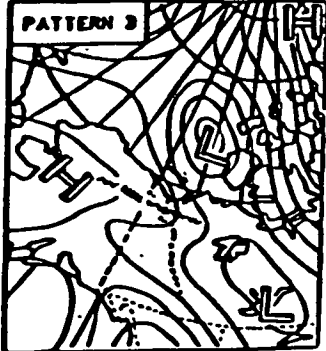
Pattern 1

Low or trough moves eastward across the Beaufort with or without a front(s) associated.
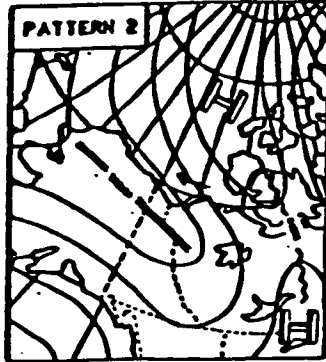
Pattern 2

Trough WNW to ESE across central or northern Alaska extending across the Yukon into the Mackenzie Valley. Ridge NW to SE across the eastern Beaufort, Amundsen Gulf or Banks Island. Often evolves into a pattern 3 or 4.

Pattern 3

Starts off as a pattern 2 or 7 (trough over Alaska). Trough moves offshore into the southern Beaufort. One or more low centres may develop in the trough. Trough and low(s) move northeastward as a ridge develops over Alaska.
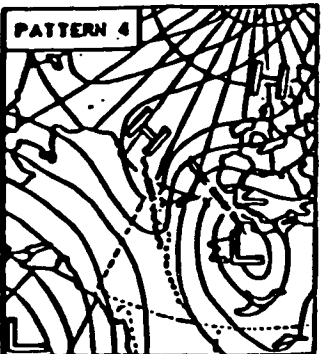
Pattern 4

Initially a deepening low over the Mackenzie Valley or the Great Arctic Lakes. As the low develops and moves off, a trough forms into the southern Beaufort. Ridge develops over the Alaska and Yukon coasts and builds into the northwestern Mackenzie Valley.

Figure 27 (a) and (b)   Storm Patterns for the Beaufort Sea Area

Figure 27(a).   Storm patterns 1-4 for the Beaufort Sea area (source: Beaufort Weather Office 1984).
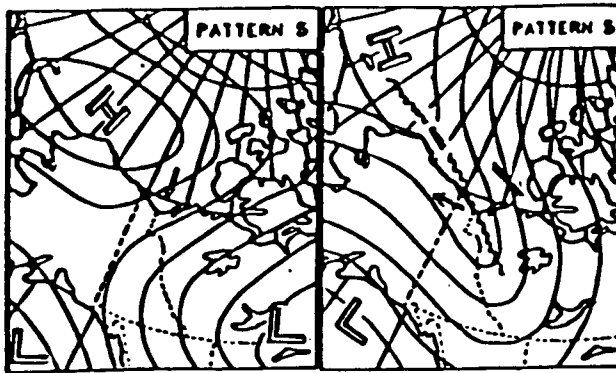
Pattern 5

Area of high pressure over the Beaufort or northern Mackenzie Valley.
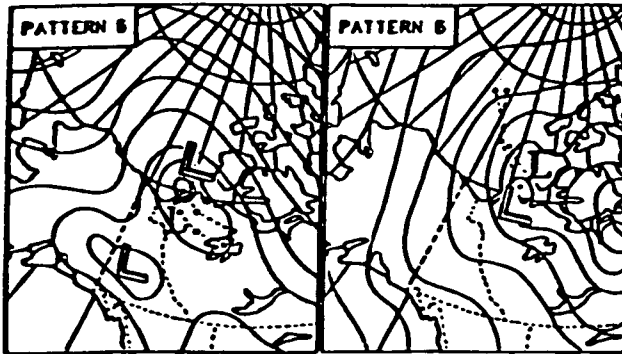
Pattern 6

Surface lows guided by cold upper lows.
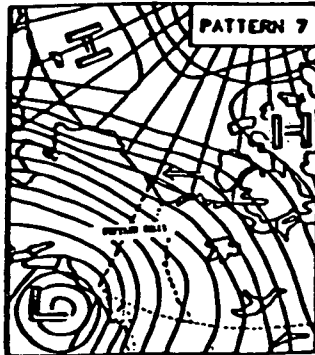
Pattern 7

