EC 7

Environmental Criteria for Canadian Waters: An Assessment of Data Resources and Design Requirements

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Prepared by

Sandra L.M. Hodgins, M.A.Sc.
Donald O. Hodgins, Ph.D., P.Eng.

Seaconsult Marine Research Ltd.
820–1200 West 73rd Ave.
Vancouver, BC V6P 6G5

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EXECUTIVE SUMMARY

Our understanding of the environmental parameters that govern offshore design is largely in statistical terms, some of which form the justification for empirical relationships, others of which define design criteria. The statistical foundations for wind criteria are outlined with emphasis on averaging period, variations with elevation and gust ratios. Probabilistic wave properties are described which explain the concepts of significant wave height, maximum wave height, and period parameters in the context of measurements and models. Extreme value analysis techniques are briefly summarized.

In the offshore areas, the main design issues are structural loading from winds and waves and a variety of consequential problems from the interaction of waves and structures. The Canadian Standards Association has recently compiled a new standard for fixed offshore structure design. The new code requirements are explained and specific wind and wave criteria are enumerated.

There are 13 major environmental databases for Canadian waters that contain meteorological or wave information from which design or operational criteria could be derived. Each is catalogued and critiqued in the context of both regional and site-specific design requirements.

Environmental studies for each of the Canadian offshore areas were identified. They were organized on a regional basis and abstracted to illustrate and assess the range of techniques employed and numerical values derived. Some evaluation of published criteria was made based on the adequacy of existing databases, known physical constraints (e.g., shallow-water and sheltering), and comparison with measured maxima. However, final judgements were not made on the confidence to be placed in specific criteria values.

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1.0 INTRODUCTION

The safe design, construction and installation of offshore structures in Canadian jurisdiction is governed by Canadian Standards Association (CSA) code. The general philosophy of the most recent code proposes that design be based on the combined environmental effect or load that has a specified annual probability of occurrence. That probability level is specified in the code as a function of risk or safety class. In the open-water season, the most important environmental factor, excluding sea ice and icebergs, is sea state in combination with wind forces.

The CSA code requires descriptions of wave conditions that include monthly and seasonal sea state climatology, storm climatology, distribution of extreme wave heights, various other wave characteristics, and coincident environmental parameters such as wind, tides and currents. Aside from very long time-series of reliable measurements, there is at present no conceivable database that could provide all these criteria with acceptable confidence.

The purpose of this review is to identify and assess the important environmental climatologies and design values that have been derived for the major Canadian offshore areas. The framework for this assessment is three-fold: a discussion in Chapter 2 of the statistical properties of winds and waves and how they are parameterized, (2) the CSA design code requirements which are presented and discussed in Chapter 3 , and (3) a critique of the database resources in the context of regional and site-specific design criteria in the succeeding chapter.

Each database review includes a summary description of the key characteristics of its construction and contents, cross-reference to bibliographic documents that have used or assessed the database, and a discussion to highlight comments and assessments from other authors in support (or possibly contradiction) of the overall findings of this study.

Chapter 5 compares published design criteria for each major offshore region from various sources. Site-specific studies that were not included in the databases of Chapter 4 are presented briefly to explain any important limitations. In most cases, criteria derived from discredited databases, which are clearly identified in Chapter 4 , are excluded from the discussion in Chapter 5 . Bibliographic citations are provided for each offshore region to facilitate identification of the primary source documents.

A few concluding observations are summarized in Chapter 6 .

2.0 STATISTICAL DESCRIPTIONS OF ENVIRONMENTAL PARAMETERS

2.1 Basic Wind Parameter Definitions

2.1.1 Wind Measurement

From a design perspective for offshore structures the wind parameters of interest occur in the atmospheric boundary layer, and mainly in the lower reaches of this layer between the sea surface and about 100 m. Given suitable instruments a wind measurement yields an estimate of the instantaneous velocity vector U(t) with a sampling frequency typically between 1 and 20 Hz. Within the boundary layer, U varies with density stratification, elevation and turbulence intensity. The turbulence intensity varies in turn with stratification and surface roughness where the latter is related in some manner to the waves on the sea surface.

Conventionally the wind vector is expressed as

$$U(t) = U + u_i(t),\ i=1,2,3 \qquad (2.1)$$

where

U is the time-averaged wind speed in the downwind direction, and defines the mean wind speed,

$u_i(t)$ are the fluctuating turbulent wind components in the downwind (i=1), crosswind (i=2), and vertical (i=3) directions.

The ui constitute the wind gust components whose magnitudes depend upon the surface roughness and the magnitude of U. Both deterministic and statistical analyses of wind measurements have focused on determining the properties of the terms on the right hand side of (2.1). In order to prescribe a design wind speed for various structural problems, most attention has been directed at finding suitable values for $U + u_1$ at a specified low probability of occurrence. Conventional practice has been to treat the statistics of U and u_1 in dependently and then add the results to give the desired wind speed.

Three issues are thus central to defining wind parameters:

(1) the averaging time T_{av} to define U,

(2) the variation of U with elevation z above mean sea level,

(3) the statistical properties of u_1 the downwind gust component colinear with U.

Each of these issues is discussed in the following sections, summarizing current practice and indicating some of the shortcomings with various approaches. The methods for extreme value analysis for the mean wind speed U are described in Section 2.4 following the discussion of basic wave parameters.

2.1.2 Averaging Times for the Mean Wind

The purpose of averaging the measured wind time-series U is to give an estimate of the mean wind U that is stable with respect to the random turbulent fluctuations at short periods, and that responds in a predictable way to atmospheric forcing at longer periods. The minimum averaging time to give a statistically stable estimate of wind speed has been given by Lumley and Panofsky (1964) assuming stationary, homogeneous and neutrally stable wind conditions as

$$T_{av} = 2\tau_i(\sigma/aU)^2 \qquad (2.2)$$

where τ_i is the integral time scale of the wind turbulence, σ is the rms wind fluctuation, U is the mean wind speed at elevation z and a is the fractional error. In neutral stability τ_i is approximately equal to z/U and σ/U has been found to be (Large and Pond, 1981)

$$\sigma/U = 0.070 + 0.0023\ U \qquad (2.3)$$

with U in m/s at an elevation of 10 m. Using these relations it can be shown that for speeds of 5 to 40 m/s with a=0.01 (1% accuracy) T_{av} ranges from 2.4 to 3.7 min. These results suggest that to achieve a 1% scatter in estimates of U the minimum averaging time should be about 4 min. At higher elevations (80-100 m) the minimum averaging time increases to over 20 min to achieve the same relative error.

While the optimum averaging time should be long with respect to the turbulent fluctuations, it should not be so long as to include real mesoscale and synoptic scale variations. At lower elevations (z< 100 m) the horizontal wind spectrum exhibits a region of low energy with periods between about 10 to 30 min. This region is known as the “spectral gap” and is often used to separate the turbulent gust regime from the meso-meteorological mean wind regime. This gap suggests that averages of 10 to 60 min should be optimal for estimating the mean wind speed. At higher elevations the spectral gap tends to disappear from wind spectra unless U is very large.

As Dobson (1981) points out, however, spectra measured by Donelan over Lake Ontario contain significant energy in the gap, and if not averaged out, will introduce scatter in the mean wind which varies with the mean wind. Analyzing North Sea data, Dobson shows that 10-min mean wind averages can be expected to contain 5 to 10% scatter associated with non- random processes in the atmosphere.

Thus the optimum wind averaging time is far from well established, and recommended practice is to average over durations of 10 min (Dobson, 1981; CSA, 1989). Hourly averages can then be formed from the 10-min averages, but the process is not reversible so that hourly averages cannot be used to derive information about shorter averaging periods. Averaging times longer than 60 min are likely to contain scatter related to mesoscale meteorological processes. Shorter averaging periods such as the 1-min or 2-min average winds that are reported in many databases, are expected to exhibit considerable scatter originating from the turbulence of the boundary layer wind.

2.1.3 Mean Wind Variation with Elevation

(a) The Power Law

Historically the atmospheric boundary layer variation of the mean wind has been empirically described by a power law of the form (see for example Plate, 1971)

$$U = U_h \ (z/h)^{1/n} \tag{2.4}$$

where h is the height of the boundary layer, U_h is the gradient wind at z=h. The exponent n, and the boundary layer thickness h are both functions of the surface roughness. Figures 2.1 and 2.2 , both from Davenport (1965), illustrate the nature of the profile for various types of roughness, and provide values for 7n. Over open water the power law exponent is approximately 0.10 to 0.16 corresponding to values of n ranging from roughly 6 to 10. The boundary layer thickness is of the order of 350 to 400 m.

The power law also provides a simple relation for translating wind speed from the 10-m reference height U_{10} to any other height, i.e.

$$U(z) = U_{10} \ (z/10)^{1/n} \tag{2.5}$$

As Plate (1971) points out the power law, although empirical, has two characteristics that make it useful: first, the profile is a good average representation of the mean wind speed over the whole boundary layer, and its form is easily integrated to yield vertically-averaged relations that are a good approximation to nature. The power law' has been applied in many practical situations, including wind tunnel modelling of wind forces on structures (Davenport. 1965).

The power law is applicable for strong winds in unstable to near-neutrally stable conditions. It does not attempt to incorporate the effects of stable stratification. The logarithmic law (see for example Plate, 1971) is sometimes used in place of (2.4), but strictly applied the logarithmic profile is correct over only the lowest 15% to 20% of the boundary layer where the assumption of constant stress is valid. This part of the boundary layer is called the surface layer.

(b) Monin-Obukhov Theory in the Surface Laver

It is widely held (see for example Kraus, 1972) that the variation of mean wind speed with height in the constant stress region of the boundary layer, for stationary, homogeneous meteorological and oceanographic conditions, can be expressed as

$$\partial U/\partial z = (u_*/kz)\phi(z/L) \qquad (2.6)$$

where u_* is the friction velocity, L is the Monin-Obukhov length, and k is von Karman's constant (=0.4).

The Monin-Obukhov length, which is a measure of atmospheric stability, may be defined, with some approximation, as

$$L = U_*^3\, T_a/(kg\, C_T[T_{10} - T_0]\, U_{10}) \qquad (2.7)$$

where Ta is the air temperature, CT is the heat flux coefficient (Stanton number), T10 is air temperature at the 10-m reference height, T0 is the air temperature at the sea surface, and g is gravitational acceleration. The influence of humidity is ignored in (2.7) which is a reasonable approximation for strong winds. Large and Pond (1982) discuss approaches to include humidity effects.

Large and Pond (1982) also give the following values for CT at 10 m:

C_{T10} = 0.00066 for L>0 (stable stratification),

C_{T10} = 0.00113 for L<0 (unstable stratification),

results that are in reasonable agreement with those reported earlier by Smith (1980), and Friehe and Schmitt (1976). Dobson (1981) notes that the uncertainty in published values for C_T is about 10%.

Equation (2.6) can be integrated from z=0 to height z, giving (Paulson, 1970)

$$U(z) = (u_*/kz)[\ln(z/z_o)-\psi] \qquad (2.8)$$

where z_o is the roughness length.

To a good approximation the functional form for $\phi(z/L)$ is given by (Dyer, 1974; Large and Pond, 1982)

$$\phi(z/L) = (1 - 16z/L)^{-1/4} \text{ (unstable conditions)}$$

$$\phi(z/L) = 1 + 7z/L \text{ (stable conditions)} \qquad (2.9)$$

Then for unstable conditions (z/L<0)

$$\psi = 2\ln((1+\phi^{-1})/2)+\ln((1+\phi^{-2})/2)-2\tan^{-1}\phi^{-1}-\pi/2 \qquad (2.10)$$

and for stable conditions (z/L>0)

$$\psi = -7z/L \qquad (2.11)$$

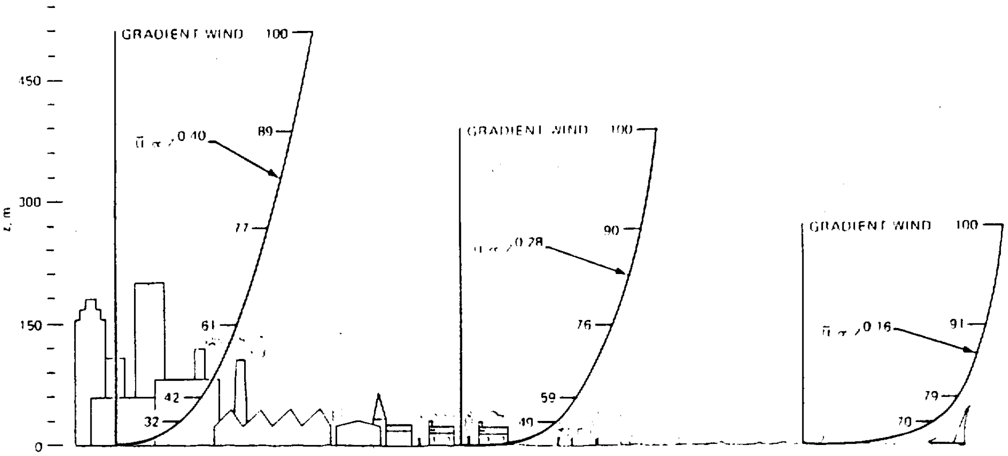


Figure 2.1 Empirical power laws over different terrain. After Davenport (1965).

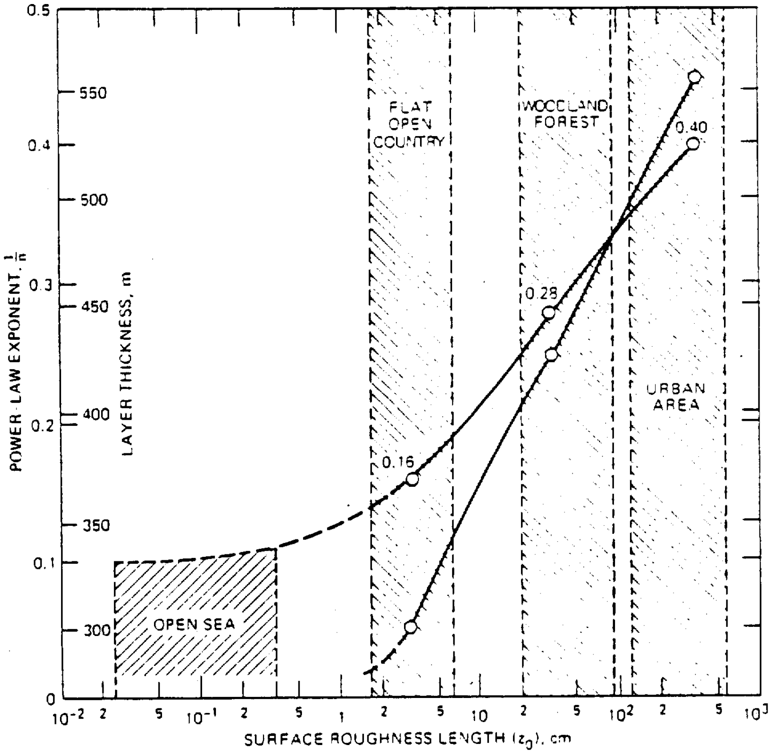


Figure 2.2 The exponent in the power law and the height of the boundary layer as functions of the roughness length and terrain type. From Davenport (1965).

With these relations the problem of specifying U(z) reduces to determining values for z_o and U_*. Both of these parameters are expected to be strong functions of sea state (see Geernaert et al. (1987) for a discussion).

In general U_* is expressed by a bulk transfer coefficient C_D in the form

$$U_*^2 = C_D (U_{10})^2 \qquad (2.12)$$

The drag coefficient C_D can be corrected for unstable or stable stratification to give the equivalent neutrally stratified value (Geernaert et al., 1987), denoted by the subscript N

$$C_{DN} = (C_D^{-1/2} + \psi/k)^{-2} \qquad (2.13)$$

and C_{DN} has been found to depend on U_{10}. Since U_{10} also depends on sea state, the drag coefficient is expected to correlate with changes in wave height, or surface roughness. In general C_{DN} has a form such as

$$C_{DN} = (0.49 + 0.065\ U_{10}) \times 10^{-3} \qquad (2.14)$$

using the values reported by Large and Pond (1981) for $U_{10} > 11$ m/s for neutrally-stratified conditions. For U_{10} of 20 m/s, C_{DN} is of the order of 1.8 x 10^{-3}. There have been many investigations to determine the drag coefficient over the past two decades, resulting in considerable variation in the coefficients in (2.14). The graph in Fig. 2.3 , reproduced from Geernaert et al. (1986), illustrates the variability found in these studies. The optimum relationship has yet to be determined; however, for many practical applications (2.14) can be used.

Charnock (1955) hypothesized that the roughness length z_o would be a function of u_* and g, yielding the relation

$$z_o = a\ U_*^2/g \qquad (2.15)$$

where the constant a is approximately 0.01. Geernaert et al. (1986) investigated this relationship, along with several others involving spectral and non-spectral wave parameters using an extensive North Sea data set. They concluded that wave field variability accounts for much of the observed variability in C_{ON} and that z_o could be estimated best from Kitaigorodskii's (1970) model when wave data are available. Geernaert et al. (1987) also give a power law relationship for C_{DN} as a function of the wave age c_o/u_* that reduces the scatter of C_{DN} from that obtained with simple mean wind relations of the form (2.14); however, one must know the sea state in order to apply the formula.

Thus given an estimate of the mean wind U at one elevation in the surface layer, it is possible to estimate U at any other elevation in this layer (up to about 60 to 70 m) with equation (2.8) taking atmospheric stability into account. For higher elevations the power law may be used but there will be more uncertainty in the mean wind speed because of the variability inherent in the power law form. Using Monin-Obukhov theory, Smith (1981) has calculated tables to correct the wind speed at one elevation to another for the applicable ranges of atmospheric stability. These tables, or equation (2.8) with the published values for CT and CDN and supporting data on temperatures over the water, can be used to construct a vertical profile of the mean wind for design purposes.

2.1.4 Gust Wind Speeds

(a) Design Wind Speed

Gust wind speeds are associated with rapid variations in wind produced by the turbulence components U_i. Typically the designer's interest has been on 1-s, 3-s and 10-s gust speeds superimposed onto the mean wind speed. If U(t) has been measured at rates greater than 1 Hz (which is necessary to estimate the variance of the horizontal wind turbulence spectrum) then the gust speeds are formed from time averages of u_i denoted by $<u_i>$. Because these time averages are well within the turbulence time scales, $<u_i>$ will exhibit large random scatter and are properly characterized by their probability distributions. The averaging interval for the gust wind speed is denoted by t_{av}.

Within the boundary layer the u_1 components are normally distributed with variance σ^2. The quantity σ/U is called the turbulence intensity, which varies with the mean wind speed U (e.g., as given in (2.3)), and σ is equivalent to the rms of the turbulent fluctuations. For design purposes the expected value of the maximum u_1 (or $<u_1>$) is often used.

The expected value of the maximum of u_1 in N observations is given approximately by

$$E(u_1)_{max}=\sigma(2\ \ln N)^{1/2}(1+\gamma/(2\ \ln N)) \qquad (2.16)$$

to order $(1n\ N)^{-3/2}$. It is assumed that the maxima of u_1 are Rayleigh distributed in deriving (2.16). γ is Euler's constant which equals 0.5772. N is the number of positive gusts ($<u_1>$ greater than 0) that occur in the averaging time for the mean wind T_{av}.

Forristall (1988) has examined the problem of determining N using the filtered wind spectrum to define the mean frequency of the fluctuations in terms of the ratio of the first to the zeroth spectral moments. The filtering corresponds to the averaging process implicit in the definition of $<u_1>$.

By modelling the turbulence with the blunt spectrum, Forristall shows that the mean frequency n_m can be expressed in terms of hypergeometric series in the form

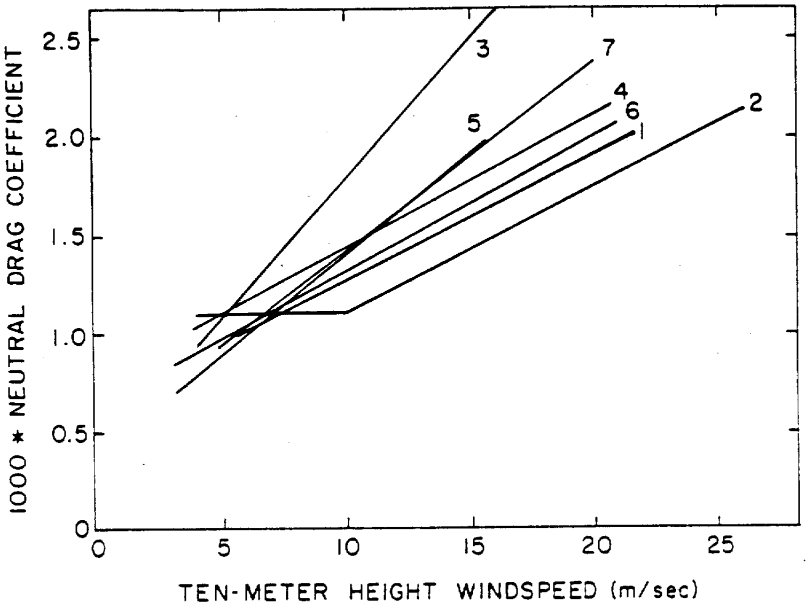


Figure 2.3 Drag coefficient wind speed regression equations. From Geernaert et al. (1986).

$$n_m = n_o\ F_1(5/3,2,3;-f_oB)/(2\ F_1(5/3,1,2;-f_oB)) \qquad (2.17)$$

where n_o = the cutoff frequency of the filter ($\simeq$ the inverse of t_{av}, the averaging time for the gust speed), $f_o = zn_o/U$, and F_1 is the hypergeometric sum for $-f_oB$. B is the fitting parameter for the blunt spectrum; Forristall found the mean value of B to be 63 for a wide range of tropical and extratropical storm wind data.

Once n_m is known, then $N=T_{av} \cdot n_m$. Since (2.16) applies to the positive values of $<u_1>$, not all values of $<u_1>$ in the filtered time-series, N is generally less than T_{av}/t_{av}. Forristall also indicates that the right hand side of (2.16) should be multiplied by a parameter I defined by

$$I = (Af_o\ F_1(5/3,1,2;-f_oB))^{1/2};\ A=42,\ B=63 \qquad (2.18)$$

For 1-s to 5-s gust speeds I is sufficiently close to 1 for all practical purposes to be ignored. At longer gust durations the value of I should be included in (2.16).

Forristall (1988) did not present data to support estimates of N derived in this manner for various cutoff frequencies, although the results for gust wind factors predicted with (2.16) and (2.17) show only a small bias (2-3% high) with measurements. Thus this method provides a practical approach to estimating a design wind given a suitable estimate of the extreme mean wind and the associated turbulence intensity.

For large N it can be shown that the probability of a single gust speed in N gust maxima exceeding the expected value $E(u_1)$ is 63%. The nature of the distribution for the maxima of u_1 is such that the chance of $u_{1,max}$ exceeding $E(u_1)_{max}$ by 10% is 0.21, decreasing to 0.05 for a 20% higher gust speed. Thus, from a design perspective there is a reasonable chance that the expected value of the gust speed will be exceeded.

(b) Estimating σ

The rms turbulent speed σ is required in (2.16); it is a fundamental parameter for the boundary layer. Considerable effort has been directed at quantifying σ by establishing the dependence of σ/U, or alternatively σ/u_*, with the mean wind, elevation z, and wave parameters (see for example Geernaert et al., 1987; Forristall, 1988; and Brown and Swail, 1989). Since σ/U and u_*/U both increase with U, σ/u_* is expected to show less variability than σ/U. The problem is that, most often, u_* must be estimated indirectly by use of relations like (2. 14) which introduce considerable uncertainty into expressions for σ involving u_*.

Mean values for σ/U typically range from 0.07 to 0. 10 for U between about 5 to 20 m/s (Brown and Swail, 1989), in good agreement with

Large and Pond's (1981) equation (2.3). For many practical problems, it appears that treating a/U=constant =0.10 or use of (2.3) will provide useful estimates of σ at high wind speeds.

(c) Gust Speed Ratios

By convention a gust speed ratio is formed with the mean wind

$$G = (U + \text{maximum } \langle u_1 \rangle)/U \qquad (2.19)$$

The gust factor is denoted by $G(t_{av}, T_{av})$ or $G(t,T)$, indicating the averaging times for both the turbulent wind and the mean wind. The maximum gust speed occurring in T_{av} is used in (2.19). The design wind can then be specified as

$$U_{design} = G(t,T) \cdot U \qquad (2.20)$$

where U is the mean wind speed at some desired low probability of exceedance and the designer chooses the gust averaging time appropriate for the structure or member of interest.

Numerous studies have attempted to establish representative average values of various G(t,T) as functions of elevation, stability, and the mean wind speed (see for example Chandler, 1985; McClintock et al., 1987; Brown and Swail, 1989). For 1-s gusts mean values of G(1,3600) range from about 1.25 to 1.35, although means in this range are not significantly different given the small sample sizes and typical standard deviations (Brown and Swail, 1989) of 0.13 to 0.05.

Alternatively one can determine the probability distribution of G, redefining G as

$$G = U(t)/U = (U + \langle u_1 \rangle)/U \qquad (2.21)$$

McClintock et al. (1987) have examined the form of the distribution for G using 308 1-Hz records from various overwater sites. The records were examined for sheltering and flow distortion effects and any suspect records were discarded. In their case the 1-s gust wind speed was defined by the 1-s sampled raw wind speed measurements. In general the records were 60 min long and the averaging for U was carried out over the record length.

McClintock et al. showed that G(1,3600) was normally distributed with $\sigma_G = 0.102 \pm 0.003$ at 95 % confidence, yielding a predictive equation for the probability density of G

$$p(G) = 3.911 \exp(-(G-1)^2/(0.144)) \qquad (2.22)$$

for mean wind speeds ranging from about 5 to 20 m/s. The influence of different stability conditions on (2.22) was not examined; however, no wind speed dependence for σ_G was found, although, as the authors note this result was not conclusive given the small number of samples once the data were stratified into speed classes. The data included in the analysis ranged from z = 10 to 85 m and all data were combined to yield the above estimate of σ_G.

McClintock et al. (1987) show that (2.22) agrees with the frequency of high values for G in various data sets. Use of (2.22) requires that the designer specify the exceedance probability Q(G) = 1-P(G) for the design gust factor in order to determine G. A gust factor of 1.35 corresponds to Q(G)=0.0003, or a 0.03% chance of exceedance.

The results from (2.16) and the last two methods for calculating a gust factor are not statistically equivalent. They may be compared, however, with an example: U=50 m/s, z= 10 m, $\sigma/U=0.10$ and t_{av} = 1 s. In this case, σ=5 m/s and (2.16) yields $u_1 = 3.6\sigma$ = 18 m/s. The gust factor as defined in (2.19) becomes 1.36, which is equivalent to many direct estimates of G, and the value obtained from the McClintock et al. approach at a low chance of exceedance (> $3\sigma_G$). Thus, in practical terms the gust factor can be evaluated, recognizing that there is uncertainty in the value. The McClintock et al. method applies to 1-s gusts for a 1-h mean wind averaging interval; the Forristall approach generalizes to other gust averaging periods, mean wind averaging periods, and elevations.

2.2 Basic Wave Parameter Definitions

When a wave record is made at a fixed location, it represents the periodic succession of wave crests and troughs that physically occurred at that location. Waveriders, which are the most common wave measuring device in Canadian waters, record the heave (vertical plane) motion of a sensor package from which the scalar sea surface displacement is calculated, but no directional information can be inferred from the recording. Directional wave buoys record three degree of freedom motions (heave, pitch and roll) from which vertical displacement and wave direction are determined.

Generally, wave recordings are relatively short, spatially-isolated samples of the complete process. Because ocean waves are described as a random signal, the length of the record and its sampling frequency will affect the values of all parameters that are calculated from it.

Regarding a wave measurement x(t) as a continuous function, three underlying assumptions are required to develop a consistent statistical picture of a sea state:

(1) The process is **stationary**, so there is no drift in the statistical behaviour of x with time; the instant at which sampling of the process begins is immaterial. In practice, the duration of stationarity depends on weather system evolution. Analysis of the

Hibernia storm data suggests that stationarity is a valid assumption for periods up to about three hours (Szabo et al., 1989).

(2) The process is **homogeneous**, meaning that the exact location of measurement does not matter. In practice, the region of homogeneity will need to be determined, particularly near landforms and in areas of complex or shallow bathymetry.

(3) The process is **ergodic**, implying that the measured sample x(t) is representative of all other possible samples such that temporal measurements $x_1(t_1)$, $x_1(t_2)$, $x_1(t_2)$, ... may represent the possible instantaneous realizations $x_1(t_1)$, $x_2(t_1)$, $x_3(t_1)$, ... The expected value of the function can be exchanged with its temporal average value.

For development of the probabilistic description of sea states, the process should have a narrow-banded spectrum, one in which the wave component frequencies are close to a central frequency. In such cases the individual wave periods will be approximately equal, maxima and minima nearly evenly spaced in time, and the sea surface may be approximated as a regular sinusoid within a slowly-varying amplitude envelope. In reality, this theoretical limitation is poorly met, but the statistical relationships are applied widely nonetheless.

2.2.1 Waves in Time Domain

It is straightforward, although time consuming, to inspect a wave record wave-by-wave to determine a wide variety of height and period characteristics, relative to the mean water level. Wave height is defined as the vertical distance between a minimum elevation (trough) and the succeeding maximum level (crest). Wave period is the elapsed time between recurrences of some unique event such as downward crossing of the mean water level.

Three basic parameters are commonly determined from wave time-series: significant wave height, mean wave period and maximum wave height. Significant wave height H_s (or $H_{1/3}$) is defined as the average height of the one-third largest waves, and the maximum wave height is the single largest wave in the sample. The mean wave period Tz is the average of all the individual wave periods.

Other parameters of importance to design that may be extracted from wave time-series are maximum crest elevation, wave steepness, and measures of wave groupiness. However whitecapping, wave breaking and Waverider response in large, short-crested seas affect the accuracy of parameters such as wave height, crest elevation and steepness for high waves.

2.2.2 Waves in Frequency Domain

Formal development and detailed discussion of the spectral theory of random wave signals may be found in many books (e.g., Kinsman, 1965; Berteaux, 1976; Sarpkaya and Isaacson, 1981; Goda, 1985). Only essential highlights are presented here.

At a point in space, the time-dependent sea surface elevation η(t) is assumed to be Gaussian distributed and can therefore be resolved as an infinite sum of wavelets of infinitesimal amplitudes and random phases. Viewed as a periodic function, the sea surface elevation may be represented as a Fourier series

$$\eta(t) = \sum_{n=-\infty}^{\infty} X_n e^{i2\pi ft} \tag{2.23}$$

with complex Fourier coefficients

$$X_n = \frac{1}{T}\int_{-T/2}^{T/2} \eta(t)e^{i2\pi ft}\,dt \qquad n = 0, \pm 1, \pm 2, \ldots \tag{2.24}$$

where T= 1/f and nf=nω/2π are the component frequencies. For a truncated series, the power in the signal is given by its variance and may be defined as

$$P(\eta) = \sigma_\eta^{\ 2} = \int_0^\infty S(f)\,df \tag{2.25}$$

where the power spectral density S(f) is given by

$$S(f) = \lim_{T\to\infty} \frac{2|X_T(f)|^2}{T} \tag{2.26}$$

In other words, given a time-series record of the sea surface elevation, the power spectral density function can be calculated as a discrete function of frequency. In practice, the frequency resolution is determined by the sampling interval, the sample duration and the extent of band-averaging that is applied during the Fourier analysis. A typical spectrum as calculated by the Marine Environmental Data Service (MEDS) with a 20-s low-frequency cut-off is defined by 62 discrete frequency bands, each 0.007324 Hz wide, from 0.0513 to 0.4980 Hz corresponding to periods of 19.5 to 2 s.

Spectral moments are defined as

$$m_n = \int_0^\infty f^n\, S(f)\; df \tag{2.27}$$

Clearly $m_0 = \sigma_\eta^2$ by virtue of (2.25) and is the area under the spectral curve. The higher order moments are used to estimate wave period parameters and to characterize spectral shape.

The mid-point of the spectral band containing the most energy is defined as the peak frequency f_o and its inverse is the spectral peak period T_p.

Although S(f) is determined from η(t), the calculation cannot be reversed. Hence, a unique time-series of individual waves cannot be determined from spectral wave model results.

Directional wave spectra S(f,Θ) may be derived from heave-pitch-roll records, and spectral wave model output has a similar definition based on discrete frequency and direction bands. By integrating over the direction Θ, S(f,Θ) devolves to the non-directional or omni-directional spectrum S(f). Occasionally S(f) may be called a uni-directional spectrum, on the assumption that all wave energy is travelling in the same direction, presumably down-wind. By convention, wave direction is the direction to which the wave is progressing.

Several empirical formulations of wave spectra exist that are based on a few parameters-- significant wave height (i.e., the area under the spectral curve), peak frequency, a directional spreading function, and perhaps shape and peakiness factors. Some formulations are based on wind speed instead of sea state characteristics. Empirical spectra are smooth, continuous functions that, to a moderately successful degree, model average wind-sea energy distributions. The JONSWAP formula has proven particularly useful. Examples of empirical spectra and discussion of how they are used in spectral wave modelling may be found in Hodgins and Hodgins (1988).

2.2.3 Probabilistic Wave Properties

Probabilistic models of wave parameters are concerned primarily with the spread of values- rather than with how the values vary with time. The probability distribution function or cumulative probability is defined as

$$P(x) = \mathrm{Prob}[x(t) \le x] \tag{2.28}$$

The probability density is defined as

$$p(x) = \frac{dP(x)}{dx} \tag{2.29}$$

and represents the probability that x(t) is within the small range x + dx.

The probability density function of the narrow-band wave amplitudes is expressed by the Rayleigh distribution (Longuet-Higgins, 1952):

$$p(a) = (2a/\langle a\rangle^2)\exp(-a^2/\langle a\rangle^2) \text{ for } a \geq 0 \qquad (2.30)$$

where a was defined as half the trough to crest height, without regard to the mean sea surface. For spectra which are narrow banded, $\langle a\rangle^2$ may be approximated by $2m_o$. The Rayleigh probability function can then be written in its usual form as

$$p(a) = (a/m_o)\ \exp\ (-a^2/2m_o) \qquad (2.31)$$

and its cumulative probability distribution is

$$P(a) = 1 - \exp\ (-a^2/2m_o). \qquad (2.32)$$

Making the assumption that the wave height H = 2a, which is consistent with the narrow-band spectrum limitation, then

$$p(H) = (H/4m_o)\ \exp\ (-H^2/8m_o) \qquad (2.33)$$

and

$$P(H) = 1 - \exp\ (-H^2/8m_o). \qquad (2.34)$$

The fraction F of waves larger than a given height H is expressed by

$$F = \int_H^\infty p(H)dH \qquad (2.35)$$

and the average of these largest waves is

$$H_F = \frac{1}{F}\int_H^\infty H\,p(H)dH \qquad (2.36)$$

By substituting the Rayleigh distribution, Longuet-Higgins (1952) has shown that

$$H_F = \sqrt{8m_0}\,[\sqrt{\ln(F)} + \frac{F\sqrt{\pi}}{2}(1 - \mathrm{erf}(\sqrt{\ln(F)}))] \qquad (2.37)$$

and thus the significant wave height $H_{1/3}$ (usually denoted as H_s and sometimes as Hm_o to emphasize its spectral origins) is approximated for narrow-band spectra as

$$H_{1/3} \simeq 4.005\sqrt{m_0} = 4.005\,\sigma_\eta \qquad (2.38)$$

There is a tendency,which ought to be resisted, to regard $H_s = 4\sqrt{m_o}$ as an exact relationship rather than an outcome of the statistical nature of waves and the underlying assumptions that the sea state is stationary and ergodic with a narrow-banded energy spectrum.

Estimations of the maximum wave amplitudes were also derived by Longuet-Higgins (1952). The probability that any amplitude a is less than a_m is $P_1(a_m)$. Thus the probability that **every** wave in N waves is less than a_m is $P_1^{N}(a_m)$. If P_1 is given by the Rayleigh distribution and N is large, Longuet-Higgins has shown that the expected value of a_m is

$$E(a_m) = \sqrt{2m_0}\,[\,\sqrt{\ln N} + \tfrac{1}{2}\gamma(\ln N)^{-1/2} + O((\ln N)^{-3/2}) \qquad (2.39)$$

where $\gamma = 0.5772$ is Euler's constant. For $N \geq 50$, this expression is accurate to within 3% of the complete expression (Sarpkaya and Isaacson, 1981). Assuming that $H_m = 2a_m$ and that N is large, the expected maximum wave height is

$$\frac{H_m}{4\sqrt{m_0}} = \frac{\sqrt{\ln N}}{\sqrt{2}} \qquad (2.40)$$

If the mean wave period is 10 s, in three hours 1,080 waves will be observed. Then the expected value of H_m is 1.87 times the significant wave height. For longer wave periods, N decreases; hence the ratio of H_m and H_s is predicted to decrease.

Forristall (1978) reported that the Rayleigh distribution overpredicts the maximum observed wave heights by about 10%. Later he demonstrated that this deviation is a function of spectral shape (Forristall, 1984).

Using (2.18) as an approximation for Hm, the probability that all N waves are less than H_m is

$$[P(H_m)]^N = [1 - (1/N)]^N \qquad (2.41)$$

So, for 1,080 Rayleigh-distributed waves, the chance that at least one wave exceeds the expected H_m is 63%, but the probability that one wave is 20% higher than the expected H_m is only about 5%. To a rough approximation then, we should anticipate observing maximum waves that are $1.87*(1.2/1.1)*H_s$ or about $2*H_s$ for the preceding example.

When considering an evolving storm sea state, there is no statistical requirement for H_m to occur in the sample of largest H_s. Analysis of almost-continuous east coast Waverider data (Seaconsult, 1988) illustrates that the largest recorded individual wave in a storm rarely occurs in the storm-maximum H_s sample. Frequently it precedes or follows the peak sea state by more than three hours.

