WAVE HINDCAST STATISTICS FOR THE HOPE BASIN, NORTH CHUKCHI AND SOUTH CHUKCHI AREAS

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Final Report
Outer Continental Shelf Environmental Assessment Program
Research Unit 519

1984

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INTRODUCTION

Wave predictions are necessary to determine the months and locations of highest risk for oil and gas development in the Chukchi Sea area. A wave hindcast scheme (Hasselmann, 1976) was used to characterize extreme wave conditions in Regions A, B and C (Fig. 1) for prescribed fetch distances. These fetch conditions were controlled by both ice cover and coastline orientation thereby becoming highly directionally dependent. Region C (Fig. 1) containing the Hope Basin and Kotzebue Sound has four primary coastline orientations (Wise et al., 1981). Region B has one, while A, existing in water depths greater than 25 meters, has none. Two ice cover positions were chosen utilizing data from Stringer (1984) and Brewer et al. (1977). The first was the extreme minimum edge (50% areal coverage) which gives a maximum fetch. The second was the mean ice edge (50% areal coverage) which gives an average fetch.

Monthly wind statistics (Brewer et al., 1977) from designated land stations bordering the Chukchi study regions and/or designated marine areas containing the Chukchi study areas were used as model wind field input. The output generated were deep water, significant wave height, period, and direction for the three regions (Fig. 1) plus breaking wave height, depth, and run-up for five coastline orientations (Fig. 1). The deep water wave heights and periods are based on the assumption of uniform steady wind conditions along each wind direction.

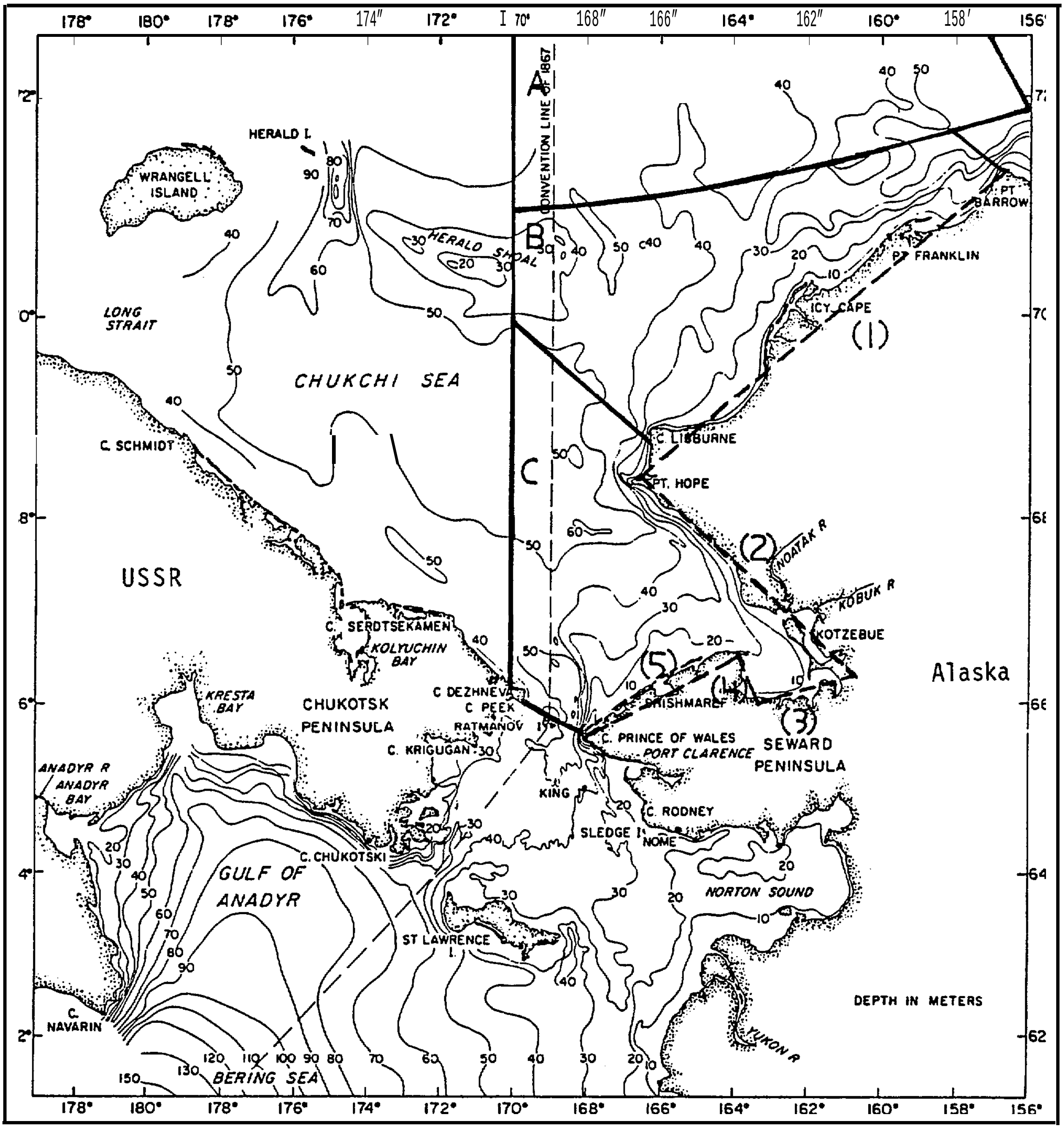

Figure 1. The three study regions A, B, and C (solid lines) and five coastlines (dashed lines) chosen for respective wave hindcast and breaking wave height analyses.

DEEP WATER WAVE HINDCAST THEORY

A parametric wind-wave model (Hasselman, 1976) was adopted for the hindcast of the deep water wave. Hasselmann's one parameter model is based on the premise that the response of the wave field to the wind input can be described by two processes which occur at different rates:

a. the rapid adjustment of the spectrum to a universal shape and an energy level such that the input by the wind in the dominant region of the spectrum is balanced by the nonlinear transfer and possibly dissipation and,

b) the slower migration of the peak toward lower frequency due to the nonlinear energy transfer across the peak.

This concept has been verified by JONSWAP'S field results (Hasselmann et al., 1973) and also by laboratory results (Wu et al., 1979). The one parameter model is limited to growing seas and cannot be extended into the swell range. The governing equation is:

$$\frac{1}{f_o}\frac{\partial f_o}{\partial \tau} + P_o \frac{\partial f_o}{\partial \eta} = -N_o f_o^{7/3} + \frac{1}{u}\left(\frac{\partial u}{\partial \tau} + \frac{\partial u}{\partial \eta}\right)$$

Where

$$P_o = 0.95$$

$$N_o = 5.5 \times 10^{-4}$$

$$\frac{\partial}{\partial \tau} = \frac{u}{g}\frac{\partial}{\partial t}, \quad \frac{\partial}{\partial \eta} = \frac{u}{g}\vec{V}_m \cdot \vec{\nabla}, \quad |\vec{V}_m| = \frac{\alpha \varsigma}{4\pi f_m}$$

$$f_o = U f_m / g, \quad \varsigma = 0.85 \text{ for } \cos^2\theta \text{ spreading factor}$$

U is wind speed, g is gradational acceleration,

f_m is peak wave frequency.

For a uniform wind field, the governing equation for predicting a local peak frequency can be simplified as:

$$\frac{\partial f_m}{\partial t} = -5.5 \times 10^{-4} \left(\frac{g}{U}\right)^{-4/3} f_m^{10/3}$$

The analytical solution of the above-equation in terms of the normalized peak wave period, $\hat{T}_p$ and normalized significant wave height, $\hat{H}_s$ can be expressed as follows:

For $\hat{X} < 3.5 \times 10^3$

$$\hat{H}_s = 1.53 \times 10^{-3} \hat{X}^{0.5}$$

$$\hat{T}_p = 0.341 \hat{X}^{0.3}$$

otherwise

$$\hat{H}_s = 0.283 \tanh (0.0125 \hat{X}^{0.42})$$

$$\hat{T}_p = 7.54 \tanh (0.077 \hat{X}^{0.25})$$

Where $\hat{X} = gX/U^2$, $\hat{H}_s = gH_s/U^2$, $\hat{T}_p = gT_p/U$ The results calculated by the above equations compare quite well with experimental observations made in other parts of the world over many years. For a given set of significant wave height (H_s), peak wave period (T_p), and wave direction (θ), a deep water directional wave spectrum $F(\omega, \theta)$ can be approximated. When a wave spectrum propagates through the shallow water region, it will be subject to the effects of shoaling and refraction. The transformed spectrum can be related to the initial wave spectrum (Battjes, 1974; Collins, 1972; Longuet-Higgins, 1957), as follows:

$$F(\omega,\theta)\, d\theta d\omega = \frac{k}{k_o} \frac{(C_g)_o}{C_g} F_o(\omega,\theta_o) \frac{d\theta}{d\theta_o} d\theta_o\, d\omega$$

Where o denotes the initial conditions and $C_g = n\omega/k$ is the group velocity. Assume the directional spectrum $F_o(w, \theta_o)$ can be decomposed in such a form that the energy distributed in different frequencies, $E_o(\omega)$, are weighted by a directional spreading factor $\phi(\theta_o)$, i.e.: $F_o(\omega,\theta_o) = E_o(\omega)\phi(\theta_o)$.

Under the assumption of parallel bottom contours, Snell's Law, i.e.: $\sin\theta/\sin\theta_o = k_o/k$, can be applied to relate the refracted wave angle θ_o to simplify the calculation, i.e.:

$$d\theta = \frac{k_o \cos\theta_o d\theta_o}{(k^2 - k_o^2 \sin^2\theta_o)^{1/2}}$$

Finally, the transformed wave spectrum can be written as follows:

$$F(\omega,\theta)\, d\theta d\omega = \frac{n_o k^2 k_o \cos\theta_o \phi(\theta_o) E_o(\omega)}{n k_o^2 [k^2 - k_o^2 \sin^2\theta_o]^{1/2}} d\theta_o\, d\omega$$

This transformed wave spectrum is valid prior to wave breaking. After wave breaking, a different approach for the calculation of wave height in the surf zone is applied.

WAVE BREAKING CRITERIA

In the ocean, as a wave exceeds certain kinematical or dynamical limits, the wave will be broken and reformed. The visible white-capping phenomena is the result of wave breaking. It has been argued (Phillips, 1958; Kitaigordiskii et al., 1975; and Thornton, 1977) that in order to satisfy the kinematical dynamical constraints of wave breaking, the wave spectrum in the high frequency range where wave breaking occurs, must have a certain universal shape existing, which is known as the equilibrium range. One can employ dimensional analysis to derive a form for the equilibrium spectrum.

The equilibrium spectrum, $\psi(\omega)$ without the effect of current can be expressed as (Kitaigordiskii et al., 1975; Thornton, 1977, and Wu et al., 1980):

$$\psi(\omega) = \alpha k^{-2} (2n\omega)^{-1}$$

where α is Phillips' equilibrium constant, n is the ratio of group velocity to wave celerity, k is the wave number and w is the angular frequency. The asymptotic forms of $\psi(\omega)$ in the deep and shallow water regions can be shown as:

$$\psi_D(\omega) = \alpha g^2 \omega^{-5}$$

and
$$\psi_s(\omega) = \frac{\alpha}{2} g h \omega^{-3}$$

respectively. The coefficient, $\alpha/2$ needs to be verified in the shallow water region.

As a wave field propagates toward the shallow water region, the process of wave dissipation, within the equilibrium range, is not sufficient to characterize the spilling, surging, or collapsing type of breakers which occur in shallow waters. "Therefore, additional shallow water wave breaking criteria are needed. Based on a combination of the state-of-the-art knowledge of breaking height, breaking depth, deep water wave characteristics, and beach slope, the breaking criterion can be described by (Wu et al., 1980):

$$H < \gamma d$$

where $\gamma = H_b/d_b$ and H_b and d_b are breaking wave height and depth, respectively, which are functions of beach slope and incident wave characteristics. The breaking wave height is determined by the combination of Goda's (1970) index and LeMehaute and Koh's (1967) wave breaking condition, i.e.:

$$H_b = 0.74 H_o \; S^{*''l''} \; (H_o/L_o)^{-0.24} \cdot (\cos\theta_o)^{0.38} \; .$$

$$\cdot \; (\cos\theta_b)^{0.28}$$

and

$$\theta_b = (0.15 + 6.4 \cdot H_o \sqrt{\cos\theta_o}/L_o) \cdot \theta_o \; .$$

for

$$0.002 < H_o \sqrt{\cos\theta_o}/L_o < 0.1 \quad \text{and} \quad 0.02\underline{6} \underline{\leq} 0.1$$

Where S is the beach slope, L_o is the deep water wave length and θ_b is the wave breaking angle.

The breaking water depth d_b is the summation of the still-water breaking depth, h_b and the maximum wave set-down, η_b at the breaking location. The still-water breaking depth h_b is (Weggel, 1972):

$$h_b = H_b / [b - (aH_b/gT_o^2)]$$

, where

$$a = 1.36g(1 - e^{-19 \cdot S}) \quad \text{and} \quad b = 1.56/(1 + e^{-19.5 \cdot S})$$

The maximum wave set-down η_b at the wave breaking point can be estimated theoretically for a solitary wave. The theoretical form of η_b is:

$$\eta_b = -H_o^2 \sqrt{g} \; T_o \cos\theta_o / [64\pi (h_b + \eta_b)^{3/2}]$$

Finally, y can be determined for a given set of initial wave conditions and beach slope. Then, the breaking condition can be established.

The combination of equilibrium spectrum check (which would limit the energy contained in the relatively high frequency range of a wave spectrum), and shallow water wave breaking conditions defines a very good breaking criterion, predicts a better breaking location, and provides a better simulation of surf zone processes.