A major Pacific storm moves toward southern Alaska. Overrunning warm air causes pressures to fall over Alaska and the Yukon. Strong cyclonic gradient eventually covers Alaska, the Yukon, the Mackenzie Valley and the southern Beaufort. Often evolves into a pattern 3.
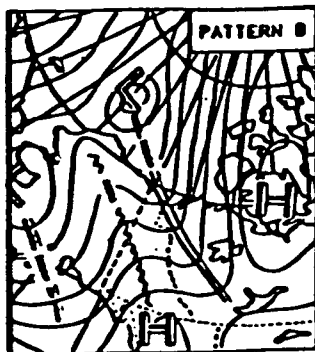
Pattern 8

Pacific disturbances migrate into the Bering Sea or Chukchi Sea. Associated troughs and ridges move northeastward across Alaska. Concurrently, a high pressure area usually lies over the western or central Arctic islands.

Figure 27(b).   Storm patterns 5-8 for the Beaufort Sea area (source: Beaufort Weather Office 1984).

The process of storm selection and description should be assisted considerably by the continuing collection of measured wind speeds both onshore and offshore since 1980. It should be noted that a rich source of synoptic weather data exists as part of the daily forecasting duties of the Beaufort Weather Office at Tuktoyaktuk. This data consists of annotated surface pressure charts updated at three-hour intervals in many instances, on a 1:1,000,000 scale map, but more often, at 1:5,000,000. The 12-hour continuous-duty roster leads to consistency in interpretation of the data and continuity in following the development of storm systems. The charts cover an eight-year period and are archived at AES Edmonton. Although they are not in a format for immediate use in wave hindcasting, the authors recommend that the effort to bring this about be investigated. Taken in conjunction with the measured wind speeds these charts may well shed some light on the sub-mesoscale disturbances, the "missed" storms that have been noted by Hydrotechnology and Seaconsult to occur in the area.

The measured wind data from the U2A anemometer at the Tuktoyaktuk DEW line site is worth scrutinizing further because it has the potential for extending the length of the wind data record to almost 25 years. Having selected the 20 or so storms, the authors recommend that probability distributions be established for their wind speeds and duration, taking care to account for the effect of subclasses within the data. The simple joint probability-based prediction method described in Section 3.2 could then be applied to arrive at the estimate of significant wave heights for the specified 100-year return period. Other sampling techniques, such as Monte Carlo, could be used in such an approach, rather than the choice of equally-spaced probabilities of exceedance, although it is doubtful if this would alter significantly the extreme values obtained.

6.2.2   Inclusion of uncertainties and their effect on extreme waves

It was emphasized in Section 4.1 that all of the uncertainties associated with the use of a hindcast model should be recognized systematically. Conventional statistical techniques can be applied to determine the reliability of a certain estimate; this is achieved by the use of confidence intervals. Suppose, however, there exists uncertainty at an intermediate step of the procedure, about the value of a certain parameter, the question then raised is, how will this uncertainty affect the end result, which in the present case is the extreme significant wave height? In this circumstance, the conventional method of analysis is not entirely adequate. It does not allow the parameter uncertainty to form an explicit and integral part of the total analysis.

The authors recommend the use of an alternative technique that exists, ,namely exchangeability (Figure 28). Instead of selecting average values for the parameters together with their confidence intervals, the parameters themselves are, in effect, treated as random quantities. As a result all the derived statistics, such as extreme values, reflect by means of their compound probability density functions (pdf) the uncertainties associated with model and distributional parameters. The result is that the pdf for the wave height spreads out over a wider range as compared to the pdf derived from the assumption in the classical approach that the parameters are constant instead of random. It is essential that the variability of these parameters be represented correctly to formulate the probabilities of extreme waves. The reason for this is that extreme values emerge from among the values situated at the very end of the likely range of the random quantity and it is precisely this tail portion of the pdf which is most sensitive to the inclusion of additional uncertainties.

The authors recommend that the various criteria for extreme value estimation -- least squares, minimum variance, maximum likelihood, and others -- be reviewed from a common standpoint. The suggested approach is based on decision theory and a unified model, including all of these possible approaches, can be structured. Criteria for the estimators based on the end product, significant wave height, should be set up. Based on these criteria, optimal choices of estimators can be made, thus eliminating much of the confusion of being confronted by a battery of estimators. As described earlier in this section, all sources of uncertainty, in the parameters and in the underlying approach, should be combined in the probabilistic modelling.