Borgman (1973) introduced a probabilistic method to determine H_m in storms that has the form

$$P(H_m) = \exp \sum_{j=1}^{J} N_j \ln [P(H)] \qquad (2.42)$$

with a storm divided into J segments, each of known duration, H_s and mean wave period T_z. For each segment, the number of waves is estimated as the duration divided by the mean wave period. The distribution of individual waves P(H) is assumed to be Rayleigh, or a modification based on Forristall's (1978) calculations.

Borgman showed that the integral implied by (2.20) has the functional form

$$1n\ 1n\ [1/P(H_m)] = -AH^2 + B \qquad (2.43)$$

So, by determining A and B (through linear regression), the probability law for the largest wave height in the storm is uniquely specified. Then $P(H_m)=0.5$ corresponds to the expected value of H_m.

Another approach to estimating H_m has been developed by Battjes (1970, 1972) based on the joint distribution of H_s and T_z normally derived from long-term measurements. The distribution $P(H_m)$ is determined by weighting each short-term Rayleigh distribution by the fraction of waves that are observed in each H_s-T_z class, and summing the weighted distributions. The distribution 1 – P(H) can be fitted with the three-parameter Weibull distribution and the resulting equation has the following form:

$$H_m = A\ [1n(N_o/N)]^B + C \qquad (2.44)$$

where N_o is the total number of waves in T_R years (e.g., 50 or 100) based on a long-term average wave period and N is the number of waves exceeding H in T_R years (ordinarily N=1). A,B and C are fitting parameters of the Weibull distribution. Equation (2.44) can be inverted to solve for N, the number of waves exceeding some height H in a selected number of years.

The period to associate with H_m is usually denoted as TH_m. A joint distribution of individual wave height and period has been proposed by Cavanie et al. (1976) as a function of significant wave height, mean wave period and spectral moments. The formulation has been tested with east coast Waverider data (Seaconsult, 1988) and reasonably good agreement was found. For a given estimate of H_m in a known sea state (H_s and T_z) the range of TH_m at a given probability of exceedance can be determined.

Haring et al. (1976) presented a modified Rayleigh distribution of crest elevation as a function of sea state and water depth which they tested with a small amount of hurricane data. No extensive verifications of this distribution with Canadian extra-tropical wave data are known. The function has been applied (MPL and Oceanweather, 1990) using Borgman’ s integral storm analysis method.

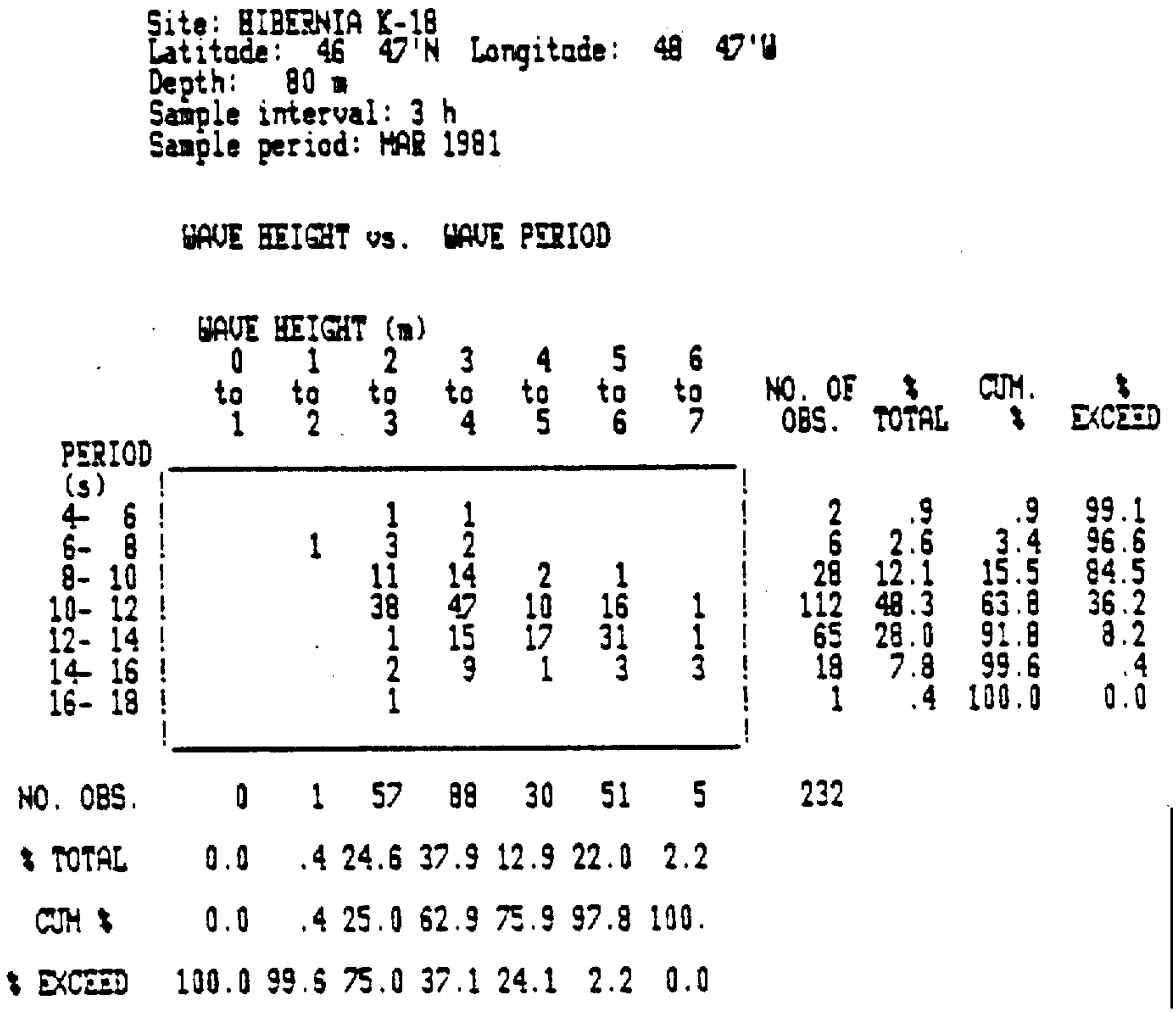
2.3 Other Presentation Methods for Continuous Data

2.3.1 Bivariate Histograms

Theoretical and semi-empirical models of the joint distributions of wave parameters exist (for example, Cavanie et al., 1976) but they depend on factors (such as mean wave period and spectral width) that are difficult to estimate reliably. For applications like fatigue analysis, the observed joint distributions are more accurate. They are normally presented as a bivariate histogram of variables x and y in tabular form which reports the number of observations that have occurred within a given range of x and a given range of y. The data are subdivided into bins of equal, but arbitrary width, and values that match a bin limit are counted in the lower bin (Fig. 2.4).

For each variable, a discrete estimate of the probability density p(x) and the cumulative probability P(x) is readily determined from the fraction of observations in each sub-class of the variable x. The exceedance probability $Q(x) = 1 - P(x)$ is often tabulated as well.

Variables for which bivariate histograms are commonly produced include significant wave height and peak spectral period, individual wave height and individual wave period, significant wave height and wave or wind direction, and wind speed and wind direction.



```
Site: HIBERNIA K-18
Latitude:  46  47'N  Longitude:  48  47'W
Depth:   80 m
Sample interval: 3 h
Sample period: MAR 1981


   WAVE HEIGHT vs.  WAVE PERIOD


     WAVE HEIGHT (m)
       0    1    2    3    4    5    6
      to   to   to   to   to   to   to    NO. OF    %     CUM.     %
       1    2    3    4    5    6    7     OBS.   TOTAL     %    EXCEED
PERIOD
 (s)   !------------------------------------!
 4-  6 !             1    1                 !     2     .9      .9    99.1
 6-  8 !        1    3    2                 !     6    2.6     3.4    96.6
 8- 10 !            11   14    2    1       !    28   12.1    15.5    84.5
10- 12 !            38   47   10   16    1  !   112   48.3    63.8    36.2
12- 14 !             1   15   17   31    1  !    65   28.0    91.8     8.2
14- 16 !             2    9    1    3    3  !    18    7.8    99.6      .4
16- 18 !             1                      !     1     .4   100.0     0.0
       !------------------------------------!

NO. OBS.     0    1   57   88   30   51    5      232

% TOTAL    0.0   .4 24.6 37.9 12.9 22.0  2.2

CUM %      0.0   .4 25.0 62.9 75.9 97.8 100.

% EXCEED 100.0 99.6 75.0 37.1 24.1  2.2  0.0
```

Figure 2.4 A typical bivariate histogram. The discrete probability estimates are defined as follows: p(x) = % TOTAL, P(x) = CUM %, and Q(x) = % EXCEED.

2.3.2 Duration or Persistence Statistics

The duration or persistence of conditions above or below some threshold can be a useful operational statistic that helps select weather windows for environmentally-sensitive activities. Storm duration (i.e., persistence of wave height above various thresholds) is an important design factor for sand islands such as the ones used in the Beaufort Sea. Since erosion depends on the history of wave action, not just maximum sea state or the probabilistic distribution of wave heights, time-series of wave height, period, and direction of the extreme sea states have to be deduced from the characteristics of observed storms.

There are several approaches to the calculations of climatological persistence, and careful documentation of methods and assumptions are key to the future utility of the statistics. Figure 2.5 illustrates a table of favourable (i.e., below threshold) persistence and its interpretation. Reliable statistics can be produced only from continuous, regularly-sampled records. In the event of missing data, realistic assumptions (such as hindcasting) must be made. Some of the parameters that are amenable to persistence calculations and prove useful operationally are wave height, wind speed, and visibility.

2.4 Extreme Value Analysis

Extreme value analysis (EVA) is routinely used to estimate the magnitude of environmental parameters to anticipate at low probabilities of exceedance, hence at long return periods. The underlying principle of EVA is to ascribe a probability of exceedance Q to a set of observed maxima x_m, and, by specifying the empirical mathematical relationship between Q and x_m, to extrapolate estimates of x_m from that function for given values of Q. There are only three extreme value distributions: the Fisher-Tippett I or FT-I or Gumbel, the Fisher-Tippett II or FT-II or Frechet, and the Fisher-Tippett III or FT-III. The Rayleigh, the Weibull, the lognormal, and the normal distributions all have the Gumbel distribution as their limiting type (Muir and El-Shaarawi, 1986).

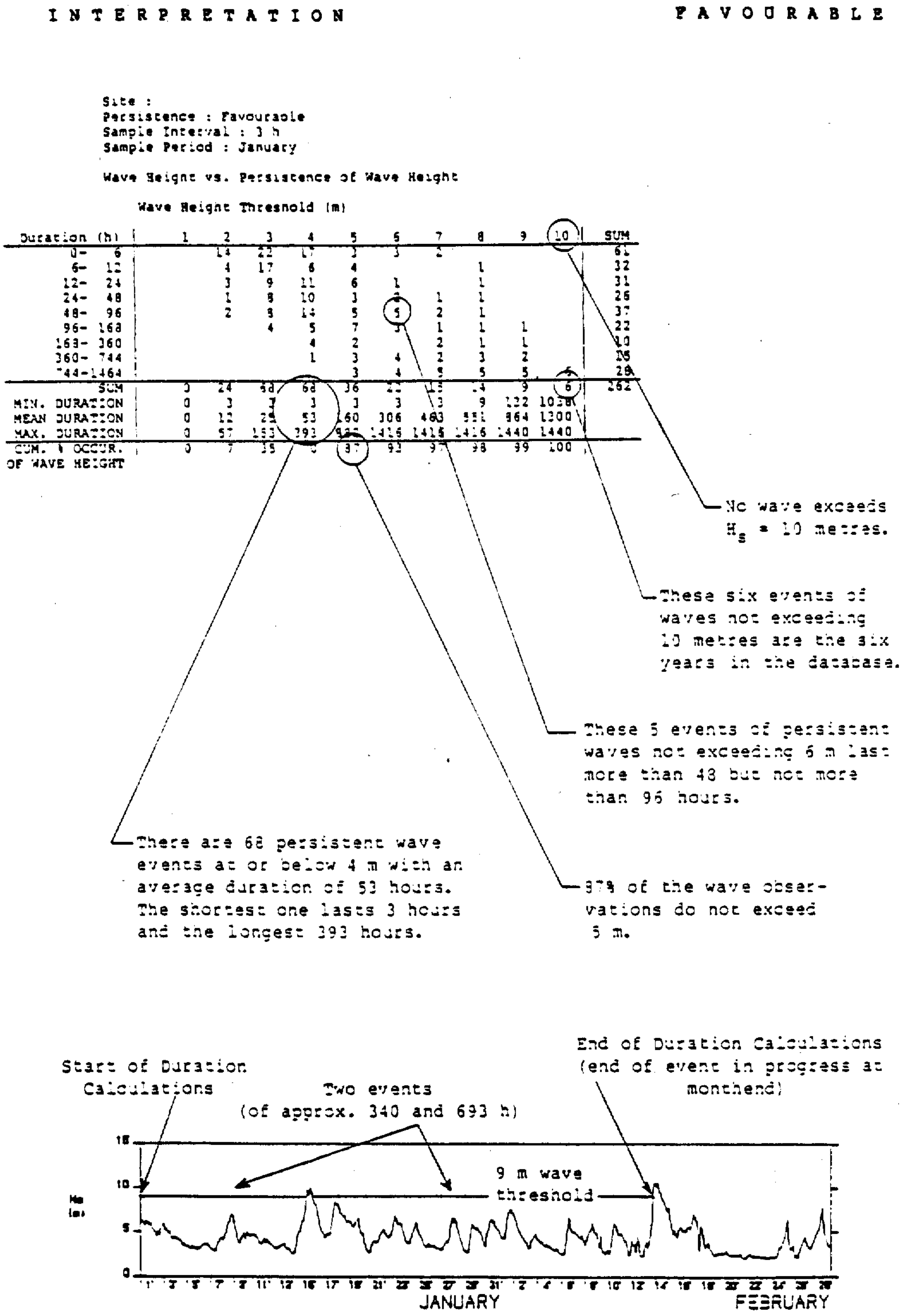
The EVA techniques require good quality data of many years duration, ideally 30 or more. Because reliable offshore wind or wave data measurements of such long duration cannot usually be obtained, hindcasting of severe historical events is a common source of input data for EVA methods.

There are four technical issues to be addressed in a discussion of EVA techniques--sampling for the maxima, EVA models of $Q(x_m)$ fitting of the samples to the models, and evaluation of the goodness-of-fit. Aspects of the first three factors affect overall confidence in the long return period predictions. There are also side issues such as inter-annual variability and spatial homogeneity which influence the EVA methods and confidence in the product. The discussion of EVA methods in this report provides an overview of the topic. Some equations are provided as examples to illustrate points of interest, but other references (e.g., Baird et al., 1986) should be consulted for a more comprehensive list of models and methods. Statistical confidence limits, which are sometimes specified for long return period estimates, are not part of the CSA code requirements.

For locations with short (sometimes non-existent) records, other methods that are not strictly of the EVA class must be used. One possibility for wave extremes that is successfully applied in sheltered or shallow-water locations is to determine extremes for a well-exposed site and develop transfer coefficients between offshore and the site of interest. This method works because models of the controlling mechanisms (refraction, shoaling, dissipation and reflection) are well known. A similar approach has been used for deriving offshore winds from shore station measurements, but confidence in the results is not high.

Another approach, applied with limited success to date, is to estimate the set of underlying parameters (such as central low pressure, rate of deepening, etc.) that define a storm with a given low probability of exceedance. From the storm parameters, the corresponding long return period wind and waves can be evaluated deterministically using established methods for hindcasting.

When some measurements are available, it is also possible to estimate the population distribution p(x) and its cumulative probability distribution P(x). If a relatively simple empirical form can be specified for P(x), then the measurements can be used to estimate the coefficients of the empirical distribution. By inverting the equation, values of x at specific low probabilities of exceedance can be calculated. This method has been used to derive monthly and seasonal extremes of waves (Bolen et al., 1989). The method assumes that the function which describes the whole range of values fits the distribution of maxima equally well (i.e. extrapolation into the tail of the distribution is valid). Muir and El-Shaarawi (1986) state that the assumption is not formally well founded, although the limiting shape of the right-hand tail of many common distributions is equivalent to the Gumbel distribution.



INTERPRETATION FAVOURABLE

Site :
Persistence : Favourable
Sample Interval : 3 h
Sample Period : January

Wave Height vs. Persistence of Wave Height

Wave Height Threshold (m)

Duration (h)	1	2	3	4	5	6	7	8	9	10	SUM
0- 6		14	22	17	3	3	2				61
6- 12		4	17	6	4			1			32
12- 24		3	9	11	6	1		1			31
24- 48		1	8	10	3	2	1	1			26
48- 96		2	8	14	5	5	2	1			37
96- 168			4	5	7	3	1	1	1		22
168- 360				4	2		2	1	1		10
360- 744				1	3	4	2	3	2		15
744-1464					3	4	5	5	5	6	28
SUM	0	24	68	68	36	22	15	14	9	6	262
MIN. DURATION	0	3	3	3	3	3	3	9	122	1038	
MEAN DURATION	0	12	25	53	160	306	483	551	864	1300	
MAX. DURATION	0	57	153	393	[illegible]	1416	1416	1416	1440	1440	
CUM. % OCCUR. OF WAVE HEIGHT	0	7	35	[illegible]	87	93	97	98	99	100	

Figure 2.5 One example of a favourable persistence table and its interpretation.

It is impossible to predict whether extrapolation based on all available data will be more or less conservative than EVA extremes from hindcast data. Bolen et al. (1989) reported that for Hibernia the 100-year extreme H_s derived from a Weibull fit to five years of Waverider measurements is essentially the same as the value obtained from extreme value analysis of a 34-year storm-based hindcast. In that example, the five years of measurements may have been from particularly stormy years. If true, the short return period extremes (at least within the duration of the sample) would tend to be over-estimated.

2.4.1 Sampling

There are two approaches to sampling an environmental parameter for the input maxima to an EVA model that are recommended by Baird et al. (1989): annual (or regularly sampled) maxima (AMAX) and peak-over-threshold (POT). A third method involving selection of the r largest events in n years is described by Muir and El-Shaarawi (1986).

In the AMAX method, the magnitude of the single largest event each year is extracted. In the POT procedure, the set of maxima is made up of the peak value in all independent events that exceed some prescribed threshold. Even if the POT threshold is high, it is most unlikely that the AMAX series of maxima will be the same as the POT set.

Strictly speaking, the extreme value distributions are applicable only to regularly sampled maxima. As a result, POT-sampled events are properly fitted with a compound distribution, such as Poisson-Gumbel, to account for the temporal distribution of severe storms. Baird et al. (1989) give the following list of the characteristics of the parent POT population:

1. the threshold must be above the mode of the parent distribution,

2. for a series of N years, 5N to 10N events must be selected to define the parent POT series (so long as criterion 1 is satisfied),

3. there must be at least two events per year,

4. the events must be independent, and

5. evidence of significant trends, jumps and inhomogeneity in the parent population must be taken into account.

With due regard to the underlying distributions (see Baird et al., 1989), the threshold should be adjusted iteratively until the magnitude of the maxima are exponentially distributed and their temporal occurrence is Poisson distributed. Typically, there are two or three times as many events in the POT series as in the AMAX list and the lowest maximum will be significantly higher than the lowest AMAX value.

Baird et al. (1989) give the following guidelines for choosing between AMAX and POT sampling:

1. For a record length of at least 25 years, AMAX sampling is sufficiently reliable.

2. For records between 10 and 25 years long, either AMAX or POT is suitable, with an increasing preference for POT as the number of years decreases.

3. For record lengths between S and 10 years, POT is suitable provided that at least 20 events are represented in the sample.

4. For records of less than 5 years duration, neither AMAX nor POT is reliable.

Storm-based hindcasting, as undertaken for Canadian waters, uses POT sampling in principle, but in practice any set of hindcast events is likely to be only a sample from the parent POT series. Inevitably, hindcasts have budgets that limit the effort that can go into identifying the parent POT series and the number of events that can be modelled. In preparing for wave hindcasts, modelling teams are working mainly with surface pressure data and wind records from which they must estimate the resulting peak sea state to decide which storms warrant hindcasting. Regional hindcasts are especially vulnerable to compromises that must balance the selection of peak events in all sub-zones of the region.

Because hindcasts generally cover more than 25 years, they could be structured as AMAX series. Although the POT subset for hindcast purposes will probably not contain an event maximum from every year, annual maxima could be extracted and treated as r events in n years on the assumption that all unrepresented years had lower peaks than the lowest hindcast maximum.

2.4.2 Extreme Value Models

Although there are only three limiting distributions of the maxima of independent, identically distributed data, there are several ordinary probability distributions that have been widely applied to environmental parameters. Some commentators (e.g., Muir and El-Shaarawi, 1986; Isaacson and MacKenzie, 1981) advocate selection of the correct probability model on goodness-of-fit criteria. Others (e.g., Baird et al., 1989) adhere more rigidly to the three limiting distributions in circumstances where they are valid.

Wind and wave extremes ought to follow the Gumbel (FT-I) distribution since moments of the data set (mean, variance, skewness) should be always positive. Its cumulative probability is written as

$$P(x) = \exp \{ - \exp [- (x - a)/b] \} \tag{2.45}$$

where a and b are coefficients to be determined from the data. The Gumbel distribution is recommended by Baird et al. (1989) in the following circumstances:

1. for AMAX-sampled data when $N \leq 25$, and

2. for AMAX-sampled data when $N > 25$ if the skewness coefficient is within acceptable limits ($0.5 + 0.15[\sqrt{N} - 5]$ and $1.1 + 0.15[\sqrt{N} - 5]$).

Muir and El-Shaarawi (1986) recommend the Gumbel distribution for all types of regularly-sampled data, including r events in n years.

The Frechet (FT-II) and the FT-III distributions may also be suitable for data for which some positive moments do not exist. The FT-III distribution applies to parameters that have an upper bound, and since wave heights are limited by steepness and breaking criteria and by fetch, it may be a useful model.

The Fisher-Tippett distributions do not apply directly to POT-sampled data. Muir and El Shaarawi (1986) recommend the Poisson-Gumbel compound distribution for extreme wave heights which has the following form:

$$P(x) = \exp \{-\lambda[1-\exp(-\exp[-\{x-a\}/b])]\} \tag{2.46}$$

where λ is the mean time between storms (the Poisson distribution parameter) and the a and b coefficients are calculated from the data. Baird et al. (1989) provide a procedure for POT-sampled data that uses a Poisson-truncated exponential compound distribution which depends on λ, the sampling threshold, and the moments of the event maxima.

The other distributions that have been used commonly are the Weibull, which is also denoted by FT-III (lower bound), and the lognormal distributions. The three-parameter Weibull model has the following definition:

$$P(H) = 1 - \exp \{-[(H - c)/b]^{a}\} \tag{2.47}$$

For particular values of the Weibull coefficients, (2.47) reduces to the Rayleigh or the exponential distribution. One drawback to the Weibull formula is that either a or c must be estimated before the remaining two coefficients can be calculated, and a convergent solution cannot always be found. As applied to waves, the lower bound may represent a low level, background sea state or a lower bound to the wave heights in the data sample.

The lognormal model of maxima has been used for three decades, although its functional form, which follows, is more complicated than other distributions:

$$P(x)=(1/\sqrt{2\pi})\int_{0}^{X}\frac{1}{ax}\ \exp\left[-\frac{1}{2}\left[\frac{\ln(x)-b}{a}\right]^{2}\right]dx \qquad (2.48)$$

2.4.3 Data Fitting Methods

Use of the distribution models depends upon obtaining reliable estimates for their parameters. There are three common methods of data fitting: least squares, method of moments, and maximum likelihood. Usually each of them will provide different estimates of the model parameters for a given data set.

(a) Least Squares

Least squares fitting has probably been the most popular technique, but it has serious drawbacks. In statistical terms, the method is inefficient and parameter estimates are biased. In applying the method, the cumulative probability equation is inverted to form a linear relationship of the form

$$x = A * P(x) + B \qquad (2.49)$$

or a non-linear equation that must be solved iteratively of the form:

$$x = A * P(x)^{C} + B \qquad (2.50)$$

requiring in either case that the probability of exceedance be specified for each sample x. The functional form of P(x) is related to the ratio of event rank and total number of samples, and is called the plotting position. Carter and Challenor (1983) give an exact form, but approximations are commonly used and Baird et al. (1986) report ten different formulas. The optimal choice depends on the extreme distribution function, and the preferred expression for the Gumbel model with 10 or more samples is the Gringorten formula:

$$P(X_{i}) = (i - 0.44) / (n + 0.12) \qquad (2.51)$$

where i is event rank (smallest equals 1) and n is the number of samples.

(b) Method of Moments

The simplest fitting calculations are by the method of moments in which the probability model parameters are expressed in closed form as functions of the first two or three moments of the model. The method is applied by equating the model moments with moments calculated from the data sample.

Statistically, the method of moments provides unbiased estimates, it is more efficient than the least squares technique, and as sample size increases the moment estimates converge to the population values. If the moments exist for a given probability model, a solution can always be found and the calculations are straightforward. For the Gumbel distribution (2.45), the moments are

$$\text{mean: } m_1 = a + \gamma b \simeq a + 0.5772\ b \tag{2.52}$$

$$\text{variance: } m_2 = (\pi^2 b^2)/6 \simeq 1.645\ b^2 \tag{2.53}$$

and these two equations are sufficient to solve for estimates of the model parameters a and b. Equation (2.45) can then be inverted to calculate x as a function of P(x), that is,

$$x = \hat{a} - \hat{b} \ln[-\ln P(x)] \tag{2.54}$$

The moments of the common distributions are provided by several authors, including Baird et al. (1986), Isaacson and MacKenzie (1981), and Muir and El-Shaarawi (1986).

(c) <u>Maximum Likelihood</u>

The maximum likelihood method estimates model parameters that give the data sample the highest probability of belonging to a distribution with those parameters. Each sample is considered to be an independent observation from the same distribution and a likelihood function is formed from the product of their individual probabilities p(x). The logarithm of the likelihood function is maximized with respect to each model parameter by equating the partial derivative to zero.

Maximum likelihood estimators converge to the true model parameters with increasing sample size, and they are unbiased (except possibly for small sample sizes according to Carter and Challenor, 1983).

Likelihood equations for the Gumbel distribution are

$$\hat{a} = -\hat{b} \ln\left[\frac{1}{n} \sum \exp(-x/\hat{b})\right] \tag{2.55}$$

and

$$\hat{b} = m_1 - \Sigma\, x \exp(-x/\hat{b}) \,/\, \Sigma \exp(-x/\hat{b}) \tag{2.56}$$

where m_1 is the mean of the sample. These equations must be solved by non-linear iterative techniques.

Maximum likelihood equations can be derived for all the standard probability distributions (see, for example, Muir and El-Shaarawi, 1986), but they can be difficult to formulate for compound distributions such as the Poisson-Gumbel.

When applying either method of moments or maximum likelihood, estimates of sample probabilities $P(x_i)$ and a plotting position formula are not required, except to plot the sample data on a probability graph. The precise plotting position formula is not important in that case so long as the same equation is used for all comparative plots.

All three methods can be applied to AMAX-sampled data, including the r samples in n years type, and to POT-sampled data. Least squares fitting is regarded now as an inappropriate method since there are simpler and better techniques. Because of their desirable statistical properties, maximum likelihood estimators are recommended for large, regularly-sampled data sets, and they are preferred for small data sets.

2.4.4 Goodness-of-Fit Criteria

Whether or not the probability model is objectively selected, it is important to assess the degree to which any model fits the data. Statistical tests have two drawbacks since such measures are relative rather than absolute. If only one model is selected on objective criteria, then the assessment of a statistical goodness-of-fit test will be largely subjective. If more than one model is used, the statistical tests will seldom be sensitive enough to discriminate among the models (Muir and El-Shaarawi, 1986).

In the absence of reliable statistical tests, there is a tendency to select the model that produces the highest extreme value estimates, arguing that if errors have been made, the results are conservative and safe. This decision should not be taken in ignorance of the data set’s characteristics or of the agreement between the probability model and the data. Specification of overly safe design criteria can have serious economic consequences without significantly improving safety.

The first test, which should always be made, is a plot of the data, usually with the environmental parameter as the independent variable and probability as the dependent variable, both appropriately transformed to yield a linear relationship. Muir and El-Shaarawi (1986) recommend a Q-Q plot with the parameter as the independent variable and the corresponding predicted value from the probability model as the independent variable. For either plot format, a plotting position formula will be required, and the same one should be used for all models. Advantages of the Q-Q plot include identical scales for all models, model comparisons can often be made visually, and simple numerical measures of goodness-of-fit such as the correlation coefficient are appropriate.

Plots of the data will reveal outliers and systematic trends in the data. If either problem is evident, its probable source must be identified and its consequence on the extreme value analysis must be assessed.

More sophisticated numerical goodness-of-fit tests may be found in advanced statistics sources (e.g., Lawless, 1982).

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3.0 DESIGN CRITERIA FOR OFFSHORE STRUCTURES

3.1 Introduction

Aside from sea ice, the most important environmental factors that affect design of offshore structures for Canadian waters are winds and waves. The design issues are structural load from winds and waves, and a host of consequential problems from waves (such as overtopping and sediment erosion). Traditionally, design for wind has been based on the static (i.e., not time-dependent) distribution of wind pressure, derived from a design wind speed with some allowance for gusts. In contrast, wave design has recognized the dynamic nature of wave forces, but the analysis techniques tended to rely on a design significant wave height and a wide variety of empirical relationships to estimate period, maximum height, and frequency-dependent energy distribution.

The Canadian Standards Association has recently compiled a new standard for fixed offshore structure design, construction and installation (CSA, 1989) that sets out the general requirements for environmental design criteria. This code proposes that design should be based on combined loads with a specified annual probability of exceedance, rather than on environmental conditions that have such a probability. Therefore, it is informative to look at the CSA code in some detail and to consider how existing environmental data can contribute to the modern design process.

3.2 Overview of the CSA Code

The new CSA code is based on the Limit States Design method incorporating load and resistance factors. The limit states fall into two categories: Ultimate Limit States which involve survival criteria and which are concerned with serious failure of the structure; and Serviceability Limit States which involve operational criteria, and which are concerned with the efficient operation of the structure. Thus Ultimate Limit States include (a) loss of equilibrium of the structure or part of the structure, considered as a rigid body (e.g. overturning, capsizing, sliding, sinking), and (b) loss of structural integrity. Serviceability Limit States deal with displacement, deformation, or motion of the structure that adversely affects the comfort of occupants, the use of the facility, or the operation of equipment.

The resistance factors, concerned with the structure’s resistance to loads, are related to (a) its ability to withstand capsizing, sliding or overturning, and (b) to the structural integrity of its members. Resistance to capsizing or overturning is a fundamental hydrodynamic property of floating vessels, and is considered routinely in the foundation design and geometry and weight distribution of fixed structures. Structural integrity is a function of the material and shape of components making up the structure. Limit state design refers to the selection of materials and shapes that will not fail through crushing, buckling, fracture, or excessive deformation under the applied load according to rules based on material behaviour and known failure modes. The process of selecting materials and shapes at safe stress levels for limit state design is well established and codified.

The new code specifies load factors for various categories of load which include environmental loads. These load factors account for the uncertainty in obtaining the estimated environmental parameters (e.g. the 100-year return wind speed) together with the uncertainty in the transformation from these parameters to the corresponding loads (e.g. in transforming from a wind speed to a wind load).

Environmental loads are categorized as those based on frequent environmental processes, such as winds, waves and currents; and on rare environmental events, such as earthquakes and icebergs. The code requires that the loads based on frequent processes can be treated in one of two ways:

- in terms of a design event (wind speed) having an annual exceedance probability <0.01;

- in terms of a load distribution function (wind load) that provides a load with an annual exceedance probability <0.01.

When determining these loads, consideration must also be given to the simultaneous occurrence of loads produced by companion processes. In the case of wave loads, these include wind, wind-driven current, and other currents, which refers to tidal and background currents. With respect to wind loads, the companion processes include waves, wind-driven currents and other currents, or sea ice, wind-driven current and other currents.

Loads produced by companion processes (e.g. wind) which are correlated with the principal-process (e.g. waves) should also have an-annual exceedance probability of less than 0.01, since both of these processes are expected to reach extreme values simultaneously. In most cases, this approach may result in somewhat conservative design criteria since the chance of the individual 100-year conditions occurring simultaneously is less than unity. Alternatively, the code permits a probabilistic method of combining loads from these correlated environmental processes. Joint load probability distributions are required for this latter approach.

Loads resulting from companion processes (e.g. tidal currents) which are independent of the principal process (e.g. waves) should have an annual exceedance probability of less than 0.95, since the companion process is then expected to possess normal values when the 100-year event of the principal process occurs.

The rules provided for translating extreme wind into load require only an estimate of the 100-year return wind speed with a known averaging period at a known elevation above the sea surface.

Additional site-specific information on wind is directed at two aspects:

- improving confidence in the 100-year return estimate;

- refining design loads through changes to the rules for translating the extreme speed into load.

Such information is not mandatory, and can be used at the discretion of the designer so long as the procedures conform to accepted practice and the load exceedance probability remains below 0.01.

The code also provides guidance on calculation methods for wave loads. For fixed structures (subject of the code) the basic information required is the 100-year return wave height and period. It is taken for granted that this information is site-specific, incorporating all effects that affect the design wave (shallow water, currents, sheltering and sea ice fetch restrictions). Any safety factor included in empirical coefficients in the load calculation methods provides a conservative margin for uncertainties associated with in the load calculation, and the design wave selection.

As pointed out in Section 3.4 , the minimum requirements for global and local loads, including air gap, is the design significant wave height and associated period(s) assuming that short-term distributions for translating significant height into individual wave height and crest elevation are demonstrated to be valid at the site.

Fatigue requires additional information on the long-term individual wave height distribution and associated periods, and structures subject to scour require design storm wave height, period and current histories.

Additional site specific information, required by the new code as part of the design and planning process, is directed at three aspects of the problem:

- improving confidence in the design wave estimate;

- demonstrating the validity of the assumptions made about the distributions of individual wave heights, crest elevations and wave periods that enter into load calculations;

- refining the structural design through use of more precise load calculation methods that require site-specific spectral or wave trace data.

In view of the above, wind and wave databases for the Canadian offshore must contain, as a minimum, the information to calculate accurately:

- 100-year wind speed with known averaging time and elevation,
- 100-year significant wave height and associated period,
- long-term individual wave height-period distribution when structural fatigue is a design consideration,
- significant wave height, period and current histories for the 100-year design storm when foundation scour is a design consideration,
- wave data on the short-term distributions of individual heights and periods,

to meet the terms of the code for the determination of wind and wave loads and wave effects.

The following two sections describe wind data requirements, and wave data needs for various design problems for a wide variety of offshore structure types, in more detail.

3.3 Wind Criteria for the Design of Offshore Structures

3.3.1 Wind Criteria and Wind Loads

The design of an offshore platform must consider wind action that gives rise to design-problems in three general areas: excessive forces or overall instability in the structure or its components; excessive displacements of the structure; and fatigue of structural elements. To address problems in these areas allowance must be made for three components of the wind force: the mean component (arising from the mean wind speed as defined in Section 2.1); the slowly varying or background component produced by the turbulence or gustiness of the wind; and the resonant component at or near resonant frequencies of the structure or element. Aerodynamic instabilities include vortex shedding, galloping, flutter and buffeting. The largest amplitudes are attained when the predominant frequency of the fluctuating pressure coincides with the natural frequency of the structure or component (see for example Walshe, 1972).

In the CSA code, all aspects of the wind design problem are treated through a static wind force per unit area, applied in a direction normal to the surface of the structure or element. The wind force w is computed from

$$w = q_{ref}\ (C_e)\ (C_s)\ (C_d) \qquad (3.1)$$

where q is the sustained wind velocity pressure in kPa derived from the 10-min mean wind at 10 m elevation above mean sea level. The code provides conversion factors for mean wind estimates that have averaging times other than 10 min.

The three coefficients in (3.1) account for the following effects:

C_e the exposure factor which converts the force to an elevation z different than 10 m using the power law (2.5) with an exponent of 0.24 (applicable for rough seas);

C_s the shape coefficient which adjusts the force for various structural shapes;

C_d the dynamic response factor for down-wind aerodynamic excitation.

The dynamic response factor is a function of four parameters: the turbulence intensity σU (as described in Section 2.1.4) which is given as 0.10 at the 10-m reference level, the background response factor B related to the principal dimension of the structure or element (which incorporates the effects of correlation of gust winds with separation distance), the resonant response factor R which is a function of the natural frequency of the structure, and a multiplicative factor that gives the expected value of the maximum gust response at the natural frequency of the element in sway mode in the down-wind direction (analogous to (2.16)).

Use of (3.1) requires an estimate of only the mean wind speed with an annual exceedance probability of less than 0.01. The averaging time of the mean wind and its elevation must be given. Specific information on the design wind, incorporating gusts as described in Section 2.1.4 for example, is not required. However, the use of other well established methods for design is allowed as an alternative to the approach described in Appendix C of the code. Such methods must consider dynamic as well as static wind forces, and for their application they will require knowledge of the statistical properties of the turbulence and the mean wind variations above the sea surface. Such properties are not explicitly stated in the code, although they are assumed in the derivation of the exposure and dynamic factors described in conjunction with (3.1).

In addition to the extreme wind loads, the code requires wind information for normal operating conditions, and other phases of design, construction, and installation:

- the monthly and seasonal frequency of occurrence statistics and average duration of specified average wind speeds from various directions;
- the persistence of particular wind speeds and directions;
- the probable velocity and duration of gusts associated with the mean wind speeds; and

- the long-term distribution of extreme mean wind speeds of specified durations (speed versus probability of exceedance).

Thus, to provide wind criteria for design, meteorological data bases must contain sufficient time-series wind data to derive both the normal and extreme wind speed criteria. The averaging time of measurements must be known as well as the height of recording, and any tendency for flow distortion (e.g. on drilling rigs) must be documented and taken into account in deriving wind statistics. Where site-specific data do not exist, the code allows for either new measurements or numerical modelling to derive the required information.

In general the categories of structure and related design problems are less relevant for wind criteria than they are for wave criteria. The background response factor B is a function of the principal dimension of the structure. For large platforms the dimension of interest is the deck width when considering the structure as a whole. For slender elements such as towers, masts and booms, and certain truss members, the relevant dimension is the length or height. Such information is very basic and readily determined for any structural type.