WAVE RUN-UP

Wave run-up is defined as the maximum vertical water displacement on the face of the structure above the still-water surface during the wave attack. Since no sound theoretical background associated with the characteristics of breaking waves has been established, the state-of-the-art calculation of wave run-up is essentially based on experimental results. Since Hunt's equation always produces a reliable estimation of wave run-up for breaking wave cases, it was adopted for the basic analytical foundation. It is as follows:

$$\frac{R}{H} = 2.3 * S * (H/T)^{-\frac{1}{2}}$$

Where R is wave run-up, S is beach slope, H and T are wave height and period, respectively.

RESULTS AND CONCLUSIONS

DEEP WATER WAVE STATISTICS

Monthly frequency tables of significant wave height (Hs) and peak wave period (Tp) for both maximum (minimum ice edge) and mean (average ice edge) fetch have been compiled for Regions A, B and C. Results show that the values of Hs and Tp are consistently larger under maximum fetch conditions as expected.

The height of the 5% highest waves (H5) is 1.73 Hs (Pierson et al., 1971). Tables of H5 were prepared for this study, but it is much simpler to take a (Hs) table value and multiply by 1.73. H5 frequency distributions can be approximated by taking the Hs tables and doubling the meter values across the top.

Region C

This is the farthest south of the three study regions and has the largest span of open water months (Kozo, 1985). The minimum ice edge position in the Chukchi Sea for May through November can be seen in Figs. 2a-8a. The mean Chukchi Sea ice edge position from June until November (shorter open water period) is shown in Figs. 3b-8b. Tables 1-7 and Tables 8-13 show Hs and Tp for maximum and mean fetch respectively. The months with the greatest amount of open water, July to October, show little difference between the corresponding maximum fetch data (Tables 3-6) and the mean fetch data (Tables 9-12) since Region C is so far from the ice edge.

The maximum Hs and Tp found for these open water months under both maximum and mean fetch conditions were 10 m and 14 s. These large waves can come from the south in July (Tables 3 and 9) and from the northeast and

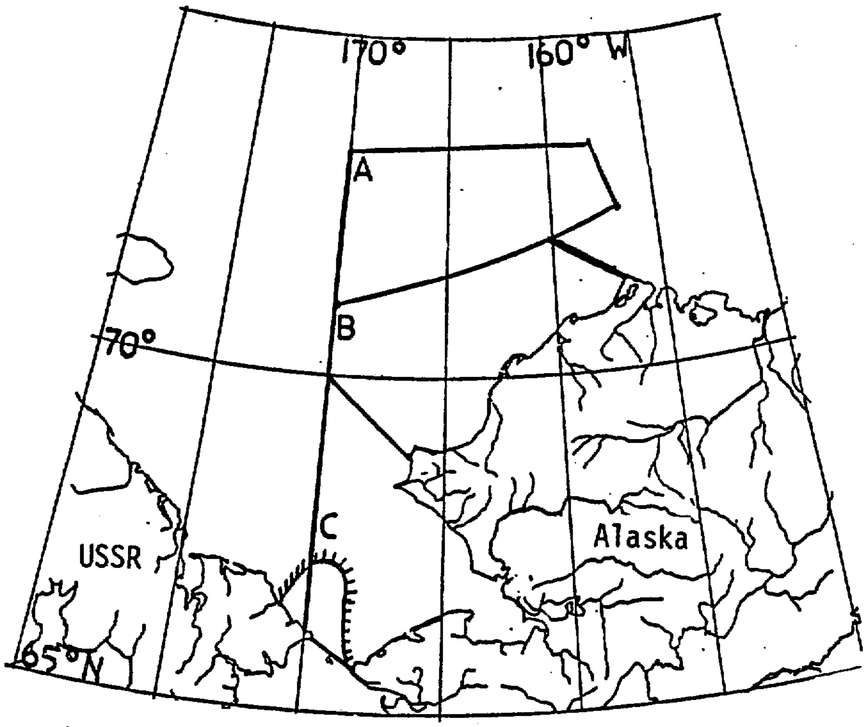

Figure 2a. The minimum sea ice extent (maximum fetch condition) in May (Stringer, 1984; Brewer et al, 1977) relative to Regions A-C.

Figure 2b. There is typically no open water in Regions A-C in May for mean sea ice extent.

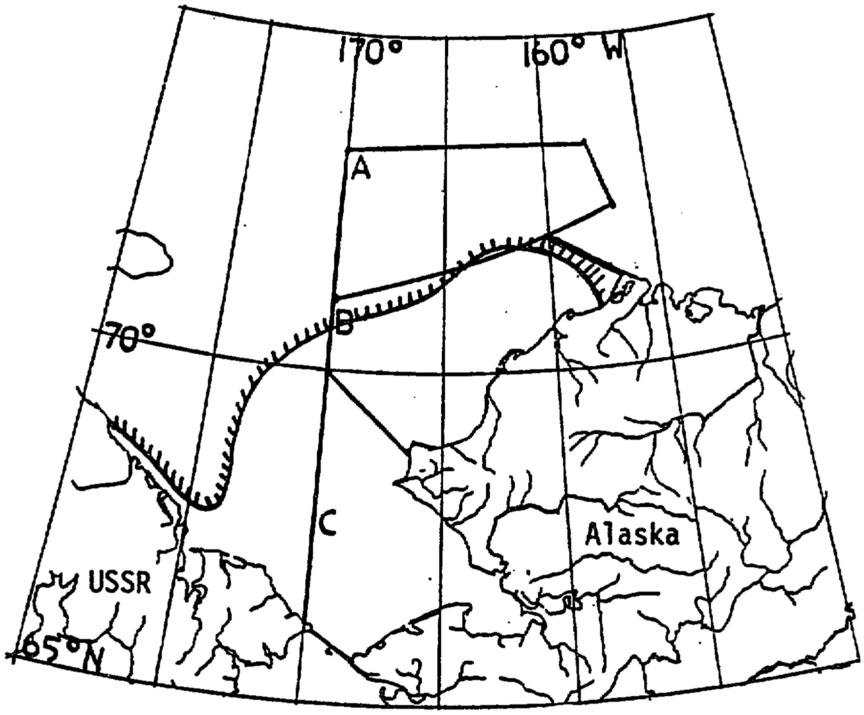

Figure 3a. The minimum sea ice extent (maximum fetch condition) in June (Stringer, 1984; Brewer et al, 1977) relative to Regions A-C.

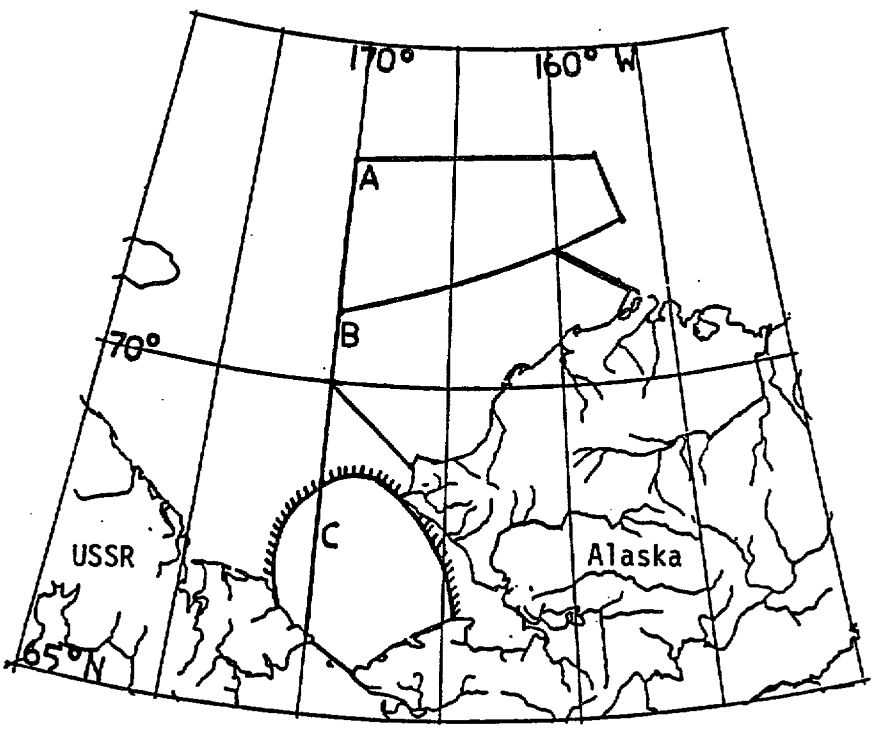

Figure 3b. The mean sea ice extent (average fetch condition) in June (Stringer, 1984; Brewer et al, 1977) relative to Regions A-C.

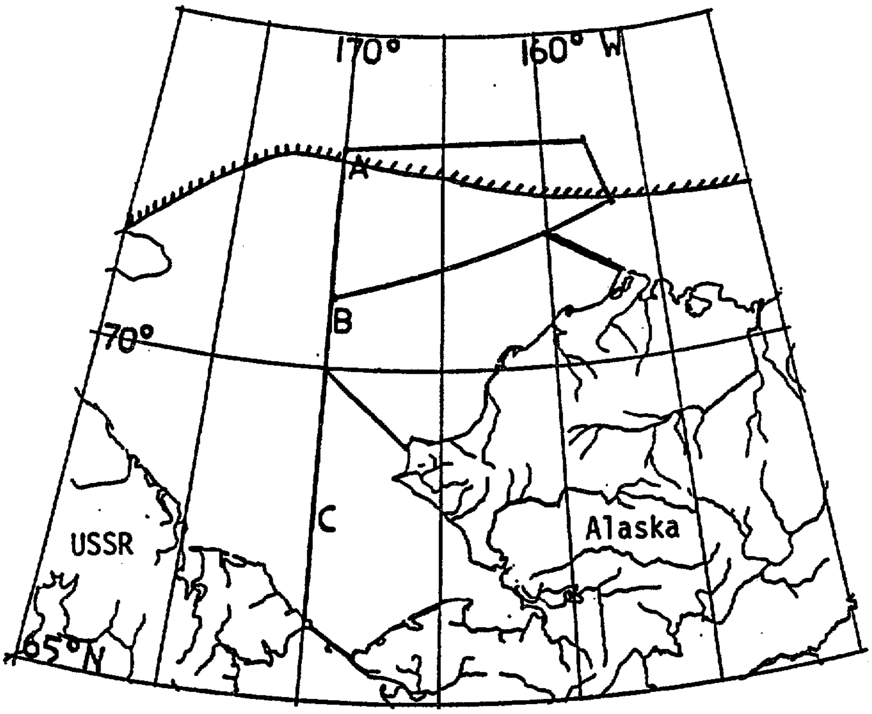

Figure 4a. The minimum sea ice extent **(maximum** fetch condition) **in July (Stringer,** 1984; **Brewer et al, 1977) relative to Regions A-C.**

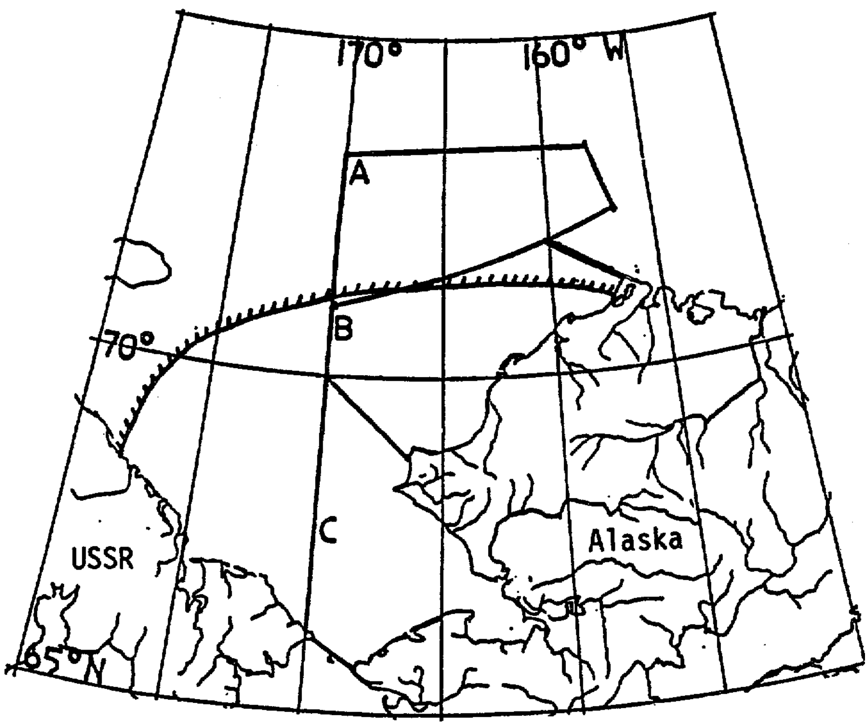

Figure 4b. The mean sea ice extent (average fetch condition) in July (Stringer, 1984; Brewer et al, 1977) relative to Regions **A-C.**

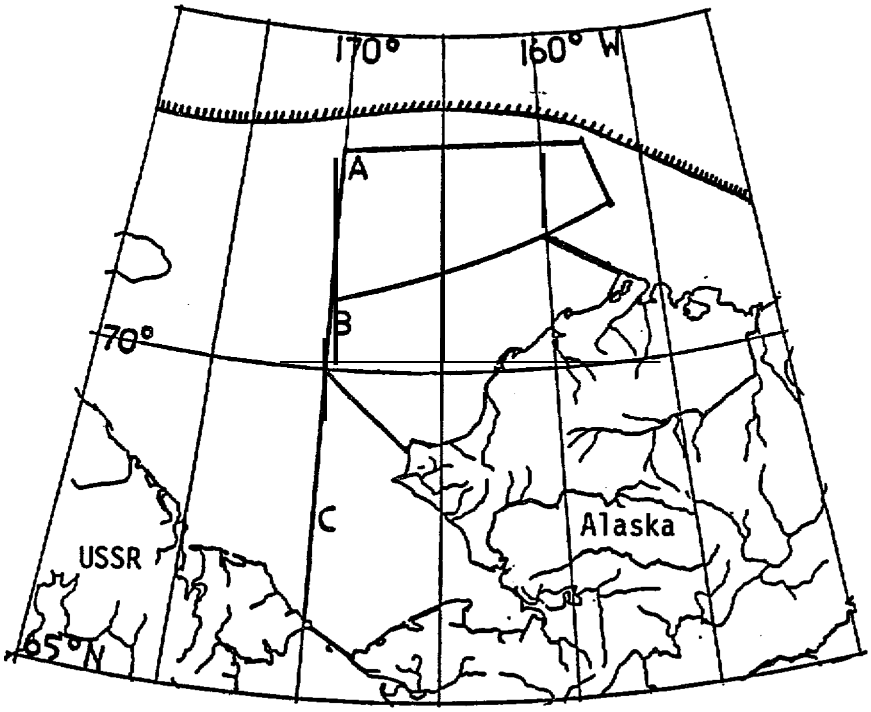

Figure 5a. The minimum sea ice extent (maximum fetch condition) **in August (Stringer, 1984; Brewer et al, 1977) relative to Regions A-C.**