CONVENTIONAL ANALYSIS

EXCHANGEABILITY

an uncertain parameter

HINDCAST

Probability Density

x

$|a_1|a_2|a_3|$

Probability Density

x

+

Probability Density

Weight function on a

Confidence intervals on a,x

ANALYSIS OF EXTREMES

confidence intervals

extremal value is a random
quantity with a pdf to
account for uncertainty
in hindcast parameters

Probability Density

EXTREMES

$x_{100,a-} \leq x_{100} < x_{100,a+}$

extremal value
e.g 100 yr H_s

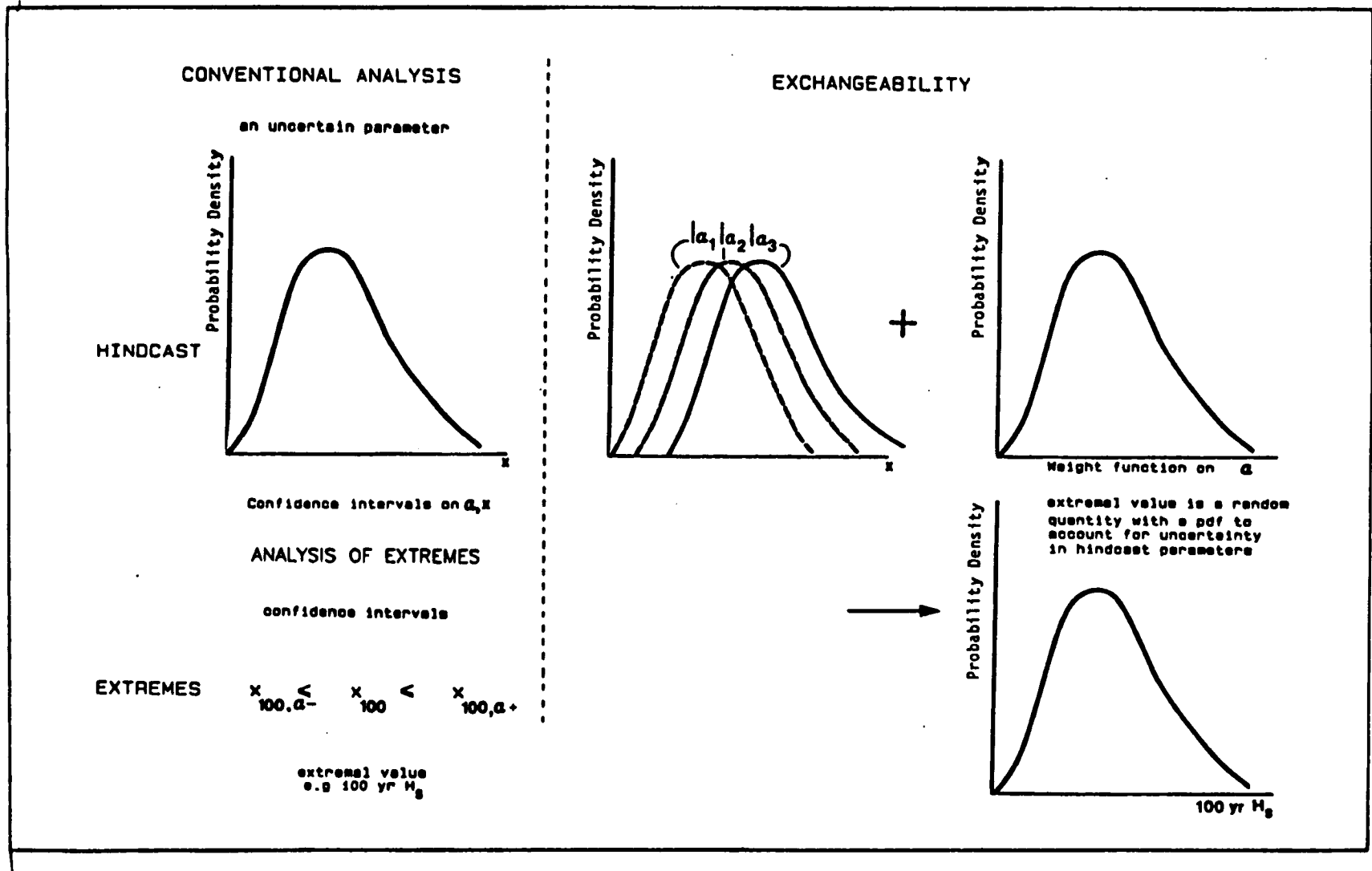Probability Density

100 yr H_s

Figure 28   An Alternative Statistical Treatment of Hindcasting

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