The dynamic response factor R is determined largely by the natural resonant frequency of the element and the span ratio defined by the principal dimension divided by the elevation of the element above mean sea level. Thus different structures are parameterized by characteristic dimensions and resonant frequencies. The wind data required are largely unaffected by the structural type. The wind loads are determined from the reference velocity pressure applied to the silhouette area of the structure.

3.3.2 Wind Data Requirements

(a) Long-term Mean Wind Statistics

Mean wind speed and direction statistics meeting the code requirements outlined in the previous section must be derived from suitable time-series spanning many years. The mean wind averaging time in the CSA code is 10 min. As discussed in Section 2.1 this averaging time is long enough to exclude most of the turbulence fluctuations in the boundary layer, and yet short enough to be unaffected by macro-meteorological variations (Fig. 3.1). The 10-min averaging time is also long enough compared with the natural vibration periods of most structures to give rise to exclusively static forces.

As shown in Fig. 3.1 the spectral gap begins to disappear as the period increases beyond about 1 h. At this and longer periods the synoptic weather patterns begin to affect the mean wind. Energy peaks at a periods between 3 and 4 days corresponding to the dominant cycle of transient weather systems at higher latitudes. Consequently wind time-series must be comprised of observations at a frequency of about once per hour in order to sample extreme wind speeds.

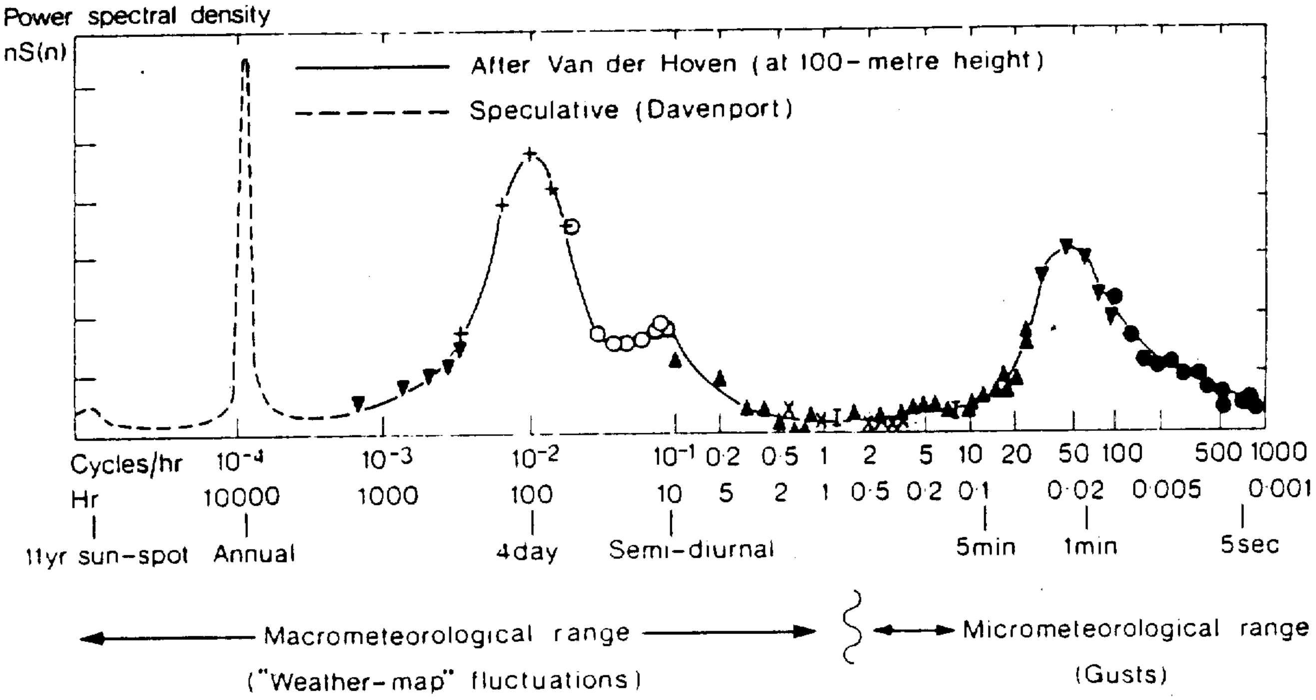

Figure 3.1 Spectrum of horizontal wind speed near the ground for an extensive frequency range. From Walshe (1972).

There are three primary sources of data on mean winds:

- instruments mounted on offshore platforms,
- shore-based instruments,
- indirect estimates of wind speeds and directions from gradient winds derived from synoptic pressure data, and empirical estimates based on knowledge of the storm systems.

All of these sources have advantages and limitations.

Offshore Rig Wind Measurements

Rig-mounted wind anemometers provide the most appropriate site-specific information, and the measurements do not require several of the corrections needed by land-based instruments. Experience has shown, however, that mounting instruments clear of up-wind obstructions on offshore platforms is usually difficult (Vickery et al., 1985). The measurements can often be corrected through use of wind tunnel tests, but the corrections are less accurate for gust wind speeds than for the mean wind, particularly if the anemometer is situated in the wake of an upstream obstruction. Moreover, the anemometer locations are often at elevations of 50 to 80 m above MSL and use of the data at lower levels requires application of one of the profile laws discussed in Section 2.1.3 . Another problem with most rig wind data concerns the averaging-time. The anemometer is usually read on a dial gauge and a visual average is estimated over one minute, and recorded on the hour. Thus the individual wind speed data points do not correspond to a true 10-min mean. This observing method also precludes any calculation of the turbulence properties of the boundary layer.

These data have the advantage of providing continuous hourly time-series while the rig is on location. Pooling data from several rigs in one area (e.g. the northeast Grand Bank) can increase the overall record length, yielding useful estimates of the normal wind climate. In general, the time-series are too short for a confident estimate of the extreme wind speed.

Shore-based Wind Observations

The principle advantage of shore-based instrumental records is their length, which is often suitable for estimating extreme wind speeds in additional to normal climate parameters. The greatest limitation to the data arises from flow disturbance produced by the surrounding topography, and a sound method to transfer coastal winds to an offshore location. In using shore-based winds it is necessary to correct for siting effects; this can be done using wind tunnel tests or numerical modelling. In addition, averaging times for Canadian meteorological instruments vary both with the anemometer type and site, and with time. These variations must also be taken into account when deriving wind parameters for offshore applications.

Derived Wind Data

Wind speed and direction data for a particular offshore location, or for an area, can be derived from gradient winds calculated from pressure distributions. The gradient winds are reduced to the required reference height by applying an atmospheric boundary layer model. In recent years, wind and wave hindcasts, and operational weather forecasting have produced some datasets that incorporate observed winds blended into the derived wind fields through kinematic analysis, generally producing a more accurate wind field representation. The main advantages to these datasets are continuous 3 to 6-hourly coverage for many years, unaffected by problems of flow distortion or instrumental error.

The main disadvantage lies in the sparsity of pressure (or wind) observations over the ocean compared with the land. Thus there is a larger, but unknown error in the computed gradient winds over water than over land. This situation is worst in the Arctic, and over the Pacific Ocean where weather systems approach the coast from the open ocean. Additional errors enter the wind estimates from the boundary layer model, particularly in situations where data to infer stability are missing.

A second approach to deriving extreme wind speeds in hurricanes makes use of simulation methods based on wind fields derived from a few parameters defining the weather system: specifically, central pressure difference, radius to maximum wind speed, forward speed, and distance from the storm track. Statistical distributions for these parameters are well known from long-term records, and predictions of extreme conditions have been successfully compared with instrumental observations in a few instances, notable for hurricanes affecting Hong Kong. Statistical wind simulation for hurricanes has been applied to the Atlantic and Gulf coasts of the United States, the Caribbean, the South China Sea, and Australia.

In areas where measurements are sparse, which is characteristic of the Canadian seaboard, such techniques are more reliable than measurements alone. Problems with observed datasets include under-sampling the storm winds spatially, and destruction of anemometers thus missing the peak wind speed in the event.

As is evident from this discussion, derivation of both normal and extreme wind criteria is a complex problem, largely because of limitations with available data. The best strategy is to use all available information by correcting and pooling data from several sources. The normal wind speed and direction climate will also indicate any requirements for approaching derivation of the long-term extreme wind speed distribution on a directional basis. Another factor to be considered in the extreme wind speed distribution is the influence of interannual variability as this may affect both the frequency and intensity of storms over the area of interest.

(b) Boundary Layer Turbulence

The CSA code does not require site-specific measurements of the properties of boundary layer turbulence, and, from an engineering standpoint, variations in turbulence intensity with elevation, boundary layer stability, and sea state, are considered to be sufficiently well known for design purposes. However, since alternative design procedures may be utilized, there may be circumstances where more detailed information than the mean wind speed is warranted.

For example, Vickery et al. (1985) reported significant differences in the integral length scales for turbulence as a function of wind direction off Sable Island. In their analysis the Harris (1963) spectrum adequately modelled the measured spectra; however, the integral length scale, used to scale the spectrum, differed for east (smaller scale lengths) and west winds (larger scale lengths). These differences were thought to be caused by the influence of cold sea surface temperatures under easterly winds which produced stable air flows rather than neutrally stable flows accompanying westerly winds.

The conclusion reached by Vickery et al. was that the integral length scale exhibits large variability, and is not always adequately described by a single value. Thus when wind spectra are required for design, site-specific measurements are desirable to quantify the variations in this parameter for a range of wind and sea state conditions. Similarly, site-specific data could be used to better specify expected variations in turbulence intensity σ/U or σ/u_* for a range of conditions.

c) Companion Loads

The treatment of design wind loads, the addition of companion loads resulting from frequent environmental processes must be taken into account. Each of these are considered to be (i) correlated with the extreme wind (such as waves); (ii) independent of the extreme wind (such as tidal currents); or (iii) mutually exclusive with another of the companion loads (such as sea ice and waves not being considered simultaneously). Thus in the CSA code, when wind is taken as the principal event, it must be treated in conjunction with (i) and (ii) in turn:

(i) waves (c) + wind-driven current(c) + other currents (i)

(ii) sea ice (c) + wind-driven current(c) + other currents (i).

Here “c” denotes a companion process which is correlated with the wind and so should have an annual exceedance probability of less than 0.01, or this may be treated using a probabilistic method that takes the correlation of loads from each environmental process into account. “i” denotes a companion process which is independent of the wind and so should have an annual exceedance probability of less than 0.95.

As part of the process for deriving extreme environmental criteria, each of the companion processes (waves, wind-driven currents and sea ice) will be analyzed for long-term distributions giving the corresponding force with an exceedance of less than 0.01. However, it is recognized that addition of these forces without accounting for the correlation between events leads to conservative design. Therefore, environmental data on winds, waves, currents and sea ice that can be used to establish the joint probability of companion environmental events, or that can be used to establish the long-term load distribution from combined loads, is desirable. Multi-year hourly time-series of wind, waves and currents would be required to establish the joint distributions.

3.4 Wave Criteria for the Design of Offshore Structures

3.4.1 Wave Information for Design

The design of offshore facilities used for oil and gas exploration and production involves a variety of problems which depend on the reliable estimation of ocean wave conditions. These include various structural loading problems, as well as problems relating to the motions of a compliant or floating structure, wave runup and overtopping, and sediment erosion. Each of these problems is related to a particular category of the principal structure, or component of that structure, and requires a particular set of criteria deriving from one or more sea states. The requirements for wave criteria in relation to various categories of offshore structure, and to the different problems which should be treated in their design, are described in this section.

Traditionally, the significant wave height is used to provide the most fundamental description of a design sea state. Beyond this parameter, the sea state may be described in increasingly greater detail in terms of:

- the peak period,
- the mean wave direction,
- the uni-directional wave spectrum,
- the directional wave spectrum,
- the variations of the significant wave height, peak period, and mean wave direction throughout a design storm event.

Some of these quantities are usually obtained by fitting a long-term probability distribution to data, which are themselves obtained by a wave hindcasting technique applied to a series of storms, or by relatively short series of measurements. A further consideration in the use of wave criteria relates to the confidence level attached to wave data. For example, the extent of the database used, or the manner in which it is derived, may influence the design criteria in different ways.

In the treatment of design wave loads, the addition of companion loads due to frequent environmental processes must be taken into account. Thus in the CSA code, when waves are taken as the principal event, this must be treated in conjunction with:

wind + wind-driven current + other currents.

The wind and wind-driven current are considered to be correlated with the waves and so should have an annual exceedance probability of less than 0.01, or treated using a probabilistic method accounting for the correlation between processes. The other currents (tidal and low frequency non-tidal currents) are considered independent of the waves, and so should have an annual exceedance probability of less than 0.95.

The CSA code indicates that the following types of wave data should be considered when planning and carrying out the various phases of design, construction and installation:

- the frequency of occurrence and the average duration of various sea states from various directions for each month and season;
- the proportion of waves that have significant heights, peak periods, and mean directions within specified ranges for each month and season;
- the nature, tracks, timing, and duration of the storms that produce the extreme sea states;
- the projected distribution of the extreme wave heights and the maximum crest elevations of these waves;
- the range and distribution of the wave periods associated with the wave heights;
- the effects of wave steepness, asymmetry, directional spreading, breaking, and groupiness on extreme and normal waves; and
- the wind velocities, tides, currents and sea ice conditions that occur simultaneously with the various sea states above.

The code also addresses other effects influenced by wave conditions, including both air gap, incorporating wave runup where necessary, and scour.

3.4.2 Categories of Structure

There are a wide variety of structural concepts which have been designed or are contemplated for offshore oil and gas exploration and production structures. A summary of these concepts is appropriate because the categories are in part indicative of the set of design problems which arise, and thus in turn of the descriptions of wave conditions which are required. The relevant categories are as follows:

Category	Structural Concept
fixed platforms	jacket platforms jack-up platforms gravity platforms
artificial islands	caisson-retained islands sacrificial beach sand islands
compliant platforms	tension leg platforms guyed towers other concepts
floating platforms	semi-submersible rigs barges used for platform transport other floating units (e.g. Kullak)
other structures	sub marine pipelines loading buoys wharfs berths

Each of these categories of structure may influence a design problem as a whole, or may contain structural components or individual members which may require particular consideration in the design process. Examples of such components include risers, mooring lines, and structural members in the splash zone.

3.4.3 Categories of Design Problem

The problems or factors which the design should address for different structures and which are influenced by wave conditions include the following:

- air gap
- global forces (on overall structure)
- local forces (on structural components)
  - submerged elements
  - elements in the splash zone subject to non-breaking wave impact
  - elements in the splash zone subject to breaking wave impact
- fatigue of structural elements and joints
- motions of a structure or of parts of the structure
- mooring system loads and motions
- ice impact

- sediment erosion

These factors depend on a variety of parameters deriving from one or more sea states. For example, some factors depend on parameters which can be directly identified, such as the maximum crest elevations required to estimate the air gap for a jacket platform. However, most other factors depend on parameters that are not so readily identified, such as wave conditions giving rise to sediment erosion.

3.4.4 Wave Criteria for Various Design Problems

The design philosophy presented in the new CSA code represents a shift from the use of prescribed environmental conditions, such as a design wave with a 100 year return period, to environmental conditions giving rise to a loading or effect with a prescribed probability of exceedance. This change implies that the wave conditions or wave criteria may not be known *a priori* and one must invariably utilize a range of possible wave conditions, each with different probabilities of occurrence, in order to obtain the desired results.

Wave criteria required for the different design problems outlined in the previous section are summarized in Table 3.1 , with the following notation:

TABLE 3.1

Summary of Wave Criteria Requirements

Design Problem	Minimum Requirements	Improved Requirements	Additional Requirements
air gap: slender	H_s	H_s,η_c	-
large	H_s	$H_s,\eta_c,T_p,\theta,U,H_m$	-
global forces and local forces: submerged elements	H_s	$H_s,T_p,\theta,S(\omega),U$	$H_m,p(H_s,T_p).$ $S(\omega,\theta),\eta(t)$
local forces: impact from non-breaking waves	H_s	H_s,T_p,θ,U	$H_m,p(H_s.T_p).$ $S(\omega,\theta),\eta(t)$
local forces: impact from breaking waves	H_s	H_s,T_p,θ,U	$H_m,\eta(t)$ description of breaking waves
fatigue analysis	$\{H_s,T_p\}$ scatter diagram	$\{H_s, T_p,\theta\}$ scatter diagram, U	$S(\omega)$, $p(H\|H_s,T_p,\theta)$
structure motions: oscillatory	H_s,T_p	$H_s,T_p,\theta,S(\omega)$	$U,S(\omega)\ ,\eta(t)$
structure motions: drift and mooring system	H_s,T_p,U	$H_s,T_p,\theta,S(\omega)$	$S(\omega,\theta)$, description of wave groups, $\eta(t)$
ice impact	H_s,U	$H_s,T_p,\theta,U,S(\omega)$	$H_s(t).T_p(t),\theta(t)$
sediment erosion	H_s,U storm duration	H_s,T_p,θ,U storm duration	$H_s(t).T_p(t),\theta(t)$

H_m	maximum individual wave height
H_s	significant wave height
$H_s(t)$	H_s variation during a storm
p( )	probability distribution
$S(\omega)$	uni-directional wave spectrum
$S(\omega\theta)$	directional wave spectrum
T_p	peak period
$T_p(t)$	T_p variation during a storm
U	current
$\eta(t)$	wave record
$\bar{\eta}_c$	maximum crest elevation
θ	mean direction
$\theta(t)$	θ variation during a storm.

Table 3.1 indicates three levels at which wave requirements may be incorporated into the determination of design loads or effects. The first represents the minimum wave requirements. often only the significant wave height, for which the pertinent problem can be examined. The use of these requirements will invariably involve assumptions relating to other parameters such as mean direction, or will involve an examination of the influence of a range of possible values of such parameters.

The second level corresponds to improved wave requirements which may be more commonly incorporated into an analysis of the problem. The third level corresponds to additional wave requirements which would be useful and which are likely to be used to a greater extent in the future, provided the corresponding data become available.

The table lists the various parameters in summary form and does not provide detailed descriptions of the requirements of each parameter’s format, such as whether or not monthly or seasonal variations are required, or the extent of the data base that is needed. Such information is specific to a particular site and is generally required in the forms listed in Section 3.4.1 . Comments on the selection of the various wave requirements are given below for each design problem.

(a) <u>Air Gap</u>

Design with respect to air gap requires a determination of the maximum water surface elevation around or beneath the structure with a specified annual probability of exceedance. This is generally obtained as the maximum crest elevation, taking account of wave run up where appropriate, superposed on the extreme water level. Somewhat different calculations are required for three categories of structure:

- fixed structures comprised of slender elements (jacket platforms, jack-up platforms) require the maximum crest elevation unaffected by the presence of the structure;
- large fixed structures (gravity platforms, artificial islands) require the maximum crest elevation which is influenced by the presence of the structure (wave runup);
- in addition to either of the above alternatives, floating or compliant structures also require those wave parameters indicated in the table for the analysis of floating structure motions.

The minimum requirement for the first two categories is the significant wave height. A conventional approach uses a long-term distribution of significant wave heights, generally obtained using extreme value analysis (Section 2.4), to estimate a design significant wave height. This is used in turn to estimate the largest individual wave height (Section 2.2.3) and then the corresponding crest elevation from nonlinear wave theory.

The accuracy of the crest elevation criterion can be improved if measurements of η_c are available. The approach is to obtain data of maximum crest elevations directly and fit these data with a long-term distribution, thus avoiding assumptions which involve the relationships between significant wave height, maximum wave height and maximum crest elevation.

For a large structure, such as a gravity platform or an artificial island, the structure modifies the wave field and this should be taken into account in calculating the run up. This is generally carried out by the application of linear wave theory using a specified wave condition. Because the geometry and orientation of the structure are now important parameters, the accuracy of wave criteria can be improved by obtaining site-specific data on peak period, mean direction, and current.

For those sites where the tidal range is large, an improved estimate of the crest elevation (above a reference datum) requires a knowledge of the probability distributions of (i) the wave crest elevations relative to the water level; and (ii) of water level changes, as influenced by tides, storm surge and subsidence of the structure over its operational lifetime.

(b) Global Loading

Specific aspects of the determination of global loading include applications to:

- slender member structures, such as a jacket or jack-up platform, for which a nonlinear wave theory is applied to the design wave condition, or to the range of wave heights to be tested;
- structures which may undergo dynamic response, for which a wave spectrum is applied in order to take account of dynamic amplification; and
- large structures, such as gravity platforms or caisson-retained islands, which diffract the waves and for which linear diffraction theory is applied to design wave conditions.

As shown in Table 3.1 the minimum requirement for global loading calculations is the significant wave height. As before, a conventional approach is to use a long-term distribution of significant wave heights to estimate a design significant wave height. This design value for Hs is used in turn to estimate the largest individual wave height, which may then be used in conjunction with different possible wave periods and appropriate wave directions to calculate the largest force. The largest force may correspond to one particular period within this range. The range of possible wave periods may be obtained from an assumed joint distribution of wave height versus wave period.

As indicated in Table 3.1 , improved requirements include the peak period, mean direction and the wave spectrum. The provision of such information replaces the corresponding assumptions which would otherwise be made.

Additional requirements include the maximum individual wave height, which enables the maximum wave conditions to be obtained directly; the joint long-term distribution of significant wave height and peak period, which provides for a more meaningful selection of wave period; the directional spectrum, so that modifications to global loading due to the effects of directional spreading may be assessed; and sample wave records typical of the most extreme conditions, which enable particular laboratory or numerical simulations to be carried out. Other improvements which may occur in the future include an accounting of freak waves and breaking waves.

(c) Local Loading

Specific aspects of the determination of local loads may be identified as follows:

- Local loading on continuously submerged structural elements. As shown in Table 3.1 , the corresponding wave requirements are the same as those for global loading.

- Local loads on structural elements in the splash zone produced by non-breaking wave impact. The requirements are similar to those of continuously submerged elements. except that the uni-directional spectrum is not particularly needed, whereas the directional spectrum would be useful in an assessment of the effects of finite crest-length on the loads on an element.

- Local loading on structural elements in the splash zone resulting from breaking wave impact. Although a suitable description of breaking waves is required, this is not generally available. Furthermore, a suitable methodology for taking account of breaking waves is also not generally available. In the absence of a description of breaking waves, the minimum and improved wave requirements included in the table provide some indication of the extent of wave breaking, and thereby enable an assessment of breaking wave effects to be made, preferably on the basis of scale model tests.

(d) Fatigue Analysis

A fatigue analysis requires the long-term distribution of individual stress levels in a structural component or joint. These are associated with the long-term distribution of individual height-period-direction combinations.

The minimum requirement for a fatigue assessment listed in Table 3.1 is a scatter diagram of significant wave height and peak period. A fundamental approach is to use this in conjunction with an assumed individual wave height distribution within each sea state to provide the long term distribution of individual wave conditions.

Improved requirements include the extension of the scatter diagram to include mean directions, and current, which may be important for fatigue due to vortex-induced loads on slender structures such as pipelines and risers.

Additional requirements include wave spectra for a range of sea states for the site in order to be able to account for dynamic response, and the distribution of individual wave heights within each sea state so that the corresponding assumption can be clarified.

(e) Motions of Floating or Compliant Structures

Motions of a floating or compliant structure are needed in the application of both survival criteria and operational criteria. These criteria may relate to the capsize of floating vessels, installation of a structure, extreme motions of a barge during dry towage of a platform, and offset requirements with respect to drilling operations.

The calculation procedure for both survival and operational criteria are similar, and from the viewpoint of determining motions a distinction may instead be made between wave-induced oscillatory motions, and drift motions. The latter are closely associated with a mooring analysis (discussed in the next section). With respect to oscillatory motions, Table 3.1 indicates that both significant wave height and peak period are needed as minimum requirements, since possible resonances of the structure may be an important consideration. A conventional approach generally involves the application of response amplitude operators which may be computed or measured, to obtain response spectra corresponding to various empirical forms for wave spectra, and thus in turn the maximum motions of the structure.

Improved requirements indicated in the table include mean direction and the wave spectrum, so that assumptions relating to these need not be made, or can be confirmed for validity.

Additional requirements shown in Table 3.1 include current and directional spectra, which can be used to provide improved motion predictions; and individual wave records which can be used to carry out model tests or time domain simulations accounting for nonlinearities in the behaviour.

(f) Mooring Analysis

The drift motions of a floating or compliant structure are generally coupled to the behaviour of the mooring system so that both these aspects are treated together. They may be required in the context of both survival criteria, including limitations on mooring loads, stresses in the system and excursions of the system, as well as operational criteria, such as the maximum offset of a platform.

The minimum requirements include current, which has a strong influence on drifting response: and both the significant wave height and peak period since the problem is relatively sensitive to the period. Improved requirements include the mean direction and wave spectrum, which would be used in place of corresponding assumptions.

Additional requirements include the variations of significant wave height, peak period and mean direction during a design sea state, so that the duration of excessive drift motions may be assessed in the context of applying operational criteria. Other additional requirements indicated include the directional spectrum; a description of wave grouping; and sample wave records, which allow particular laboratory or numerical simulations to be carried out.

(g) Ice Impact

For iceberg or bergy bit impact, the trajectory and velocity of the ice mass are required for application to an impact model. Apart from the influence of currents, wave conditions may also be important, particularly for smaller icebergs and bergy bits. Since both drifting and oscillatory motions may be required, the wave requirements are similar to those for both kinds of motions of a floating offshore structure. However, because of uncertainties in the problem, including iceberg configuration and location and ice properties, drift motions are presently not determined to the same precision as for offshore structures. Consequently the requirements indicated in the table do not fully correspond to both sets of structure motion requirements.

(h) Sediment Erosion

Sediment erosion differs from many of the other loads and effects considered in that erosion is cumulative. As a result its dependence on storm duration is relatively strong, in contrast to many other loads and effects which depend on storm duration simply through its effect on maximum wave height. The extent of sediment erosion near the base of structure within a particular storm depends primarily on the storm intensity. The cumulative erosion over the service life of the structure or between remedial measures depends on the sequence of individual storms.

The minimum requirements shown in Table 3.1 include current, significant wave height, peak period and wave direction time-series for the design storm. These data allow either numerical or scale modelling of erosion effects.

Improved requirements include information on time-series of these parameters for a sequence of representative storms in one or more years that could be used to estimate cumulative damage from erosion.

(i) Duration of Exposure

Many of the design problems described here arise within a limited or intermittent duration of exposure to various wave conditions. Examples include the open water season in the Beaufort Sea, wave conditions during installation of a platform or during other specific short-term operations; ice impact loads for which only wave conditions during a particular season is of importance. For all these problems, the requirements of wave conditions should be applicable to conditions which may occur or be forecast to occur within such durations. In certain cases, the determination of the corresponding load or effect requires a particular statistical treatment of wave data to take this into account.

3.4.5 Sensitivity to Wave Parameters

In order to assess the level of confidence of the various loads or effects which are determined, there is a need for the provision of confidence bands on various wave parameters. There is an additional need for confidence levels of such data to be as high as possible, so that these will result in a correspondingly high confidence levels of the resulting loads and effects.

In a number of design problems, the load or effect of interest is approximately proportional to wave height so that the confidence level of the load or effect corresponds to that of the wave height adopted. This applies to air gap, global loads on large structures, and oscillatory motions of floating and compliant structures. Other loads or effects are more sensitive to wave height, possibly proportional to wave height squared, so that any errors in the selection of wave height are magnified in the resulting load or effect. This applies to loads on drag-dominated structures, local loads, wave drift motions, mooring loads, and sediment erosion.

With respect to other wave parameters, the peak period is perhaps the second-most important, particularly in problems which involve resonant behaviour. There is less sensitivity to other wave parameters, although detailed sensitivity studies are required to assess these factors quantitatively.

A related issue concerns the relative abilities of either a hindcasting procedure or direct wave measurement to be able to (i) provide confidence levels of various wave parameters, and (ii) provide the higher confidence levels. This matter can be assessed by numerical simulations using, say, a Monte Carlo method, applied to specific sets of data. The choice of either hindcasting or measurement in providing higher confidence levels is often site specific, and depends ultimately on the quality of available data, either for a hindcast or for measurements, the duration of available wave records, and the accuracy of instrumentation.

3.4.6 Present Research Directions

Several of the improved and additional data requirements identified in Table 3.1 are designed to take advantage of the results of present research directed at the description of sea states in the context of wave loading problems and offshore design. Two recent meetings at which the progress and needs of such research was outlined include the E & P Forum (1989) workshop on “Wave and Current Kinematics and Loading” and the NATO (1989) Advanced Research Workshop on “Wave and Current Kinematics.”

At both of these meetings, emphasis was given to the importance of an adequate description of a combined wave-current field for use in offshore design. Ideally, the current magnitude, direction and profile with depth specified to be used in conjunction with design wave conditions should be obtained. This presents some difficulties in the collection and extrapolation of suitable data relating to combined waves and currents. Methods for incorporating such data into design are also in need of further development. Although currents have been included in Table 3.1 , the level of detail required, which is indicated above, is not shown in the table.

The importance of freak waves was also emphasized. A number of the problems identified in Section 3.4.4 are influenced by the single largest wave height or crest elevation that occurs. Although these parameters are generally obtained using conventional statistical methods, the possible existence of freak waves at a site may not be revealed by such procedures, particularly those applied to wave hindcasting. In the future, wave measurement programs should identify the possible existence of freak waves, and methods of providing improved design values of wave height and crest elevation which take account of freak waves should be developed.

A third topic which was emphasized is the description of breaking waves and the influence of breaking waves in the design process. Further research is needed both on improved descriptions of the wave environment to account for breaking waves, as well as on improved methods of taking account of such waves in design.

3.5 References

CSA, 1989. Preliminary Standard S471-M1989: General Requirements, Design Criteria, the Environment, and Loads. Part I of the Code for the Design, Construction, and Installation of Fixed Offshore Structures. Canadian Standards Association.

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4.0 THE ENVIRONMENTAL DATABASES

There are just two basic types of environmental databases--those based on observations of nature and those based on reconstruction of nature's behaviour as inferred from some observation.

4.1 Observational Databases

The limitations of every observational database are two-fold: the errors in the physical measurement or estimate apparatus, including recording, transmission and transcription; and validity of the data in spatial and temporal contexts.

Visual estimates of key parameters such as wind velocity and wave height are notoriously error-prone. At their best, they are imprecise and biased. Such data are rarely used in structural design, never in preference to other data sources.

The fundamental measurement techniques (such as wind anemometers and Waverider buoys) that are routinely used for collecting environmental data are decades old. Directional wave buoys are one example of a more recent development, but they are not in routine use. The advantage in old technology is database consistency and the disadvantage is lack of improvement in data accuracy or precision. However, the most serious errors in measurements are not the inherent ones published in the manufacturers' brochures, but the ones that plague to some extent almost every physical measurement program--instrument calibration, physical positioning in relation to contamination sources, severe climate (e.g., icing, or waves and currents that exceed mooring designs), radio interference, collisions or other accidents involving transient (or even tender) vessels, vandalism. Many of these possible problems are undetectable at the time of data collection, and even if they are noted by the collection agency, their presence may not be apparent to the end-user of the data.

Nearly all historical measurements have been made at a point, and typically for relatively short periods of time. Whether they are useful or not for input to a particular design study depends on the spatial and temporal validity that they have. Evaluation of these characteristics requires training and experience because each situatiOn must be considered individually with due regard for the influence of the environment on the data (e.g., in spatial terms, bathymetry on wave data and landforms or elevation on winds; in temporal terms seasonality or interannual variability and sampling interval).

Measurements are the only basis for the derivation of design criteria such as wind gust statistics, wave spectra, and zero-crossing wave parameters Some of these factors can be expressed fairly reliably as empirical functions of wind speed or wave height, others cannot.

There are two major observational databases for the Canadian offshore--the Comprehensive Ocean-Atmosphere Data Set (COADS), containing the offshore wind measurements (as well as the historical visual ship observations) and the Canadian Wave Climate Study which resulted in the national archive of wave measurements. Both of them are reviewed in this report.

4.2 Hindcast Databases

Hindcasting is the art and science of inferring one environmental parameter from historical records of another data set. There are two prime examples that are considered in this report: hindcasting winds from surface pressure data and the subsequent hindcasting of waves. The hindcasting of currents from winds and water property fields and the estimation of structural icing from atmospheric parameters may one day be as important in offshore design as wind and wave modelling, but until such models are verified with reliable measurements, their role is limited.

Because hindcasting procedures try to mimic the natural physical processes, they usually determine the hindcast parameter over a large spatial extent, in sharp contrast with traditional point measurements. However, the other side of that coin dictates that the forcing conditions (pressure or wind) must also be specified over the same space. The immediate ramification of this requirement is that hindcasts may be unreliable in data-sparse regions (including, unfortunately, most of the Canadian coastal waters).

Another problem with past hindcasts and the resulting data archives is poor spatial resolution. Almost all hindcast models operate on a fixed, usually rectangular, grid at which input forcing conditions must be specified and at which the hindcast parameters are output. Grid dimensions for open ocean modelling are typically 100 to 400 km which often will prove inadequate for future site-specific design studies.

The more serious consequence of the hindcast grid dimensions is that landforms can only be resolved at the grid scale, so that small, but important features like bays, headlands and islands are either missing or of out-sized proportions. In addition, a hindcasting rule-of-thumb states that the largest errors probably will be found at grid points next to boundaries (i.e., land in wave modelling)--partly because the landforms are but crudely described, and partly because some modelling assumptions begin to lose validity near boundaries. Sable Island is a prime example of an important local feature whose influence (sheltering and refraction) is absent in most North Atlantic wave hindcasts.

Another general limitation in hindcast wave databases arises from the fact that wave models use an imposed spectral form that is at best an approximation to nature, and certainly does not exhibit the variability found in measurements. For this reason, hindcast peak spectral period (a discrete quantity) is typically less reliable than wave height (an integral property).

The science of hindcasting involves the specification in mathematical terms of the governing physical processes to be modelled; the art that inevitably enters the more reliable hindcast procedures involves conditioning of input, model and output to optimize hindcast accuracy. Tailoring of input data may include some smoothing, interpolation onto the model grid, and often some reanalysis and adjustment of the resulting field. Most models have "calibration coefficients" that are tuned to particular input (perhaps compensating for known biases in the input) and sometimes to particular geographical situations. Output may be blended with historical measurements, particularly if it becomes input to a subsequent hindcast model.

Although wind hindcasting is usually a necessary precursor to wave hindcasting, the wind fields are not ordinarily suitable to derive design wind conditions--they may be the best input to produce the best wave hindcast, but they need not be the equivalent of wind anemometer measurements. Fetch limitations created by land or sea ice can lead to moderate or low sea states during severe wind events. Hence, the true set of wind extremes may not coincide in time with the true set of wave extremes. Another factor that is sometimes overlooked is the effect of temporal and spatial smoothing of hindcast wind fields. In some cases it can be too great to extract combined wind and wave criteria from the input and output of a wave hindcast.

The earliest hindcasts produced continuous time-series of environmental parameters that span many years. The site-specific and more recent regional hindcasts have been storm-based studies. Both of these approaches have advantages and disadvantages.

In the storm-based hindcasts, emphasis is placed on identifying and modelling just the most severe events that typically last two or three days. At most, probably 10 to 15 days per year, on average, need to be modelled, including spin-up and decay time. Clearly computational effort is just a fraction of the continuous hindcast method. It then becomes practical to use more sophisticated models (e.g., shallow-water wave formulations), to use finer grids and most-importantly to employ more human decision-making (e.g., kinematic wind analysis). The major disadvantage to storm-based hindcast results is that they are essentially limited to derivation of extremes of the hindcast parameters.

Continuous hindcasts are computationally onerous, and the only practical approach is to rely heavily on objective analysis techniques. Experience has shown that the accuracy of these hindcasts is inferior to high-quality storm-based methods. However, a great potential advantage to continuous modelling is that the time-series products provide a much wider range of design criteria, including seasonal extremes, annual and seasonal normals, and duration or persistence statistics.

4.3 Environmental Databases for Canadian Waters

There are just a few primary environmental databases that are of sufficient spatial or temporal scope to warrant review. They are

- Beaufort Sea Wind Hindcast [wind only]
- Canadian Wave Climate Study [waves only]
- Coastal Meteorological Stations, including lighthouses [meteorology only]
- Comprehensive Ocean-Atmosphere Data Set (COADS), including by logical extension all updates of Canadian ship and rig observations [meteorology & waves]
- Geostrophic Wind Climatology (GWC) Hindcast [wind only]
- Lancaster Sound Wave Hindcast [waves only]
- METOC Wave Database [waves only]
- Naval Environmental Data Network (NEDN) Database [meteorology & waves]
- NOAA Data Buoy Office (NDBO) [meteorology & waves]
- Ocean Weather Stations (OWS) [meteorology & waves]
- ODGP East Coast Wind & Wave Hindcasts [wind & waves only]
- Spectral Ocean Wave Model (SOWM) Wind and Wave Hindcast [wind & waves only]
- Wave Information Study (WIS) Wind and Wave Hindcast [wind & waves only]

Of these thirteen databases, only COADS encompasses all the standard meteorological parameters but it includes only the most basic wave parameters. Many of the others are hindcasts using software tools of varying scientific sophistication and with underlying databases of varying quality. The following pages describe each of these databases in turn and provide a summary discussion based on review of the primary database reference document and on comments published by other reviewers. Bibliographic information for the documents that are referenced by numbers is provided in Appendix 1 .

An assessment of the suitability of each database for extraction of climatological descriptions and of extremes estimates is provided on a rough qualitative scale that should be interpreted as follows:

good   generally reliable with few caveats; confidence in derived design criteria will be relatively high

fair   may be useful with caution, although specific caveats apply, depending upon database limitations, particular applications may yield good or poor results; assessment of confidence in derived products will probably be difficult

poor   a generally inadequate database that would not yield reliable design parameters; not recommended for use

n/a   an inapplicable database for the indicated parameter set.