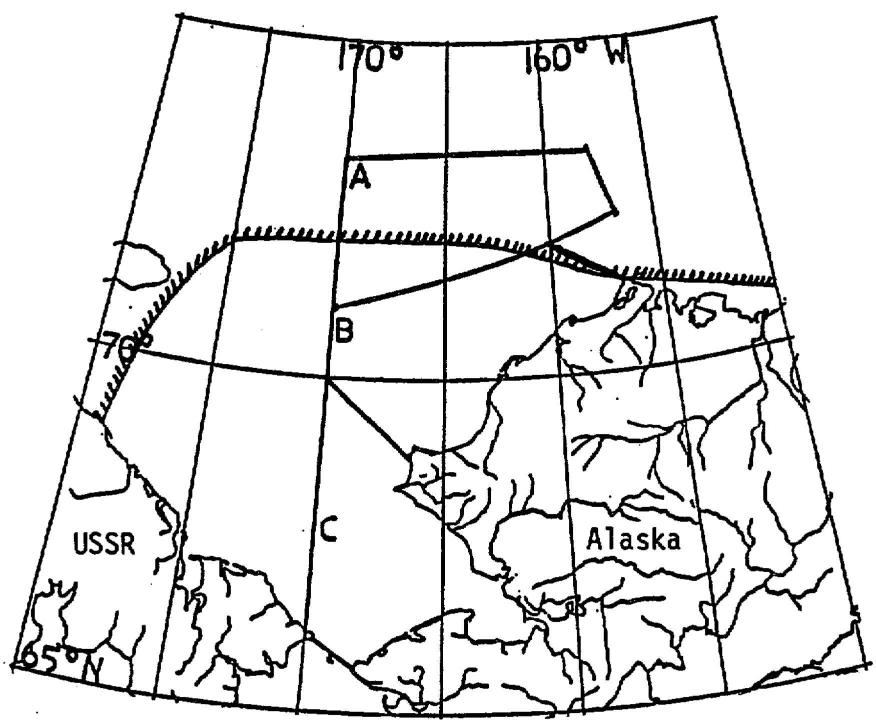

Figure 5b. The mean sea ice extent (average fetch condition) in August (Stringer, 1984; Brewer et al, 1977) relative to Regions A-C.

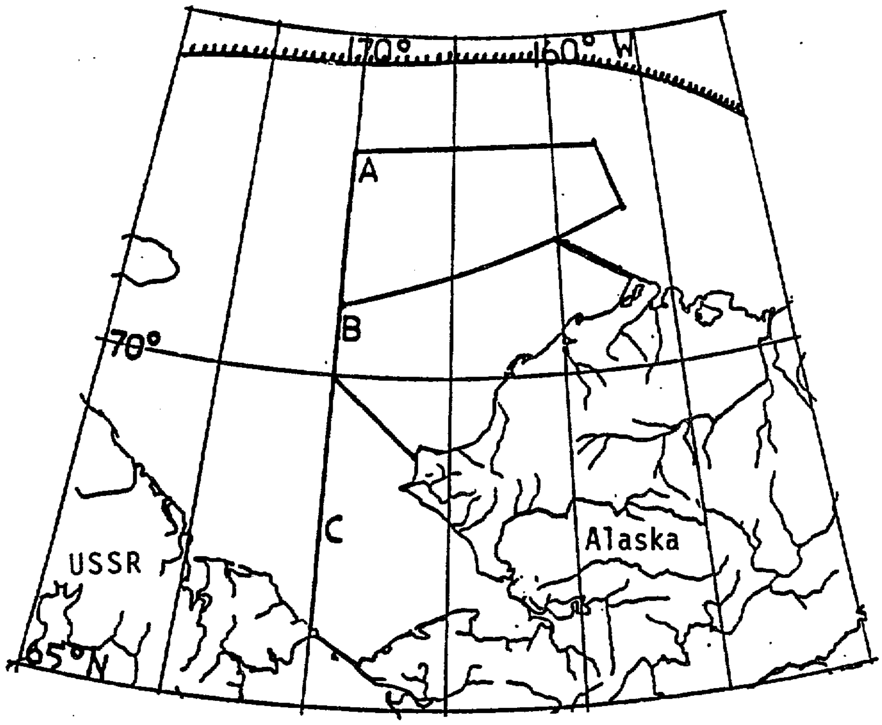

Figure 6a. The minimum sea ice extent (**maximum** fetch condition) in **September** (Stringer, 1984; Brewer et al, **1977)** relative to Regions **A-C.**

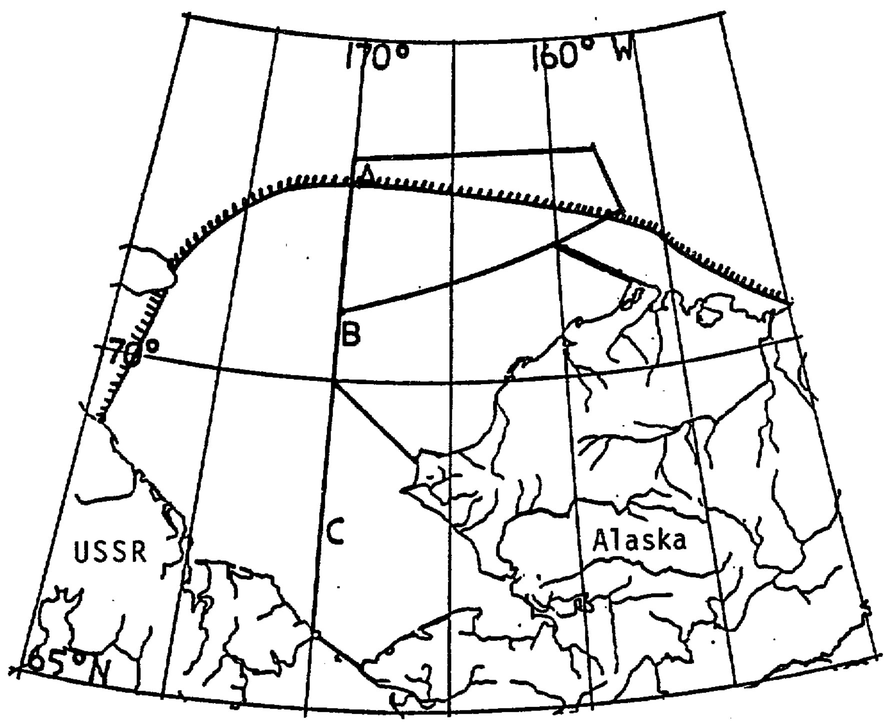

Figure 6b. The mean sea ice extent (average fetch condition) in September (Stringer, 1984; Brewer et al, 1977) relative to Regions A-C .

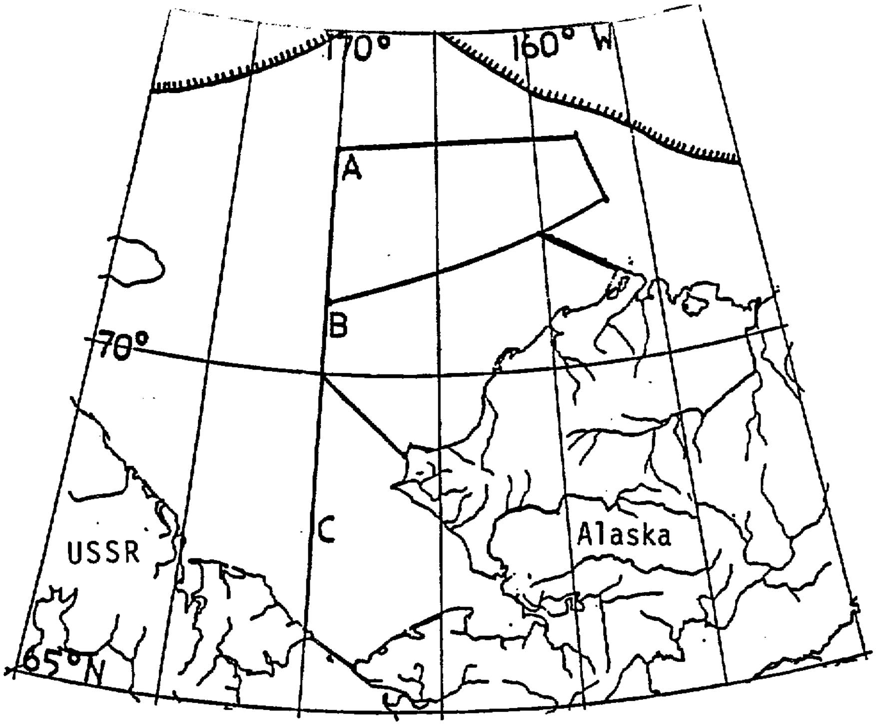

Figure 7a. The minimum sea ice extent (maximum fetch condition) in October (Stringer, 1984; Brewer et al, 1977) relative to Regions A-C.

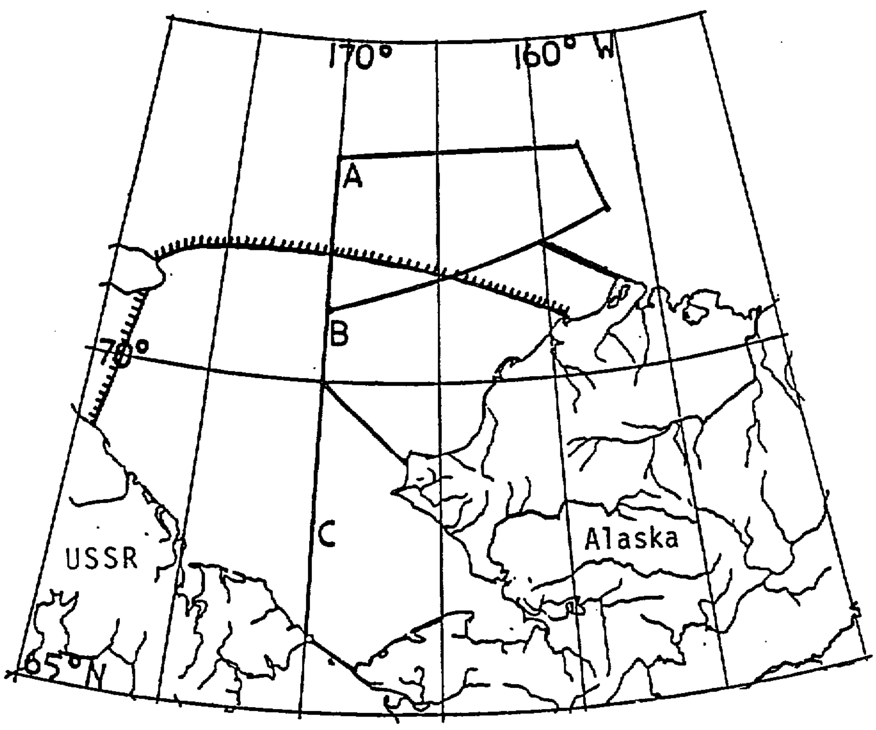

Figure 7b. The mean sea ice extent (average fetch condition) in October (Stringer, 1984; Brewer et al, 1977) relative to Regions A-C.

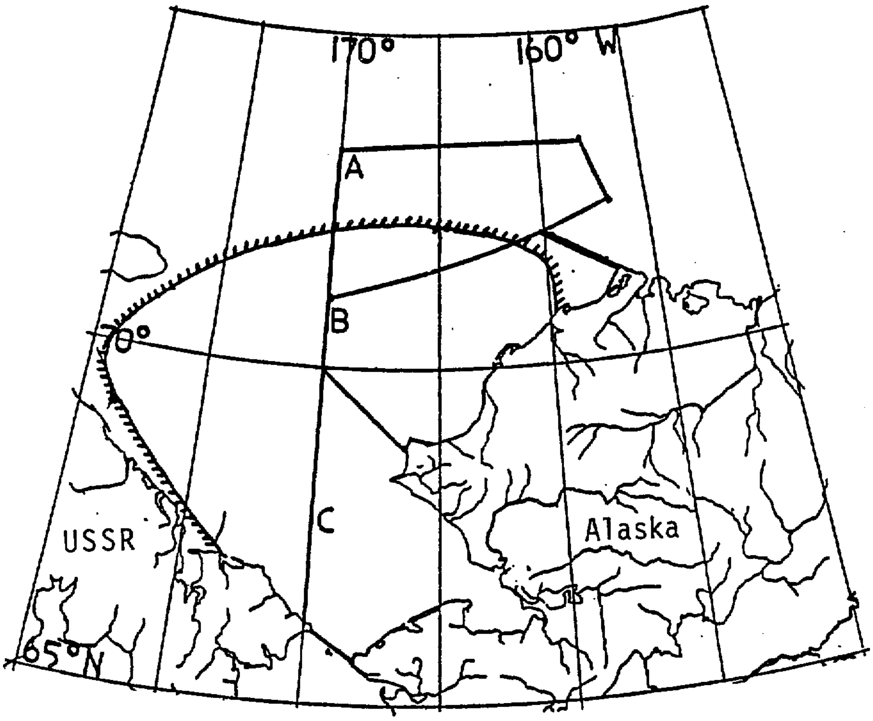

Figure 8a. The minimum sea ice extent (maximum fetch condition) in November (Stringer, 1984; Brewer et al, 1977) relative to Regions A-C.