Database Name: ***Beaufort Sea Wind Hindcast***

Parameter(s): wind speed and direction, surface pressure
Geographic Domain: 68-76°N and 120-162°W
Time Period: 1957 through 1985

Source: Marine Environmental Data Service, Ottawa (first contract agency)

Atmospheric Environment Service, Downsview (archive; 2nd contract)

Primary Reference: Agnew, T., B. Eid, W. Skinner and V. Cardone, 1989. Beaufort Sea Wind/Wave-Storm Hindcasting. 2nd Int. Workshop on Wave Hindcasting and Forecasting, Vancouver, p. 192-202.

MacLaren Plansearch Limited, 1989. Hindcasting Extreme Beaufort Sea Storms. CCC Report No. 89-12, Atmospheric Environment Service, Downsview.

Other Documents: [131]

Description: A 20-storm wind hindcast using a blend of objective and kinematic analysis on a 1° latitude by 3° longitude grid at a 10-m reference elevation, thought to be available on a 3-h time step. Ten storms were selected based on wind severity (peak speed and duration) and data adequacy; the other ten were selected based on measured events in the Waverider database.

Fourteen additional storms have been hindcast using only objective analysis on a 20′ latitude by 1° longitude grid at a 10-m reference elevation for a 6-h time step: 10 winter events and 4 open water season storms prior to 1976.

Limitations:

- verification of wind fields with wind measurements from the first 20 storms shows large scatter and a tendency to a low bias (of up to 5 knots) in the hindcast values
- uncertainty in the Beaufort wind measurements is thought to be large in 1977 and 1978
- there are probably too few hindcast storms during open water season to form an extreme value set, given the complexity of identifying true severe wave events in the Beaufort Sea caused by the interaction of wind and sea ice
- a wave hindcast [131] using the wind fields from the first 20 storms revealed that some storms

did not have an adequate spin-up period before expected peak wave conditions

- the same study [131] concluded that some intense storms were not adequately resolved spatially
- the storm selection and wind hindcast procedures are inhomogeneous
- verification of the 14-storm hindcast cannot be extensive since measurements are lacking but problems with 7 storms were reported

Suitability:

	Regional	Site-Specific
Climatology	fair[1]	fair[1]
Extreme	fair[1]	fair[1]

[1] rating is uncertain, but lack of good data for verification and varying storm selection criteria mean that winds should be used with caution

Database Name: ***Beaufort Sea Wind Hindcast***

Discussion:

Environmental hindcasting in the Beaufort Sea poses difficulties that are not encountered to the same degree on the east or west coasts. Small-scale storms in the Beaufort are thought to produce some of the strongest winds, but they will frequently be under-resolved by the relatively coarse grids that are used to construct hindcast wind fields. On the other hand, the surface pressure and wind data to justify finer grids do not exist.

Hindcasting of wind over ice presents problems that are important in the arctic offshore areas. MacLaren Plansearch used a parametric technique based on Overland (1985). For three broad ice categories, a 10-m elevation wind is estimated from the geostrophic wind through application of scaling and rotation factors. The degree of success obtained by them with this model has not been quantified.

Accurate wave hindcasting in the presence of unconsolidated pack ice is almost impossible. Because the wind is the dominant factor in movement of sea ice, there must be a dynamic water-ice boundary in the wave model. In itself, such a formulation is straightforward, but the temporal and spatial resolution of the pack movement is inadequate in the historical sea ice database. SAR overflight records in recent years provide some much needed guidance if they can be made available, but they apply to only a minority of severe storms.

The storm selection has been based, in part, on a severity index defined as the peak wind speed times the duration in excess of some speed threshold (30 knots in the first 20 storms and 34 knots in the remaining 14). However, some storms with low values of the severity index (between 48 and 300) have been hindcast while apparently more severe storms (index values between 450 and 2808) have not. The 34 storms may or may not represent an extreme set for peak wind speeds, but for other design parameters such as wave height and storm surge, the data set almost certainly requires additional events. It is not clear that conventional wind and wave hindcasting will be successful for the Beaufort Sea given the large uncertainties and gaps in the historical databases.

Additional References:

Overland, J.E., 1985. Atmospheric Boundary Layer Structure and Drag Coefficients over Sea Ice. J. Geophys. Res., 90, 9029-9049.

Database Name: ***Canadian Wave Climate Study***

Parameter(s): one- or two-dimensional wave spectra, significant wave height, peak period, time-series of sea surface elevation, wave direction from directional buoys

Geographic Domain: Canadian coastal waters where offshore drilling has occurred
Canadian long-term coastal wave stations
Canadian regional and site-specific wave studies

Time Period: 1970-present (about 20 years maximum); variable at any specific site, and frequently less than one year

Source: Marine Environmental Data Service, Ottawa

Primary Reference: MEDS Users Guide. Marine Environmental Data Service, Ottawa.

Other Documents: [4][5][9][13][17][20][59][61][75][77][111][113][114][116][124][133]

Description: Waverider data are typically three-hourly recordings, but many oil-industry records are continuous 20-minute samples when sea-states exceed 4 m. WRIPS data are 1.5- or 3-hourly and directional data are normally 3-hourly. Waverider data accuracy is reportedly within 3%.

Limitations:

- most time-series are less than one year long at any one site
- temporal and spatial coverage is governed largely by drilling activity on the east coast and in the Beaufort Sea
- normally, wave buoys are not deployed when sea ice may be present
- some locations have poor quality, intermittent data
- the archive is neither up-to-date nor complete and listings of the historical holdings are out-of-date
- some recent data in the archive are considered to be proprietary which makes the archive awkward to use
- the data can be cumbersome and are expensive to acquire
- the WRIPS data have not been systematically archived

Suitability:	Regional	Site-Specific
Climatology	good[1]	good[1]
Extreme	fair[2]	fair[2]

[1] good where there are many years of data (at the long-term stations), especially if spatial variability is weak and many short time-series can contribute to a regional average (such as on the Grand Banks)

[2] if interannual variability is not significant (e.g., some enclosed, fetch-limited water bodies or in some months/seasons) extremes calculated from relatively short time-series can be superior to hindcast estimates.

Database Name: ***Canadian Wave Climate Study***

Discussion:

Canadian wave data are archived and distributed by MEDS. The bulk of the data are from the non-directional Waverider or WRIPS (satellite-transmitting) buoys that were deployed in conjunction with offshore oil exploration on the east coast and in the Beaufort Sea. There are also a few long-term coastal wave stations (Tofino, Logy Bay, Osborne Head).

There have been two major government-sponsored wave studies that collected directional wave data--one on the north coast of B.C. and one on the Scotian Shelf. Other studies sponsored by ESRF (extension of the west coast wave climate study, Beaufort sediment dynamics study, and Sable Island shallow water wave study) also collected directional wave data. At least some of these data are available from MEDS.

MEDS estimates that calibrated Datawell Waverider buoys provide estimates of wave height that are accurate to within 3%. Peak period estimates are a function of the spectral resolution and low frequency cut-off value; the longer the period (generally higher sea states), the poorer the period resolution is. Until the mid-1980's, MEDS imposed a 20-s cut-off for most of the data they processed. In hindsight, it was a bad idea since any energy in the longer periods was discarded in computing Hs.

The wave records available from MEDS are generally of high quality, but detailed examination of the sea surface time-series [113] has identified problems with some individual records. Often, the effect of these problems on the spectral products (e.g. Hs) will be minor, but the extraction of maximum wave height, maximum period and similar zero-crossing parameters must be carefully quality controlled.

One problem with the buoy data is access to recent information because there is a significant delay in acquisition, archiving and dissemination of measured wave data. Since MEDS no longer owns the buoys that are deployed in conjunction with offshore exploration, the data are considered proprietary to the wellsite operator.

For several years MEDS deployed and maintained a WRIPS buoy at Hibernia during the open water season. It was recently learned that MEDS did not permanently archive these measurements, because they were for real-time operational use [pers. comm., J. Gagnon, MEDS].

Additional References:

none

EC 7

Database Name:	***Coastal Meteorological Stations***
Parameter(s):	wind, air temperature, visibility, also sea state at lighthouses
Geographic Domain:	Canadian Coastal Stations (see list below)
Time Period:	site dependant; earliest records from about 1870; computerized data archive from about 1947 at some airports and from 1953 at other sites
Source:	Atmospheric Environment Service Canadian Climate Centre, Downsview
Primary Reference:	MANOBS: Manual of Surface Weather Observations. Environment Canada, Ottawa.
Other Documents:	[2] [11] [18] [19] [23] [28] [29] [30] [31] [33] [36] [37] [38] [41] [44] [45] [47] [49] [76] [77] [80] [90] [97] [121] [134] [137] [144] [150]
Description:	Coastal meteorological stations include the AES reporting network and some west coast lightstations; the main locations are:

East Coast	Arctic	West Coast
Hopedale	Resolution I.	Victoria
Cartwright	C. Hopes Advance	Amphitrite Pt.
Belle Isle	Nottingham I.	Estevan Pt.
Gander	Cape Dorset	Spring I.
St. John's	Churchill	Cape Scott
St. Lawrence	P. Baleine	Bull Harbour
Grindstone I.	Chesterfield	Port Hardy
Sydney	Inoucdjouac	Alert Bay
Shearwater	Hall Beach	Pointer I.
Sable I.	Komakuk	Ivory I.
Yarmouth	Tuktoyaktuk	McInnes I.
Arctic	Sachs Harbour	Ethelda Bay
Brevoort I.	Alert	Bonilla I.
Cape Dyer	Isachsen	Prince Rupert
Cape Hooper	Mould Bay	Triple I.
Clyde	Rea Point	Green I.
Frobisher	Resolute	Langara
		Sandspit
		Cape St. James
		plus St. of Georgia stations

Limitations:	· topography influences wind statistics to some undefined extent, usually as a function of direction.

- some stations (e.g., Sable I.) are unrepresentative of over-water winds even though the sites seem nearly ideal
- some stations report only during daylight or on irregular schedules
- quality control of individual reports cannot be exhaustive
- wave data are visual estimates

Suitability:

	Regional	Site-Specific
Climatology	poor	fair[1,2]
Extreme	poor	fair[1,2]

[1] coastal recording sites are usually inadequate for overwater marine climatology

[2] fair for long-term data with careful scrutiny of maxima; poor for waves, which are visual observations, & winds

Database Name: ***Coastal Meteorological Stations***

Discussion:

The coastal meteorological reporting stations provide a good database of sufficient length to derive climatological information that has been quality controlled to some extent. Unfortunately, the spatial applicability of many stations is severely limited by the local topography. In mountainous areas like the west coast, application of these data to offshore situations is not recommended.

Even in locations that seem to be fairly level and well exposed, wind data must be critically evaluated--Sable Island is a prime example of a nearly ideal location that is unrepresentative of the surrounding area. Several studies have noted that the AES Sable Island anemometer winds are lower than measurements from other sources in the vicinity [47] [77].

There is also a digitized dataset of east coast lighthouse marine weather reports, commencing not earlier than 1979, that is available from AES. Its quality is unverified and it is known to contain some Beaufort scale wind data.

In conjunction with oil exploration and the Polar Continental Shelf projects, surface synoptic reports were recorded at various location in the high Arctic between 1973 and 1984.

Additional References:

Brown, R.D., 1988. Marine Climate Directory Datasets and Services. Atmospheric Environment Service, Canadian Climate Centre Internal Report No. 88-1.

Database Name:	***COADS Comprehensive Ocean-Atmosphere Data Set (including Canadian Vessel Marine Surface Observations and Canadian Drill Rig Surface Observations)***
Parameter(s):	observed meteorological and sea-state variables
Geographic Domain:	worldwide through 1979, Canadian waters thereafter
Time Period:	1854-1979 worldwide; to the present for Canadian waters
Source:	Atmospheric Environment Centre Canadian Climate Centre, Downsview
Primary Reference:	Slutz, R.J., S.J. Lubker, J.D. Hiscox, S.D. Woodruff, R.L. Jenne, D.H. Joseph, P.M. Steurer, and J.D. Elms, 1985. Comprehensive Ocean-Atmosphere Data Set Release 1. NOAA/ERL, Boulder, Colorado. also Woodruff, S.D., R.J. Slutz, R.L. Jenne and P.M. Steurer, 1987. A Comprehensive Ocean-Atmosphere Data Set. *Bull. Amer. Meteor. Soc.*, **68**(10), 1239-1250.
Other Documents:	[13] [14] [28] [29] [30] [31] [33] [37] [38] [41] [42] [43] [45] [47] [49] [55] [57] [69] [111]
Limitations:	· no rigorous quality control · inhomogeneous data quality · variable spatial data distribution · inhomogeneous sampling frequency · possible fair-weather bias · majority of data are unsuitable for time-series analysis

Suitability:

	Regional	Site-Specific
Climatology	good[1]	poor[2]
Extreme	poor	poor

[1] good provided adequate consideration is given to data quality, with careful review of outliers, and to temporal-spatial data distribution characteristics.

[2] poor unless there are many observations that are well-distributed over a long time period, or unless spatial variability is weak.

Database Name: ***COADS Comprehensive Ocean-Atmosphere Data Set***

Discussion:

The COADS database was assembled and is distributed by NOAA. For the purposes of this review, it is assumed that COADS (as distributed) includes all the Canadian offshore data through 1979, and that all more recent AES holdings of the same type of Canadian data are in a compatible format and are adequately described by COADS documentation. COADS is assumed, therefore, to encompass all public-domain rig data, all ship observations, and any meteorological buoy data for Canadian waters.

For most of the temporal span of this database, COADS is synonymous with transient shipboard observations. Over time the methods of observation, reporting, collection and digitization of these data have changed, and thereby more or less unknown inhomogeneities and errors have been introduced. Slutz et al. report that “the resulting errors, as well as simple recording or transmission errors, occur very frequently.” While millions of errors have been eliminated, many others undoubtedly remain but are impossible to identify and correct. Therefore, care and attention to possible inhomogeneities (e.g., anemometer elevation and wind sampling duration) is essential, and large numbers of observations are required to render the errors statistically insignificant. Some sort of check for possible outliers should also be considered.

Transient ship reports of wind have two possible problems: fair-weather bias throughout the database and observer bias that resulted in overestimation of wind speed in the early years when estimates were based on Beaufort force scale. Quayle (1974) has argued that the two effects cancel each other. There may also be differences in averaging period of anemometer wind speed.

Drilling rig weather reports are also part of COADS. Wind data were one-minute mean values until recently, but anemometer elevations are typically about 80 to 110 m and must be reduced to equivalent lower elevations for comparison with other data sources. At times, a hand-held anemometer has been used at deck level. Wave data are from Waverider buoys when they are available and visual estimates when they are not.

Hogben and Lumb (1967) reported that, on average, visual estimates of local wind-sea Hs from voluntary ships overestimate measured values of significant wave height in excess of 7.5 m and they gave Hs = 2.55 + 0.66 Hv as the relationship between the two.

MEDS [13] considered the use of COADS (visual) wave data on behalf of the Royal Commission on the Ocean Ranger Marine Disaster and concluded that they are “not considered to be sufficiently precise for estimating the extreme events required for the design of ocean structures.” The authors also remarked that “the observed [wave] period is unreliable.”

COADS is the primary source of the other meteorological parameters.

Additional References:

Hogben, N. and F.E. Lumb, 1967. Ocean Wave Statistics. Her Majesty’s Stationary Office, London.

Quayle, R.G., 1974. A Climatic Comparison of Ocean Weather Stations and Transient Ships Records. *Mariners Weather Log*, 18, 307-311.

Database Name:	***GWC Geostrophic Wind Climatology Hindcast***
Parameter(s):	geostrophic wind speed, direction
Geographic Domain:	northern hemisphere roughly 40-90°N; 40-170°W
Time Period:	1946-89 (44 years)
Primary Reference:	[30] Swail, V.R., L.D. Mortsch and D.A. Carr, 1984. Intercomparison of Marine Wind Data Sets. Canadian Climate Centre Report No. 84-15.
Other Documents:	[25][26][28][31][32][33][36][37][38][41][44][57][69][90][135]
Description:	Gradient winds calculated 6-hourly on the FNOC 381-km grid from surface pressure fields, unmodified for boundary-layer effects. From 1946-78, FNOC gridded pressure fields blended with ship observations of pressure; thereafter, surface pressures in the NEDN (FNOC) operational data set.
Limitations:	· known bias to weak pressure gradients in FNOC data · no standard boundary-layer modification is applicable · GWC directions are biased because of geostrophic assumption · GWC speeds tend to be biased high · grid is too coarse for most site-specific applications, particularly near coasts · there are some data gaps [21] · only hindcast results up to 1978 have been reported in detail · method is inadequate where local effects dominate the wind field such as west coast nearshore locations

Suitability:

	Regional	Site-Specific
Climatology	fair	fair
Extreme	fair	fair

Database Name: ***GWC Geostrophic Wind Climatology Hindcast***

Discussion:

The GWC database was derived by AES [25, 32] from the 6-hourly FNOC surface pressure archive (the same starting point for SOWM and WIS wind fields). The FNOC grid is a square mesh superimposed on a polar stereographic projection and has a true scale of 381 km in the vicinity of 60°N.

In using the FNOC archive, two general problems must be considered. (1) The FNOC central pressure is consistently too high, giving pressure gradients that are too weak (Corson et al., 1982). Application of a standard planetary boundary layer model to the gradient wind will produce wind speeds that are biased low. (2) Because the grid is so coarse, small scale features cannot be well represented. In addition, the FNOC pressure values have considerable uncertainty for times and locations with few observations giving the database, and derivatives from it, uneven spatial and temporal quality [30].

The GWC database approximates surface wind with geostrophic wind calculated as the balance between the horizontal pressure force and Coriolis acceleration at the centre of each FNOC grid box. The effects of isobar curvature, weather system movement and planetary boundary layer (stability and surface friction) are not included.

The GWC database is difficult to assess because (1) it is neither a true geostrophic wind estimate nor a true surface wind estimate, and (2) there are few points of comparison. It has been compared to the other FNOC pressure-based hindcasts, OWS data, ship reports, coastal weather stations, rig winds, NOAA buoy data, two years of hand-extracted geostrophic winds in the Arctic and SEASAT altimeter data, most commonly in terms of annual and monthly mean statistics and monthly maxima.

On a mean monthly basis, GWC wind speed agrees with observations at the four OWS locations (Bravo, Charlie, Delta and Papa), typically to within 1-2 knots, averaged over 16-20 years [69]. The OWS locations are remote and probably dominate the FNOC pressure values in their vicinity--particularly Bravo and Papa--although whether or not the OWS data contribute to better than average pressure gradient estimates is unclear.

When compared with hand-extracted geostrophic winds at 11 arctic sites, GWC is shown to underestimate the mean geostrophic scalar wind speed by about 20% on average [37], confirming the results of Corson et al. (1982) for the east coast. Wind directions from the GWC database show the tendency of true geostrophic winds to be biased about 200 clockwise.

Based on comparisons between GWC and some reasonably well-exposed shore stations (e.g., Resolution I. and Resolute) there appears to be a tendency for GWC to underestimate the mean monthly surface wind speed in the open water summer months [37]. As a result, it appears that GWC wind speed may not always be a conservative estimate of surface wind. GWC site-specific winds should be carefully evaluated against other data resources to determine the most appropriate scaling factors.

Additional References:

Corson, W.D., D.T. Resio and C.L. Vincent. 1982. Wave Information Study for U.S. Coastlines, Report I: Surface Pressure Field Reconstruction for Wave Hindcasting Purposes.
U.S. Army Engineer Waterways Experiment Station Technical Report HL-80-11, Vicksburg, MS.

Database Name:	***Lancaster Sound Wave Hindcast***
Parameter(s):	significant wave height, peak period, direction (and wind speed)
Geographic Domain:	three sites, at approx. 74.25°N and 77°W, 83°W and 89°W
Time Period:	1956-71 and 1974-78 (21 years)
Source:	Atmospheric Environment Service, Downsview
Primary Reference:	[26] Lachappelle, P.A. and J.B. Maxwell, 1983. Winds and Waves in Lancaster Sound and Northwestern Baffin Bay. Canadian Climate Centre Report 83-7, Atmospheric Environment Service, Downsview.
Other Documents:	[13]
Description:	This is an SMB parametric wave hindcast using the GWC database as wind input during the open water season from June through October. Hindcast time-series are hourly.
Limitations:	· verification data are minimal to support the hindcast and verification results are inconclusive · the GWC wind speed is believed to overestimate surface wind speed · the GWC direction data are known to be biased due to lack of a marine boundary layer model · wind field curvature was not considered to limit hindcast fetch · minimum monthly ice conditions were assumed to maximize fetch

Suitability:

	Regional	Site-Specific
Climatology	poor	poor
Extreme	poor	poor

Database Name: ***Lancaster Sound Wave Hindcast***

Discussion:

To date, this hindcast is the only known attempt to model the wave climate of Lancaster Sound and the northwestern portion of Baffin Bay. Because the data are unverified (and the wave hindcast is largely unverifiable), and because the hindcast techniques do not meet modern standards, this database is not suitable for design wave calculations and most likely overestimates normal climatological statistics.

This database is not listed in the AES Marine Climate Directory, Datasets and Services (1988) and may not be available for general distribution. However, the wind input is available from the GWC database.

Additional References:

none.

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Database Name:	***METOC Wave Data***
Parameter(s):	significant wave height, peak period, direction
Geographic Domain:	North Atlantic between 25°N and 70°N
Time Period:	1970-80 (11 years) 1972-86 (15 years) for maximum Hs
Source:	Marine Environmental Data Service, Ottawa Bedford Institute of Oceanography, Dartmouth, NS Atmospheric Environment Service, Downsview
Primary Reference:	[15] Neu, H.J.A., 1982. 11-Year Deep-Water Wave Climate of Canadian Atlantic Waters Can. Tech. Rep. Hydrogr. Ocean Sci. 13.
Other Documents:	[13] [24] [57] [106] [116] [148]
Description:	The digital METOC databases were derived from the METOC charts which represent a blending of wave forecasts, visual observations and measured data for the entire North Atlantic Ocean. The wave height data are extracted on a 5° square grid--BIO used the central value (to the nearest 0. 1 m) and AES (METOC) recorded the maximum value within the square (to the nearest metre). Period and direction are the nearest observation or measurement. The time-series is 12-hourly.
Limitations:	· cannot be verified because there are no **independent** wave data · digitization of the data from hand-drawn charts may be prone to errors · precision is only 1 m (AES-METOC version) or 0. 1 m (BIO version) for wave height, 1s for period and 45° for direction · time-series is relatively short · inhomogeneous data quality, dependent on the availability of observations and measurements; a difficult database to use as a result · 12-hour temporal resolution is poor in stormy seasons · 5° grid resolution is too coarse for most site-specific uses

Suitability:

	Regional	Site-Specific
Climatology	fair[1]	fair[2]
Extreme	poor	poor

[1] ought to be good where there are always enough observations and measurements contributing to the METOC charts

[2] fair, possibly good, depending on the location and its proximity to shipping lanes or wave measurement sites; not suitable for shallow-water or near-shore locations

Database Name: ***METOC Wave Data***

Discussion:

Historically, the METOC database has not been held in high esteem for a variety of reasons--it is essentially a forecast product and therefore constrained by operational timing requirements, it relies heavily on ship observations (which are not renowned for their accuracy and may be prone to fair weather bias), the hindcast methods used to supplement the ships' data are parametric (i.e., not based on modern principles of wave physics), and the blending of ship observations, hindcast estimates and buoy measurements results in a product that is spatially and temporally inhomogeneous in quality.

MEDS [13] reviewed the METOC database on behalf of the Royal Commission on the Ocean Ranger Marine Disaster and concluded that (1) "in areas where there have been sufficient ship reports over the years and throughout the seasons of the year, the METOC data as published by Neu (1982) are good for [operational] applications" and (2) "the METOC data [are] not as reliable for [estimation of return periods for extreme events] as a carefully prepared hindcast."

Because the database construction embodies real-time observations and accounts for the presence of sea ice, it is more reliable for climatological assessments than either the WIS or SOWM hindcasts.

Additional References:

none

Database Name:	***NEDN MetOcean Data***
Parameter(s):	surface pressure, surface winds, wave height, period & direction data, many other standard met. parameters
Geographic Domain:	northern hemisphere
Time Period:	June 1974 to 1987 (13 years); pressure data to 1989 (15 years)
Source:	Atmospheric Environment Service Canadian Climate Centre, Downsview
Primary Reference:	[19] KelResearch Corporation, 1985. Evaluation of Naval Environmental Data Network (NEDN) Data Set. Canadian Climate Centre Report No. 85-10, Downsview.
Other Documents:	[36] [47] [41] [44] [57] [70]
Description:	meteorological and oceanographic parameters derived by numerical objective analysis and prognoses from a blended mixture of man-machine products. Wave data are derived from the SOWM wave forecast model. data are archived on the FNOC 381-km grid on a 6-h time step
Limitations:	· several months of data are missing and several months have incomplete observations · the observational network for surface pressure over northern Canadian waters is very sparse; hence reliability of surface winds is doubtful · grid resolution is too coarse to resolve small, intense storms · grid wind speeds are biased high compared with OWS and NOAA buoy data · wind directions do not agree well with observations · wave height tends to be overpredicted on a monthly mean basis · comparisons have been on done on a mean monthly basis only, not as a systematic time-series verification

Suitability:

	Surface Pressure and Temperature Parameters	
	Regional	Site-Specific
Climatology	fair[1,2]	fair[1,2]
Extreme	n/a	n/a

	Wind & Wave Data	
	Regional	Site-Specific
Climatology	poor	poor
Extreme	poor	poor

[1] if there are adequate observations at all times in the region

[2] possibly good if site is close to a reliable grid point

Database Name: ***NEDN MetOcean Data***

Discussion:

The Naval Environmental Data Network (NEDN) is a component of the U.S. Navy Integrated Fleet Weather Central System. The data products are derived from primarily numerical objective analyses and prognoses, but blended with observations of winds and pressures.

The NEDN grid is the same as the FNOC one--a square mesh superimposed on a polar stereo-graphic projection with a true grid scale of 381 km at 60°N.

The most extensive assessment of NEDN data was done by KelResearch for AES [19]. They found that the gridded data should be interpolated to the geographical location of interest rather than using the nearest grid-point values. Care should be taken to exclude land points from interpolation for over-water parameters.

The gridded surface pressure data (which is probably the most accurate parameter) were created by re-analysis of the sea level pressure data, using ship observations, historical surface pressure analyses and 500 mb information [37]. This pressure data set forms the basis for the GWC hindcast for 1978-89.

Surface winds are analysis winds produced at the analysis time based on blending of a first guess wind (based on sea level pressure) and global wind reports. Boundary layer winds are 19.5-m gradient forecast winds derived from surface pressure prognoses. KelResearch [19] found that the surface wind fields are more accurate than the boundary layer winds.

Based on comparisons with OWS Charlie (Atlantic), OWS Papa (Pacific) two NOAA buoys (one located SW of Nova Scotia and one in the Gulf of Alaska), and Hibernia rig data, this study concluded that "agreement ... was very much dependent on the parameters themselves ... In most cases, the grid values were higher than the corresponding observations." In addition, the report authors found that "there were [conspicuous] seasonal trends to the errors."

However, atmospheric pressure, sea surface temperature, air temperature, and dew point fields were found to agree well with observations.

The NEDN wave data have the same error characteristics as SOWM and GSOWM forecast fields. Based on quality assessment of these products in other studies [17, 61], the NEDN wave data are judged to be unsuitable for climatological or extreme value analyses.

Additional References:

none

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Database Name:	***NOAA Data Buoys***
Parameter(s):	wind speed & direction, sea level pressure & temperature, air temperature, significant wave height and average wave period
Geographic Domain:	U.S. Atlantic coast, Gulf of Alaska, U.S. Pacific coast [and Gulf of Mexico]
Time Period:	1976-present (about 13 years), variable from site to site
Source:	National Oceanographic Data Center, Washington, D.C.
Primary Reference:	Climatic Summaries for NOAA Data Buoys available from NODC.
Other Documents:	[17][19][61][69]
Description:	Winds are 3-hourly 8.5-min means at 10 or 5 m above sea level; reported accuracy is ±1.9 knots or 10% and ±10°. Significant wave height and wave period are derived from spectral estimates of 20 min records; reported accuracy is ±0.5 m and ±1s.
Limitations:	· the east coast buoys are too far south to be of any direct relevance except for Georges Bank · the west coast and Gulf of Alaska buoys have been positioned well offshore, so their utility is limited · the NOAA buoys are considered by operational weather forecasters to be less accurate at high wind speeds than reported

Suitability:

	Regional	Site-Specific
Climatology	poor[1]	fair[2]
Extreme	poor	fair[2]

[1] may be useful for some wave climatology applications

[2] limited temporal coverage and questioned reliability of wind reports in high seas downgrade confidence in this database; other parameters good

Database Name: ***NOAA Data Buoys***

Discussion:

The NOAA buoys are a useful database for some limited applications. The most common usage is in construction of storm climatologies and for verification of wind and wave hindcasts. On the west coast, the NOAA buoys are almost the only source of wave data for proving wave models.

The NOAA buoys are instrumented to measure near-surface wind speed and direction, air temperature, surface pressure, surface water temperature, and wave height and period. Aside from transient ships-of-opportunity, drilling rig, and some coastal lightstation datasets, coincident sets of these parameters do not exist. The major advantages of the buoy data over the other sources are the fixed location (unlike ships) for relatively long periods of time (unlike ships and drilling rigs) and the well-designed instrument package (unlike the mixture of visual and measured data from ships and lighthouses).

In operational weather forecasting offices on both the east and the west coasts of Canada and the U.S.A., meteorologists routinely apply local correction factors to the NOAA buoy wind speeds. For example, in Halifax they double the speed, and in Seattle they use the peak speed as the mean (pers. comm., V. Swail, AES). The perceived underestimation of high wind speeds may result from the low anemometer height (5 or 10 m) in sea states of roughly the same or greater magnitude. The relatively long 8.5-min vector average may also contribute to the apparent bias.

Additional References:

Climatic Summaries for NOAA Data Buoys published by the U.S. Department of Commerce and available through the NOAA National Oceanographic Data Center in Washington, D.C.

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Database Name: ***ODGP East Coast Wind & Wave Hindcast***

Parameter(s): wind speed and direction; significant wave height, peak spectral period and mean direction; and two-dimensional wave spectra

Geographic Domain: Grand Banks, Scotian Shelf and Georges Bank coarse grid: 25°N-67.5°N; 20°W-80°W fine grid: 38.75°N-53.75°N; 42.5°W-the coast

Time Period: 1957-1988 (32 years)

Source: Atmospheric Environment Service
Canadian Climate Centre (contracting agency)

Primary Reference: MacLaren Plansearch Limited and Oceanweather Inc., 1990. Wind/Wave Hindcast Extremes for the East Coast of Canada. Unpublished contractor report.

Other Documents: [17][61]. See also Sections 5.1 and 5.2 of this report.

Description: A storm-based hindcast of the most severe wave-generating events in F each of the three major hindcast regions, Grand Banks, Scotian Shelf and Georges Bank. Storm selection procedures identified 68 severe storms, based on previous hindcasts, historical wave measurements, ship observations, and weather maps. Georges Bank events included 10 tropical storms; in the other areas the hindcast was exclusively of extra-tropical storms. For the 24-h period centred on the expected peak sea state, kinematic wind fields were constructed on the fine grid.

The deep-water ODGP wave model produced directional spectra for 24 directions and 15 frequencies (with central periods from 3.2 5 to 25.7 5). The time step was 2 hours and the fine grid size was approximately 100 km in the E-W direction and 69.5 km in the N-S direction.

Extremal analysis of the top 30 hindcast events was performed assuming the data set represented peak-over-threshold values modelled by the Gumbel distribution. Peak period, maximum wave height and crest elevation were estimated from empirical relationships.

Limitations:

- in sea states of 9.5 m or greater, the modelled peak wave results over-estimate peak measurements by roughly 2 m based on verification with MEDS Waverider data.

- shallow-water effects were omitted, but begin to be important in severe storms for depths of less than about 100 m.
- storm selection was based on regional considerations, and thus the storm sets are not necessarily suitable for specific sites; expected to be most applicable to the Northeast Grand Banks and to deep water along the eastern edge of the Scotian Shelf.
- Hmax and Hc have been calculated empirically without regard to the local applicability of the relationships.
- wind maxima that coincide with peak hindcast sea state were extrapolated to long return periods; these values are not conservative.

Suitability:

	Regional	Site-Specific
Climatology	n/a[1]	n/a[1]
Extreme	good[2]	fair[3]

[1] except storm climatology

[2] fair to poor in shallow water and toward edges of regions.

[3] good for NE Grand Banks, but use with caution on Scotian Shelf

Database Name: ***ODGP East Coast Wind & Wave Hindcast***

Discussion:

The wave model is almost the equivalent of earlier ODGP versions; the one reported change is a modification to the high frequency spectral range that makes the model less empirical and more responsive to the stage of wave development in the tail of the spectrum. The exact effect of this change is not reported. A minor decrease in total energy is expected based on an earlier report [17] which stated that the older versions "inflate the total variance ... at short fetches." On the other hand, Oceanweather have found that in rapidly changing wind fields, the treatment can produce slightly higher sea states.

In application, the obvious changes are to a smaller grid mesh size and to a shorter model time step. One benefit is improved resolution of landforms. In principle, more spatial detail can be incorporated in the wind fields, but it is not clear that there is enough meteorological information to do so. Temporally, wind fields are still defined at the 6-hour surface pressure map times and interpolated to the model time step.

The reported hindcast skill is not quite as good as in other ODGP applications. Some known error in the Waverider database that results from a 20-s low-frequency spectral cutoff has not been accounted. Another source of over-estimation in Hs on the Grand Banks will arise from neglect of shoaling. These points are discussed in more detail in Section 5.2.2 .

The extreme value analysis (eva) method was a peak-over-threshold (POT) selection with the resulting maxima fitted with the Gumbel model using the method of moments. Based on recent evaluations of eva techniques (Baird et al., 1989; Muir and El-Shaarawi, 1986), there are some minor theoretical discrepancies in this application. (1) The storm population was not complete enough to include at least two storms from each year, and in effect, the appropriate threshold was pre-judged to some extent. (2) Strictly speaking, a compound distribution such as Poisson-Gumbel is the correct statistical choice of eva model. (3) For a 32-year hindcast, AMAX sampling is preferred to POT, and the hindcast results could be viewed as a censored ANIAX sample. The effect the eva procedures may have on the calculated extremes is thought to be small, but has not been investigated further.

Contoured maps of 50- and 100-year Hs, Hmax and wind speed are presented based on open ocean, deep-water, most probable extreme values. There is no indication of the areas where the hindcast results do not apply (i.e., where shoaling, refraction, sheltering and bottom friction are not negligible, or where the storm set no longer represents regional maxima).

The contoured wind maps, although labelled 50- and 100-year return wind speed, are in fact extrapolation of the wind speed that coincided in time with the hindcast peak sea state. They are intended to provide the joint wind and wave maxima, but the values should not be used uncritically as they are not conservative estimates of coincident wind speed. The distribution of hindcast wind maxima is not presented.

Additional References:

Baird, Hydrotek and J.F. Lawless, 1989. Review and Assessment of Procedures for Extreme Value Analysis for Selected Geophysical Data: Phase III, Guidelines and Recommended Methodology for Undertaking Extreme Value Analysis. CCC Report No. 89-7, Atmospheric Environment Service, Downsview.

Muir, L.R. and A.H. El-Shaarawi, 1986. On the Calculation of Extreme Wave Heights: A Review. OceanEngng. 13(1), 93-118.

Database Name: ***OWS Ocean Weather Stations***

Parameter(s): anemometer winds, meteorological observations, and wave observations

Geographic Domain:

OWS Papa	50.0°N 145.0°W
OWS Bravo	56.5°N 51.0°W
OWS Charlie	52.7°N 35.5°W
OWS Delta	44.0°N 41.0°W

Time Period:

OWS Papa	January 1951 to June 1981
OWS Bravo	1946-1974
OWS Charlie	1956-81 (at least)
OWS Delta	January 1946 to June 1946 September 1949 to June 1973

Source: Atmospheric Environment Service
Canadian Climate Centre, Downsview

Primary Reference: none

Other Documents: [19] [30] [31] [33] [38] [43] [121] [135]

Description: Weatherships recorded the same parameters as ships-of-opportunity, but at a fixed location on a regular (1- or 3-h) schedule by trained observers. The data are nearly continuous and therefore suitable for analyses like persistence which are impossible with transient ship observations.

Limitations:

- general inapplicability of data collected at sites that are remote from areas of offshore development interest
- ship-induced distortions and motions introduce errors in wind measurements
- inhomogeneity may exist since many different ships (with differing characteristics, including anemometer height) were used at any one site

Suitability:

	Regional	Site-Specific
Climatology	poor	good
Extreme	poor	good

Database Name: ***OWS Ocean Weather Stations***

Discussion:

The Ocean Weather Station (OWS) wind data are one-minute mean values and are believed to be of high quality for ship observations. The most common usage of these data is in construction of storm climatologies and for verification of wind and wave hindcasts.

Wind speed errors have been estimated (Blanc, 1986) and reported by AES [43]. Aside from sensor accuracies (±1 m/s or less), Blanc expects a systematic error of + 10% to +20% from superstructure flow distortions, and a random error due to ship motion of ±6% in an average sea state of 2.23 m (and increasing in storms). These data are therefore least accurate when wind speeds (and wave heights) are highest.

OWS Papa was located in the North Pacific from 1951 to 1981 and OWS Bravo provided data from 1946 to 1974 in the Labrador Sea. OWS Charlie and Delta in the mid-North Atlantic Ocean are too far offshore to have significance for Canadian waters.

Additional References:

Blanc, T.V., 1986. The Effect of Inaccuracies in Weathership Data on Bulk-derived Estimates of Flux, Stability and Sea-surface Roughness. *J. Atmos. Oceanic Technol.*, **3**, 12-26.

Database Name:	***SOWM Wave Hindcast***
Parameter(s):	Deep-water, two-dimensional wave spectra, significant wave height, peak period, dominant direction
Geographic Domain:	northern hemisphere
Time Period:	1956-75 (20 years) Atlantic; 1964-76 (13 years) Pacific
Source:	Marine Environmental Data Service, Ottawa
Primary Reference:	Lazanoff, S.M. and M.M. Stevenson, 1977. A Twenty Year Northern Hemisphere Wave Spectral Climatology. Proc. NATO Symposium on Turbulent Fluxes Through the Sea Surface, Wave Dynamics and Prediction, France.
Other Documents:	[13][17][33][41][57][61]
Description:	A spectral deep-water wave hindcast using 6-hourly FNOC 381-km gridded pressure fields, blended with surface pressure and wind velocity measurements, and gradient wind velocities modified to account for air column stability. Wave spectra are 15 frequencies by 12 directions at 6-h time step.

Limitations:

- wind data are known to be biased low from underestimation of pressure gradients
- high-quality wave data for verification do not exist
- limited comparisons with wave measurements from various sources indicate that SOWM wave heights are biased high
- grid is too coarse to resolve wind fields of small, intense storms
- grid is too coarse to resolve coastlines
- sea ice was not considered

Suitability:

	Regional	Site-Specific
Climatology	poor	poor
Extreme	poor	poor

Database Name: ***SOWM Wave Hindcast***

Discussion:

The SOWM wave hindcast was reviewed by MEDS [13] for the Royal Commission on the Ocean Ranger Marine Disaster. The authors of this report concluded that ”the SOWM wave data provide a poor definition of the wave climate of the [North Atlantic] area.” They based this conclusion on

(a) poor shoreline resolution which overestimates fetch for westerly winds;
(b) failure to consider the effects of ice cover in the northern areas;
(c) absence of bathymetric and current effects;
(d) discussions in technical publications on the hindcast verification.

The hindcast data set cannot be verified conclusively because there are no reliable, long-term wave measurements close to SOWM grid points.

The report authors also note the following: “...the major investigators, who are affiliated with the U.S. Navy, The American Bureau of Shipping Hoffman Maritime Consultants Inc. and New York University, without exception enthusiastically endorsed the SOWM 1956-75 data when discussing the application of these data to ship design and evaluation.”

There are no known studies of the Pacific Ocean SOWM data with application to Canadian waters, although Chen and Hoffman (1979) made some comparisons that included Weather Station Papa in the North Pacific. They reported rms errors of 8.5 knots in wind speed and 3.9 ft (1.2 m) in significant wave height based on 325 comparisons. The corresponding mean biases as reported were 2.4 knots and 0.8 ft (0.24 m).

The spectral ocean wave model (SOWM) was used twice daily by the Fleet Numerical Oceanographic Center as a wave forecasting tool for the U.S. Navy. In June 1985, the global-spectral ocean wave model (GSOWM) replaced SOWM. Clancy et al.(1986) report that GSOWM verification statistics are uniformly better than SOWM (rms error of 0.93 for GSOWM versus 1.34 for SOWM compared to NOAA buoy wave data).

MacLaren Plansearch [17] conducted an 8-month comparison of SOWM forecast waves with wave buoy data at five sites on the east coast. In this study SOWM forecast wave heights tended to overestimate measurements with a mean bias of as much as 0.94 m on the Grand Banks. GSOWM wave forecasts were compared [61] with data collected during the

CASP experiment. Based on 2 months of winter sea state comparisons between GSOWM analysis-time waves and a NOAA buoy located about 400 km due south of Cape Cod, the GSOWM tends to overpredict Hs by almost 50% on average for wave observations over about 4 m (Khandekar et al., 1987).

Additional References:

Chen, H.T. and D. Hoffman, 1979. The Implementation of the 20-year Hindcast Wave Data in the Design and Operation of Marine Structures. Offshore Technology Conference, Vol. 4, p. 2495.

Clancy, R.N1., J.E. Kaitala and L.F. Zambresky, 1986. The Fleet Numerical Oceanography Center Global Spectral Ocean Wave Model. *Bull. Amer. Meteor. Soc.*, **67**(5), 498-512.

Khandekar, M.L., B.M. Eid and V. Cardone, 1987. An Intercomparison Study of Ocean Wave Models During the Canadian Atlantic Storms Program (CASP)--Some Preliminary Results. Proc. Int. Workshop on Wave Hindcasting and Forecasting, Halifax, ESRF Report No. 065, Ottawa, p. 209-220.

Database Name:	***WIS Wind Hindcast***
Parameter(s):	wind speed, direction
Geographic Domain:	Northwest Atlantic
Time Period:	1956-75 (20 years)
Source:	Marine Environmental Data Service, Ottawa
Primary Reference:	Corson, W.D., D.T. Resio and C.L. Vincent, 1980. Surface Pressure Field Reconstruction for Wave Hindcasting Purposes. U.S. Army Corps of Engineers Waterways Experiment Station, Wave Information Study for U.S. Coastlines, Tech Rep. HL-80-11
Other Documents:	[30] [37] [57] [69] [74] [90] [101] [102] [107] [116] [135]
Description:	Objective wind fields created from digitized FNOC pressure charts on a roughly 381-km mesh. Severe storms were digitized on a four times finer grid within a coastal subgrid along the U.S. Atlantic seaboard. Some degree of wind field blending was achieved at the junction of these two grids.
Limitations:	· wind speeds are biased low due to underestimation of pressure gradients, demonstrated by several studies · there are discontinuities between the main coarse grid and the fine coastal grid that affect the Canadian east coast

Suitability:

	Regional	Site-Specific
Climatology	poor	poor
Extreme	poor	poor

Database Name: ***WIS Wind Hindcast***

Discussion:

The Wave Information Study (WIS) wind and wave hindcast was carried out by the U.S. Army Engineer Waterways Experiment Station (EEES). To improve on the FNOC digital pressure data (which result in underestimation of central pressures, and hence wind gradients), a fine "Coastal Grid Border" was defined with a four-times finer resolution of pressure in severe and moderately severe storms. The edge of this fine grid bisects the Gulf of St. Lawrence from (roughly) the N.S. -N.B. border to the northern tip of Newfoundland and proceeds out to its eastern boundary at (again roughly) 45°W.

Resio [12] conducted an evaluation of the WIS databases for MEDS, concentrating on verification of the wave results. He found that the meshing of the two grids was not adequate and serious discontinuities in the two pressure fields across this boundary apparently occurred. As a result of that study, it was Resio's recommendation that "the winds or pressure fields from [the WIS] study [not] be used in future Canadian hindcasts."

Various comparisons between WIS winds and other data have been reported. Seaconsult [116] found the mean monthly WIS wind speed on the Grand Banks to be consistently 1 to 5 knots lower than reduced rig measurements (1972-82), reduced geostrophic, and 551-10 area 4 winds in every calendar month. Monthly maxima in the rig data exceeded monthly WIS maxima (except in March and August) by as much as 31 knots.

AES [30] found that the maximum WIS wind speed in the complete 20 years is just 59 knots and concluded that "any use of the [WIS] data for design winds is completely unacceptable."

KelResearch [69] in a study for AES found that "the [WIS] wind speeds at all stations were lower than observations, except for Sable Island." They also found that WIS winds tend to underpredict high wind speeds.

A Pacific Ocean hindcast is available from WES. Its suitability for Canadian waters has not been assessed, although the quality of its results is expected to be about the same as the Atlantic hindcast.

Additional References:

none

EC 7

Database Name:	***WIS Wave Hindcast***
Parameter(s):	deep-water, two-dimensional wave spectra, significant wave height, peak period and dominant direction for wind sea - and for swell
Geographic Domain:	Northwest Atlantic
Time Period:	1956-75 (20 years)
Source:	Marine Environmental Data Service, Ottawa
Primary Reference:	Corson, W.D., D.T. Resio, R.M. Brooks, B. Ebersole and R.E. Jensen, 1981. Atlantic Coast Hindcast, Deepwater Significant Wave Information. U.S. Army Waterways Experiment Station, Vicksburg, MS.
Other Documents:	[9] [12] [13] [74] [101] [102] [107] [113] [116]
Description:	A spectral deep-water wave hindcast using WIS winds derived from digitized pressure charts Wave spectra are 20 frequencies by 16 directions at 3-h time step.
Limitations:	· only a few hindcast time-series were archived, so spatial resolution is poor · coarse grid does not resolve coastline adequately · sea ice cover was not considered · most of the Canadian water archived time-series are for grid points next to land where errors are apt to be greatest

Suitability:	Regional	Site-Specific
Climatology	poor	poor
Extreme	poor	poor

Database Name: ***WIS Wave Hindcast***

Discussion:

The WIS wave hindcast has been reviewed by MEDS [13] for the Royal Commission on the Ocean Ranger Marine Disaster, by Baird and Readshaw [9] and by D.T. Resio [12] for MEDS, by Seaconsult [113] for Mobil and by Oceanweather [110] for Mobil.

Because there are so few measurements during the period of the WIS hindcast, some of these studies [12, 110] resort to comparing the WIS model with other models and trying to draw generalized conclusions. Resio [12] deduced that discontinuities between the coarse and fine (coastal) pressure grids in severe and moderately severe storms caused serious errors in the hindcast wind and wave fields. As a result, he concluded that “in terms of extreme waves ... results for the Scotian Shelf area should probably not be used.”

Seaconsult [113] compared WIS sites on and north of the Grand Banks with the coincident Grand Banks Waverider data (spanning in both comparisons roughly 9 months). On the Grand Banks, WTS underestimated, on average, Hs observations in excess of about 5 m. For the more northerly sites, observations in excess of about 3 m were underpredicted by WIS.

A Pacific Ocean hindcast is available from WES to suitability for Canadian waters has not been assessed, although the quality of its results is expected to be about the same as the Atlantic hindcast.

Additional References:

none

5.0 ENVIRONMENTAL CRITERIA FOR CANADIAN WATERS

Geographically, the Canadian offshore may be divided roughly into the following major coastal regions:

Scotian Shelf
Grand Banks
Labrador Sea
Davis Strait
Baffin Bay and Lancaster Sound
Beaufort Sea
West Coast.

In each of these seven areas, some oil and gas exploration has been proposed or undertaken. On the Scotian Shelf near Sable Island, on the Grand Banks and in the Beaufort Sea significant hydrocarbon-bearing reservoirs have been found. In preparing exploration and development plans for these locations, design and operational criteria have been derived from the data resources described in Chapter 4 . In this chapter, the important studies that lead to design criteria are reviewed, region by region.

The climatological wind criteria that are routinely required include: the distribution of wind speed as a function of direction on monthly, seasonal and annual bases; favourable and unfavourable persistence on a monthly basis; and characterizations of storm climatology, which typically include storm tracks, storm type, and maximum sustained wind in severe storms as a function of direction. Sources of these criteria are noted in this chapter, but detailed discussion is not warranted.

Wind extremes are expressed in terms of a site-specific wind speed profile as a function of return period for various averaging times at a statistically-prescribed confidence level. The speeds are derived as empirical functions of elevation and averaging period from an extreme value analysis of wind data at one elevation and one characteristic time-scale. Because few of the published studies provide all of this information, and none address wind gust or turbulence criteria other than empirically, the emphasis in this chapter is on maximum observed or hindcast values and low probability estimates of the mean wind speed at some return period to allow intercomparison of various studies.

Wave criteria are more extensive than their wind counterparts. Although all parameters can be determined empirically from significant wave height at a specified return period, the majority of wave parameters ought to be based on high-quality, site-specific measurements. Only the long return period significant wave height (and perhaps its dominant direction) can be derived with confidence from hindcast data sets.

In the following discussion of regional wave criteria, the emphasis is on observed or hindcast maxima and estimates of long return period significant wave height at the main petroleum exploration sites, consistent with meeting the minimum CSA code requirements described in Chapter 3 . Only a few site-specific industry studies have examined the improved and additional wave requirements described in Table 3.1 . The reader is referred to these studies for details.

Evidence of structural icing and some statistics of the extreme rates and accumulations are briefly noted for each region. Since there are few observations, various models are employed to hindcast specific events based on meteorological parameters. Because these models are not well verified, extremes derived from them are not quoted in this report.

5.1 Scotian Shelf

Exploration for oil and gas began in the 1960s on the Scotian Shelf. In 1979, a significant gas discovery was made at the Venture site near the eastern tip of Sable Island (Fig. 5.1), about 175 km southeast of the nearest landfall in Nova Scotia. In 1983, the Venture Environmental Impact Statement was published (Mobil, 1983) and public hearings were held to review its contents. Physical environmental criteria in the EIS document were based almost exclusively on existing public domain data: COADS, Sable Island and shore wind stations, and the WIS wind and wave hindcast, supplemented with intermittent proprietary data from rigs. Between 1984 and 1986, the Venture Development Project (under the direction of Mobil Oil Canada, Ltd.) undertook a more concerted design phase to formulate the necessary criteria for the Venture site, the sub-sea gas pipeline route and its shore base in the vicinity of Canso. The new studies included wind and wave hindcasting, extensive analysis of wellsite wind and wave data, and other oceanographic studies that pertained mainly to requirements for the pipeline. Shortly after the end of the design phase, decline in the world energy prices caused an indefinite delay in the development plans for the Venture gas field.

In 1973, oil was also found on the Scotian Shelf at the Cohasset site, and in 1990 LASMO Nova Scotia Limited applied to the Canada-Nova Scotia Offshore Petroleum Board to proceed with extraction of oil on a seasonal basis from Cohasset and Panuke sites to the west of Sable Island (Fig. 5.1). Agreement has been reached with scheduled production to begin in 1992.

The Scotian Shelf runs shore-parallel to Nova Scotia. It is about 200 km wide and between 100 and 200 m deep over much of its southern area. There are extensive banks less than 50 m deep over most of the northern part of the Shelf, comprised of Banquereau Bank on the south side of the Laurentian Channel and, in the immediate vicinity of Sable Island, Western, Middle, Emerald, and Sable Island Banks. Sable Island, near the outer edge of the Shelf, is a low profile, somewhat mobile sand island. Locally, the ocean is shallow: at the main Venture well sites the water depth is about 20 m and about 40 m at Cohasset-Panuke.

Severe weather systems in this area tend to be extratropical winter cyclones that track roughly shore-parallel from southwest to northeast with the trajectory of central low pressure passing either to the east or to the west of Sable Island (Brown et al., 1986; Lewis and Moran, 1984). Hurricanes in the late stages of their evolution can reach this area on occasion between July and October (Neumann et al., 1978).

The data resources on the Scotian Shelf are fairly extensive, but few of them are suitable for site-specific design criteria at the shallow sites of interest. The presence of Sable Island causes considerable modification to wave (and current) fields, and although there are long-term wind measurements from Sable Island, the flow field is sufficiently distorted by the landforms to make them unreliable over-water estimates (see, for example, Richards et al., 1987).

5.1.1 Wind Criteria

Wind resources for the Scotian Shelf include rig observations, ship reports (but not usually from the immediate vicinity of Sable Island), and various hindcasts carried out for public and private sponsors. The recent wind hindcasts have been performed by Oceanweather Inc., in conjunction with MacLaren Plansearch, for input to the wave models. The wind fields are constructed from 6-hourly surface pressure charts augmented with observations of pressure and wind from ships and rigs, either for specific storms as in the east coast regional hindcast (MPL and Oceanweather, 1990) and in the Venture site hindcast (Seaconsult, 1987) or on a continuous basis as in the PERD-financed wave climate database (Eid et al., 1989). Kinematic analysis, which ought to produce the most accurate wind fields, is only performed for storm-based hindcasts, and only for a few charts near the expected storm peak.

A summary of some wind criteria estimates is presented in Table 5.1 , many of which are based on the AES records from the Sable Island anemometer. It has been known for at least 20 years that this wind station is not representative of over-water winds (OSEI, 1971), but the record, now 100 years long, is thought to be valuable if it can be correlated to offshore winds. Several attempts have been made to calculate either speed- or direction-dependent sheltering factors based on shore measurements (Richards et al., 1987) and rig

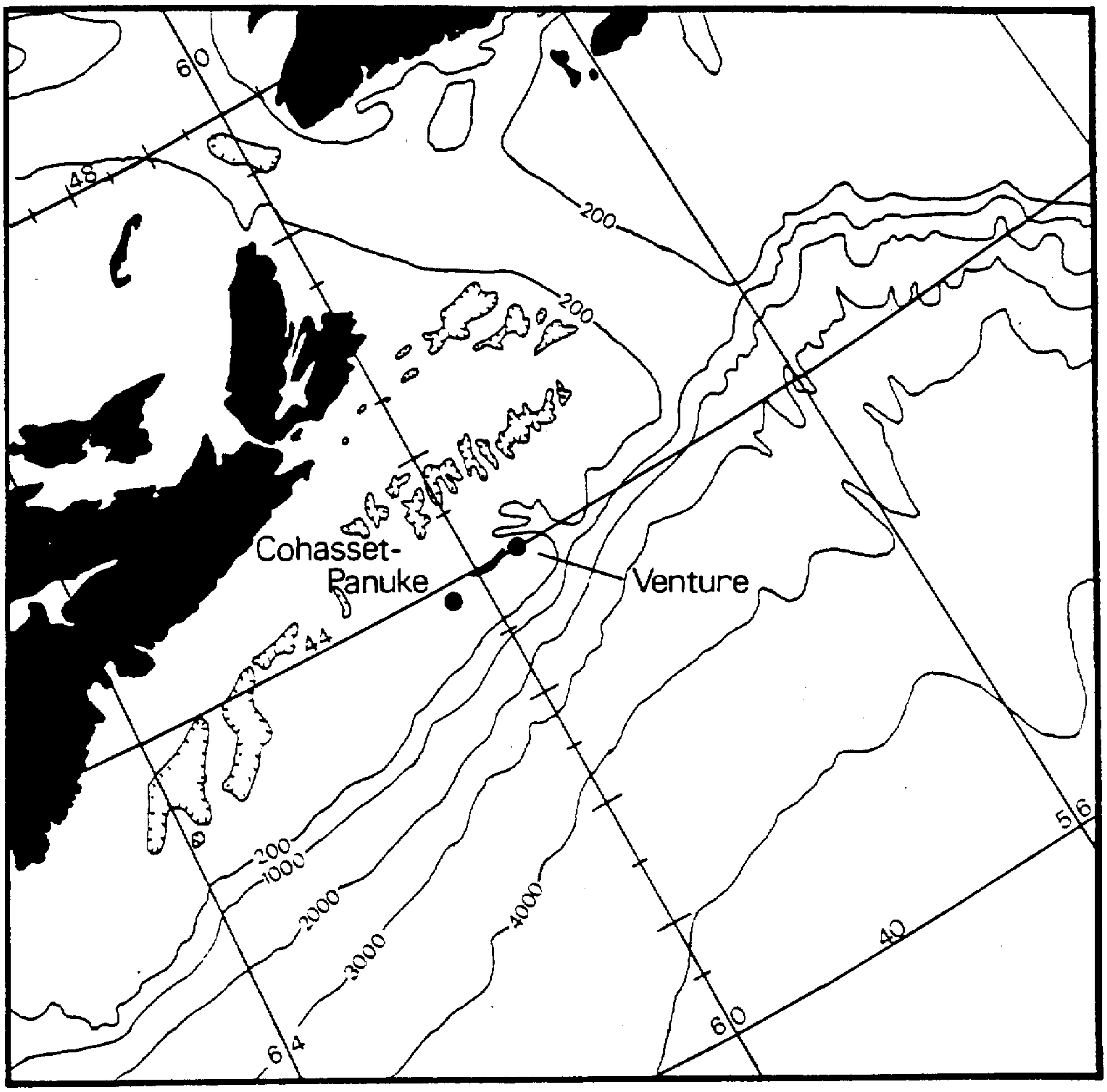

Figure 5.1 The Scotian Shelf and the two proposed offshore development sites.

measurements (OSEI, 1971; Seaconsult, 1984; Hodgins and Hodgins, 1988). Each of these studies recommends acquisition of more offshore data to improve the coefficient estimates, some of which are unexpectedly large, exceeding 1.3 for a 10-m elevation wind from southerly and easterly directions.

As an extreme, GWC estimates for the Sable area compare favourably with other data sources, implying roughly a 10-m reference elevation and a 1-min mean averaging period for GWC. Other studies have suggested that GWC winds are about equivalent to rig winds on the Grand Banks at about 80 m (Swail et al., 1984). However, a match in 100-year extreme values should not be interpreted as statistical equivalency of two databases. GWC at Sable, for example, is not consistently in reasonable agreement with ship observations in the area: it underpredicts monthly maxima in February through May and overpredicts in all other months, by as much as 18 knots (33%) in July (Swail et al., 1984).

5.1.2 Wave Criteria

The bathymetric relief of the Scotian Shelf is very complex, particularly in the vicinity of Sable Island where the Venture gas field and the Cohasset-Panuke oil reserves are located (Fig. 5.2). Wave criteria for these sites must account fully for the shallow-water effects of shoaling, refraction, wave breaking and bottom dissipation. To date, three shallow-water wave hindcasts have been completed. One was a 25-storm hindcast for the Venture site (Seaconsult, 1987), another was a research study that included modelling of four storms, three of which had directional wave measurements for comparison (Hodgins et al., 1989), and the third involved a simplified model on a one-dimensional grid of measurements made during the CASP experiment (Eid et al., 1989; Eid et al., 1987.

One of the differences between deep- and shallow-water wave modelling is illustrated by the refraction pattern in Fig. 5.3a . A deep water wave crest approaching Sable Island from the- west-southwest is travelling perpendicular to the 80-m contour initially. As it progresses, the part in shallower water slows down, causing the wave crest to bend locally toward alignment with the bottom contours. In the process, wave energy from different parts of the initial wave front is focused near the eastern end of the Island. In a deep-water simulation a wave path cannot be deflected by bathymetric features. As a result, provided Sable Island was resolved on the grid, a deep-water model would predict that the eastern end of the Island would be sheltered from these WSW waves. Conversely, the energy shadow that develops east of Sable Island in the shallow-water version would be directly in the wave path in a deep-water hindcast.

Table 5.1

Some Wind Criteria from Published Sources for the Scotian Shelf and Sable Island

Location	Wind Speed (knots)	Return Period	Record Period	Data Source
Sable I. AES winds	72.	100-year	unknown	Mobil (1983) 1-min mean, elev. unknown
Venture wellsite	110.	100-year	39 years (prior to 1971)	Mobil (1983) 1-min mean, 30 ft (9 m) based on modification of Sable I. 1-h mean winds
Venture wellsite	106.	100-year	1941-71	OSEI (1971) 1-min mean, 30 ft (9 m) 30 storm hindcast
Venture wellsite	90.	100-year	1956-82	Seaconsult (1984) 1-min mean, 10 m based on modification of Sable I. 1-h mean winds
Sable I. AES winds	68.	100-year	not specified	Richards et al. (1987) averaging period unknown elevation unknown
Sable GWC	97.	100-year	1946-78	Mortsch et al. (1985) ref. elev. indeterminant averaging period unknown
Scotian Shelf ODGP	56.	100-year coincident with max H_s	1951-84	MPL&Oceanweather (1990) at 20 m, 1-h mean
[DnV adj.	60.			at 10 m, 1-min mean]
Sable "offshore"	75.	observed	76-03-11	Richards et al. (1987) ref. elev. unknown averaging period unknown
Venture wellsite	60.	observed	83-10-25	Seaconsult (1987) at 20 m, 1-h mean adjusted for input to ODGP

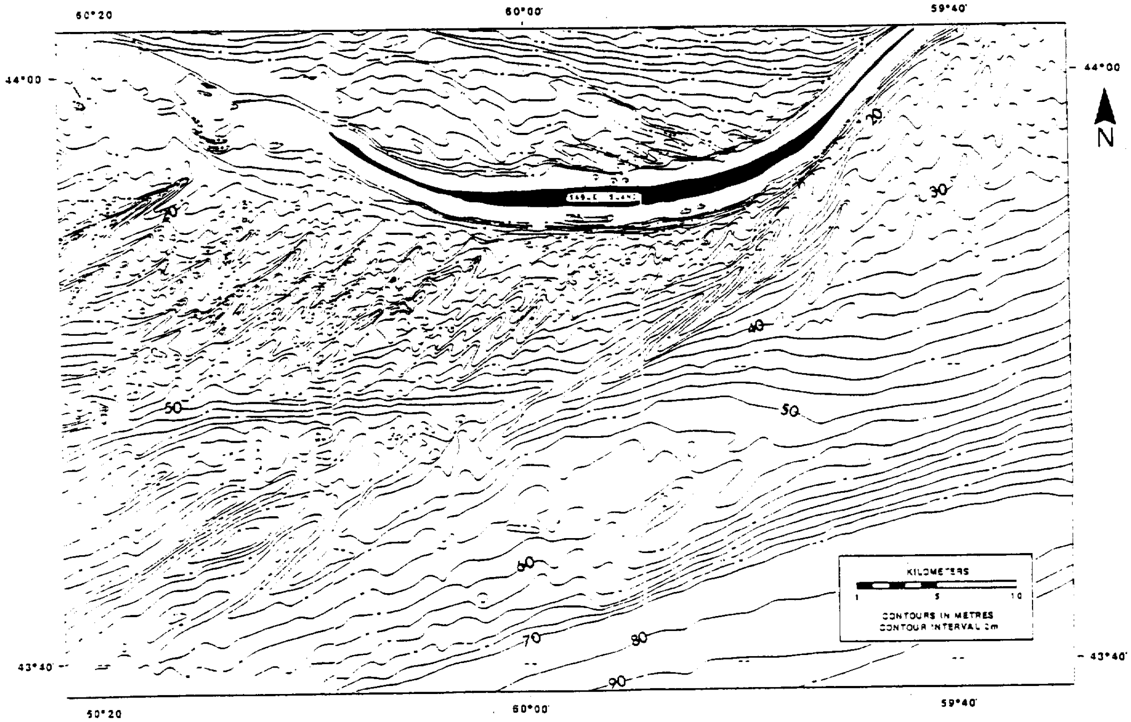

Figure 5.2 Bathymetric detail in the vicinity of Sable Island from Canadian Hydrographic Service surveys in 1982. From Hodgins et al. (1989).

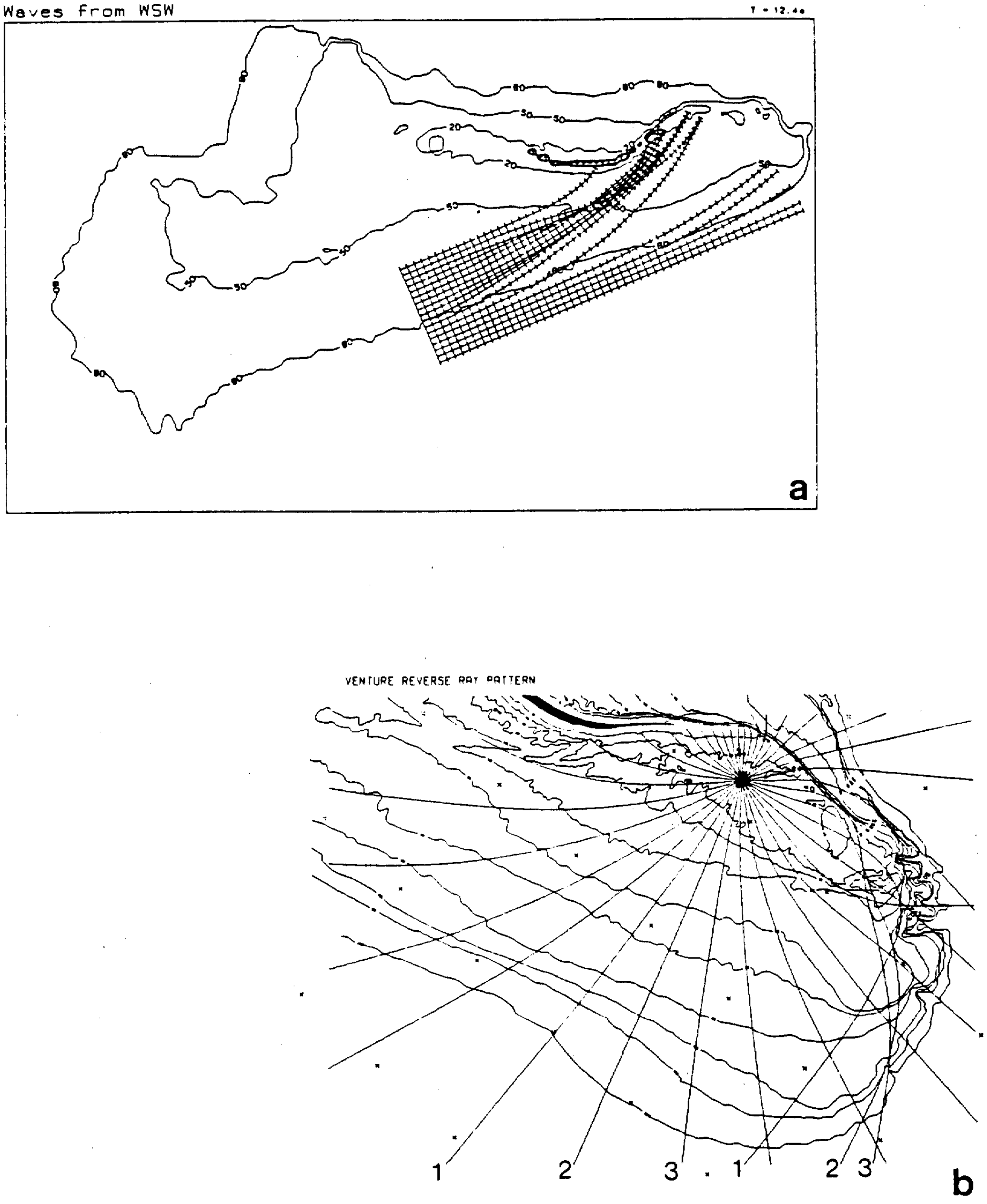

Figure 5.3 Refraction diagrams for Sable Island Bank. (a) 12.4 s waves approaching from WSW, from Hodgins and Hodgins (1988) and (b) reverse ray pattern for 15.3 s waves, from Seaconsult (1984).

The degree of refractive bending is a function of wave period relative to depth and of the angle between the wave crest and the bottom contours; the longer the period or shallower the water, the more extreme the bending, but at the same time, the more aligned the crest and the contours, the less severe the bending. Fig. 5.3b illustrates the combined effects in a reverse ray diagram that sows the range of source directions from which 15.3-s period waves can arrive at the same site off the east tip of Sable Island.

This diagram shows that, theoretically at least, deep-water wave energy from different locations (labelled 1, 2 and 3) that is initially travelling in the same direction will converge at the site of interest from different directions. This crossing wave phenomenon is possible according to wave theory, but has not been observed. It cannot be detected in conventional directional wave theory, but has not been observed. It cannot be detected in conventional directional wave buoy data since two wave components at the same frequency cannot be distinguished directionally.

Resolution of landforms and bathymetric detail is critical to successful shallow-water wave modelling, but the grids are about 50 to 100 times finer than typical deep-water model meshes. To achieve practical computational efficiency, a deep-water hindcast is used to generate wave energy spectra as boundary conditions for shallow-water modelling at sites on the banks around Sable Island, provided there are enough storms with the required directional characteristics.

The regime of validity for deep-water wave approximations is governed by depth (d) and wave period (T), and deep water is defined by d/gT2 greater than about 0.08. This inequality is the same as the conventional rule-of-thumb: waves begin to feel the bottom when depth is half the wave's length. For a depth of 80 m, wave energy at periods less than about 10 s can be considered deep-water. Design waves on the Scotian Shelf are expected to have peak energy in the 12 to 18 s range and hence will be influenced by the bottom on the Banks. At shallow sites, the maximum wave height may be depth-limited.

On the Scotian Shelf, modifications to deep-water energy spectra in severe storms should be expected on all the banks in the lea of the banks. The types of changes could include increase or decrease in total energy, shifts in direction of the long-period components and variations in peak period. The net effect is site-specific, particularly in regions of rapid bottom change such as the east side of Sable Island Bank. In consequence, model and measurement results for this region need to be carefully scrutinized and not too freely intercompared.

Deep-water estimates of predominant wave direction and peak spectral period should not be used as indicative of shallow-water conditions.

Evidence of the poor modelling of shallow-water Tp with a deep-water model is given by Eid et al. (1989) in data from the 3-year continuous PERD hindcast. On a climatological basis, they found that modelled and measured Tp were, in practical terms, uncorrelated and calculated a correlation coefficient of 0.49 for more than 2400 points of comparison. Part of the problem is recognized in the inability to model swell from distance sources which can dominate in low sea states.

Table 5.2 presents some wave criteria for the Scotian Shelf, but only the deep-water offshore values can be evaluated on an equivalent basis. The recent east coast regional hindcast deep-water estimates are considerably lower than previous predictions, but are not necessarily unreasonable in comparison with the observed maxima on the Shelf. There are no other known extreme value estimates for shallow-water sites. Although 25-storm wind and wave hindcast was performed for Venture Development Project (Seaconsult, 1987), extremes were not calculated.

Inspection of the fairly extensive coincident Waverider data confirms the expected variability in peak sea state over the northeast part of the Scotian Shelf. Data collected during the ESRF shallow-water wave experiment on the seaward side of Sable Island (Hodgins et al., 1989) also illustrate the shallow-water modification of storm wave energy. Selection of the correct set of severe storms for hindcasting extremes at particular sites in the vicinity of Sable Island will be considerably more difficult than for open ocean locations.

5.1.3 Structural Icing Criteria

Reports of vessel icing are relatively frequent on east coast south of Labrador, particularly in the waters between the Scotian Shelf and the Grand Banks (Roebber and Mitten, 1987). Since there are no definitive regional icing studies and little information in the historical data to distinguish between the Scotian Shelf and the Grand Banks in terms of incidence or intensity, the reader is referred to Section 5.2.3 for a general discussion of icing observations and models.

Table 5.2

Some Wave Criteria from Published Sources for the Scotian Shelf and Sable Island Area

Location	Wave Height Hs (m)	Return Period	Record Period	Data Source
Offshore Sable I [d = 200 m]	15. (approx)	100-year	1970-80	Neu (1982) METOC charts
Offshore Sable I [d = 200 m]	11.4 (approx)	100-year	1957-88	MPL & Oceanweather (1990) Deep-water hindcast
Offshore Sable I [d = 120 m]	14.2	100-year	1941-71	OSEI (1971) Deep-water hindcast
Venture well area [d = 20 m]	15.1	100-year	1941-71	Mobil (1983), OSEI (1971) Deep-water hindcast modified for shallow effects
Venture well area [d = 24 m]	12.7	100-year	1941-71	Mobil (1983), OSEI (1971) Deep-water hindcast modified for shallow effects
Venture wellsite [d = 50 m]	8.4	observed maximum	1980-84 in Dec 81	MEDS Waverider wellsite summary Venture B-43
Banquereau Bank [d = 66 m]	9.0	observed maximum	1980-84 in Feb 84	MEDS Waverider wellsite summary Louisbourg J-47
Sable I. Waverider [d = 22 m]	6.1	observed maximum	1980-84 in Oct 83	MEDS Waverider wellsite summary Sable Island

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5.2 Grand Banks

The Grand Banks of Newfoundland form a subsea plain at about 80 m depth southeast of the Avalon Peninsula (Fig. 5.4). Offshore exploration for petroleum resources began in 1973 and 1974 at widely scattered sites between 44°N and 47°N. The culmination of the exploration phase to date has been the discovery three significant oil reservoirs on the northeast shoulder of the Banks at Hibernia (1979), Terra Nova (1984) and Whiterose (1984). With Mobil Oil Canada, Ltd. as proponent, the Hibernia Development Project was undertaken and the Environmental Impact Statement was issued in May 1985 for a gravity base structure at the wellsite and shuttle tankers moving oil to shore (Mobil, 1985). It is the first and only major Canadian offshore development project to reach the construction phase. Full production should commence by 1997. Petro-Canada has not published its plans for Terra Nova, but is thought to favour a floating production system. Husky Oil has not announced plans for Whiterose development either.

There have been a number of accidents in conjunction with oil activities on the Grand Banks that were partly related to environmental conditions. The most well-known, and most costly, was the sinking of the drilling rig Ocean Ranger and the loss of 84 lives on the night of February 14-15, 1982. Due to faulty ballasting control the rig developed a 10° to 15° list during a severe storm, capsized and sank. The severe wind and sea conditions made launching of lifeboats from the rig difficult and limited the effectiveness of the rescue vessels. A reconstruction of events leading to the sinking and descriptions of the unsuccessful rescue attempts were published by the Royal Commission on the Ocean Ranger Marine Disaster (1984).

Positive results of this event were the focus that was brought to bear on operational safety of people and equipment in harsh maritime environments, and the realization that flawed designs and human error can produce a fatal combination with less warning than wind and waves.

The storm climatology of the Grand Banks has been addressed in a number of reports. A descriptive climatology of the Grand Banks may be found in Seaconsult (1982) in terms of circulation patterns, climate controls, cyclogenesis, and statistical summaries of regional climatology and severe weather. Storm tracks of tropical cyclones in the North Atlantic are published by NOAA (Neumann et al., 1978, and updates), illustrating generally at least one or two storms per year that approach the Grand Banks area, although rarely with hurricane intensity. Mobil (1985) reported a study of the 1973-79 named tropical storms and hurricanes that showed about 10% of them passed in the vicinity of Hibernia, usually in the late summer or early autumn. Lists of severe storms have been published by Lewis and Moran (1984), Brown et al. (1986), Cardone et al. (1989a), and MPL and Oceanweather (1990).

Because Hibernia and other nearby drilling sites have been almost continuously occupied between June 1979 and May 1989 there is a large volume of marine weather and wave data that were collected by the drilling rig operators. The only significant gaps in the public-domain data up to January 1986 are winds from mid-February through mid-April 1982, and waves and/or winds for brief periods during the peak of each iceberg season. Mobil used five years of these well site data to specify the normal meteorological operating conditions for Hibernia. There is also a reasonably large COADS data set for the Grand Banks area which is part of the trans-Atlantic shipping corridor and a major fishing area.

With the preparation of development plans, many environmental studies were undertaken by Mobil as the operator and proponent for Hibernia to define the Grand Banks' climatological normals and extremes, ultimately for design purposes. As one part of the process, a series of wind and deep-water wave hindcasts was conducted for the Hibernia site.