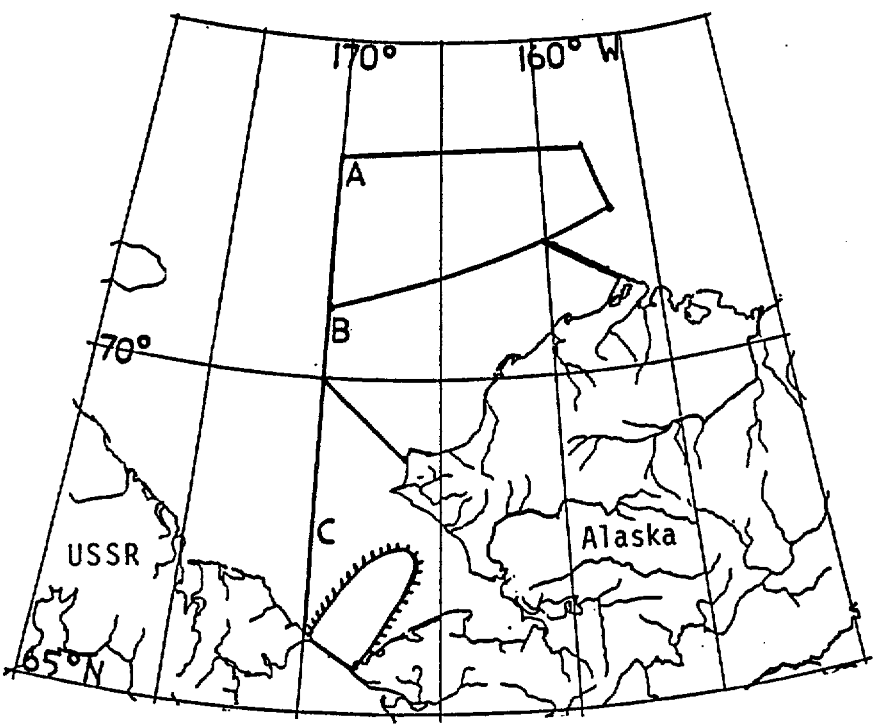

Figure 8b. The mean sea ice extent (average fetch condition) in November (Stringer, 1984; Brewer et al, 1977) relative to Regions '-c"

Hs (m)	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	TOTAL
N	21	11	5	+										37
NE	5	2	+											7
E	2	2	+											4
SE	+	+	+											1
S	8	6	4	3	2	0	0	1	1	.				25
SW	3	2	1	+										6
W	+	+	+	+										1
NW	4	3	+	+	+									7
CALM	12													12
TOTAL%	55	26	11	4	2	0	0	1	1	+				100

Table 1a. The predicted frequency of significant wave heights (Hs) in meters for waves from eight specified directions in May. These data were derived from wind velocity histogram (Brewer et al., 1977) compiled at stations near Region C for maximum fetch conditions.

Tp(S)	2.	4.	6.	8.	10.	12.	14.	16.	TOTAL %
N	2	19	15	1					37
NE	1	4	2						7
E	+	2	2	+					4
SE	+	1	+	+					1
S	1	7	6	4	5	2			25
SW	1	2	2	2					7
W	+	+	+	+					+
NW	1	3	3	+	+				7
CALM	12								12
TOTAL %	18	38	30	7	5	2			100

Table 1b. The predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in May. These data were derived from wind velocity measurements (Brewer et al., 1977) compiled at stations near Region C for maximum fetch conditions.

Hs (m)	1.	2.	3.	4.	5.	6.	7.	8.	9,	10.	11.	12.	13.	TOTAL %
N	16	6	3	0	1	+								26
NE	8	1	+	0	+	+								10
E	5	1	+											6
SE	+	+	+	0	+	+	0	+	+					1
S	10	7	6	4	0	2	1	0	+	+				30
SW	4	2	1	1	+	0	+							8
W	+	0	0	0	0	+	+	+						+
NW	2	2	0	1	+	+								5
CALM														
TOTAL%	59	19	10	6	2	3	1	+	+	+				100

Table 2a. The predicted frequency of significant wave heights (Es) in meters for waves *from* eight specified directions in June. These data were derived from wind velocity histograms (Brewer et al., 1977) compiled at stations near Region C for maximum fetch conditions.

Tp(S)	2.	4.	6.	8.	10.	12.	14.	16.	TOTAL %
N	3	1	3	6	3	1			26
NE	1	7'1		+	+				9
E	+	5	1	+					6
SE	+	+	+	+	+	+			1
S	2	8	7	6	6	1	+		30
SW,	1	3	2	2	+	+			8
W	+	+	0	0	+				1
NW	+	2	2	1	+				5
CALM	14								14
TOTAL%	21	38	19	13	8	1	+		100

Table 2b. The predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in June. These data were derived from wind velocity measurement (Brewer ●t al., 1977) compiled at stations near Region C for maximum fetch conditions,

Hs (m)	1	2	3	4	5	6	7	8	9	10	11	12	13	TOTAL %
N	4	0	1	+	+									5
NE	8	0	3	1	+									12
E	19	2	+	+	+	0	+							22
SE	6	1	+	0	+	+	0	+						8
S	4	4	3	0	2	1	1	0	+	+				15
SW	3	5	4	3	1	0	+	+	+					16
W	3	1	+	0	+	+								4
NW	5	0	1	+	+									6
CALM	12													12
TOTAL%	64	13	13	4	4	1	1	+		+				100

Table 3a. The predicted frequency of significant wave heights (Hs) in meters for waves from eight specified directions in July. These data were derived from wind velocity histograms (Brewer et al., 1977) compiled at stations near Region C for maximum fetch conditions.

Tp (S)	2	4	6	8	10	12	14	16	TOTAL %
N	1	1	3	+	+				5
NE	1	3	7	1	+				12
E	3	16	2	+	+				22
SE	1	5	1	+	+	+			8
S	+	4	4	3	3	1	+		15
SW	+	3	5	7	1	+	+		16
W	+	3	1	+	+				4
NW	1	2	3	+	+				6
CALM	12								12
TOTAL%	19	37	26	12	5	1	+		100

Table 3b. The predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in July. These data were derived from wind velocity measurements (Brewer et al., 1977) compiled at stations near Region C for maximum fetch conditions.

Hs (m)	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13	TOTAL %
N	8	0	6	4	2	1	+							21
NE	5	0	3	2	1	0	1	+						12
E	4	2	1	1	+	+								8
SE	4	3	1	0	+	+								8
S	4	4	4	0	2	+	+							14
SW	5	2	1	1	+	0	+	+	+					10
W	4	2	1	0	1	+	+	+						9
NW	7	0	3	2	1	0	+	0	+					13
CALM	5													5
TOTAL%	46	13	20	10	8	2	1	+	+					100

Table 4a. The predicted frequency of significant wave heights (Es) in meters for waves from ●ight specified directions in August. These data were derived from-wind velocity histograms (Brewer et ●l., 1977) compiled at stations near Region C for maximum fetch conditions.

Tp (S)	2.	4.	6.	8.	10.	12.	14.	16	TOTAL %
N	1	3	10	4	2	1	+		21
NE	1	2	5	2	1	1	+		12
E	+	4	2	2	+	+			8
SE	1	3	4	+	+				8
S	+	4	4	4	2	+			14
SW	1	4	2	2	+	+	+		10
W	1	3	2	1	1	+	+		9
NW	1	3	6	2	1	+			13
CALM	5								5
TOTAL%	11	26	35	17	8	3	+		100

Table 4b. The predicted frequency of pesk wave periods (Tp) in seconds for waves coming from eight specified directions in August. These data were derived from wind velocity ❑easurements (Brewer et al., 1977) compiled at stations near Region C for maximum fetch conditions.

Hs (m)	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13	TOTAL %
N	5	0	5	4	3	0	1	0	1					19
NE	6	0	3	2	2	0	1	0	+	+				14
E	6	3	1	1	+									11
SE	5	2	2	+	+									9
S	5	2	3	0	1	+	0	+						11
SW	3	2	1	0	1	o	+	+	+	+				7
W	4	2	1	0	1	+	+							8
NW	6	0	5	3	2	0	1	0	1					18
CALM	3													3
TOTAL%	43	11	21	10	10	+	3	+	2	+				100

Table 5a. The predicted frequency of significant wave heights (Ifs) in meters for waves from eight specified directions in September. These data were derived from wind velocity histograms (Brewer et al., 1977) compiled at stations near Region C for maximum fetch conditions.

Tp(S)	2.	4.	6.	8.	10.	12	14	16	TOTAL %
N	1	1	3	9	3	2			19
NE	1	2	6	2	2	1	+		14
E	1	5	3	1	1				11
SE	1	4	2	1	1	+	+		9
S	1	4	2	3	1	+			11
SW	+	3	2	1	1	+			7
W	1	3	2	1	1	+			8
NW	+	3	8	3	2	2			18
CALM	3								3
TOTAL%	9	25	28	21	12	5	+		100

Table 5b. The predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in September. These data were derived from wind velocity measurements (Brewer et al., 1977) compiled at stations near Region C for maximum fetch conditions.

Hs (m)	1.	2.	3.	4.	5.	6.	7.	8.	9,	10,	11,	12,	13	TOTAL %
N	4	0	8	10	9	6	3	+	+					40
NE	1	0	3	3	1	0	1	+						9
E	2	1	2	1	+	0	+							6
SE	1	1	+	0	1	+	1	+						5
S	7	3	2	0	1	1	1	1	+					16
SW	5	1	+	+	+	0	+	+						7
W	2	1	1	0	+	+								5
NW	1	0	1	2	1	1	+	+	+					7
CALM														5
TOTAL%	28	7	18	16	14	9	7	1	+					100

Table 6a. The predicted frequency of significant wave heights (Hs) in meters for waves from eight specified directions in October. These data were derived from wind velocity histograms (Brewer et al., 1977) compiled at stations near Region C for maximum fetch conditions.

Tp(S)	2.	4.	6.	8.	10	12,	14,	16	TOTAL %
N	+	1	3	8	19	9	+		40
NE	+	+	4	3	1	1	+		9
E	+	2	1	3	+	+			6
SE	+	1	1	+	1	1			5
S	1	6	3	2	2	2	+		16
SW	1	4	1	+	+	+			7
W	+	2	1	1	+	+			5
NW	+	+	1	1	2	2	+		7
CALM:	5								5
TOTAL%	9	17	15	19	25	15	+		100

Table 6b. The predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in October. These data were derived from wind velocity measurements (Brewer et al., 1977) compiled at stations near Region C for maximum fetch conditions.

Hs (m)	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13	TOTAL. %
N	4	6	0	6	6	0	3	2	0	+				27
NE	1	3	3	0	3	2	0	1	0	+	+			13
E	1	2	2	2	+	0	1	+	+					8
SE	+	+	+	0	+	+	0	+	+	+				2
S	7	2	2	0	2	1	0	2	1	1				18
SW	5	1	+	+	+	0	+	+	+					8
W	2	2	1	0	1	+	+	0	+					7
NW	3	3	2	1	0	1	1	0	+					11
CALM	6													6
TOTAL%	29	19	10	9	13	5	6	6	2	1	+			100

Table 7a. The predicted frequency of significant wave heights (Hs) in meters for waves from eight specified directions in November. These data were derived from wind velocity histograms (Brewer ●t al., 1977) compiled at stations near Region C for maximum fetch conditions.

Tp (S)	2.	4.	6.	8.	10.	12.	14.	16	TOTAL. %
N	+	1	6	6	9	2	+		27
NE	+	1	3	3	5	1	+	+	14
E	+	1	2	4	1	+	+		9
SE	+	+	+	+	+	+	+		2
S	1	6	2	2	3	3	1		18
SW	1	4	1	+	+	+	+		7
W	+	2	2	1	1	+			6
NW	+	3	3	3	1	1			11
CALM	6								6
TOTAL%	8	18	23	20	21	8	2	+	100

Table 7b. The predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in November. These data were derived from wind velocity measurements (Brewer et al., 1977) compiled at stations near Region C for maximum fetch conditions.

Hs (m)	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	TOTAL %
N	16	6	3	1	+									26
NE	8	1	+	+	+									9
E	5	1	+											6
SE	+	+	+	+	+	+	+							1
S	10	7	6	4	2	0	1	+	+					30
SW	4	2	1	1	+	+								8
W	+	0	0	0	+									1
NW	2	2	1	+	+									5
CALM														14
TOTAL%	60	19	11	6	3	+	1	+	+					100

Table 8a. The predicted frequency of significant wave heights (Hs) in meters for waves from eight specified directions in June. These data were derived from wind velocity histograms (Brewer et al., 1977) compiled at stations near Region C for mean fetch conditions.

Tp(s)	2.	4.	6.	8.	10.	12.	14.	16.	TOTAL %
N	3	13	6	4	+				26
NE	1	7	1	+	+				9
E	+	5	1	+					6
SE	+	+	+	+	+	+			1
S	2	8	7	10	3	+			30
SW	1	3	2	2	+				8
W	+	+	0	0	+				1
NW	+	2	2	1	+				5
CALM	14								14
TOTAL%	22	38	19	18	3	+			100

Table 8b. The predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in June. These data were derived from wind velocity measurements (Brewer et al. ,1977) compiled at stations near Region C for mean fetch conditions.

Hs (m)	1.	2.	3.	4.	5.	6.	7.	8.	9,	10,	Il.	12.	13	TOTAL
N	4	1	0	+	+									5
NE	8	3	1	0	+									12
E	19	2	+	+	+	0	+							22
SE	6	1	+	0	+	+	0	+						8
s	4	4	3	0	2	1	1	0	+	+				15
SW	3	5	4	3	1	0	+	+	+					16
w	3	1	+	0	+	+								4
NW	5	1	0	+	+									
CALM	12													12
TOTAL%	64	18	9	4	3	1	1	+	+	+				100

Table 9a. The predicted frequency of significant wave heights (Hs) in meters for waves from eight specified directions in July. These data were derived from wind velocity histograms (Brewer ●t al., 1977) compiled at stations near Region C for mean fetch conditions.