5.2.1 Wind Criteria

Table 5.3 lists some representative wind extremes for the Hibernia area, and in the process illustrates two problems with superficial comparisons of wind criteria: (1) the lack of consistency in the averaging period and in the reference elevation, and (2) interpretation of wind extremes that are based on maximum wave-generation selection criteria. In their EIS document, Mobil (1985) presented four estimates of wind extremes, seeming to imply that they could be fairly compared. One was based on ship observations, one derived from a misinterpretation of the WIS database wind averaging period, one based on maxima from a storm- based wave hindcast, and one derived from the GWC unmodified geostrophic database. Mobil's observation that one of these estimates agreed reasonably well with the maximum record in 100 years of ships' data was largely a coincidence.

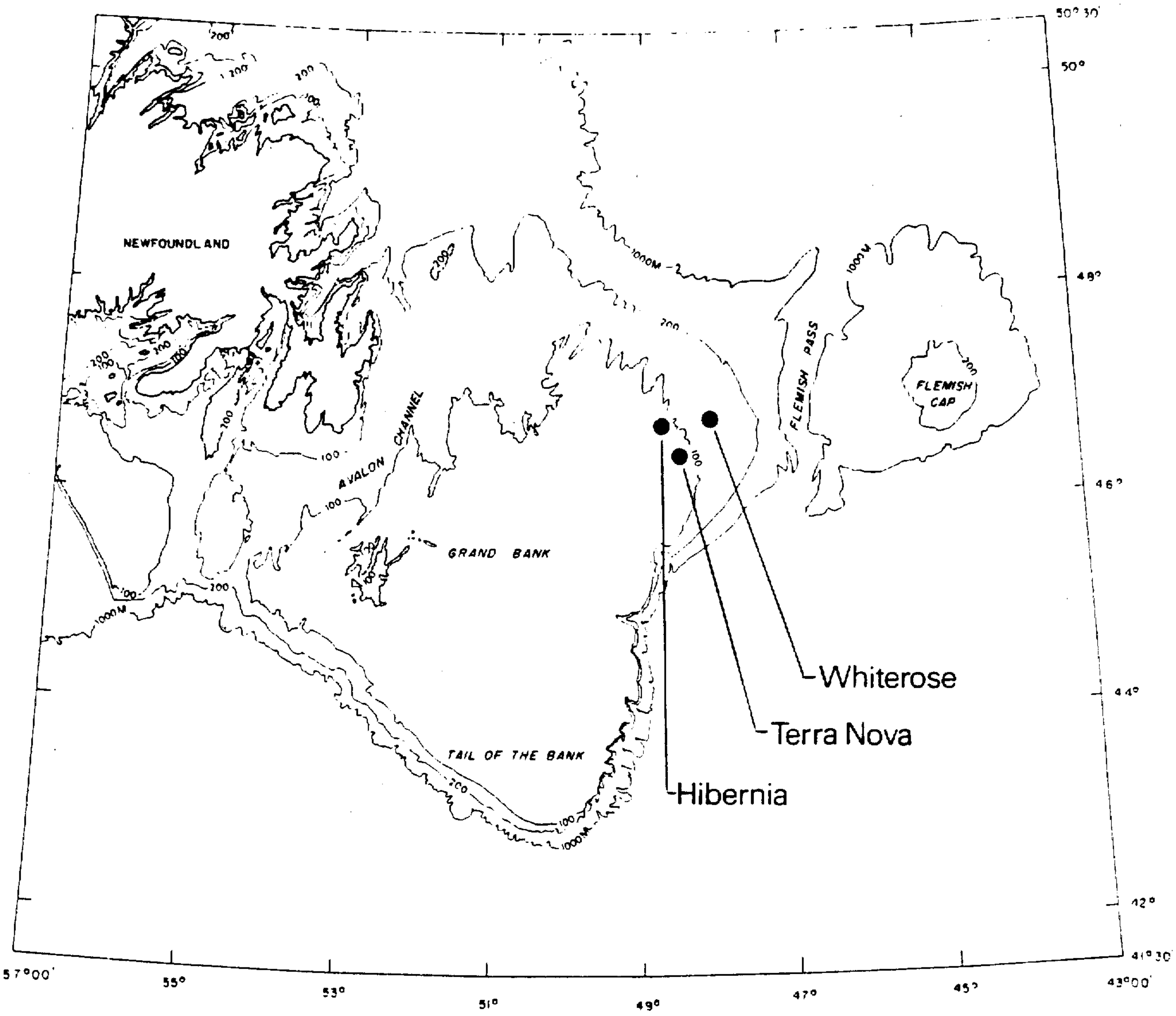

Figure 5.4 The Grand Banks of Newfoundland showing the locations of the three significant oil discoveries.

In fact, wind extremes that are independent of other environmental factors have not been derived from a reliable data set for the Grand Banks except by Weibull analysis of six years of rig measurements (Seaconsult, 1988). Based on an assumption that the rig data are representative of 1-h mean winds at 80 m and using accepted scaling rules (Det norske Veritas, 1977), Seaconsult estimated the expected 50-year return period 1-h mean wind to be 65 knots at 20 m and 89 knots at 80 m, values that agree well with the more reliable estimates in Table 5.3 .

Setting aside some objections to Weibull extrapolation, there are other uncertainties in rig-mounted anemometer measurements. They are subject to flow distortion from a rig’s superstructure which could be directionally dependent. Except by wind tunnel modelling of each rig, the effects cannot be accounted for accurately, but generally, flow distortion would tend to lower the undisturbed wind speed. Because the anemometer is usually mounted atop the derrick at 70 to 90 m above sea level, the records cannot be compared directly with surface measurements or wind model output without adjustment to a common reference elevation.

The wind data sets that are prepared for wave hindcasting contain only those storm events that are likely to generate severe sea states. They may exclude or underestimate mesoscale effects in the vicinity of fronts. A rapidly developing system may be omitted if it appears to have insufficient duration to cause extreme wave conditions or it may be so poorly resolved in the pressure database that its intensity is underestimated. Weather systems with fetch restriction due to sea ice are probably excluded as well. The extreme statistics that result from the joint specification of severe sea state and coincident wind are useful for design, but they are not necessarily good estimates of the extreme wind criteria. In their review of Mobil’s Hibernia Development Plan (Mobil, 1985), the Canada-Newfoundland Offshore Petroleum Board (CNOPB, 1986) concluded that adequate consideration had not been given to mesoscale events and their effect on wind extreme estimates for 1-min means and 3-s gusts.

Most wind hindcasts have wind fields derived from 6-hourly surface pressure charts through application of a marine planetary boundary layer (MPBL) model. A description of Cardone’s MPBL may be found in MPL (1984). In a kinematic analysis and data blending procedure such as the one used by Oceanweather near the peak of a storm (MPL and Oceanweather,1990), wind speed reports from ships and rigs, nominally 1-min or 2-min means, are transformed to effective neutral winds at the reference elevation required by a particular wave model. The result is a 6-hourly time-series of wind fields that are interpolated

Table 5.3

Some Wind Criteria from Published Sources for the Grand Banks

Location	Wind Speed (knots)	Return Period	Record Period	Data Source
Hibernia rig winds	80.	observed extreme	in Feb 1975-83	Mobil (1985) 1-min mean at about 80 m
Hibernia COADS	90.	observed extreme	1880-1981	Mobil (1985) 1-min mean, various heights, incl. rigs
Hibernia WIS	91.	100-year	1956-75	Mobil (1985), McDonald & Evans (1981) at 20 m assuming WES is 6-h mean, then scaled to 1-min mean
Hibernia ODGP	78.	100-year	1951-80	Mobil (1985), Oceanweather (1982) at 10 m, 1-min mean scaled from 1-h
Hibernia ODGP	75.	100-year	1951-84	Cardone et al. (1989a) at 20 m, 1-h mean max. hindcast wind speed
N.Gr.Banks GWC	110.	100-year	1946-78	Mortsch et al. (1985) ref. elev. indeterminant averaging period unknown
Hibernia area ODGP	65.	100-year coincident with max H_s	1957-88	MPL & Oceanweather (1990) assumed to be at 20 m, 1-h mean

in time (linearly by Oceanweather) to the wave model time step, typically two or three hours. MPL and Oceanweather (1990) specify that each wind field represents the 1-hour average wind, in spite of the fact that it is partially calibrated to 1-min or 2-min mean observations, and hence nominally biased slightly high. However, it is possible that errors of this magnitude are subsumed in grosser assumptions concerning thermal gradients and stability that are required by MPBL modelling. In fact, limited time-series comparisons of ODGP winds with reduced rig measurements (MPL and Oceanweather, 1990) give the impression that ODGP wind speed tends to be a little low on the Grand Banks.

5.2.2 Wave Criteria

Wave data archives for the Grand Banks are probably the most extensive regional database for Canadian waters. Until the mid-1980s, the data were collected with instruments owned and maintained by MEDS, and the data were made available at nominal cost in a variety of useful formats. In recent years, wave data collection at wellsites has become the sole responsibility of each offshore operator and hence the data are not distributed without permission of the oil companies. In principle, all wave records are centrally archived by MEDS, but in practice their holdings appear incomplete, perhaps because there is little impetus to acquire and process proprietary data.

Wave measurements were used by Mobil to define seasonal and monthly criteria based on Weibull extrapolation of five years of Hs (Bolen et al., 1989). The spatial variability in significant wave height on the Grand Banks was shown to be weak though comparison of coincident measurements (Seaconsult, 1985). The increasing H_s trend from west to east that METOC chart analysis predicts (Neu, 1982) was not observed. As a result, it is reasonable to splice or average time-series from different sites to make a nearly-continuous record. From this time-series, persistence statistics were also derived.

One of the potential weaknesses of the Weibull analysis listed by Bolen et al. (1989) is the failure of Weibull fitting (using all available data) to distinguish between many maxima of short duration and few maxima of long duration. In both cases the probability distributions could be equivalent, but the distributions of independent maxima would be quite different. Gumbel analysis says that, on average, one expects 2% of independent sea states to peak at the 50-year return level in 100 years. It does not say how many times on an hour-by-hour basis that the 50-year return H_s will occur, but clearly that level is achieved at least twice in the 100-year event, twice in the 99-year event, and so on. The Weibull result says that 2% of all sea state conditions (i.e., about 730 hours in 100 years) are expected to exceed the 50-year return value. In this respect, the

Weibull extreme values contain more information than the Gumbel ones, but confidence in Weibull extrapolation is usually lower because the data sets are relatively short.

To overcome limitations in the Waverider database length, Mobil commissioned a series of storm-based wave hindcasts for the Hibernia site using Cardone's ODGP wave model (Oceanweather, 1982; Cardone et al., 1989a; Szabo et al., 1989a; Szabo et al., 1989b; Cardone et al., 1989b). In all cases, deep-water wave physics was assumed, and any potential shallow-water effects were neglected. Fig. 5.5 illustrates the effect of refraction on 10-s and 16-s waves as calculated by Evans-Hamilton (Mobil, 1985). The 10-s waves are essentially unmodified, but the longer period wave fronts begin to bend appreciably. The predicted result is energy focusing (increased height) of south-southwest wave trains and energy spreading (decreased height) of west-southwest waves. It is reasonable to expect spectral peak energy in extreme storms to be from wave periods of 15 s or more. In comparison with places like Sable Island or exposed coastal headlands and bays, the influence of refraction on the design wave estimation is small.

Another shallow-water effect of some importance in the extreme Grand Banks storms is shoaling which is manifest in modifications to wave height and length (but not period) as waves move from deeper to shallower water. The initial change is a *decrease* in height to a theoretical minimum of 92% of the deep-water height (see, for example, Sarpkaya and Isaacson, 1981). In 80 m of water, for wave periods between 10 s and 30 s, linear wave theory predicts that due to shoaling alone wave height will be less than the deep-water incident wave height with the maximum reduction for waves of about 16.5 s period. - As a result, deep water model results for the Grand Banks will tend to be conservative (over-estimating H_s) by ignoring shoaling.

One of the weaker aspects of hindcast studies is storm selection. Originally the Mobil hindcast set contained merely 20 events from the 1951-80 period, and it was clear that at least two of them were not the most severe wave-generating events. Intervenors at the EIS hearings were concerned that the most appropriate storm population had not been selected (CNOPB, 1986). Based on Waverider measurements, the sample size was increased to 29 storms in the period from 1951 through 1984; only 26, all of which exceeded 8.4 m, were used in extremal analysis and more than half of them occurred in the 10 years since drilling began on the Banks. Details of the selection methods may be found in Szabo et al. (1989a).

A more recent storm selection by Ocean weather and MacLaren Plan search for a regional east coast hindcast, including the Grand Banks, identified 41 events with peak H_S exceeding 8.0 m between 1957 and 1988. The selection procedure is described in detail in MPL and Oceanweather (1990). This set excluded at least 7 from Mobil's Hibernia storm set between 1965 and 1983 in which hindcast peak H_s was between 8.6 m and 12.1 m, but included 13 storms from the period between 1959 and 1983 in which H_s exceeded 8.3 m that were not on Mobil's hindcast list. For the period from 1981 though 1985, Table 5.4 lists the recorded maxima in the MEDS Waverider database and identifies the events that were hindcast for Mobil and for the regional east coast study. At best, each hindcast storm set has to be viewed as a subset of the true set of event maxima.

Although compromises are inevitable, the selection of storms should not distort the distribution of sea state maxima. Two examples (Fig. 5.6) illustrate some problems that can develop. In one case, two distinct storm peaks were hindcast, but only one maximum H_s was extracted; in the second case, the less intense storm was not hindcast although its measured sea state exceeds the peak of several events that were modelled. If choices like that are made when good data resources are available, it seems probable that they occur at other times also.

Aside from aiding in storm selection, measurements are invaluable for wave model calibration and verification. During high seas, wave data are recorded nearly continuously with one sample every 20-min, which provides excellent temporal resolution. MPL and Oceanweather (1990) present 34 site-specific time-series verifications of ODGP on the Grand Banks and Scotian Shelf with Waverider data collected during 10 different storms. MEDS spectral estimates of H_s were smoothed with a 7-point running average of H_s2 to better match the 2-h-model time step. In general, ODGP tends to systematically over-estimate significant wave height even though ODGP wind speeds are often a little lower than the equivalent rig winds. The peak-to-peak H_s difference comparison using smoothed measurements varied between + 3 m and - 1 m. In some storms the difference is sometimes quite small while the mean bias over the length of the event is 2 m or more. The reported mean error in ODGP wave heights on the Grand Banks is 1.29 m.

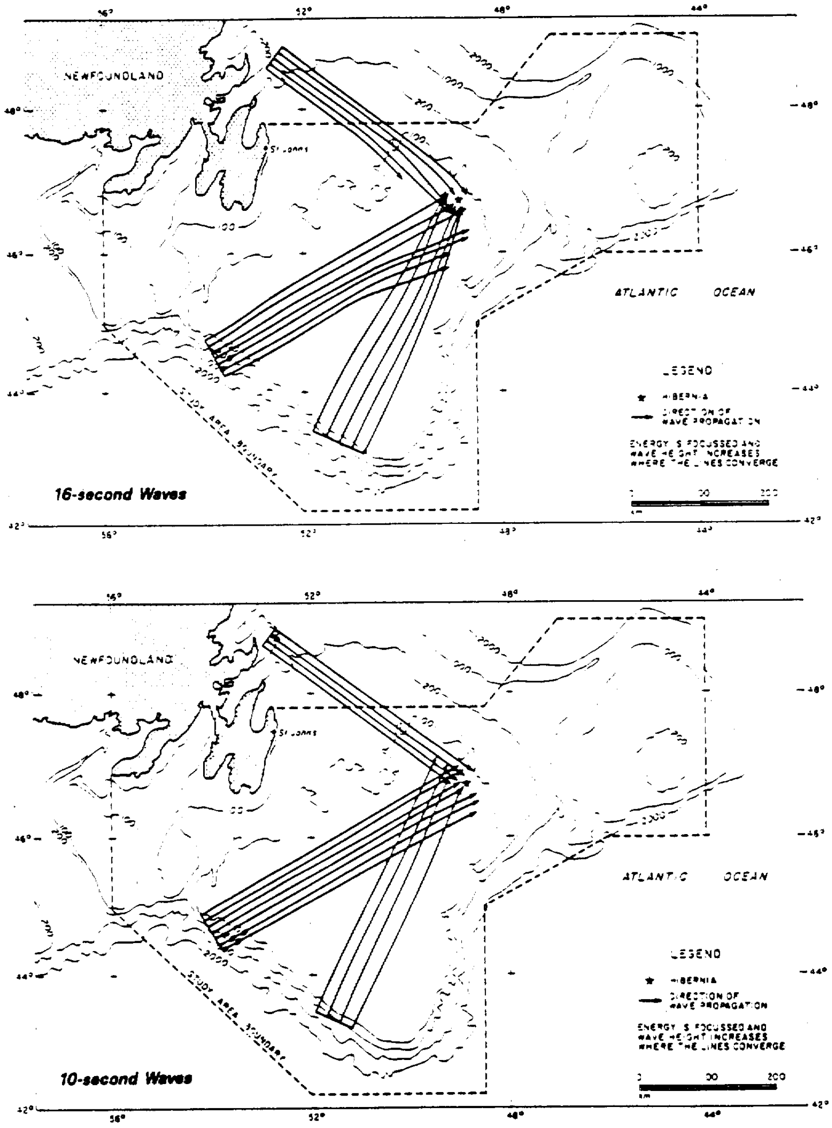

Figure 5.5 Refraction diagrams for Hibernia for particular wave periods and directions. From McDonald and Evans (1981) and reproduced in Mobil (1985).

Table 5.4

Grand Banks Storm-Maximum Significant Wave Height

Storm No.	Site Name	Max. WR Storm[1] Hs (m)	Rank	Mobil Storm[2] Hs (m)	ODGP Storm No.	ODGP Storm[3] Hs (m)	Time of Peak[1] Hs yy	mm	dd	hhmm
1	Sheridan J-87	8.2	24		460		81	9	27	1911
1	Hibernia K-18	7.9	31		460		81	9	28	129
2	Nautilus C-92	8.1	25		461		81	11	1	202
2	Hibernia K-18	8.1	26		461		81	10	31	2359
3	W F Foam L-23 [4]	10.9	5	11.7	467	12.6	82	1	16	1700
3	Hibernia J-34	10.7	6	11.7	467	12.6	82	1	16	1827
3	Nautilus C-92	10.5	8	11.7	467	12.6	82	1	16	1308
4	Hibernia J-34	9.4	14		468		82	1	18	2113
4	Nautilus C-92	8.8	18		468		82	1	18	1956
4	W F Foam L-23 [4]	8.8	17		468		82	1	18	2000
5	Nautilus C-92	8.6	20	9.2	472		82	2	2	1901
5	Hibernia J-34	8.0	28	9.2	472		82	2	2	2003
5	W F Foam L-23	7.9	32	9.2	472		82	2	2	1715
6	W F Foam L-23	13.3	3	13.4	474	13.4	82	2	14	2313
7	N Dana I-43	10.1	10	8.6	479		82	12	10	1943
8	N Dana I-43	9.4	15	9.2	491		83	3	8	2328
9	Hibernia K-14	10.0	11	8.8	495		83	11	29	531
9	Terra Nova K-08	9.9	12	8.8	495		83	11	29	836
9	N Dana I-43	8.4	23	8.8	495		83	11	29	1000
10	Hibernia K-14	8.5	22		497		83	12	4	2302
10	N Dana I-43	7.6	34		497		83	12	5	532
10	Terra Nova K-08	7.4	38		497		83	12	5	109
11	Trave E-87	13.8	1	11.2	499	13.3	83	12	22	1819
11	N Dana I-43	13.4	2	11.2	499	13.3	83	12	22	1905
12	N Dana I-43	9.3	16	8.8	500		83	12	26	208
13	Voyageur J-18	7.2	41		503		84	3	11	559
14	Archer K-19	7.2	42				84	10	27	559
14	Whiterose N-22	6.8	45				84	10	27	818
14	S Mara C-13	6.8	46				84	10	27	500
15	Conquest K-09	8.1	27		511		84	12	26	1600
15	Whiterose N-22	7.5	35		511		84	12	27	1734
15	W B Nevis B-75	7.5	36		511		84	12	27	1315
15	Beothuk M-05 [4]	7.5	37		511		84	12	27	2053
15	Mara M-54	7.4	39		511		84	12	27	1159
16	Conquest K-09	8.6	21		512	9.0	85	1	6	1800
16	W B Nevis B-75	8.0	29		512	9.0	85	1	6	1809
16	Beothuk M-05	8.0	30		512	9.0	85	1	6	1747
17	Conquest K-09	11.1	4		515	11.4	85	1	29	334
17	W B Nevis B-75	10.6	7		515	11.4	85	1	29	41
17	Mara M-54	10.4	9		515	11.4	85	1	29	19
18	Terra Nova K-17	7.4	40				85	10	12	1955
19	Terra Nova K-07 [4]	7.2	43		520		85	11	16	900
20	Terra Nova I-97 [4]	7.7	33				85	11	28	1500
21	Terra Nova I-97 [4]	6.9	44		521		85	12	1	900
22	Terra Nova I-97 [4]	8.7	19		523	9.9	85	12	16	300
23	Terra Nova I-97 [4]	9.8	13		524		85	12	19	1800

[1] reprocessed MEDS wellsite wave data

[2] Cardone et al. (1989a)

[3] MPL and Oceanweather (1990)

[4] not continuously recorded

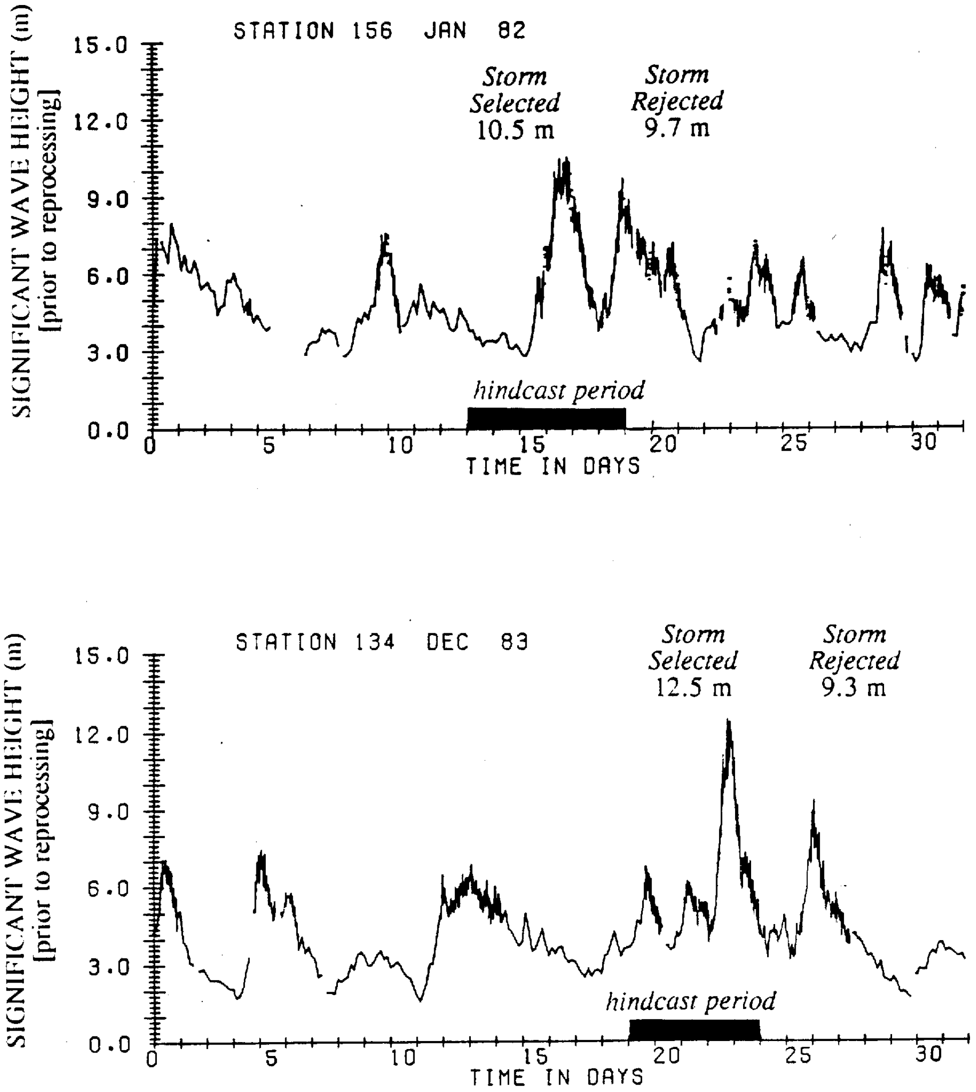

Figure 5.6 Time-series of Grand Banks wave height illustrating possible flaws in storm selection procedure.

There is clearly large variability in storm-generated sea state energy from one 20-min sample to the next. If the objective of wave hindcasting is to model the one-, two- or three-hour mean-sea state, then some compensation for the observed variance in H_s must be included in reported maxima. The ODGP model as used in the regional east coast hindcast appears to be biased sufficiently high that the observed sea state variability is already accounted. Without smoothing of the Waverider data, the reported peak-to-peak error is 0.53 m based on all Grand Banks and Scotian Shelf verification storms. For the Grand Banks alone, the peak-to-peak error statistic is not reported, but is probably about 1 m since the Scotian Shelf hindcast errors are relatively small.

One source of error that has not been widely explored is to be found in the MEDS spectral estimates of H_s that have a low frequency cutoff of 20 s. A clear example of the problem is illustrated by the storm of December 22, 1983. During wave-by-wave processing of this event, it was noted that the storm’s peak significant wave height, calculated as the average of the one-third highest waves, was almost 1 m greater than the reported MEDS spectral estimates (Szabo et al., 1989b). The difference was traced to the inappropriate low frequency cutoff and confirmed by spectral reprocessing of the sea surface elevation data with a cutoff of approximately 30 s (Seaconsult, 1988). Corrections to the most severe sea state data will improve the ODGP verification statistics (see Table 5.4 in which only the storm of January 16, 1982 is seriously over-estimated at the peak).

Table 5.5 presents some representative extreme H_s estimates for the Hibernia region of the Grand Banks. Included for comparison are some values from sources that are less reliable than the ODGP hindcasts. Excluding the METOC extreme which is based primarily on visual observations, the 100-year return period H_s estimates are in agreement. The METOC overestimation is consistent with analyses reported by Jardine (1979) which illustrate that the distribution of observations is biased to give higher probabilities to high sea states.

Table 5.5

Some Wave Criteria from Published Sources for Hibernia and the Grand Banks

Location	Wave Height Hs (m)	Return Period	Record Period	Data Source
Hibernia	14.4	100-year	1951-84	ODGP hindcast Mobil (1985) Borgman model; mean value
Hibernia	14.3	100-year	1980-84	Waverider database Bolen et al. (1989) Weibull model; mean value
Hibernia	14.3	100-year	1957-88	ODGP regional hindcast MPL&Oceanweather (1990) Borg man model; mean value
Hibernia	15.6	100-year	1970-80	METOC chart analysis Neu (1982) lognormal; mean value
Hibernia area	13.8	observed maximum	1980-85	Waverider database Seaconsult (1988) re-processed MEDS data

Other wave parameters have been estimated for Hibernia’s long return period sea states. Seaconsult (1985) investigated the ratio of H_m to H_s for 12 severe events in the Waverider database using careful quality control of the sea surface elevation data. That study showed that the ratio is quite variable and was observed to exceed 2 at some time in most storms. In another study of 23 Grand Banks storms (Seaconsult, 1988), it was found that the maximum wave height in a storm tended to occur before peak sea state was achieved. Three ratios were calculated:

(1) based on the two storm-maximum values without regard to time of occurrence, for which the average was 1.7 in a range from 1.3 to 2.2;

(2) based on the time-coincident values from the record containing H_m(storm-max), for which the average was 1.9 in a range from 1.3 to 2.4; and

(3) based on the time-coincident values from the record containing H_s(storm-max) for which the average was 1.5 in a range from 1.3 to 1.9.

Cardone et al. (1989a) report a value for ratio (1) of 1.84±0.06 based on a Borgman storm integral of hindcast data and a modified Rayleigh distribution of individual wave heights. MPL and Oceanweather (1990) used 1.869 for the Hibernia site. The largest wave in the Grand Banks data set up to the end of 1985 was 24.8 m high in a record from December 22,-1983 (Fig. 5.7); the ratio of H_m to H_s in this record is 1.8. The ODGP ratios are reasonable, but not overly conservative.

Concern was expressed at the Hibernia EIS hearings that episodic wave occurrence had not been adequately addressed in the extreme wave height estimates (CNOPB, 1986). Such waves are sometimes called freak or rogue waves to denote their rare, unpredictable appearance in relation to the background sea state. A catalogue of some suspected episodic wave events and a discussion of possible explanations can be found in LeBlond (1982). In the Grand Banks database of storm waves, there is no evidence of such events.

Wave period parameters and spectral energy distributions from hindcasts should not be used in design since their empirical formulation is too strictly prescribed to model nature well. On the Grand Banks there is little reason not to rely on measurements since at least the two most severe hindcast storms are well represented in the Waverider database. Peak spectral period is correlated with significant wave height as is individual wave period and height, but the period distribution is observed to have a relatively broad range (Seaconsult, 1988) that is predicted to be asymmetric about the mode for extreme individual waves (Cavanie et al., 1976). There is a wealth of spectral data for the Grand Banks. Empirical JONSWAP spectra can be prescribed readily as a function of wave height based on fitting to the measurements as described by LeBlond et al. (1982). Some directional spectral measurements were made during moderate storm conditions at the Terra Nova wellsite in the fall of 1985 (storms 19-23 in Table 5.4) in which some evidence of multi-directional sea-states was found (Seaconsult, 1988).

5.2.3 Structural Icing Criteria

The majority of reported vessel icing observations in Canadian waters occur on the Grand Banks and in the waters south of Newfoundland (Roebber and Mitten, 1987). Freezing spray is the usual cause of ice accretion and may be the result of wind-blown spray from whitecapping waves or of impact between waves and a vessel. Ice accumulation can cause serious stability problems for small vessels by increasing mass above the water line. Brown and Roebber (1985) report the following typical icing event characteristics on the east coast: the average duration of icing events is 15 hours, although some events exceed 80 hours; icing rates of the order of 7-10 cm/24 h; and accretion thicknesses of 5-6 cm.

Drilling rigs are less susceptible to severe icing because the exposed surfaces are mainly columns, diagonal members and anchor chains, all located below the working deck. There are a few documented cases of icing on drilling platforms while operating on the Grand Banks (see, for example, Brown and Horjen, 1989).

Because there is no suitable database of reliable icing observations, modelling is used to estimate extreme icing rates and accumulations. These models are calibrated and verified with observations and then used to hindcast severe events using historical meteorological data. A review of a wide range icing models that have been used in the past is presented by Brown and Roebber (1985). The large degree of empiricism in the models and the lack of reliable ice accretion data from vessels are the main factors that contribute to the generally poor performance of spray icing models (Brown and Horjen, 1989; Brown and Roebber, 1985).

Two models for icing on drilling platforms (RIGICE and ICEMOD) are described in detail by Brown and Horjen (1989) with verification results from wind tunnel experiments and case studies on the Grand Banks. ICEMOD is a time-dependent model developed by the Norwegian Hydrotechnical Laboratory and RIGICE is a continuous steady-state formulation developed by AES, Downsview. While both models provide good predictions for warmer water, low wave height conditions, neither was successful for cold water, high wave conditions that are typical of Grand Banks icing events. In the latter case, both models overpredicted the accreted ice mass.

Based on the outcome of the Brown and Horjen study, extreme spray icing statistics cannot be estimated reliably for drilling platforms on the Grand Banks with existing models.

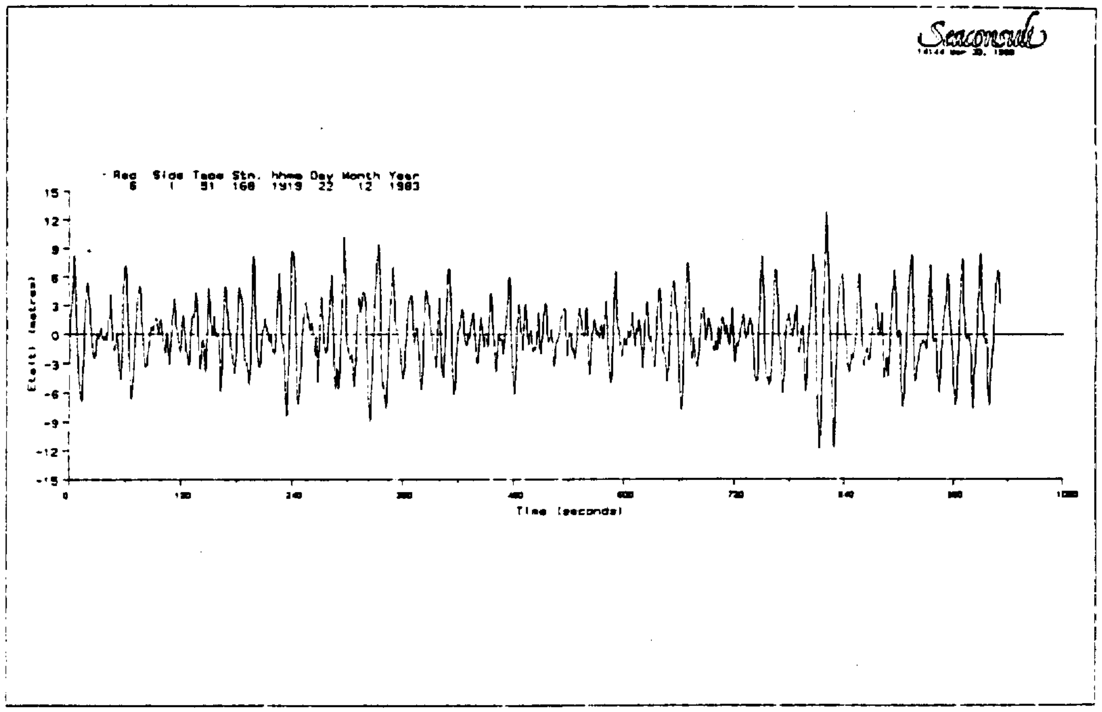

Figure 5.7 Time-series of measured sea surface elevation containing the largest measured individual wave in the Grand Banks database.

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5.3 Labrador Sea

The Labrador Sea lies between Greenland and the Labrador coast, and is considered to extend south to about 53°N for the discussion presented here. The South Labrador Sea is exposed on the east side to the North Atlantic and thus its climate is influenced by North Atlantic cyclones and the wave climate is prone to swell. The petroleum leases in the Labrador Sea extended in a relatively narrow band on the Labrador Shelf, about 50 to 100 km offshore (Fig. 5.8). Exploration was active in this area from 1971 to the early 1980s, resulting in at least 23 drilled wells. Environmental conditions, particularly sea ice and icebergs, led to short, expensive drilling seasons.

In comparison with areas further north, the Labrador Sea has a relatively good body of historical climate data. From 1946 to 1974, the Ocean Weather Ship Bravo was centrally located in the area, roughly midway on a line joining the southeastern tip of Labrador and the southern end of Greenland. There has been enough ship traffic and drillship activity in the South Labrador Shelf area in the open water season (mid-July to late November) to derive fairly reliable climatological statistics from the COADS database. Hogben and Lumb's (1967) wave statistics included the Labrador Sea in their most northerly Atlantic zone although the extent of the zone is too great to provide meaningful statistics for the Labrador Shelf. The METOC office in Halifax has produced wave charts for the area from which extremes have been derived (Neu, 1982), but like Hogben and Lumb's data, the METOC forecast domain does not extend to the northern Labrador Shelf.

Bursey et al. (1977) presented a brief climatology of the Labrador Sea, including expected storm tracks and some mean monthly statistics. They mention unofficial reports of katabatic (down slope) winds that approach 200 knots in the Torngat Mountains area adjacent to the northern Shelf. Offshore they found no evidence of hourly mean winds exceeding 100 knots. Climatological summaries such as MEP (1984) suggest that the Labrador Sea has a weather environment (wind, visibility, temperature) that is midway between its neighbours, more severe than Davis Strait to the north and less severe than the Grand Banks to the south. Because the principal storm tracks are from the south, the description by Keliher et al. (1978) is also useful.

5.3.1 Wind Criteria

As in most areas, the longest continuous measurements at sites closest to the offshore well sites are from shore stations: in this case, Hopedale, Cartwright, and Battle Harbour (on the southeast tip of Labrador). Analyses by Bursey et al. (1977) and Petro-Canada (1980) have demonstrated that the local shore stations are not representative of the marine wind climate.

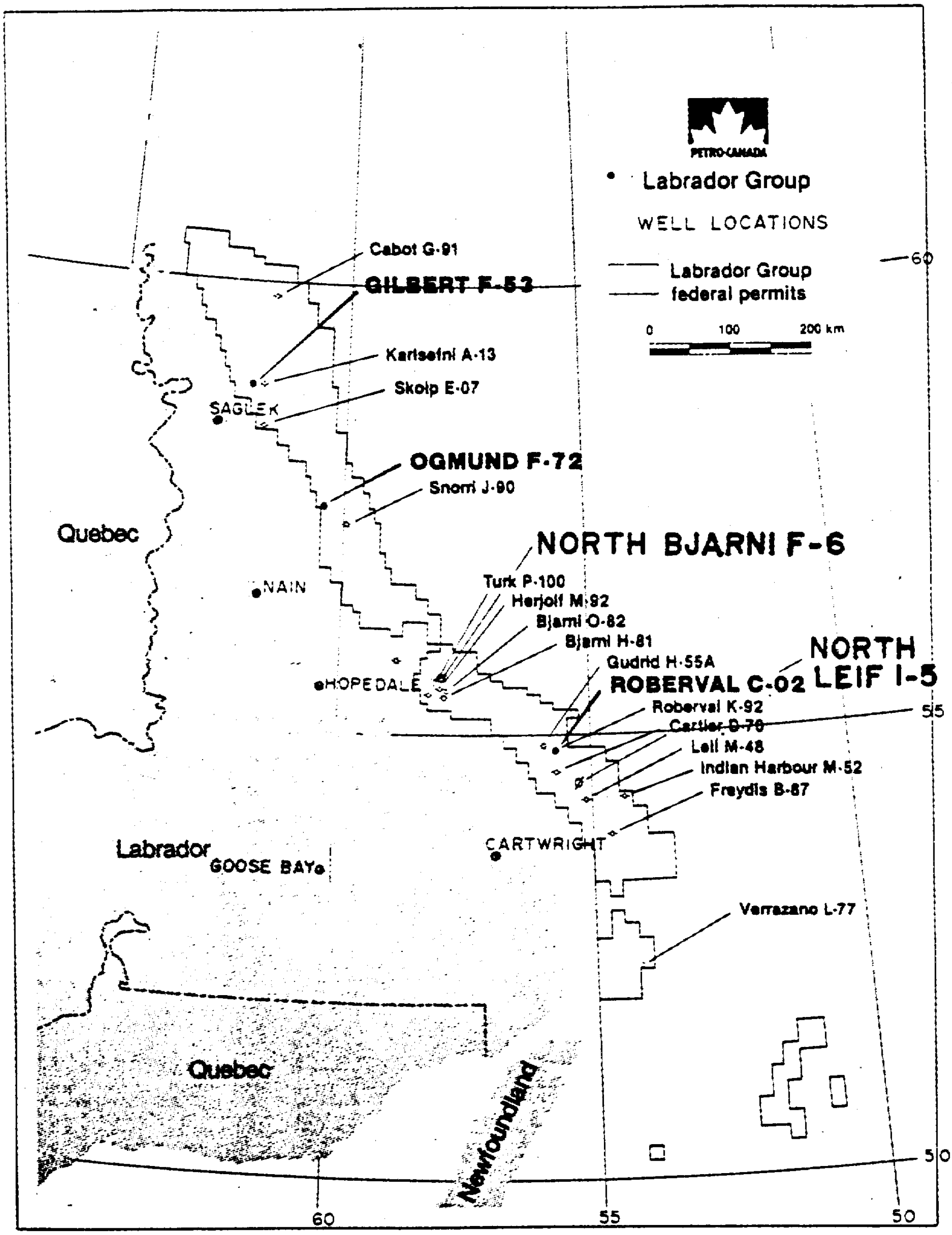

Figure 5.8 The Labrador Sea offshore lease permit areas. From Eastern Offshore News, 3(1).

OWS Bravo recorded the most reliable marine weather in the area, and this data set is a standard by which hindcast data are evaluated. Petro-Canada (1980) felt that the Bravo wind regime was more intense than on the Labrador Shelf, but they did not quantify the amplification. Contoured plots of the GWC monthly mean wind fields do show a diminishing trend in wind speed from Bravo to the central and north coast, but in the open water season the gradient is weak.

Davidson (1983) compared GWC (1946-75) and drilling rig winds (1973-80) for the northern and southern Labrador Shelf areas. For the central Labrador Sea he used GWC and Bravo (1946-71). His tables show that GWC tended to slightly overestimate high wind speed in relation to Bravo records. On an annual basis, Bravo winds exceeded 49 knots less than 1 % of the time whereas 2.7% of GWC winds were greater than 49 knots. August, GWC tended-to be biased low in comparison with rig winds on the northern Shelf where GWC had almost 7% fewer wind speeds exceeding 19 knots. On the southern Shelf in August, GWC and rig winds were in good agreement. In October, GWC winds were biased slightly low on the northern Shelf, but were considerably higher than the rig winds on the southern Shelf. October GWC maximum winds on the southern Shelf exceeded 78 knots although rig measurements were never higher than 58 knots. While the rig data are limited and conclusions drawn from them may be weak, the trends to GWC over-prediction in the winter and under estimation in the summer are also found in other arctic observations.

Aside from GWC and Bravo there are no resources with enough data to estimate long return period marine winds. Swail (1985) and Mortsch et al. (1985) published extremes based on a Gumbel analysis with method of moments fitting of the GWC database. From Mortsch et al. (Fig. 5.9) the contours of mean monthly wind speed are essentially along the axis of the Labrador Sea, i.e. shore-parallel, with values diminishing from the centre towards either coast. The calculated extreme wind speed contours are roughly perpendicular to the coasts and diminish in magnitude from south to north. For this seeming contradiction to occur, the variability in wind speed must be higher near the coasts to offset the lower mean value. From the extreme value analysis results, Bravo extremes would tend to over-predict conditions on the northern Shelf and under-predict wind speed extremes on the southern Shelf.

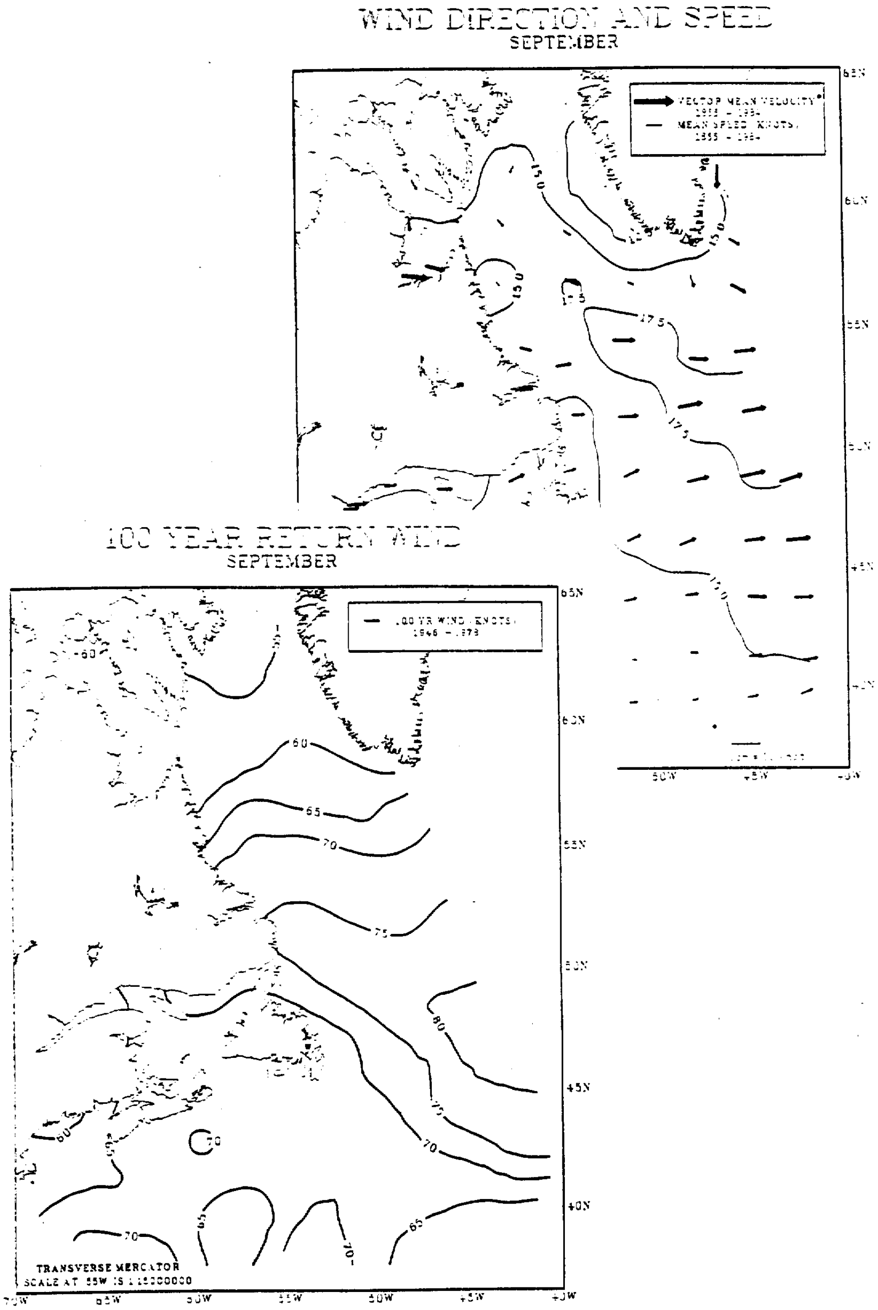

Figure 5.9 Mean and 100-year return period wind speed for September based on the GWC database. From Mortsch et al. (1985).

Table 5.6

Some Wind Criteria from Published Sources for the Labrador Sea and Labrador Shelf

Location	Wind Speed (knots)	Return Period	Record Period	Data Source
OWS Bravo	90.	observed extreme	in Feb 1946-74	Swail et al. (1984)
Bravo area GWC	99.	hindcast extreme	in Jan 1946-78	Swail et al. (1984)
rig winds S. Shelf	≤48.6	observed extreme	for Sept 1973-80	Davidson (1983) (extracted from histograms)
rig winds N. Shelf	≤68.0	observed extreme	for Sept 1973-80	Davidson (1983) (extracted from histograms)
OWS Bravo	62.	observed extreme	for Sept 1946-74	Swail et al. (1984)
OWS Bravo	100. (approx)	100-year	1946-74	Swail et al. (1984)
Bravo area GWC	102. (approx)	100-year	1946-78	Swail et al. (1984)
GWC S. Shelf	105. (approx)	100-year	1946-78	Mortsch et al. (1985)
GWC N. Shelf	100. (approx)	100-year	1946-78	Mortsch et al. (1985)
GWC S. Shelf	70-75 N-S	100-year	for Sept 1946-78	Mortsch et al. (1985)
GWC N. Shelf	57-70 N-S	100-year	for Sept 1946-78	Mortsch et al. (1985)

Note: Wind averaging times and reference elevations vary between sources of data, but are less relevant in this comparison than geographical separation of the locations and methods used to derive extreme values.

Table 5.6 presents some representative values from available reports on maximum observed and estimated extreme wind statistics for the Labrador Sea. The data are not particularly consistent. Although Bravo winds are expected to be stronger than on the Labrador Shelf, the extreme September Bravo observation in 29 years is 62 knots while the maximum September rig measurement on the North Shelf, in no more than 8 years, is about 68 knots. Based on GWC extrapolation, that rig observation was likely a 100-year return event for that month. This limited review of the Labrador wind data suggests that a better hindcast model and more marine data measurements are required on the Labrador Shelf to derive reliable long return period wind statistics.

5.3.2 Wave Criteria

Wave measurements were made at most of the Labrador wellsites using Waveriders and the data are available from MEDS. They are necessarily of short duration and restricted to the Labrador Shelf area; they are not suitable for extrapolation with confidence to long return periods. Visual observations were made at OWS Bravo and are expected to be more reliable than transient ships-of-opportunity reports which have been analyzed and published by Hogben and Lumb (1967) with corrections by Hogben (1974). Neither COADS nor Hogben and Lumb are of much direct use for design criteria.

The METOC office in Halifax prepares 12-hourly wave charts for the Labrador Sea based on a combination of observations (both visual and measured) and hindcasting. The chart data are not considered to be good estimates of sea state when there are few observations. It has also been reported (Keliher and Gibson, 1978) that METOC arbitrarily reduced forecasts of severe sea states. Long return period wave heights have been estimated from the METOC database and published by Neu (1982).

Group Five (1978) undertook a wave hindcast for four locations on the Labrador Shelf for the Labrador Group for the months of July through December. They used automated methods to extract geostrophic winds from the 1970-77 AES synoptic weather charts and reduced the winds to the 10-m level using Hasse and Wagner relationships, ignoring air-sea temperature differences. Their hindcasting method was an automated Bretschneider nomogram technique based on mean wind speed, fetch and duration that accounts for wave growth and decay. Wind field curvature was considered to limit fetch but sea ice, which is not present until December at the earliest, was not.

When comparing the hindcast with Waverider data, Group Five noted that swell, which was not modelled, was at times a significant component of the wave measurements. The report’s authors described the verification as ranging from “relatively poor” in October 1973 to excellent” in

October 1975. Notwithstanding the shortness of the hindcast data set, a Gumbel extreme value analysis was performed using all independent storms with maximum $\overline{H_S}$ of 10 feet (3 m) or more. The authors did not consider the predicted extremes to be reliable beyond the 15-year return period.

Table 5.7 contains some representative values of observed and hindcast extreme H_S values and long return period sea state estimates. Extrapolation of the Group Five hindcast at the 10-year return period is in reasonable agreement with the observed maxima from measurements made over about 7 seasons, but the METOC estimate is appreciably higher. Based on comparisons at Hibernia between METOC and other extreme estimates, the Labrador values are expected to be over-estimated by at least 1 m at the 100-year return level. Improved hindcasting on either a regional or site-specific basis would require better wind data than are now available.

5.3.3 Structural Icing Criteria

Superstructure icing occurred at OWS Bravo from October through May on average (Petro Canada, 1980), but there are few reports of icing reported on the Labrador Shelf (Brown and Roebber, 1985). Chiefly, this observation is due to the presence of sea ice cover, and the absence of vessels, during the winter months of strong winds and low temperatures. Of the existing reports, most occur in March and December and 98% are attributed to freezing spray, with or without freezing fog or rain. The severity in terms of reported accreted thickness and icing rate is lower on the Labrador Shelf than on the Grand Banks or south of Newfoundland. While these findings are reasonable, they are based on few observations.

Table 5.7

Some Wave Criteria from Published Sources for the Labrador Sea and Labrador Shelf

Location	Wave Height Hs (m)	Return Period	Record Period	Data Source
Indian Harbour M-52 S. Shelf	9.4	observed extreme S. Shelf	in Oct 1975	MEDS Wave Summary Station 94
Indian Harbour M-52 S. Shelf	13.2	hindcast of observed extreme	Oct 1975	Group Five (1978)
Indian Harbour M-52 S. Shelf	10.8	10-year	July-Oct 1970-77	Group Five (1978)
S. Shelf area	12.5 (approx)	10-year	1970-80	Neu (1982)
S. Shelf area	16-18 (approx)	100-year	1970-80	Neu (1982)
Snorri J-90 N. Shelf	6.7	observed extreme N. Shelf	in Oct 1975	MEDS Wave Summary Station 18: last record of the season, may precede peak
Snorri J-90 N. Shelf	7.2	hindcast of observed extreme	Oct 1975	Group Five (1978)
Snorri J-90 N. Shelf	7.8	10-year	July-Oct 1970-77	Group Five (1978)
Bravo area	12.8 (approx)	10-year	1970-80	Neu (1982)

5.3.4 References

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5.4 Davis Strait

From the offshore operators' point of view, Davis Strait is the body of water between Baffin island and Greenland, extending north from Resolution Island at the entrance to Hudson Strait to 70°N, roughly at the latitude of Clyde on the east coast of Baffin Island and Disko Island on Greenland's west coast (Fig. 5.10). From some perspectives, this region overlaps southern Baffin Bay and northern Labrador Sea. In the late 1970s there were extensive petroleum leases that covered most of the Canadian side of Davis Strait. In 1979 Esso drilled a well at Gjoa G-37 in the middle of the Strait at about 66°N that was dry and abandoned. Aquitaine (later Canterra) began a drilling program at Hejka A-72, about 100 km northeast of Resolution Island, and confirmed a gas find in 1980 (Pallister, 1981). Interest in petroleum exploration in this area waned rapidly following the significant discoveries on the Grand Banks.

Before drilling was permitted in Davis Strait, the Minister for Indian Affairs and Northern Development required that "a comprehensive environmental assessment" had to be conducted (DIAND, 1981). In response, a joint industry-government initiative known as the Eastern Arctic Marine Environmental Studies (EAMES) project was undertaken between 1976 and 1980. Two general study areas were defined: Baffin Bay and Lancaster Sound in the north and a region in the south encompassing the northern Labrador Sea, Ungava Bay, Frobisher Bay and southern Davis Strait; central Davis Strait was omitted. A summary of the EAMES project (DIAND, 1981) lists their published study reports for the southern section, but includes only one climatological study and one wave climate study for southern Davis Strait. Clearly, the emphasis of EAMES was on regional biology.

Climatological information for the region has been published by Maxwell (1980) based primarily on meteorological shore station records up to 1972, but including some comparisons with marine data from the ships-of-opportunity program. MEP (1984) prepared an offshore climatology from the COADS database. They used observations up to 1981 from the Davis Strait marine weather forecast area which extends from 70°N to 65°N (at the northern tip of the entrance to Cumberland Sound).

As part of the EAMES project, NORDCO prepared a climatological assessment of the Esso acreage that includes an apparently thorough discussion of storm climatology for the area (Keliher et al., 1978). Other east coast storm climatologies (Lewis and Moran, 1984 and Brown et al., 1986) are less useful because they are less focused on Davis Strait and not restricted to the open water season.

5.4.1 Wind Criteria

Keliher et al. derived surface wind estimates for the Esso site by calculating geostrophic winds, apparently by hand, from AES 6-hourly weather charts for the months of September through November from 1958 to 1977 (20 years). They applied reduction factors to the geostrophic values that varied by directional octant and were subjectively selected based on stability considerations. The factors varied from 95% for north and northwest to 75% for south and southeast. There is no suggestion in their report that wind direction was adjusted. Monthly statistics were presented in graphs, but extremes were not calculated. The largest wind speeds were approximately 35-40 knots in September and October, and 40-45 knots in November. In each case, the probability of the maximum range was less than 1 %.

Based on MAST analysis of ship observations between 1892 and 1981 in the Davis Strait marine forecast area, MEP (1984) tabulated mean monthly statistics of wind speed which indicate that Davis Strait is in a weaker wind regime than the South Labrador Sea, Grand Banks and Scotian Shelf. In October, the reported mean monthly wind speed is greater than 36 knots 5% of the time. In July and August the same statistic has a value of 25 knots. Maxwell (1980) showed for marine area 29 in south-central Davis Strait (centred at about 64.5°N 60°W) the hourly wind speed will exceed 28 knots 5% of the time in the July-to-October period. All other marine areas in the Davis Strait region have lower wind speeds at the 5% exceedance level.

Using shore station records and marine observations between July and October, Maxwell (1980) also calculated mean wind statistics and used them to estimate water-to-land speed ratios. In the Davis Strait region, only Resolution Island airport winds were close to adjacent marine winds (ratio= 1.05 based on almost 3400 observations). By contrast, the Cape Dyer ratio was 1.69 (from almost 2300 marine data values) and the Brevoort Island value was 1.46 (although only 870 offshore reports were available).

Maxwell also reports the annual mean and extreme hourly wind speeds for the standard shore stations. Although it is not clear, the extreme value seems to be the largest observation in the data set. At Resolution Island airport the quoted extreme is 78 knots, and hence about 82 knots in the adjacent offshore area by applying Maxwell’s 1.05 ratio. Maxwell also gives a 20-year return period wind speed of 85 knots for Resolution Island airport, or 89 knots offshore. This extreme estimate is based on annual observed maxima, but details of the analysis methods are not presented.

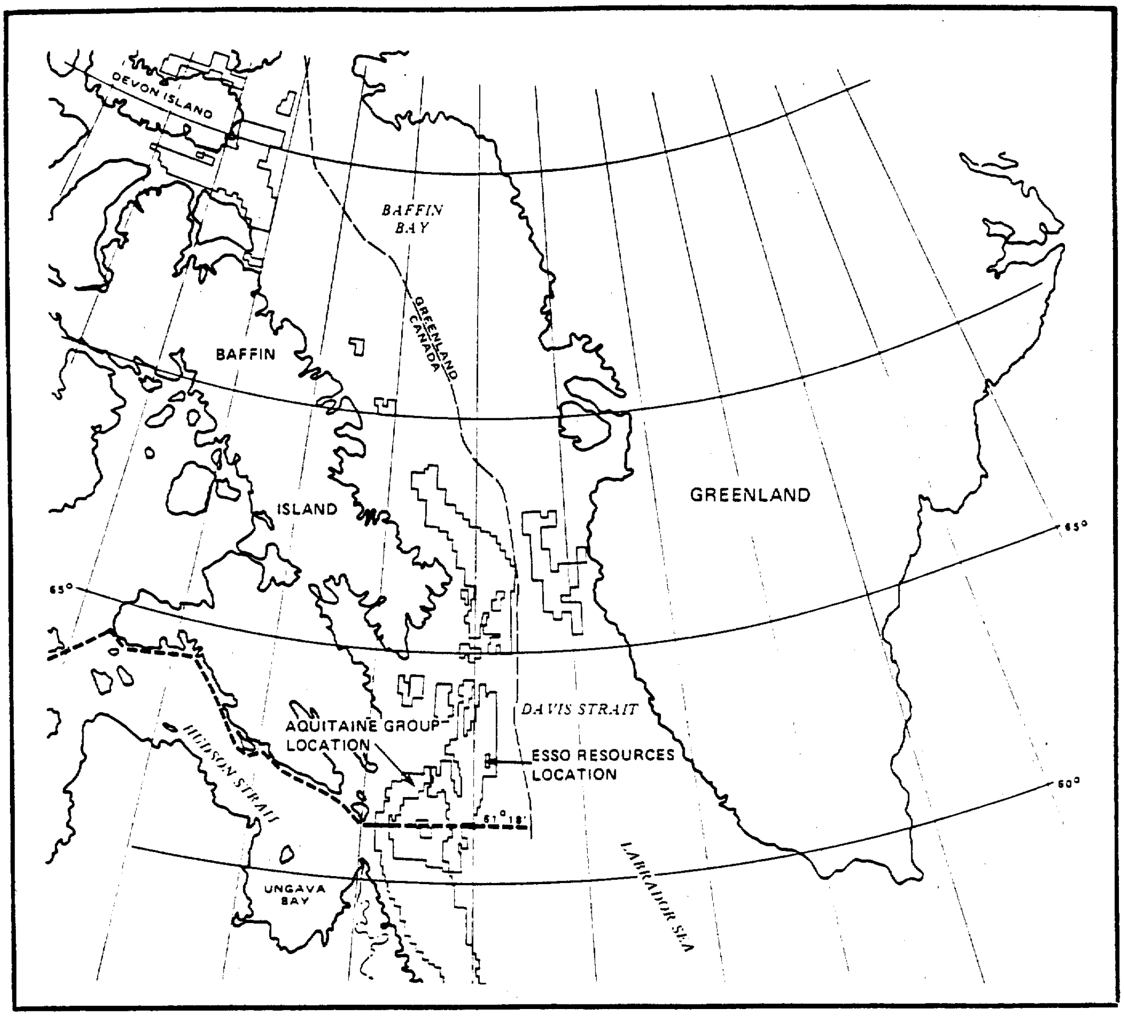

Figure 5.10 The Davis Strait area showing federal petroleum permit areas in 1979. Adapted from *Eastern Offshore News*, **1**(1).

The GWC database has a grid point close to Resolution Island that was included in a comparison by Olson (1986). He found that GWC over-estimated the mean wind speed in January-February by more than 20%, but considerably underestimated it in August-September(5.7 versus 2.2 knots). Using the GWC database, Swail (1985) estimated a 100-year return period wind speed in September of roughly 55 knots for Davis Strait. Based on Olson's comparison, it seems likely that the summer extreme estimates are low. In November the 100-year return prediction varies between about 75 knots at the latitude of Resolution Island and less than 55 knots at the north end of the Davis Strait region, but the accuracy of these estimates cannot be assessed. On an annual rather than monthly basis, the 100-year return-period wind speed varies from about 93 knots at Resolution Island to 65 knots near 700 N. Compared to Maxwell's (1980) 20-year return derivations, GWC extremes appear to be low for Davis Strait.

5.4.2 Wave Criteria

Using surface wind time-series derived by Keliher et al. (1978), Keliher and Gibson (1978)estimated a corresponding significant wave height time-series using a computerized implementation of the Bretschneider nomogram method (LaLande, 1975 and Venkatesh, 1975). The geostrophic winds were reduced by subjective factors on a directional basis to account for atmospheric stability. In this case, there were two sets of factors: one for unstable conditions, which the authors believe are applicable, and a lower one for relatively stable-regimes to test sensitivity. Fetch was considered fairly carefully to account for landmass restrictions and for assumed isobar curvature. Since only September, October and November were hindcast, sea ice was not a factor.

Keliher and Gibson (1978) present their results as height and direction histograms, time-series listings for events with winds exceeding about 40 knots, and bivariate histograms of wave height and direction. Using their preferred geostrophic wind reduction factors, the calculated maximum wave height in 20 years was 13.4 m with a corresponding average wind speed of 65 knots on October 21,1967. They did not calculate extreme values with this data set.

A rough indication of low probability wave height levels can be gleaned from published analyses of the METOC charts. The chart domain does not extend beyond the Labrador Sea,but since the wind regime and wave height diminishes with increasing latitude in this region,an upper limit on H_S at long return periods can be extracted. From examination of contoured H_S plots published by Neu (1982) the estimated 10-year return period H_S value at the latitude of Resolution Island is about 11 m and the 100-year value in the same location is 16 m. These estimates are in reasonable agreement with the Keliher and Gibson (1978) hindcast.

There are three partial years of Waverider measurements at the Aquitaine (Canterra) wellsites near Resolution Island. Each year the buoy was removed by the first week of October, so severe winter storms are not represented in the records. The largest significant wave height in the data set is 5.35 m on July 26, 1980. From the spectral wave information, it appears to be a locally generated sea state with a peak spectral wave period of about 10.5 s. At other times, swell energy is present that is characterized by 2 to 3 m significant wave height with peak period in the 12 to 14 s range.

5.4.3 Structural Icing Criteria

The MEP (1984) climatological analysis of marine data indicates reports of vessel icing exceeding 6 cm/24 h in October and November. Otherwise, there are no known studies of either climatological or extreme structural icing in Davis Strait.

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5.5 Northwestern Baffin Bay and Lancaster Sound

Lancaster Sound provides a study in the conflict between environmental protection and economic development of natural resources because the area is a major ecological habitat for arctic mammals, birds, fish and marine plant life. The primary issues have been reported in a useful review by Milne and Smiley (1978).

In the 1970s offshore petroleum leases were issued for the waters north of Baffin Island. They extended westward from about 76°W to 85°W to include the eastern halves of Lancaster Sound and Jones Sound (see Fig. 5.11). Seismic surveys were carried out on acreage leased by Norlands Petroleums, Magnorth Petroleum, Petro-Canada and Shell Canada Resources that revealed large favourable geological structures (Pallister, 1981). Several oceanographic studies were undertaken, principally by Petro-Canada, to understand the primary factors that affect safe operations in the area: sea ice, icebergs and water mass circulation. Norlands' proposal to drill was rejected in 1979 by the Federal Environmental Assessment and Review Office pending further study of the environmental issues. Petro-Canada's plans for drilling were postponed indefinitely in 1982.

Lancaster Sound is the eastern entrance to the Northwest Passage which has been proposed as a main transportation corridor to move arctic resources to southern markets. To date, there has been little pressure to advance this option due to relatively depressed markets for petroleum products.

All studies reviewed here were completed between 1977 and 1983, and the principal ones have been summarized by Fraser (1983).

5.5.1 Wind Criteria

From the environmental design perspective, this region is exceedingly data deficient. Local topography influences most arctic monitoring sites and renders them unrepresentative of overwater conditions. Funnelling (acceleration through constricting passes), katabatic (downslope)flows and anabatic (upslope) flows are observed phenomena in this part of the eastern arctic (Maxwell, 1980; Parker and Alexander, 1983). There is also a tendency for east-west channelling in Lancaster Sound (Maxwell et al., 1980). In consequence of these local wind effects, most shore station data are not reliable for other than local criteria. The obverse argument means that regional wind hindcasts may not yield representative criteria near shorelines.

Over-water wind records from transient ships are not plentiful, and are limited to the open water season from July to October. The only database with reliable, regularly-sampled data that applies to the entire region is the NEDN archive. The distribution of NEDN grid points is shown in Fig. 5.11 .

In this area, wind maxima are not as large as in other offshore regions. However, wind is an important operational factor in the approaches to and entrance of Lancaster Sound because it is one force that governs sea ice and iceberg movement, and it promotes development of freezing spray.

General climatology for the area may be found in Maxwell (1980). Presentations are in terms of monthly mean and extreme wind speed, mean monthly wind direction, and monthly maximum wind speed persistence observations at shore stations, but due to local wind modification, these data are of limited use for specification of environmental criteria. Some marine data from transient ships are also presented, although the analysis period ended in 1973. A useful description of storm climatology for the open-water season is provided by Fraser (1983).

The only long-term, continuous wind observations from a site that is relatively unaffected by local topography are from Resolute on the south shore of Cornwallis Island, some 400 km west of the entrance to Lancaster Sound (Lachapelle and Maxwell, 1983). Maxwell et al.(1980) compared 20 years of Resolute wind data, measured at 65 m, with all available observations from marine area 12 east of Lancaster Sound in northwest Baffin Bay (approximately 1000 reports over 32 years). They found reasonable agreement in the summer (July-September), but by October, the marine winds are stronger than the Resolute data. Based on this comparison, they concluded that Resolute winds could provide statistical estimates of normal conditions for northwest Baffin Bay, at least for July through September,without modification to speed or direction. However, possible sheltering to the northeast and southwest, and observations of extremely unsteady surface winds during moderate northeasterly flow aloft need to be considered.

As noted in the AES Climatological Station Data Catalogue for the North, Resolute wind data were determined from 45B autographic records (i.e., one-hour mean wind speed) until the end of 1966. Thereafter, one-minute mean values have been read from a U2A dial. This change in averaging period may cause a small increase in wind speed statistics after January 1, 1967, and more variability in speed and direction observations.

Maxwell et al. (1980) also derived extreme wind estimates for northwest Baffin Bay from the Resolute data. Adjustment factors were applied based on low-level air stability and wind direction for wind speeds greater than or equal to 20 knots to estimate over-water winds. The adjustments were not verified, probably due to lack of high speed marine observations. The extreme value analysis “follows the Gumbel technique,” but details of sampling and fitting have been omitted. The

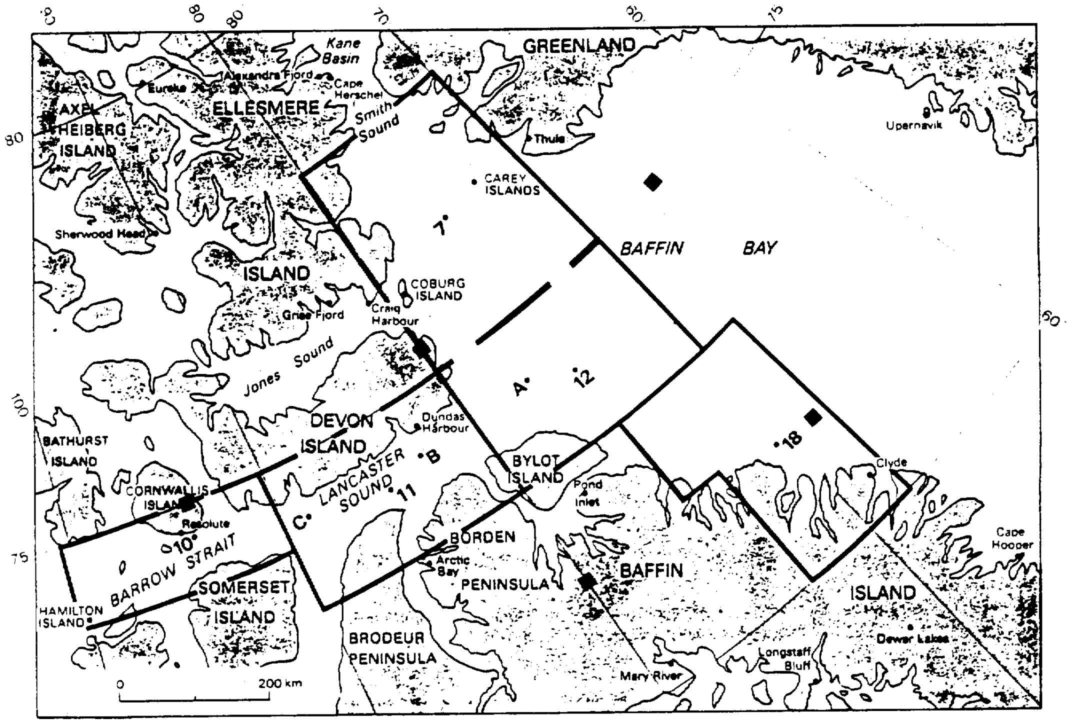

Figure 5.11 Northwestern Baffin Bay and Lancaster Sound showing the marine area definitions (7, 10, 11, 12, 18), the Lachapelle and Maxwell (1983) hindcast sites (A, B, C), and the NEDN grid locations (■). Adapted from Fraser (1983).

method used to determine the confidence limits is not explained and may not be valid.

The gridded NEDN surface pressure data have been used twice to derive geostrophic winds as estimates of surface winds for Lancaster Sound and northwest Baffin Bay. Lachapelle and Maxwell (1983) concentrated on the eastern arctic, whereas Swail (1985) addressed all-Canadian offshore areas to produce the GWC database. Because the NEDN pressure gradients tend to be weak, surface winds that-are derived from them will also tend to be weaker than the true surface speed. Comparisons have shown that unmodified geostrophic wind speeds, calculated from NEDN surface pressure fields, agree reasonably well with surface wind measurements at sites like OWS Bravo and Resolute (Lachapelle and Maxwell, 1983; Olson, 1986). However, the expectation that the NEDN-based geostrophic winds should exceed the true surface wind speed is not realized in all cases. Olson (1986) found, for example, that ship data had higher mean and maximum wind speed values in his data set (August/September 1975-77) than either GWC or Resolute shore station data. Comparison plots in Lachapelle and Maxwell (1983) suggest the same trend to higher marine observations in Lancaster Sound and northwest Baffin Bay. As a result, confidence in NEDN-based geostrophic winds is low in this region, and the surface wind extremes derived from them should not be considered necessarily conservative.

Table 5.8 presents some representative wind criteria from published sources. They are indicative of the range of estimates that have been derived, but none are suitable for design criteria.

5.5.2 Wave Criteria

Since there are no wave measurements, wind and wave hindcasting are essential to estimate design wave and coincident wind criteria. The only source of verification data is from the COADS database, although the objections to wave observations from transient ships are numerous. Continuous hindcasts are necessary to derive wind and wave persistence statistics for marine locations.

Both Maxwell et al. (1980) and Lachapelle and Maxwell (1983) estimated significant wave height from wind data using the Bretschneider nomogram approach (U.S. Army, 1977). Although the hindcasting methods were unsophisticated, they were probably appropriate for the quality of available wind, wave and ice cover data. Maxwell et al. used the modified Resolute winds and applied them in northwest Baffin Bay while Lachapelle and Maxwell used the NEDN-based geostrophic estimates to hindcast waves at three locations (see Fig. 5. 11).

The two hindcasts for marine area 12 differ in their procedures. Maxwell et al. (1980) used selective storm hindcasting based on wind speed, direction, duration and fetch. Ice cover charts for each storm were consulted to determine fetch. Descriptions of the study suggest that a mean wind speed, determined over the event duration, was used to obtain a single estimate of Hs for each storm. This method does not account for variability in the wind field such as growth and decay in speed and turning wind directions, and it is therefore approximate at best. If directional shifts were ignored, the procedure could tend to over-estimate H_S by over-long estimates of the duration of the mean wind speed.

Lachapelle and Maxwell (1983) automated the wave hindcast procedure to produce a continuous H_S time-series for the June through October period for the years 1956-71 and 1974-78. Although details of the method are not provided, they apparently accounted for wind speed and direction evolution. Fetch estimates were based on straight line distances to land or ice without regard to isobar curvature. Ice edges were imposed at climatological monthly minimum limits, thereby giving maximum fetches. Fraser (1983) concluded that the wave hindcast results in Lancaster Sound (Lachapelle and Maxwell points B and C) were invalid because the derived winds did not account for topographic effects and, hence, were too light. At point A in marine area 12, the wave height is probably over-estimated due to over-long fetch values.

In both wave hindcast studies, there are so many unquantifiable sources of error that confidence in the results and in extremes derived from them is low. Neither set of authors described their methods of extreme value analysis in more detail than comments such as “based on Gumbel statistics.” Table 5.9 presents some published significant wave height estimates from the hindcasts and from observations; none of them are appropriate for design criteria.

Table 5.8

Some Wind Criteria from Published Sources for Lancaster Sound and Northwest Baffin Bay

Location	Wind Speed (knots)	Return Period	Record Period	Data Source
Resolute	56.7	observed extreme	Sept 1953-72	Maxwell (1980)
Resolute area GWC	48.	hindcast extreme	Aug/Sept 1946-78	Olson (1986)
Resolute area ship data	52.	observed extreme	Aug/Sept 1975-77	Olson (1986)
Marine Area 12	47.2	hindcast extreme	Sept 1946-78	Lachapelle and Maxwell (1983)
Marine Area 12	51.1	50-year	Sept 1946-78	Lachapelle and Maxwell (1983)
Marine Area 12	61.6	50-year	July-Oct 1946-78	Maxwell et al. (1980)
Marine Area 12	50. (approx)	100-year	Sept 1946-78	Swail (1985)

Table 5.9

Some Wave Criteria from Published Sources for Northwest Baffin Bay

Location	Wave Height Hs (m)	Return Period	Record Period	Data Source
Marine Area 12	7.3	observed extreme	1956-78	Lachapelle and Maxwell (1983)
Marine Area 12	8.7	hindcast extreme	July-Oct 1956-71 1974-78	Lachapelle and Maxwell (1983)
Marine Area 12	9.0	20-year	July-Oct 1956-71 1974-78	Lachapelle and Maxwell (1983)
Marine Area 12	8.1	20-year	July-Oct 1954-77	Maxwell et al. (1980)

5.5.3 Structural Icing Criteria

Maxwell et al. (1980) also estimated structural icing rates for severe temperature and wind conditions in marine area 12 during the open water season, again based on adjusted Resolute wind data. The estimates were determined by linear interpolation of nomograms published by Mertins (1968). Sea surface temperature was set at 1°C for September and 0°C for October. Consideration was not given to sources other than freezing spray, and all events were treated as independent occurrences.

As with other variables, the statistical methods were not described. At the 20-year return period, Maxwell et al. (1980) forecast 18.2 cm accumulation of structural icing. Based on this data set, Fraser (1983) estimated that the threshold for severe icing (≥ 7 cm/24 h) is met or exceeded 31.2 hours per year on average.