Tp(S)	2.	4.	6,	8.	10.	12.	14,	16	TOTAL, %
N	1	1	3	+	+				5
NE	1	7	3	1	+				12
E	3	16	2	+	+				22
SE,	1	5	1	+	+	+			8
s	+	4	4	3	3	1	+		15
SW	+	3	5	7	1	+	+		16
W	+	3	1	+	+				4
NW	1	2	3	+	+				6
CALM	12								12
TOTAL%	19	41	22	12	5	1	+		100

Table 9b. The predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in July. These data were derived from wind velocity measurements (Brewer et al., 1977) compiled at stations near Region C for mean fetch conditions.

Hs (m)	1	2	3	4	5	6	7	8	9	10	11	12	13	TOTAL %
N	8	0	6	4	2	1								21.
NE	5	3	0	2	1	1	+							12
E	4	2	1	1	+	+								.8
SE	4	3	1	0	+	+								8
S	4	4	4	0	2	+	+							14
SW	5	2	1	1	+	0	+	+	+					10
W	4	2	1	0	1	+	+							9
NW	7	0	3	2	1	+	0	+						13
CALM														5
TOTAL%	46	16	17	10	8	3	+	+	+					100

Table 10a. The predicted frequency of significant wave heights (Hs) in meters for waves from eight specified directions in August. These data were derived from wind velocity histograms (Brewer et al., 1977) compiled at stations near Region C for mean fetch conditions.

Tp (S)	2	4	6	8	10	12	14	16	TOTAL %
N	1	3	10	4	2	1			21
NE	1	2	5	2	2	+			12
E	+	4	2	2	+	+			8
SE	1	3	4	+	+				8
S	+	4	4	4	2	+			14
SW	1	4	2	2	+	+	+		10
W	1	3	2	1	1	+			9
NW	1“3		6	2	1	+			13
CALM	5								5
TOTAL%	11	26	35	17	9	2	+		100

Table 10b. The predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in August. These data were derived from wind velocity measurements (Brewer et al., 1977) compiled at stations near Region C for mean fetch conditions.

Hs (m)	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13	TOTAL %
N	5	0	5	4	3	0	1	0	1					19
NE	6	0	3	2	2	0	1							14
E	6	3	1	1	+									11
SE	5	2	2	+	+									9
S	5	2	3	0	1	+	0	+						11
SW	3	2	1	0	1	0	+	+	+	+				7
	4	2	.1	0	1	+	+							8
NW	6	0	5	3	2	0	1	0	1					18
CALM	3													3
TOTAL%	43	11	21	10	10	+	3	+	2	+				100

Table ha. The predicted frequency of significant wave heights (Hs) in meters for waves from eight specified directions in September. These data were derived from wind velocity histograms (Brewer ●t al., 1977) compiled at stations near Region C for ❑ean fetch conditions.

Tp(S)	2.	4	6.	8.	10.	12.	14.	16	TOTAL %
N	1	1	8	4	3	2			19
NE	1	2	6	2	2	1	+		14
E	1	5	3	1	1				11
SE	“1	4	2	1	1	+	+		9
S	1	4	2	3	1	+			11
SW	+	3	2	1	1	+			7
W	1	3	2	1	1	+			8
NW	+	3	8	3	2	2			18
CALM	3								3
TOTAL%	9	25	33	16	12	5	+		100

Table 11b. The predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in September. These data were derived from wind velocity measurements (Brewer et al., 1977) compiled at stations near Region C for mean fetch conditions.

Hs (m)	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	TOTAL %
N	4	8	0	10	9	6	3	+						40
NE	1	3	3	0	1	1	+	+						9
E	2	1	2	1	+	0	+							6
SE	1	1	+	0	1	+	1	+						5
S	7	3	2	0	1	1	1	1	+					16
SW	5	1	+	+	+	0	+	+						7
W	2	1	1	0	+	+								5
NW	1	0	1	2	1	1	+	+						7
CALM	5													5
TOTAL%	28	18	10	13	14	10	6	1	+					.100

Table 12a. The predicted frequency of significant wave heights (Hs) in meters for waves from eight specified directions in October. These data were derived from wind velocity histograms (Brewer et al., 1977) compiled at stations near Region C for mean fetch conditions.

Tp (S)	2.	4.	6.	8.	10.	12.	14.	16.	TOTAL %
N	+	1	11	19	9	+			40
NE	+	1	3	3	2	+			9
E	+	2	1	3	+	+			6
SE	+	1	1	+	1	1			5
S	1	6	3	2	2	2	+		16
SW	1	4	1	+	+	+			7
W	+	2	1	1	+	+			5
NW	+	+	2	2	2	+			7
CALM	5								5
TOTAL%	10	17	23	31	16	3	+		100

Table 12b. The predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in October. These data were derived from wind velocity measurements (Brewer et al., 1977) compiled at stations near Region C for mean fetch conditions.

Hs (m)	1	2	3	4	5	6	7	8	9	10	11	12	13	TOTAL %
N	4	12	6	5	+									27
NE	1	3	3	3	2	1	+							13
E	1	4	2	1	+									8
SE	+	+	+	+	+									2
S	7	2	2	2	1	3	1							18
SW	5	1	+	+	+	+	+							8
W	2	3	1	+										7
NW	3	5	2	1										11
CALM	6													6
TOTAL%	29	30	18	13	4	4	2							100

Table 13a. The predicted frequency of significant wave heights (Hs) in meters for waves from eight specified directions in November. These data were derived from wind velocity histograms (Brewer et al., 1977) compiled at stations near Region C for mean fetch conditions.

Tp (S)	2	4	6	8	10	12	14	16	TOTAL %
N	+	4	12	11	+				27
NE	+	1	3	6	3	+			14
E	+	1	4	3	+				9
SE	+	+	+	+	+				2
S	1	6	2	4	4	1			18
SW	1	4	1	+	+	+			7
W	+	2	3	1					6
NW	+	3	5	3					11
CALM	6								6
TOTAL%	8	2	31	29	9	2			100

Table 13b. The predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in November. These data were derived from wind velocity measurements (Brewer et al., 1977) compiled at stationa near Region C for mean fetch conditions.

southwest in September (Tables 5 and 11). Since Hs is independent of Tp, the joint probability of occurrence p (Hs, Tp) = p(Hs)•p(Tp) (Guttman and Wilks, 1965). As an example, using the percentage frequency from Table 3 (a, b) or Table 5 (a, b) for Hs and Tp their joint occurrence probability is + • + = ∿ (5×10^{-3}) " (5×10^{-3}) or .0025% in Region C for July or September. The largest possible Hs and Tp found were 11 m and 16 s respectively for waves from the northeast at maximum fetch in November (Table 7, Fig. 8a). This maximum fetch condition has a 1% probability of occurrence in Region C and is also independent of Hs and Tp. Therefore, the joint probability of all three occurring is 1 •+ •+ = ∿ $(1 \times 10^{-2}) \cdot (5 \times 10^{-3})^2$ or .00000025%. Region C usually has limited open water in November (Fig. 8b) which also eliminates the chances for large waves (Table 13).

Most potentially destructive wave directions are from the south for the months of May to July and from the north to northeast for the months of August to November which correspond to the change in vector mean winds and fetch for these months (Brewer et al., 1977).

Region B

This region is just above C and has a shorter open water period. The minimum ice edge position in the Chukchi Sea for June through November can be seen in Figs. 3a-8a. The mean Chukchi Sea ice edge position from July until October (shorter open water period) is shown in Figs. 4b-7b. Tables 14-19 and Tables 20-23 show Hs and Tp for maximum and mean fetch respectively. The months with the greatest amount of open water for Region B are August and September. They show little difference between the corresponding maximum fetch Tables 16-17 and the mean fetch Tables 21-22 since the ice edge is far away from Region B for both cases.

Hs (m)	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	TOTAL %
N	12	2	+											14
NE	14	5	4	1	+									24
E	6	4	3	2										15
SE	2	+	+	+										3
S	3	+	+	0	′	+	+	0	+					4
SW	8	0	2	1	+	0	+	0	+					12
W	10	+	+	0	+									11
NW	9	+												9
CALM														8
TOTAL%	72	12	10	4	1	1	+	+	+					100

Table 14a. The predicted frequency of significant wave heights (Hs) in ❑eters for waves from eight specified directions in June. These data were derived from wind velocity histograms (Brewer et al., 1977) compiled at stations near Region B for maximum fetch conditions.

Tp(S)	2.	4.	6.	8.	10.	12.	14.	16	TOTAL %
N	1	11	2	+					14
NE	1	13	5	5	+				24
E	+	6	4	5					15
SE	+	2	+	+					3
S	1	2	+	+	+	+			4
SW	1	7	2	1	+	+			12
W	1	8	1	+	+				11
NW	1	8	+						9
CALM	8								
TOTAL%	15	57	15	12	1	+			100

Table 14b. The predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in June. These data were derived from wind velocity measurements (Brower et al., 1977) compiled at stationa near Region B tor maximum fetch conditions.

Hs (m)	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13	TOTAL %
N	4	1	+	0	+									5
NE	8	3	1	+										12
E	19	2	+	0	+	+	+							22
SE	6	1	+	+	+	0	+							8
S	4	4	0	3	2	1	0	1	0	+	+			15
SW	3	0	5	4	3	0	1	0	+	o	+	+		16
W	3	0	1	+	+	0 ″	+							4
NW	5	1	+	0	+									6
CALM	12													12
TOTAL%	6 4	1 2	8	8	5	1	1	1			/+	+	+	100

Table 15a. The predicted frequency of significant wave heights (Hs) in meters for waves from eight specified directions in July. These data were derived from wind velocity histograms (Brewer et al., 1977) compiled at stations near Region B for maximum fetch conditions.

Tp (S)	2.	4.	6.	8.	10.	12.	14.	16.	TOTAL %
N	1	3	1	+	+				5
NE	1	7	3	1					12
E	3	16	2	+	+	+			22
SE	1	5	1	+	+				8
S	+	1	7	3	3	1	+	+	15
SW	+	1	7	4	3	1	+	+	16
W	+	1	3	+	+	+			4
NW	1	4	1	+	+				12
CALM	12							12	100
TOTAL%	19	38		25		9 7	2 +	+	100

Table 15b. The predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in July. These data were derived from wind velocity measurements (Brewer et al., 1977) compiled at stations near Region B for maximum fetch conditions.

Hs (m)		2	3	4	5	6	7	8	9	0	2	3	TOTA
N	8	1	+	0	+								9
NE	14	5	0	1	+	+							20
E	11	5	2	0	1	+							19
SE	5	1	+	+	+								6
S	4	1	0	1	1	0	+						7
SW	7	0	3	1	1	0	+	0	+				12
W	7	0	1	1	1	0	+						10
NW	7	0	1	+	+	0	0	0	+				8
CALM													9
TOTAL%	72	13	7	4	4	+	+	0	+				100

Table 16a. The predicted frequency of significant wave heights (Hs) in ❑eters for waves from eight specified directions in August. These data were derived from wind velocity histograms (Brewer et al., 1977) compiled at stations near Region B for maximum fetch conditions.

Tp(S)	2.	4.	6.	8.	10.	12.	14.	16	TOTAL, 0/0
N	1	7	1	+	+				9
NE	1	5	13	1	+				20
E	1	10	5	2	1				19
SE,	1	4	1	+	+				6
S	+	2	3	1	1				7
s W	+	3	7	1	1	+			12
W	1	3	4	1	1	+			10
NW	1	3	4	+	+	+			S
CALM	9								9
TOTAL%	15	37	38	6	4	+			100

Table 16b. The predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in August. These data were derived from wind velocity measurements (Brewer et al., 1977) compiled at stations near Region B for maximum fetch conditions.

Hs (m)	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	TOTAL %
N	7	1	0	+	+									8
NE	16	0	6	4	+									26
E	12	6	5	2	0	+	+							25
SE	6	1	+	+	0	+								7
S	5	1	0	1	+	0	+							7
SW	5	0	2	1	+	0	+							8
W	3	0	2	+	+	+								6
NW	3	1	0	1	+	0	+							6
CALFI	7													7
TOTAL%	64	10	15	10	1	+	+							100

Table 17a. The predicted frequency of significant wave heights (Hs) in meters for waves from eight specified directions in September. These data were derived from wind velocity histograms (Brewer et al., 1977) compiled at stations near Region B for maximum fetch conditions.

Tp (S)	2	4	6	8	10	12	14	16	TOTAL %
N	1	3	4	+	+				8
NE	1	6	15	3	1	+			26
E	1	11	6	5	2	+			25
SE	1	5	1	+	+				7
S	+	5	1	1	+				7
SW	1	1	5	1	+	+			8
W	+	1	4	+	+	+			6
NW	+	1	3	1	+	+			6
CA M									7
TOTAL%	12	33	39	12	4	+			100

Table 17b. The predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in September. These data were derived from wind velocity measurement (Brewer et al., 1977) compiled at stations near Region B for maximum fetch conditions.

Hs (m)	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13	TOTAL %
N	2	1	0	+	+									3
NE	14	7	0	4	2	+								27
E	14	6	4	0	2	+								26
SE	12	1	+	+	+									13
S	7	2	0	1	+	0	+							10
SW	3	0	2	1	+	0	+	0	+					7
W	2	1	0	+	+									4
NW	2	0	1	+	+									3
CALM	7													7
TOTAL%	63	18	7	7	5	+	1	0	+					100

Table 18a. The predicted frequency of significant wave heights (Hs) in meters for waves from ● ight specified directions in October. These data were derived from wind velocity histograms (Brewer et al., 1977) compiled at stations near Region B for maximum fetch conditions.

Tp (S)	2.	4.	6.	8.	10.	12.	14.	16	TOTAL %
N	+	1	2	+	+				3
NE	1	6	14	4	2				27
E	1	13	6	4	2				26
SE	2	10	1	+	+				13
S	1	3	5	1	+				10
SW	+	1	4	1	+	+			7
W	+	1	2	+	+				4
NW	+	1	2	+	+				3
CALM	7								7
TOTAL%	12	36	36	11	5	+			100

Table 18b. The predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in October. These data were derived from wind velocity measurements (Brewer et al., 1977) compiled at stations near Region B for ❑aximum fetch conditions.

Hs (m)	1.	2.	3.	9.	5.	6.	7.	8.	9.	10.	11.	12.	13.	TOTAL. %
N	2	1	+	+	+									3
NE	11	7	7	3	0	2	+							30
E	10	6	6	3	0	2	+							27
SE	8	1	1	+	+									11
S	4		1	0	1	+ 0	+	+						7
SW	3	1	0	2	1	0	1	+	0	0	+			9
W	2	1	0	1	+	+	0	+						5
NW	2	1	+	0	+	+								3
CALM	5													5
TOTAL%	47	19	15	11	2	5	1	+	0	0	+			100

Table 19a. The predicted frequency of significant wave heights (Hs) in meters for waves from eight specified directions in November. These data were derived from wind velocity histograms (Brewer et al., 1977) compiled at stations near Region B for maximum fetch conditions.

Tp(S)	2.	4.	6.	8.	10.	12.	14.	16	TOTAL. %
N	+	2	1	+	+				3
NE	1	10	7	10	2	+			30
E	1	9	6	9	2				27
SE	1	7	1	1	+				11
S	+	2	3	1	+	+			?
SW	+	1	3	3	1	+	0	+	9
W	+	+	3	1	+	+			5
NW	+	2	1	+	+				3
CALM.	5								5
TOTAL%	11	34	25	25	5	+	0	+	100

Table 19b. The predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in November. These data were derived from wind velocity measurements (Brewer et al., 1977) compiled at stations near Region B for maximum fetch conditions.

Hs (m)	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	TOTAL %
N	4	1	+	+										5
NE	8	3	1	+										12
E	19	2	+	0	+	+	+							22
SE	6	1	+	+	+	0	+							8
S	4	4	0	3	2	1	0	1	0	+	+			15
SW	3	5	0	4	3	1	0	+	0	+	+			16
W	3	1	+	0	+	+								4
NW	5	1	+	+										6
CALM	12													12
TOTAL%	64	18	2	8	5	2	0	1	0	+	+			100

Table 20a. The predicted frequency of significant wave heights (Hs) in meters for waves from eight specified directions in July. These data were derived from wind velocity histograms (Brewer et al., 1977) compiled at stations near Region B for mean fetch conditions.

Tp(S)	2.	4.	6.	8.	10.	12.	14.	16.	TOTAL %
N	1	3	1	+					5
NE	1	7	3	1					12
E	3	1 6	2	+	+	+			22
SE	1	5	1	+	+				8
S	+	1	7	3	3	1	+	+	15
SW	+	1	7	4	4	+	+	+	16
W	+	3	1	+	+				4
NW	1	4	1	+					
CALM	12								12
TOTAL%	19	40	23	9	8	1	+	+	100

Table 20b. The predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in July. These data were derived from wind velocity measurements (Brewer et al., 1977) compiled at stations near Region B for mean fetch conditions.

Hs (m)	1	2	3	4	5	6	7	8	9	10	11	12	13	TOTAL %
N	8	1	+	+										9
NE	14	5	1	+	0	+								20
E	11	5	2	0	1	+								19
SE	5	1	+	+	+									6
S	4	1	0	1	1	0	+							7
SW	7	0	3	1	1	0	+	0	+					12
W	7	1	0	1	1	0	+							10
NW	7	1	+	0	+	0	+							8
CALM	9													9
TOTAL%	72	15	6	3	4	+	+	0	+					100

Table 21a. The predicted frequency of significant wave heights (Hs) in meters for waves from eight specified directions in August. These data were derived from wind velocity histograms (Brewer et al., 1977) compiled at stations near Region B for mean fetch conditions.

Tp (S)	2	4	6	8	10	12	it	16	TOTAL %
N	1	7	1	+					9
NE	1	13	5	1	+				20
E	1	10	5	2	1				19
SE	1	4	1	+	+				6
S	+	2	3	1	1				7
SW	+	3	7	1	1	+			12
W	1	3	4	1	1				10
NW	1	6	1	+	+	+			8
CALM	9								9
TOTAL%	15	48	27	6	4	+			100

Table 21b. The predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in August. These data were derived from wind velocity measurements (Brewer et al., 1977) compiled at stations near Region B for mean fetch conditions.

Hs (m)	1.	2.	3.	9.	5.	6.	7.	8.	9,	10,	11.	12.	13	TOTAL %
N	7	1	+	0	+									S
NE	16	6	4	0	+									26
E	12	6	5	2	0	+	+							25
SE	6	1	+	+	0	+								7
S	5	1	0	1	+	0	+							7
SW	5	0	2	1	+	0	+							8
W	3	0	2	+	+	+								6
NW	3	1	1	0	+	+								6
A M														
TOTAL%	64	16	14	5	1	+	+							100

Table 22a. The predicted frequency of significant wave heights (Hs) in meters for waves from eight specified directions in September. These dats were derived from wind velocity histograms (Brewer et al., 1977) compiled at stations near Region B for mean fetch conditions.

Tp(S)	2.	4	6.	8.	10.	12.	14,	16	TOTAL %
N	1	6	1	+	+				8
NE	1	15	6	3	1	+			26
E	1	11	6	5	2	+			25
SE	1	5	1	+	+				7
S	+	5	1	1	+				7
SW	1	1	5	1	+	+			8
W	+	.1	4	+	+	+			6
NW	+	3	1	1	+	+			6
CALM	7								7
TOTAL%	'12	47	25	12	4	+			100

Table 22b. Tbe predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in September. These data were derived from wind velocity measurements (Brower et al., 1977) compiled at stationa near Region B for mean fetch conditions.

Hs (m)	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	TOTAL %
N	2	1	+	+										3
NE	14	7	4	2	+									27
E	14	6	4	2	o	+								26
SE	12	1	+	+	+									13
S	7	2	0	1	+	0	+							10
SW	3	2	0	1	+	+	0	+						7
W	2	1	0	+	+									4
NW	2	1	+	0	+									3
CALM	7													7
TOTAL%	63	21	8	7	1	+	+	+						100

Table 23a. The predicted frequency of significant wave heights (Hs) in meters for waves from eight specified directions in October. These data were derived from wind velocity histograms (Brewer et al., 1977) compiled at stations near Region B for mean fetch conditions.

Tp(S)	2.	4.	6.	8.	10.	12.	14.	16.	TOTAL %
N	+	2	1	+					3
NE	1	13	7	6	+				27
E	1	13	6	6	+				26
SE	2	10	1	+	+				13
S	1	3	5	1	+				10
SW	+	1	4	1	+				7
W	+	1	2	+	+				4
NW	+	2	1	+	+				3
CALM	7								7
TOTAL%	12	45	27	15	1				100

Table 23b. The predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in October. These data were derived from wind velocity measurements (Brewer et al., 1977) compiled at stations near Region B for mean fetch conditions.

The maximum Hs and Tp found in the major open water months were 9 m and 12 s respectively (Tables 16 and 21, August) for waves coming from the southwest and northwest. Using the percentage frequency from Table 16 (a, b) or Table 21 (a, b) the joint probability of occurrence for Hs and Tp is $+ \cdot + = \sim (5 \times 10^{-3})$ " (5×10^{-3}) or .0025% in Region B for August. The largest possible Hs and Tp found were 12 m and 16 s respectively for waves from the southwest at maximum fetch in July (Table 15, Fig. 4a). This maximum fetch condition also has a 1% probability of occurrence in Region C and is independent of Hs and Tp. Therefore, the joint probability of the largest wave, calculated as for Region C (above), will equal ∿.00000025%. Region B usually has the ice edge on its northern border (Fig. 4b) which means that winds from the south will create the largest waves.

Most potentially destructive wave directions are from the south and southwest for all the months of open water in Region B. This is generally due to the sea ice edge at it's northern boundary reducing the total fetch for northerly winds.

Region A

This is the farthest north of the three regions studied and, therefore, has the shortest open water season. It also has no complicating coastal areas so that the deep water statistics will apply to the entire region. The minimum ice edge position in the Chukchi Sea for July through November can be seen in Figs. 4a-8a. In November (Fig. 8a) the minimum sea ice position still covers more than 50% of the region. The mean Chukchi Sea ice edge position from August to October is shown in Figs. 5b-7b. Tables 24-28 and Tables 29-31 show Hs and Tp for maximum and mean fetch respectively. Due to the proximity of the ice edge there is considerable difference between corresponding maximum and mean fetch tables in all months.

Hs (m)	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	TOTAL. %
N	4	1	+	+										5
NE	8	3	1	+										12
E	19	2	0	+	+	o	+	+						22
SE	6	1	+	+	0	+	+							8
S	4	0	4	3	2	0	1	0		o	+	+		15
SW	3	0	5	4	3	0	1	0	:	0	+	+		16
W	3	1	0	+	+	+								4
NW	5	1	+	+										6
CALM	12													12
TOTAL%	64	9	11	8	5	+	2	+	1	0	+	+		100

Table 24a. The predicted frequency of significant wave heights (Hs) in meters for waves from eight specified directions in July. These data were derived from wind velocity histograms (Brewer et al., 1977) compiled at stations near Region A for maximum fetch conditions.

Tp(S)	2.	4.	6.	8.	10.	12.	Pi.	16	TOTAL. 0/0
N	1	3	1	+					5
NE	1	7	3	1					12
E	3	9	9	+	+	+			22
SE	1	5	1	+	+	+			8
S	+	1	7	3	2	2	+	+	15
SW	+	1	7	4	3	1	+	+	16
W	+	1	3	+	+				4
NW	1	4	1	+					6
CALM	12								12
TOTAL%	19		31	32 9	6	3	+	+	100

Table 24b. The predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in July. These data were derived from wind velocity measurements (Brewer et al., 1977) compiled at stations near Region A for maximum fetch conditions.

Hs (m)	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	TOTAL %
N	8	1	+	+										9
NE	14	5	1	+	0	+								20
E	11	5	0	2	1	0	+							19
SE	5	1	+	0	+	+								6
S	4	0	1	1	1	0	+							7
SW	7	0	3	1	1	0	+	0	+					12
W	7	0	1	1	1	0	+							10
NW	7	1	+	+	0	0	+							8
CALM	9													9
TOTAL %	72	13	6	5	4	+	+	0	+					100

Table 25a. The predicted frequency of significant wave heights (Ha) in meters for waves from eight specified directions in August. These data were derived from wind velocity histograms (Brewer et al., 1977) compiled at stations near Region A for maximum fetch conditions.

Tp (S)	2.	4.	6.	8.	10.	12.	14.	16.	TOTAL %
N	1	7	1	+					9
NE	1	13	5	1	+				20
E	1	3	12	2	1				19
SE	1	4	1	+	+				6
S	+	2	3	1	1	+			7
SW	+	3	7	1	1	+			12
W	1	3	4	1	1	+			10
NW	1	6	1	+	0	+			8
CALM	9								9
TOTAL %	15	41	34	6	4	+			100

Table 25b. The predicted frequency of peak wave perioda (Tp) in seconds for waves coming from eight specified directions in August. These data were derived from wind velocity measurements (Brewer et al., 1977) compiled at stations near Region A for maximum fetch conditions.

Hs (m)	1	2	3	4	5	6	7	8	9	10	11	12	13	TOTAL %
N	7	1	+	+										,
NE	16	6	3	0	1	+								26
E	12	6	0	5	2	+	0	+						25
SE	6	1	0	+	+	+								7
S	5	o	1	1	+	o	+							7
SW	5	0	2	1	+	0	+							8
W	3	0	2	+	+									6
NW	3	1	1	0	+	+								6
CALM	7													/
TOTAL%	64	15	9	8	4	+	+	+						.100

Table 26a. The predicted frequency of significant wave heights (Hs) in meters for waves from eight specified directions in September. These data were derived from wind velocity histograms (Brewer et al., 1977) compiled at stations near Region A for maximum fetch conditions.

Tp(S)	2	4	6	8	10	12	14	16	TOTAL %
N	1	6	1	+					8
NE	1	15	6	3	1	+			26
E	1	4	13	5	2	+			25
SE	1	3	3	+	+	+			7
S	+	3	3	1	+	+			7
SW	1	1	5	1	+	+			8
W	+	1	4	+	+				6
NW	+	3	1	1	+	+			6
CALM	7								7
TOTAL%	12	36	36	12	4	+			100

Table 26b. The predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in September. These data were derived from wind velocity measurements (Brewer et al., 1977) compiled at stations near Region A for maximum fetch conditions.

Hs (m)	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	TOTAL %
N	2	1	+	0	+									3
NE	14	7	4	0	2	+								27
E	14	6	0	4	2	0	+							26
SE	12	1	+	0	+	+								13
S	7	0	2	1	+	0	+							10
SW	3	0	2	1	+	0	+	0	+					7
W	2	0	1	+	+									4
NW	2	1	+	0	+									3
CALM	7													7
TOTAL%	63	16	9	6	5	1	+	0	+					100

Table 27a. The predicted frequency of significant wave heights (Hs) in meters for waves from eight specified directions in October. These data were derived from wind velocity histograms (Brewer et al., 1977) compiled at stations near Region A for maximum fetch conditions.

Tp(S)	2.	4.	6.	8.	10.	12.	14.	16.	TOTAL %
N	+	2	1	+	+				3
NE	1	13	7	4	2	+			27
E	1	5	14	4	2				26
SE	2	10	1	+	+				13
S	1	3	3	3	+	+			10
SW	+	1	4	1	+	+			7
W	+	1	2	+	+				4
NW	+	2	1	+	+				3
CALM	7								7
TOTAL%	12	37	33	13	5	+			100

Table 27b. The predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in October. These data were derived from wind velocity measurements (Brewer et al., 1977) compiled at stations near Region A for maximum fetch conditions.