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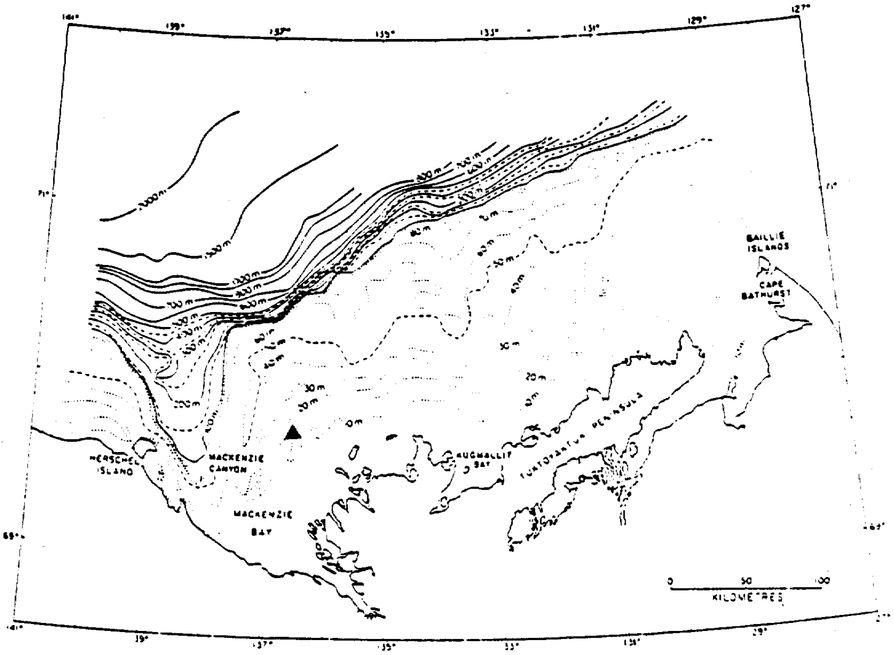
5.6 Beaufort Sea

The area of interest in the Beaufort Sea is mainly on the continental shelf and extends roughly from Herschel Island on the west side of Mackenzie Bay to Cape Bathurst at the western entrance to the Amundsen Gulf (Fig. 5.12). In this area, the shelf is gently sloping and wide; the 100-m isobath is approximately 150 km offshore.

In the Beaufort, conventional drillships and rigs have a limited scope of operation. In water less than about 20 m deep, which represents at least 25 % of the area, artificial island technology has been employed: sandbag-retained, sacrificial beach and caisson-retained forms have been used. A sandbag-retained island or similar concept has a stabilizing armour on moderately sloped sides to minimize wave and current erosion. The sacrificial beach island has a long, gradual slope to dissipate wave energy through erosion, but it requires large amounts of dredged fill. Issungnak, in 20 m of water with a 135-m diameter at 6.3 m above water, required almost 5 million cubic metres of fill (Pallister, 1981). The caisson-retained island is comprised of a steel shell filled with sand and water ballast seated on a sand berm. The steel structure has side slopes of 600 to 900, thereby reducing the requirements for fill.

Hydrocarbon production in this area has also examined the feasibility of a pipeline to export products to the south through the Mackenzie Valley. Proposed pipeline routes have focussed- on shore crossings at North Point on Richards Island as one possibility. Significant design problems are associated with the stability of trenches during construction, the stability of backfill, and the stability of the pipeline under storm wave and current loads. A discussion of the relevant geotechnical considerations and measurements of storm-induced sediment transport and pore water pressure changes is given in Hodgins et al. (1986) and Hodgins (1988).

For both fixed platform construction in shallow water, and for pipeline design and construction, the serious open-water season problems occur during storms. Destruction of the Minuk sand island platform and drilling rig by erosion in a prolonged storm in September 1985 emphasized the importance of wave height and duration when considered the effects of severe weather. The minimum wave criteria for design thus consist of time histories of wave height, period, and direction (Table 3.1) for severe storms. In general the 100-year return period Hs value by itself is insufficient.



▲ Minuk: 69°42'06"N
136°27'07"W

Figure 5.12 Map of the Beaufort Sea showing the Minuk exploratory drilling site on the continental shelf.

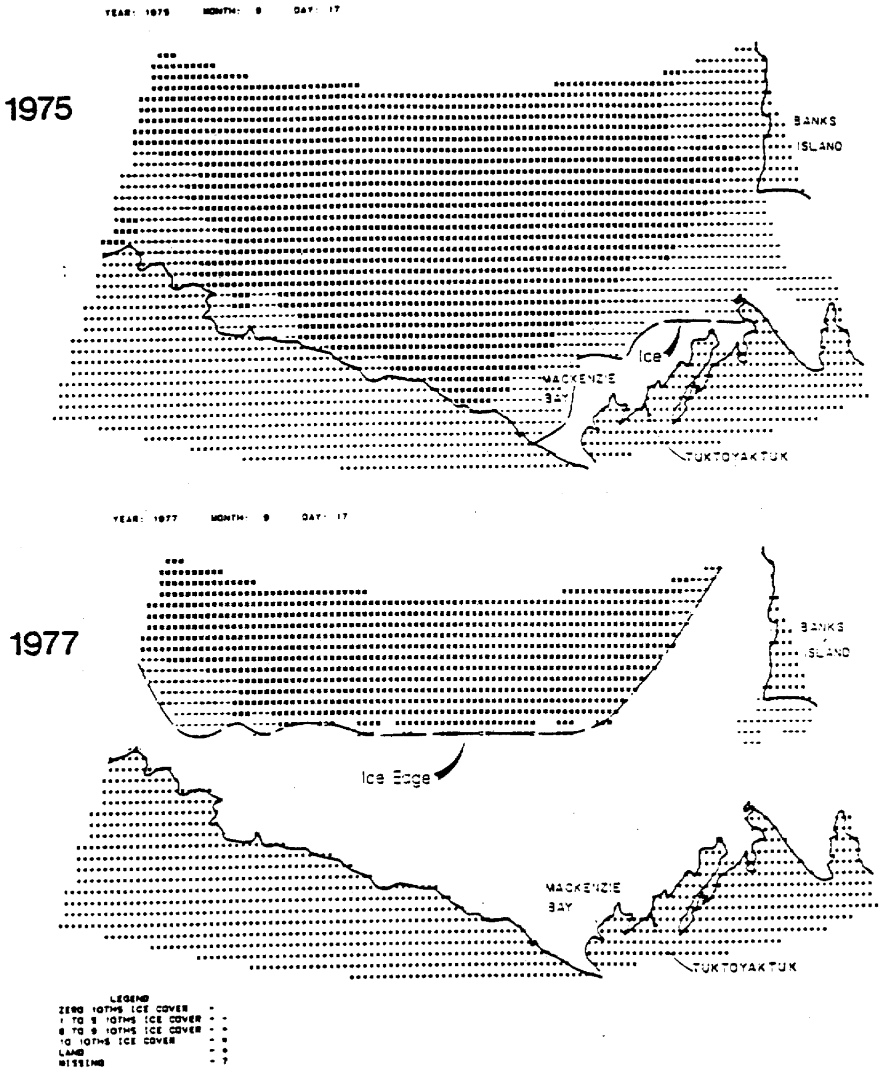


Figure 5.13 Beaufort Sea ice maps for the week of September 17 in 1975 and 1977. (Source: Hodgins, 1983)

The open-water season in the Beaufort is governed by break-up of the pack ice. AES weekly ice charts usually indicate some open water from June through October (Seaconsult, 1982). However, the year-to-year variability can be quite extreme as illustrated by the contrast in open water in the week of September 17 for 1975 and 1977 (Fig. 5.13). Often, as in the 1975 map, there is a wide marginal ice zone that can quite mobile under storm conditions.

Early, quite limited discussions of both normal and severe weather during the open-water season are presented in the publications of Burns (1973) and Berry et al. (1975). However, in each publication the review of the nature and characteristics of major storms was limited to a few case studies. A more comprehensive storm climatology was prepared by Hodgins and Harry (1982) using 12 years of CMC chart data (1970-1981). This climatology classified storms affecting the Beaufort Sea into three categories by trajectory (and hence peak wind direction over open water) and derived statistics on monthly occurrence and central pressure.

By combining the storm occurrence frequencies with open water fetch occurrence statistics, the joint frequency of severe wave generating conditions was examined.

More recent reviews of Beaufort Sea storm climatology were prepared by Mep (1986) and Lewis (1987), and hindcast winds for a set of severe events, covering both the open-water summer season and the winter months, are contained in the Beaufort Sea Wind Hindcast.

5.6.1 Wind Criteria

Extreme wind criteria for this area were derived in a number of hindcast studies conducted in the early 1970’s and the early 1980’s; the results were summarized in Hodgins (1983) and several of the criteria derived from measured winds, or from an analysis of grid point pressure data, are summarized in Table 5.10 . The overwater extremes are interpreted as 1-h mean wind speeds at a reference height of 10 m (or indeterminate) and are assumed to apply to an offshore site removed from the influence of land on the wind profile (e.g. the Minuk site in Fig. 5.12). The three offshore values agree well considering the independence of data sources and treatment of overland to overwater wind speed.

It is often stated in the cited reports for the Beaufort Sea that offshore winds are much stronger than the winds measured at coastal stations. The last two entries in Table 5.10 (Agnew et al.,1987), which were derived from measurements at Sachs Harbour and Tuktoyaktuk, illustrate this conclusion: the offshore wind speeds are about 40% higher than extremes along the coast.

Olson (1986) shows that the GWC winds near Tuktoyaktuk compare favourably with the Tuk anemometer data for extreme speed, but are less reliable for wind direction. However, the offshore ships-of-opportunity data indicate that both Tuk and GWC winds speed extremes are about 30% low, confirming the bias noted previously.

Given the general lack of multi-year wind observations over open water in the Beaufort Sea,derivation of wind criteria must rely upon transforming coastal measurements to the site of interest, upon wind hindcasting methods, or a combination of both approaches.

5.6.2 Wave Criteria

As exploration for hydrocarbon resources commenced in this region, hindcast studies for extreme wave criteria were commissioned by various operators. The studies conducted in the early 1970’s were constrained by data on winds and the results have been extensively reviewed by Hodgins (1983) and Murray and Maes (1986). The results from the earlier studies were superceded by two later studies (Hodgins et al., 1981; Baird and Hall, 1981), and some proprietary industry studies. In each case, however, the emphasis was place on determining the significant wave height at long return periods.

Some of the results for H_S at a 100-year return period are summarized in Fig. 5. 14 : the hindcasts based on parametric wave models forced by overwater winds transformed from coastal stations cluster between 5 and 7 m. The Seaconsult (Hodgins et al. 1981) study, based on maximum open water wave generating area, gave a 100-year return value of 11 m over the shelf. All results apply to deep water. Hodgins (1983) later argued that consideration of the sea ice restrictions on fetch would reduce this 100-year extreme to between 8 and 9 m. A definitive deep water wave height criterion is presently unavailable.

Table 5.10

Some Wind Criteria from Published Sources for the Beaufort Sea

Location	Wind Speed (knots)	Return Period	Record Period	Data Type and Source
offshore Beaufort open-water season	67.	100-year	1956-1974	coastal winds transformed to overwater winds Berry et al. (1975)
offshore Beaufort open-water season	59.	100-year	1970-1978	coastal winds transformed to overwater winds Baird and Hall (1980)
offshore Beaufort open-water season	60.	100-year	n.a.	hindcast storm winds Hodgins et al. (1981)
Sachs Hbr. September	46.	100-year	unknown	coastal winds unmodified Agnew et al. (1987)
Tuktoyaktuk September	43.	100-year	unknown	coastal winds unmodified Agnew et al. (1987)

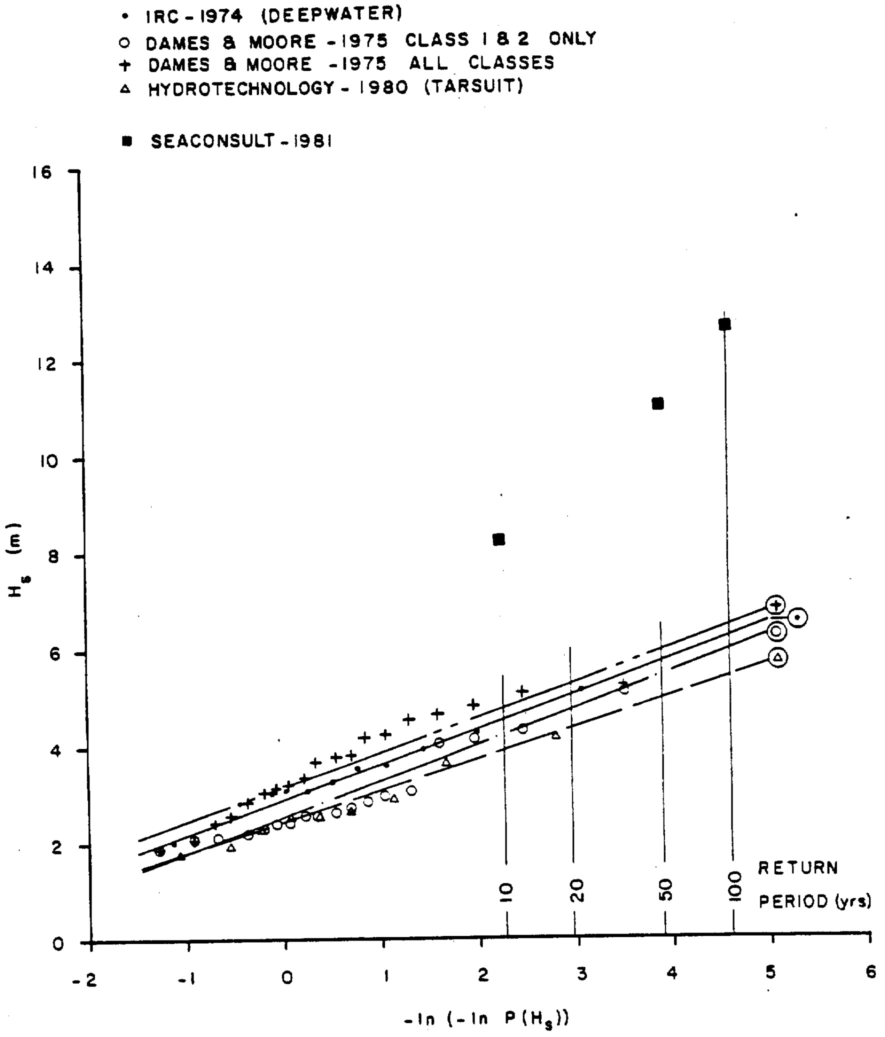


Figure 5.14 Comparison of extreme signficant wave height estimates in deep water over the continental shelf. (Source: Hodgins, 1983).

Wave height criteria in shallow water will be highly site specific, and close to shore, will be governed by breaking limits. A careful study of extreme wave heights and spectra at two sites inside Kugmallit Bay is reported by Seaconsult (1987). In that study deep water spectral wave hindcasting was used to derive boundary conditions for a spectral shallow water transformation model that was used to derive the near-shore criteria.

The loss of the Minuk sacrificial beach island in 1985 called into question the design practice for such structures, and focussed attention onto the whole problem of storm intensity,combining such parameters as significant wave height, peak period, direction, and associated currents and storm surge water levels as these vary throughout the duration of the storm. The issue in deriving extreme criteria for structures subject to erosion, and subject to damage by wave overtopping, became one of determining design storm histories, rather than one value of H_s with an annual exceedance probability of less than 0.01.

The most recent study of design storm criteria is a proprietary study conducted by Gulf Canada Resources Limited (Hodgins, 1989). The analysis of storm histories was based on 62 measured events in the Waverider database (hindcast data were not considered reliable enough for this purpose, although such data provide useful estimates of extreme wave heights). The Waverider data were transformed into deep water, and then shoaled and refracted into shallow water using a spectral wave model (Hodgins and Niwinski, 1987) for several production and pipeline sites. Using a new approach, non-dimensional storm profiles of H_s and T_p were derived from the 62 site-specific shallow water histories. The relevant scaling parameters were the peak significant wave height in the storm, the associated peak period, and the storm duration.

The extreme storm profiles were then derived by carrying out an extreme value analysis of H_s, taking wave breaking into account, and duration D. Peak period was assumed to be correlated with H_s, and the correlation of duration with wave height was also considered. Similar analyses of 21 current meter time-series yielded storm current profiles and the lag of the current with the wave response. The final result was given as hourly time-series of H_s, T_p and U at return periods between 5 and 100 years. Guidelines on the directions of coincident currents and waves were also provided.

These results were derived from measured data, including the extremal analysis for H_s, because existing parametric and spectral hindcasts do not predict the entire storm history with sufficient accuracy. The problem of accuracy can be appreciated in that erosion varies as wave height raised to a power between 2 and 5, and with the duration of the wave heights above a threshold for sediment movement. Hindcast wave accuracy using spectral models with two-dimensional wind field resolution is directly related to the quality of wind input, and to the quality of the sea ice information (Seaconsult, 1988).

It is widely recognized that wind hindcasting in the Beaufort Sea is difficult because of the lack of reliable offshore wind observations; the sparseness of the pressure observing network, particularly for storms moving southeastward; mesoscale influences from the British and Richardson Mountains; and the boundary layer dynamics of winds moving off sea ice over open water. Generally the lack of wind observations greatly reduces the effectiveness kinematic wind modelling, and the paucity of pressure data renders surface pressure maps inaccurate, and hence also the winds derived from them. Lack of data also makes fronts, and other mesoscale effects, difficult to incorporate into hindcast wind fields.

Historical sea ice data for hindcasting purposes are limited, particularly prior to 1984-85 and the introduction of SLAR and SAR overflight imagery collected by offshore operators. The limitations pertain mainly to ice edge identification and the changes on open-water areas during storms as winds move the ice. Spectral wave models are sensitive to variations in the wind fields, and to the shape and size of the open water area. In addition to the ice edge, industry hindcasts of the Minuk September 1985 storm demonstrated the importance of ice strips and patches, usually not associated with the ice edge on ice charts, in damping waves and consequently producing large spatial variability (>2 m) in the predicted wave field, independently of shallow water effects and storm trajectory. These small ice features generally fall below the normal grid scales used in the spectral models, and hence, require special treatment in the hindcast modelling process.

It is apparent that reliable wind and wave hindcasting in the Beaufort Sea demands more data than are generally available, and that historical storm wind fields contain sometimes sizeable errors (MacLaren Plansearch, 1989). Thus, wind hindcasts from storms will be of limited use for hindcasting wave time-series over the continental shelf, and the wave data will be over lower confidence than has been obtained on the east coast of Canada.

5.6.3 Structural Icing Criteria

Berry et al. (1975) attempted to calculate sea spray icing criteria for the Beaufort using the relevant weather conditions (wind and air temperature) measured at Sachs Harbour, and at Cape Parry, together with Mertin’s (1968) ship icing nomogram. The final results were presented as total accreted ice thickness in a storm as a function of return period. At an annual exceedance probability of 0.01, these thicknesses ranged from 36 (Sachs Harbour) to 50 cm (Cape Parry). Brown and Roebber (1985) examined the number of icing occurrences reported from the area and concluded that spray icing is a potentially serious concern, but that the Berry et al. criteria could be as much as 2 to 3 times too high. They reasoned that the restrictions on wave growth presented by the sea ice, which was not accounted for by Berry et al. in their application of Mertin's nomograms, would lead to an overestimate of the extreme total ice thickness.

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5.7 West Coast of Canada

Two maritime regions on the west coast of Canada have distinct climatologies. The outer coast, comprised of the west coast of Vancouver Island, Queen Charlotte Sound, Hecate Strait, Dixon Entrance and the Queen Charlotte Islands, has a normal and extreme wind and wave climate similar to the other regions considered in this study. On the other hand, the inner waters of the Strait of Georgia and Juan de Fuca Strait exhibit a milder climate, produced by the sheltering influence of the surrounding land masses. To date the greatest interest in hydrocarbon exploration centres on the north coast, taking in the West Coast of the Charlottes, Dixon Entrance, Hecate Strait and Queen Charlotte Sound. These areas are shown in Fig.5.15 --all of the areas designated in this figure are the marine forecast areas used by the Atmospheric Environment Service. The following discussion is restricted to the outer coast.

Normal climate information for the region has been derived by Brown et al. (1986) and by Brown (1987) using several data sources, including COADS, coastal and lightstation measurements, ships-of-opportunity observations and GWC data. A catalogue of severe storms has been compiled by Lewis and Moran (1985), and a climatological description of maximum wave-producing storms was described by Hodgins and Nikleva (1986) for the 32 largest events in the MEDS archive. Murty et al. (1983) present statistics for explosively deepening storms, and describe typical characteristics for these severe events.

Davidson (1982) analyzed the coastal and lightstation wind data along the north coast for their speed and directional persistence properties from the perspective of oil spill scenario modelling. He concluded that these data could be used for modelling purposes but that the spatial variability was sufficiently large to warrant use of all sources of data in any scheme to derive wind fields.

Danard et al. (1985) describe a mesoscale wind model for the British Columbia coast designed to take orographic modifications into account. Model applications for strong wind fields without a well defined cyclonic circulation were moderately successful; however, the authors concluded that improvements to the model were warranted.

5.7.1 Wind Criteria

Extreme wind speed criteria are contained in the Marine Climatological Atlas - Canadian West Coast (Brown et al., 1986). Wind speeds with a return period of 100 years are tabulated for several areas in Table 5.11 . The same data are shown in contoured form for the northeast Pacific Ocean (Fig. 5. 16). Along the coast extreme wind speeds range from 87 to 92 knots, similar in their severity to the east coast; the Cape St. James speed of 102 knots pertains to a reference level of 100 m above sea level. At the ocean weather ship Papa location the 100-year return speed is 102 knots, at a 20-m reference elevation. The coastal extremes thus imply a trend to less severe winds closer to land than experienced at the weather ship (50° N, 145°W).

There are, however, numerous reports of wind speeds ranging from 80 to 90 knots along the outer coast in storms (Lewis and Moran, 1985), and a few reports at coastal lightstations of winds exceeding 90 to 95 knots. Although one must be careful interpreting coastal winds,

these observations suggest that the extreme values for Bowie and the two west coast areas shown in Table 5.11 are not conservative, and designers should use the values with caution.

The wind extremes were derived from several data sources combining site specific observations with ship reports over broad ocean areas (Brown et al., 1986). Thus, the wind speed values are properly interpreted as a spatially averaged estimate of the 1-h mean wind. Local effects may give rise to differences produced by sheltering or intensification, particularly in Hecate Strait and Dixon Entrance. For example, locations in or near the large mainland fjords may experience strong outflow winds during arctic cold air outbreaks. Speeds exceeding 90 knots have been reported in some inlets during outflow conditions (Environment Canada, 1987).

Improved wind criteria, accounting for the spatial variability around the Queen Charlotte Islands and along the west coast of Vancouver Island from orographic effects, could be obtained through hindcasting of storms producing the strong winds over a particular area. Hodgins and Nikleva (1986) noted that different types of storms, distinguished by their trajectory and pressure distributions, gave rise to severe weather on different parts of the coast.

In that study, Hodgins and Nikleva also found that pressure chart reanalysis, and kinematic wind analysis incorporating frontal motion, was difficult, generally requiring more data than were available to give confidence in the results close to the coast. The difficulties arise because Pacific storms form and intensify over open water; the observing network there is small to begin with and biased away from the most severe weather. The accuracy of storm trajectories on surface pressure maps also appeared to be lower than on the east coast and satellite imagery was found to be of great value for storm reanalysis.

A wind hindcast would logically focus on extratropical storms since these will give rise to the extreme wind speeds in most areas. However, the influence of outflow winds in certain inlets cannot be ignored, and an extreme value analysis must examine both populations of events. Data on outflow winds are limited.

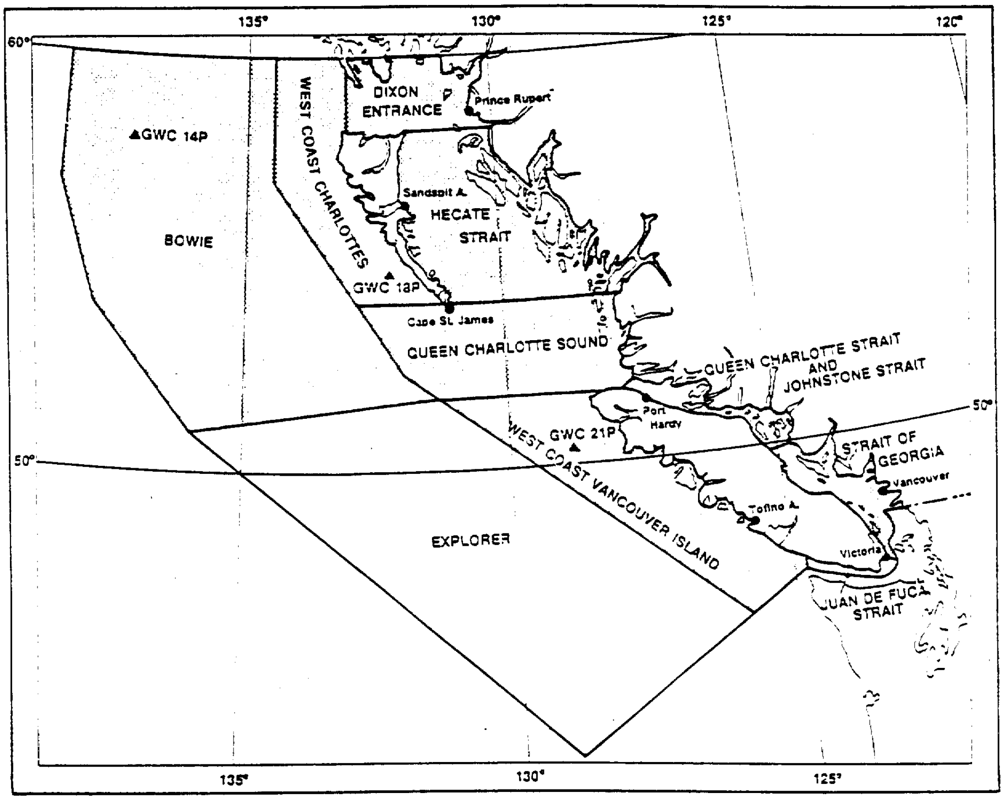

Figure 5.15 Map of the west coast showing the marine forecast areas.

Table 5.11

Extreme Wind Criteria from Brown et al. (1986) for the West Coast

Location (Fig. 5.15)	Wind Speed (knots)	Return Period	Record Period	Data Type and Source
Bowie	92	100-year	> 20 years	GWC, ocean weather ship, coastal stations
Cape St. James	102	100-year	> 20 years	coastal winds 100 m above MSL
West coast Charlottes	92	100-year	> 20 years	GWC, ocean weather ship, coastal stations
West coast Vancouver I.	87	100-year	> 20 years	GWC, ocean weather ship, coastal stations

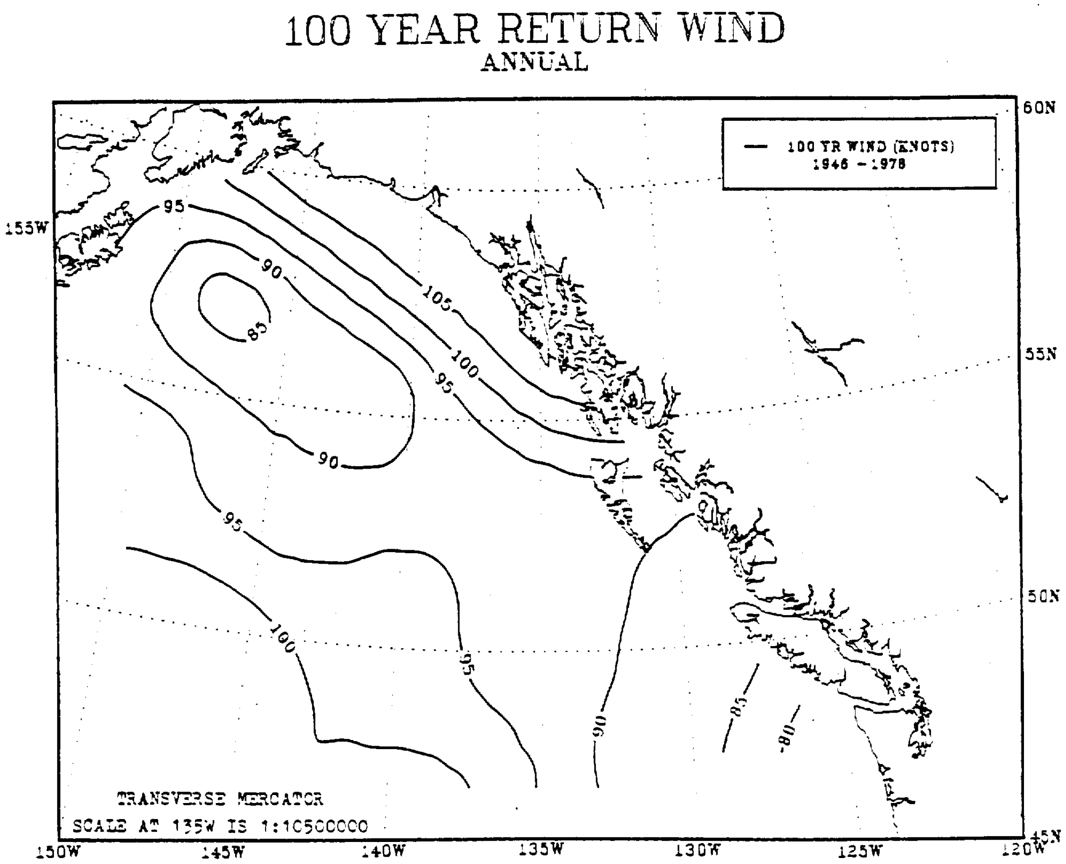

Figure 5.16 Contour map of the 100-year return wind speed derived by Brown et al. (1986).

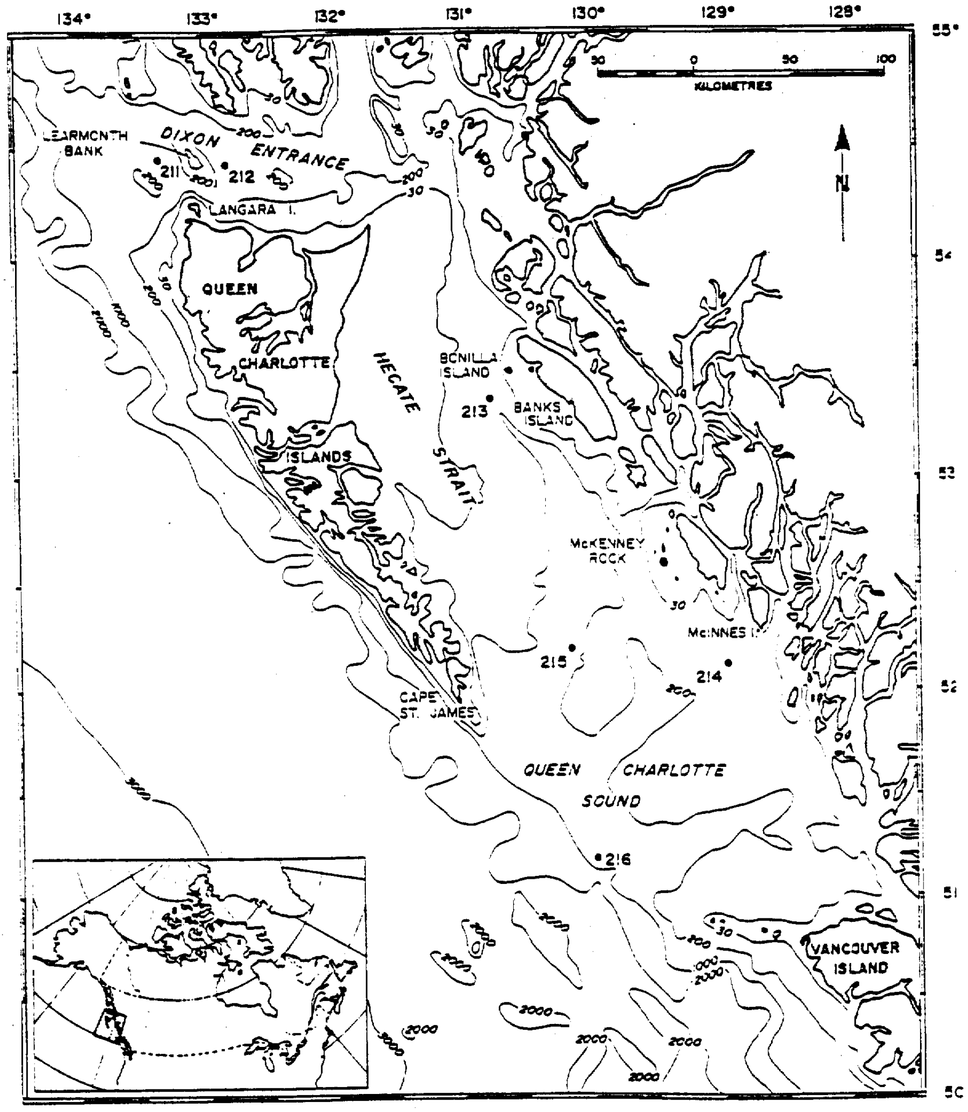

Figure 5.17 Map of the north coast of B.C. showing wave measurement locations for the period 1984 to 1988.

5.7.2 Wave Criteria

Combined wave height and period statistics in the form of monthly means and 95% exceedance values derived from the COADS database have been prepared for the marine forecast areas shown in Fig. 5.15 by Brown (1987). However, as Brown notes, the quality of the data is highly variable and the wave criteria must be treated with caution. Monthly normal wave data were also derived from the ships-of-opportunity data set by Brown et al. (1986). These criteria provide some information on month-to-month variations in the wave climate, but are not suitable for design purposes.

Observations from exploratory drilling rigs operated by Shell Canada in 1968-69 yielded significant wave height estimates of 15 to 16 m during severe weather. One observation was gauged against the rig and is likely accurate within ±2 m. In view of the severity of the wave climate, an extensive measurement program was commenced on the north coast in 1982 (Juszko et al., 1985; Dobrocky, 1987) and continued through March 1988.

The measurement locations are shown in Fig. 5.17 , and were chosen to be representative of areas of most interest for hydrocarbon exploration. Measured wave data are also available off Tofino on the west coast of Vancouver Island. These observed data provide quantitative normal wave criteria suitable for design that capture some of the expected seasonal variations.

The limitations arise mainly from the short record length, and the large degree of spatial variability which became apparent in the wave climate along the coast. Wave climate statistics from the first three years of the program are discussed in Juszko et al. (1985), Hodgins et al. (1985) and Dobrocky (1987).

Hodgins et al. (1985) provide a preliminary estimate of extreme wave heights to be expected in the area. At the 100-year return period significant wave heights were found to range from 14 m offshore and in the mouth of Dixon Entrance, to 16 to 17 m in Queen Charlotte Sound. The maximum measured wave heights during the first two years of the measurement program exceeded 11 m. Confidence in these extreme values is low because of the short databases and the methods of extreme value analysis (Weibull analysis). Nevertheless, they indicate that the design sea states are severe.

The hindcast results reported by Hodgins and Nikleva (1986), together with the measurements, demonstrated that storm-generated sea states diminish significantly into Hecate Strait and Dixon Entrance. Extreme wave criteria for the west coast can be derived by hindcasting, as has been done on the east coast, to take the spatial variability into account. Important factors to be considered in the wave-hindcasting include shallow water effects, and wave-current interaction, particularly in Hecate Strait. Hindcasting specifications are discussed in Hodgins et al. (1985).

5.7.3 Structural Icing Criteria

Sea spray icing is a potential hazard along the British Columbia coast. There are numerous historical incidents of severe icing on vessels (ESL, 1985) and Environment Canada (1987) describes icing as a marine weather hazard. Wise and Comiskey (1980) designate the north coast as an area of light to heavy icing potential with accumulations of 0.25 to 1 inch/hour under the most extreme conditions.

The cold air temperatures and high winds required for icing generally occur during arctic cold air outbreaks over the province that produce outflow winds in coastal inlets (Brown and Roebber, 1985). Thus the icing potential is greatest along the coast and diminishes seaward.

ESL (1985) measured ice accretion rates at Green Island, off the mouth of Portland Inlet on the north coast. Documented icing rates ranged from light (0. 1 to 0.25 inches/hour) to extreme (>1.25 inches/hour). The categories used to classify the accretion rates were the same as used by Wise and Comiskey (1980); thus, the measurements were for the most part consistent with Wise and Comiskey’s regional description, but rare instances of very heavy icing do occur in winds exceeding 60 km/h in conjunction with air temperatures below -8°C. Such atmospheric conditions are normally found in inlets during outflow winter winds and are not generally prevalent over the coastal waters where temperatures are moderated by the sea water, and wind slacken in speed.

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6.0 SUMMARY OF KEY FINDINGS

The CSA design code for offshore structures requires, as a minimum, reliable estimates of the 100-year return period significant wave height and wind speed. How these numbers are obtained is immaterial so long as they are demonstrably conservative, site-specific estimates. In the Beaufort Sea, at sites where erosion is a problem, time histories of waves and currents are required.

The data that are of most value for the derivation of site-specific design criteria are measurements, but the existing time-series are too short to derive reliable 100-year extremes. Storm-based hindcasting of wind and wave fields has been applied with reasonable success in **deep** water from the Scotian Shelf to the Grand Banks. Similar hindcasts are in progress for the Beaufort Sea and the west coast, and climatologies are about to be published for the east coast that will include the Gulf of St. Lawrence and the Labrador Sea (pers. comm., V. Swail, AES).

None of the regional hindcasts has been unreservedly successful because compromises are always necessary: on model formulation, on spatial and temporal resolution, on the balance between objective and subjective analysis, and on the number of hindcast events. The consequence, however, has been a series of hindcast databases in which confidence is low at many locations of interest to offshore operations such as in shallow water near Sable Island, in the Beaufort Sea, and at the various land falls, harbours and construction sites likely to be affected by offshore oil and gas production. Site-specific studies, which may build on the climatological and offshore, deep-water information from the better regional databases, are required for design criteria.

The observations to be found in the Canadian Wave Climate Study (MEDS archive) and the Canadian Drill Rig Surface Observations (COADS database) are of primary importance for the specification of normal criteria. They are also the most reliable resource for estimating seasonal and monthly extremes. Every effort should be made to collect, document and make available all wave data from Canadian waters.

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