Hs (m)	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	TOTAL %
N	2	1	+											3
NE	11	7	10	2	+									30
E	10	6	6	3	2	+								27
SE	8	1	1	+	0	+								11
S	4	0	1	1	+	0	+	0	+					7
SW	3	1	0	2	1	1	0	+	0	0	+			9
W	2	1	1	+	0	+	+							5
NW	2	1	+											3
CALM														5
TOTAL%	47	18	19	9	4	2	1	+	+	0	+			100

Table 28a. The predicted frequency of significant wave heights (Hs) in meters for waves from eight specified directions in November. These data were derived from wind velocity histogram (Brewer et al., 1977) compiled at stations near Region A for maximum fetch conditions.

Tp(S)	2.	4.	6.	8.	10.	12.	14.	16.	Fre-%
N	+	2	1	+					3
NE	4	7	14	5	+				30
E	1	9	6	9	2	+			27
SE	1	7	1	1	+				11
S	+	2	3	1	+	+			7
SW	+	1	3	2	1	1			9
W	+	2	1	1	+				5
NW	+	2	1	+					3
CALM	5								5
TOTAL%	14	32	30	20	3	1			100

Table 28b. The predicted frequency of peak wave perioda (Tp) in seconds for waves coming from eight specified directions in November. These data were derived from wind velocity measurements (Brewer et al., 1977) compiled at stations near Region A for maximum fetch conditions.

Hs (m)	1	2	3	4	5	6	7	8	9	10	11	12	13	TOTAL
N	8	1	+											9
NE	14	5	1	+										20
E	11	5	2	0	1	+								’19
SE	5	1	+	+	+									6
S	4	1	0	1	1	0	+							7
SW	7	0	3	1	1	0	+	0	+					12
W	7	1	1	0	1	+								10
NW	7	1	+	+										8
CALM	9													9
TOTAL%	72	15	7	2	4	+	+	0	+					100

Table 29a. The predicted frequency of significant wave heights (Hs) in meters for waves from eight specified directions in August. These data were derived from wind velocity histograms (Brewer et al., 1977) compiled at stations near Region A for mean fetch conditions.

Tp(S)	2	4	6	8	10	12	N	{6	TOTAL %
N	1	7	1	+					9
NE	1	13	6	+					20
E	1	10	5	2	1				19
SE	1	4	1	+	+				6
S	+	2	3	1	1				7
SW	+	3	7	1	1	+			12
W	1	6	1	1	1				10
NW	1	6	1	+					8
CALM	9								9
TOTAL%	15	51	25	5	4	+			100

Table 29b. The predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in August. These data were derived from wind velocity measurement (Brewer et al., 1977) compiled at stations near Region A for mean fetch conditions.

Hs (m)	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13	TOTAL. %
N	7	1	+	+										8
NE	16	6	3	1	+									26
E	12	6	5	2	+	+								25
SE	6	1	+	+	0	+								7
s	5	1	1	+	0	+								7
SW	5	0	2	1	+	0	+							8
w	3	2	0	+	+	+								6
NW	3	1	1	+	+									6
CALM	7													7
TOTAL%	64	18	13	5	+	+	+							100

Table 30a. The predicted frequency of significant wave heights (Hs) in meters for wavea from eight specified directions in September. These data were derived from wind velocity histograms (Brewer et al., 1977) compiled at stations near Region A for mean fetch conditions.

Tp(S)	2.	9.	6.	8.	10	12.	14.	16	TOTAL %
N	1	6	1	+					8
NE	1	15	6	3	1				26
E	1	11	6	5	2	+			25
SE	1	5	1	+	+				7
S	+	5	2	+					7
SW	1	1	5	1	+	+			8
W	+	1	4	+	+	+			6
NW	+“3		1	1	+				6
CALM	7								7
TOTAL%	12	47	26	11	4	+			100

Table 30b. Th. predicted frequency of peak wave periods (Tp) in seconds ‘or waves coming from eight specified, directions in September. These dais were derived from wind velocity measurements (Brewer et al., 1977) compiled at stations near Region A for mean fetch conditions.

Hs (t-n) 1 2 3. 4. 5. 6. 7. 8. 9. 10. 11. 12. 13 TOTAL %

N	2	1	+						3
NE	14	11	2						27
E	14	6	4	2					26
SE	12	1	+						13
S	7	3	+						10
SW	3	2	1	0	+	+	0	+	7
W	2	1	+	0	+	+			4
NW	2	1	+						3
CALM	7								7
TOTAL %	63	26	8	2	1	+	0	+	100

Table 31a. The predicted frequency of significant wave heights (Hs) in meters for waves from eight specified directions in October. These data were derived from wind velocity histograms (Brewer et al., 1977) compiled at stations near Region A for mean fetch conditions.

Tp(S)	2.	4.	6.	8.	10.	12.	14.	16.	TOTAL %
N	+	2	1	+					3
NE	1	13	11	2					27
E	1	13	10	2					26
SE	2	10	1	+					13
S	1	6	3	+					10
SW	+	3	2	1	+	+			7
W	+	?	1	+	+				4
NW	+	2	1	+					3
CALM	7								7
TOTAL %	12	51	30	6	1	+			100

Table 31b. The predicted frequency of peak wave periods (Tp) in seconds for waves coming from eight specified directions in October. These data were derived from wind velocity measurements (Brewer et al., 1977) compiled at stations near Region A for mean fetch conditions.

The maximum Hs and Tp found for maximum fetch conditions (1% probability) were 12 m and 16 s respectively for waves generally from the south to southwest in July, (Table 24). The joint probability of this large wave in July is ∿.00000025%. The maximum Hs and Tp found for average fetch conditions were 9 m and 12 s respectively for waves from the southwest in August (Table 29). The joint probability of occurrence for this wave is . 0025%.

Most potentially destructive large wave directions are from the south and southwest for all the months of open water in Region A. This is due to the sea ice edge, which usually exists at or within its northern boundary, reducing the total fetch for northerly and northeasterly winds which are the most common.

Five Percent Highest Waves ,

The maximum Hs for Regions A, B and C was 12 m. The height of the 5% highest waves (H5) conversion factor (1.73) applied to 12 m, results in a 20.8 m wave. The probability of this large wave is, however, less than .00000025% (see above) in any month.

WAVE BREAKING STATISTICS

The five shoreline orientations (Wise et al., 1981) included in this section (Fig. 1) are contained in Region C (2-5) and Region B(1). Frequency tables of breaking wave height (H), breaking water depth (D) and wave run-up (R) were derived from equations in the WAVE BREAKING CRITERIA and WAVE RUN-UP sections above and additonal considerations of the joint probabilities of Hs, Tp and wave direction. Table 32 shows the beach slope, appropriate region statistics (A, B or C), and major wave directions contributing to the

TABLE 32

Coastline	1	2	3	4	5
Beach Slope	1/65	1/65	1/100	1/100	1/130
Regional Wave Statistics Used in Deep Water Basin	B	c	c	C/local waves	C
Wave Direction Contributing to H, D and R	N,SW W,NW	w, Sw S,SE	NW	E	

Table 32. The beach slope, appropriate region statistics (A, B, or C) and major wave directions contributing to the calculation of H, D and R.

calculation of H, D and R. The beach slopes were taken from standard nautical charts (NOS 16003, 1975 and DMA 16002, 1977) and computed by taking the minimum distance of the 10 fathom curve to the coast. This results in maximum slopes which give worst possible run-up conditions. The typical demarcation lines between the nearshore (breaker zone) and offshore regions are characterized by the water depth contours of 5 m, 5 m, 3 m, 3 m and 5 m for coastlines 1, 2, 3, 4, and 5 respectively. These contours are generally parallel to and inside the 10 m contour lines shown in Fig. 1. For some unusually large waves, however, a maximum breaking wave height of 10 m and breaking water depth of 16 m was calculated. The relatively shallower breaking water depths for coastline 3 and 4 (Fig. 1) are due to their short fetches and smaller locally generated waves.

The monthly and combined average (all possible months) frequency tables of H, D and R for maximum and mean fetches involving coastlines 1-5 are presented in Tables 33-42. The wave run-up in all tables is less than 1 m due to the relatively gentle beach slopes found. This 1 m run-up means that structures in these shore areas will be relatively safe. However, a pollutant such as oil may be washed far inland if the terrain slope is also gentle.

Coastline 1

This is the farthest north and longest coastline in the study (Fig. 1) and it is open to wave impingement from June through November (Fig. 3a-8a) under minimum ice edge conditions (Table 33). Table 32 shows that the main wave directions contributing to H, D and R are from the N, SW, W and NW. Table 33f shows that November would be the most destructive month with 28% of its wave breaking heights equal to 3 m or greater and 23% of its breaking wave depths, 4 m or greater. November also shows a remote possibility

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	85	10	5	+	+												100
D	83	5	1	0	2	+	+	+	+								100
R	100																100

Table 33a. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 1 in June under maximum fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	7	6	1	6	7	1	+	+	+	+							100
D	74	14	9	2	1	+	+	+	+								100
R	100																100

Table 33b. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 1 in July under maximum fetch conditions,

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	78	17	3	2	1	+	+	+	+	+							100
D	75	18	3	2	1	1	+	+	+	+	+	+					100
R	100																100

Table 33c. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 1 in August under maximum fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	75	15	5	3	2	+	+										100
D	74	14	4	3	2	2	1	+									100
R	100																100

Table 33d. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 1 in September under maximum fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	88	10	2	+	+	+											100
D	8	8	8	3	1	+	+	+	+	"	+						100
R	100																100

Table 33e. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 1 in October under maximum fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	55	17	12	10	3	2	1	+	+	+							100
D	54	1013		8	8	3	2	1	1	+	+	++					100
R	100	+															

Table 33f, Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 1 in November under maximum fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	76	14,		6	3	1	+	++	+	+							100
D	74	12	7	3	2	1	1	+	+	+	+	+	+				100
R	100																100

Table. 33g. Average of Tables 33(a-f) under maximum fetch conditions for Coastline 1.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	78	15	6	1	+	+	+										100
D	74	15	9	2	+	+	+	+	+								100
R	100	+															100

Table 34a . Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 1 in July under mean fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	78	18	2	1	1	+	+	+									100
D	75	18	4	1	1	1	+	+	+	+							100
R	100																100

Table 34b. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 1 in August under mean fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	85	10	4	1	+												100
D	84	8	5	2	1	+	+										100
R	100																100

Table 34c. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 1 in September under mean fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	89	9	1	1	+	+											100
D	88	8	4	+	+	+	+										100
R	100																100

Table 34d. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 1 in October under mean fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	83	13	3	1	+	+	+	+									100
D	80	12	6	1	1	+	+	+	+	+							100
R	100																100

Table 34e. Average of Tables 34(a-d) under mean fetch conditions for coastline 1.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	86	9	4	1	+	+	+	+									100
D	84	8	4	2	2	+	+	+	+	+							100
R	100																100

Table 35a. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 2 in June under maximum fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	67	11	11	7	3	1	+	+	+	+							100
D	65	10	10	5	6	3	1	+	+	+	+	+	+	0	+	+	100
R	100																100

Table 35b. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 2 in July under maximum fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	65	15	10	5	4	1	+	+	+								100
D	63	14	9	6	5	2	1	+	+	+							100
R	100																100

Table 35c. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 2 in August under maximum fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	78	i’	691	+	++	+											100
D	77	6	583	1	++	+	+										100
R	100																100

Table 35d. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 2 in September under maximum fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	83	12	3	2	+	+	+	+									100
D	81	10	4	3	1	1	+	+	+	+							100
R	100																100

Table 35e. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 2 in October under maximum fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	73	14	4	4	2	2	1	+	+	+							100
D	70	13	6	3	2	2	1	1	1	1	+	+	+				100
R	100																100

Table 35f. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 2 in November under maximum fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	67	14	10	6	2	1	+	+	+	+							100
D	68	12	8	5	4	2	1	+	+	+							100
R	100																100

Table 35g. Average of Tables 35(a-f) under maximum fetch conditions for coastline 2.

(M)	1	2	3.4	5	.6..7	8.9	10	11	12	13	14.15	.16.								%
H	6	7	1	1	1	1	7	3	1	+	+	+	+							100
D	6	5	1	0	1	0	5	6	3	1	+	+	+	+	+	+	0	+	+	100
R	100																			100

Table 36a. Frequency table of breaking wave height (1[), breaking water depth (D), and wave run-up (R) for coastline 2 in July under mean fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	65	15	10	5	4	1	+	+	+								100
D	63	14	9	6	5	2	1	+	+	+							100
R	100																100

Table 36b. Frequency table of breaking wave height (II), breaking water depth (D), and wave run-up (R) for coastline 2 in August under mean fetch conditions.

(M)	1	Z	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H																	
D																	
R																	

Table 36c. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 2 in September under mean fetch conditions.

(M)	1	2	3	4	5	.6..7	8.9	10	11	12	13	19.15.16					%
H	83	12	3	2	+	+	+	+									100
D	81	10	4	3	1	I	++	+	+								100
R	100																100

Table 36d. Frequency table of breaking wave height (}1), breaking water depth (D), and wave run-up (R) for coastline 2 in October under mean fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	72	11	8	6	2	1	+	+	+	+	+	+	+	0	+	+	100
D	70	10	7	6	4	2	l	+	+	+							100
R	100																100

Table 36e. Average of Tables 36(a-d) under mean fetch conditions for coastline 2.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	19	15	16	%
H	96	3	1	+	+	+											100
D	9	5	3	1	1	+	+	+									100
R	100																100

Table 37a. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 3 in June under maximum fetch conditions.

(M)	1	Z	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	96	3	1	+	+												100
D	9	5	4	1	+	+	+										100
R	100																100

Table 37b. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 3 in July under maximum fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	90	5	4	1	+	+	+	+	+								100
D	88	4	332	+	++	+	+	++									100
R	100																100

Table 37c. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 3 in August under maximum fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	9	5	4	1	+	+	+										100
D	93	5	1	1	+	+	+	+	+	+							100
R	100																100

Table 37d. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 3 in September under ❑aximum fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	65	14	10	8	3	+	+										100
D	6	2	1	2	1	1	6	4	3	2		+	+	+			100
R	100																100

Table 37e. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 3 in October under maximum fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	90	43		2	1	+	+	+									100
D	89	4	3	2	1	1	+	+	+	+	0	+					100
R	100																100

Table 37f. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 3 in November under maximum fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	87	6	4	2	1	+	+	+	+								100
D	87	5	4	2	1	1	+	+	+	+	+	+					100
R	100																100

Table 37g. Average of Tables 37 (a-f) under maximum fetch conditions for coastline 3.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	96	3	1	+	+												100
D	95	4	1	+	+	+											100
R	100																100

Table 38a. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 3 in July under mean fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	90	5	41+	+	++	+											100
D	8	8	4	3	3	z	+	+	+	+	+	+	+				100
R	100																100

Table 38b. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 3 in August under mean fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	95	4	1	+	+	+											100
D	93	5	1	1	+	+	+	+	+	+	++						100
R	100																100

Table 38c. Frequency table of breaking" wave height (H), breaking water depth (D), and wave run-up (R) for coastline 3 in September under mean fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	70	15	8	5	2	+	+	+									100
D	6	8	1	4	7	6	3	2	+	+	+	+					100
R	100																100

Table 38d. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 3 in October under mean fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	86	7	4	2	1	+	+	+	+								100
D	85	7	331	1	++	+	+	+	+								100
R	100																100

Table 38e. Average of Table 38(a-d) under mean fetch conditions for coastline 3.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	9	8	2	+													100
D	9	4	5	1													100
R	100																100

Table 39a. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 4 in June under maximum fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	9	6	4	+	+	+											100
D	82		17	1	+	+											100
R	100																100

Table 39b. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 4 in July under maximum fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	9	5	3	2	+	+											100
D	9	3	5	2	+	+											100
R	100																100

Table 39c. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 4 in August under maximum fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	85	12	3	+	+	+											100
D	8	2	1	0	5	3	+	+	+								100
R	100																100

Table 39d. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 4 in September under maximum fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	/		0	8	2	+	+	+									100
D	8	5	1	0	3	2	+	+	+								100
R	100																100

Table 39e. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 4 in October under maximum fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	92	15		1	1	+	+										100
D	92	1	4	2	1	+	+	+	+	+							100
R	100																100

Table 39f. Frequency table of breaking wave height (N), breaking water depth (D), and wave run-up (R) for coastline 4 in November under maximum fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	93	5	2	+	+	+	+										100
D	88	8	3	1	+	+	+	+	+	+							100
R	100																100

Table 39g. Average of Tables 39(a-f) under maximum fetch conditions in coastline 4.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	96	4	+	+	+												100
D	82	17	1	+	+												100
R	100																100

Table 40a. Frequency table of breaking wave height (11), breaking water depth (D), and wave run-up (R) for coastline 4 in July under mean 'etch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	95	3	2	+	+												100
D	93	5	2	+	+												100
R	100																100

Table 40b. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 4 in August under mean fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	87	12	1	+	+												100
D	85	10	3	2	+	+											100
R	100																100

Table 40c. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 4 in September under mean fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	95	3	2	+	+	+											100
D	90	8	1	1	+	+	+										100
R	100																100

Table 40d. Frequency table of breaking wave height (11), breaking water depth (D), and wave run-up (R) for coastline 4 in October under mean fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	93	6	1	+	+	+											100
D	87	10	2	1	+	+	+										100
R	100																100

Table 40e. Average of Tables 40(a-d) under mean fetch conditions for coastline 4.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	80	15	4	1	+	+											100
D	70	20	7	2	1	+	+	+									100
R	100																100

Table 41a. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 5 in June under maximum fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	90	8	2	+	+	+											100
D	86	11	2	1	+	+	+										100
R	100																100

Table 41b. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 5 in July under maximum fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	70	15	6	7	2	+	+	+	+	+							100
D	65	12	8	7	6	'	++	+	+	++	+						100
R	100																100

Table 41c. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 5 in August under maximum fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	65	18	12	3	2	+	+	+	+								100
D	63	16	11	5	3	2	+	+	+	+	+						100
R	100																100

Table 41d. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 5 in September under maximum fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	0/o
H	75	15	5	3′	2	+	+	+	+								100
D	73	14	4	5	2	2	+	+	+	+	+						100
R	100																100

Table 41e. Frequency table of breaking wave height (N), breaking water depth (D), and wave run-up (R) for coastline 5 in October under maximum fetch conditions.

(M)	1	2	3	9	5	.6	..7	8	.9	10	11	12	13	14	.15	.16		.0/O
H	57	12	11	8	7	3“	1	1	+									100
D	5	6	1	0	1	0	5	7	6	3	2	1	+	+	+	0	+	100
R	100																	100′

Table 41f. Frequency table of breaking wave height (N), breaking water depth (D), and wave run-up (R) for coastline 5 in November under maximum fetch conditions.

(M)	1	2	3	9	5	.6	..7	8	.9	10	11	12	13	19	.15	.16	.0/o
H	72	14	‘7	4	2	1	+	+	+	+							100
D	69	14	7	4	3	2	1	+	+	+	+	+	+				100
R	100																100

Table 41g. Average of Tablea 41(a-f) under maximum fetch conditions for coastline 5.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	80	15	5	+	+	+											100
D	70	20	7	2	1	+	+										100
R	100																100

Table 42a. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 5 in June under mean fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	91	8	1	+	+	+											100
D	86	12	2	+	+	+	+										100
R	100																100

Table 42b. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 5 in July under mean fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	70	15	7	6	2	+	++		+	+							100
D	65	12	8	7	6	2	+	+	+	+	+	+	+				100
R	100																100

Table 42c. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 5 in August under mean fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	65	18	12	3	2	+	+	+	+								100
D	63	16	11	5	3	2	+	+	+	+	+						100
R	100																100

Table 42d. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 5 in September under mean fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	79	16	4	1	+	+	+										100
D	76	15	5	2	2	+	+	+	+								100
R	100																100

Table 42e. Frequency table of breaking wave height (H), breaking water depth (D), and wave run-up (R) for coastline 5 in October under mean fetch conditions.

(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	%
H	7	7	1	4	6	2	1	+	+	+	+	+					100
D	72	15	7	3	2	1	+	+	+	+	+	+	+				100
R	100																100

Table 42f. Average of Tables 42(a-e) under mean fetch conditions for coastline 5.

for a 10 m breaking wave in 13 m of water depth (< .5%). The joint probability of this occurrence is $(5 \times 10^{-3}) \cdot (1 \times 10^{-2})$ or .005% since the minimum ice edge position has a 1% probability of existence. The run-up should never exceed 1 m during the study months (Table 33g).

Coastline 1 will normally (Table 34, mean sea ice conditions) be open to destructive waves from only July through October (Figs. 4b-7b). The main wave directions are from N, SW, W, NW (Table 32). July is the month (Table 34a) where most damage can be done with 7% of the breaking wave heights at 3 m or above and 2% of its breaking wave depths at 4 m or greater. An 8 m breaking wave in 10 m water depth has a .5% probability during mean ice edge conditions. Again, the run-up should never exceed 1 m for all the study months (Table 34e).

Coastline 2

Table 32 shows that the main wave directions contributing to H, D and R are from the W, SW, S and SE for this coastline (Fig. 1). Table 35 was constructed for maximum fetch conditions (minimum sea ice extent) which have open water from June through November (Figs. 3a-8a). July waves have the most potential destruction along coastline 2. Table 35b shows that 23% of the wave breaking heights are 3 m or greater and 15% break in 4 m depths or greater. It is also possible (July) for a 10 m high wave to break in 16 m water depths. The probability of this wave occurring is .5% since the coastline orientation precludes wave impingement from fetch dependent directions to the north and July will always have open water to the south and southwest of this coastline (Fig. 4).

Coastline 2 will normally (Table 36, mean sea ice edge) be open to destructive waves from July through October (Figs. 4b-7b). The main wave directions are from the W, SW, S and SE (Table 32). Tables 36a and 35b are identical for July since the major wave propagation directions are unaffected by sea ice in this month. Again, July is the month with greatest potential for destruction (see above paragraph). The combined average (Table 36e) statistics for the open water months affecting this coastline reflect the influence of July on the maximum wave breaking height (10 m) and breaking water depth (16 m).

Coastline 3

The wave direction (Table 32) contributing to H, D and R is from the NW for this coastline (Fig. I). Table 37 was constructed for maximum fetch conditions (mimimum sea ice extent) which have open water from June through November (Figs. 3a-8a). Table 38 (mean sea ice extent) was constructed for mean fetch conditions which have open water from July through October (Figs. 4b-7b). October is the most potentially destructive month for either maximum (Table 37e) or mean (Table 38d) fetch conditions. These maximum and mean tables show 21% and 15% breaking wave heights at 3 m or greater with 26% and 18% breaking in 3m depth or greater (respectively). The largest wave breaking height (9 m) and breaking depth (12 m) is seen in August for both fetch conditions also (Tables 37c and 38b). Their occurence probability is .5% since the maximum fetch and mean fetch conditions do not affect the statistics in these months with large expanses of open water. The run-up in all months studied should be less than 1 m (Tables 37g and 38e).

Coastline 4

This coastline is the most protected (Fig. 1) of the five examined in this study. The major destructive wave direction is from the east thereby making land boundaries the primary reasons for limited fetch as long as sea ice is not present. Table 39 (minimum sea ice extent) statistics are for maximum fetch conditions which have open water from June through November (Figs. 3a-8a). Table 40 (mean sea ice extent) statistics are for mean fetch conditions which have open water from July through October (Figs. 4b-7b). September waves are most severe under both maximum and mean fetch conditions. For maximum fetch, 15% of breaking wave heights and 18% of breaking wave depths equal 2 m or more (Table 39d). For mean fetch, 13% of breaking wave heights and 15% of breaking wave depths equal 2 m or more(Table 40c). November statistics (maximum fetch only, Table 39f) show a remote possibility (.005%) for a wave breaking height of 7 m and a breaking depth of 10 m. Again the run-up does not exceed 1 m in any of the study months (summarized in Tables 39g and 40e).

Coastline 5

This is the farthest south coastline (Fig. 1) in the study and it is open to wave impingement from June through November (Figs. 3a-8a) under minimum ice edge conditions. Table 32 shows that the main wave directions contributing to H, D and R are from the N, NW and W. Destructive wave impingement can exist in the months of June through October for mean ice edge conditions (Figs. 3b-7b). The statistics for July through October are almost identical (Tables 41b-e and 42b-e) for maximum or mean fetch conditions since coastline 5 is so far from the ice edge during these months. September is potentially the most destructive of these typical open water months (Table 41d or 42d). It has 17% of its wave breaking heights and 21% of its wave breaking depths greater than or equal to 3 m. For the typical open water months, the highest breaking wave (10 m) and greatest breaking wave depth (13 m) also occurs in August with a probability of .5%. November statistics (maximum fetch only, Table 41f) show a remote chance (.005%) of a wave breaking height of 9 m and a breaking depth of 14 m. The run-up does not exceed 1 m in any study month (summarized in Table 41g and 42f).

SUMMARY

A wave hindcast technique was used to determine the months and locations of highest risk to oil and gas development in the Chukchi Sea area. Parameters required were fetch, wind duration, wind velocity, water depth and beach slope. From these, significant deep water wave heights and periods were tabulated for Chukchi regions A, B and C (Fig. l.). The tabulations were used later to produce statistics of breaking wave heights and depths for five coastline orientations (Fig. 1). as defined by Wise et al. (1981).

Fetch conditions were controlled by both sea ice cover (Kozo, 1985) and coastlines thereby becoming highly directionally dependent. Wind duration and velocity data were taken (Brewer et al., 1977) from designated land stations bordering the Chukchi study regions and/or designated marine areas. Water depths and beach slope were obtained from standard nautical charts and worst cases (steepest) used for slopes.

Deep water significant wave heights in Region C (Fig. 1) can reach 10 m coming from the south in July and from the northeast and southwest in September. The large waves coming from the northeast direction are due to the increased September fetch (Fig. 6b). The most potentially destructive wave directions are from the south in May (minimum sea ice extent) through July and from the north to northeast in August through November. Region B can have 9 m (Hs) waves in August, from both the southwest and northwest. The waves from the northwest are due to a larger fetch distance in the latter direction by August (Fig. 5b). Most potentially destructive wave directions are from the south and southwest for July through October. Region A, the farthest north of the three regions, can have 9 m waves (Hs) from the

southwest in August during average sea ice conditions. The most destructive wave directions are from the south and southwest for August through October, the main months of possible open water. The height of the 5% highest waves is 1.73 x (significant wave height), therefore extreme waves of 15.5-17 m are possible in the three study regions.

Wave breaking statistics were compiled for five coastlines (Fig. .1). Coastline 5, the farthest south (greatest fetch) is the one facing the most probable damage from waves. The main wave impingement directions are from the N, NW and W. September appears as the most severe of the typical open water months with a 17% probability of breaking wave heights at 3 m or above and a maximum height of 9 m possible. Wave run-up will be 1 m or less on all five coasts in all months, which implies limited damage on structures, but possible inland inundation for gentle sloping topography.

FURTHER STUDY

A summer wave parameter study through deployment of floating buoys in deep water offshore from the five coastlines should be started. Geostrophic wind histograms from historical data should be developed for the three regions on a monthly basis. Since many of the arctic coastal wind sites are affected by orography, the geostrophic directions and a modified wind speed (Kozo, 1984) would be a better input to the wave hindcast model.

ACKNOWLEDGEMENTS

This study was funded by the Minerals Management Service, U.S. Department of the Interior, through interagency agreement with the National Oceanic and Atmospheric Administration, U. S. Department of Commerce, as part of the Outer Continental Shelf Environmental Assessment Program.

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