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Measurements of ridge sails in the Beaufort Sea

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Ice pressure ridges in the southern Beaufort Sea near Tuktoyaktuk were surveyed in April 1986. Sail cross-section profiles and ice-block dimensions of ridges of extreme heights were measured at several locations along the outer edge of the landfast ice. Statistical distributions of sail heights as well as correlations between sail dimensions and between ice block dimensions are obtained. Geographical distribution of sail dimensions and longitudinal changes along individual ridges are examined.

Key words: ridges, landfast ice, sea ice, ridge sails, ridge statistics, Beaufort Sea.

Les crêtes de pression des glaces dans le sud de la mer de Beaufort près de Tuktoyaktuk ont été analysées au mois d'avril 1986. Les profils en coupe des voiles et les dimensions des blocs de glace des crêtes de très grande hauteur ont été mesurés à plusieurs endroits le long de la bordure extérieure de la glace bordière. La répartition statistique des hauteurs des voiles et les relations entre les dimensions des voiles et celles des blocs de glace ont été obtenues. La répartition géographique des dimensions des voiles et les modifications longitudinales le long de crêtes individuelles ont été examinées.

Mots clés : crêtes de glace, glace bordière, glace de mer, voiles de crête, statistiques des crêtes, mer de Beaufort.

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Introduction

Pressure ridges usually develop during deformation of floating sea ice covers. Studies of the ridging processes are motivated by the need to understand large-scale ice movements and the forces producing them. As may be intuitively expected, compressive stresses in an ice cover are limited by the values associated with building of pressure ridges. The size of ridges would be proportional to normal stresses. Ridges can also exert relatively high forces on offshore structures and icebreakers.

An understanding of ridge building processes and forces is an important component in the study of the movement and deformation of the polar pack in the Arctic basin and the development of models to forecast ice movements. It also has application in the study of pack ice driving forces and the establishment of "limit-force loads" on offshore structures (Croasdale 1984).

Early observations of ridges and ice rubble hummocks were documented by Zubov (1945), and a brief historical account of ridge and ice rubble sightings was given by Kovacs and Sodhi (1980). Some field studies dealt with the statistical distribution of sail heights and keel depths (e.g., Hibler *et al.* 1972, 1974; Wadhams 1976, 1978, 1983; Weeks *et al.* 1980; Wadhams *et al.* 1985; Wadhams and Davy 1986). Others were concerned with the geometry of ridges and produced typical cross sections of sails and keels (e.g., Weeks *et al.* 1971; Kovacs 1972; Kovacs *et al.* 1973; Rothrock and Thorndike 1980; Evers 1986). Results from a number of projects concerning ice ridging in the Canadian Beaufort Sea are presented in the "Beaufort Sea – Mackenzie Delta Environmental Impact Statement" (1982). Tucker and Govoni (1981) and Tucker *et al.* (1984) examined ridge sail dimensions and structure in the Alaskan Beaufort Sea. They attempted to correlate sail geometry to ice block dimensions and investigated the geographical variations of ridges.

The first analytical study of pressure ridging was conducted by Parmerter and Coon (1972) who developed a kinematical model that apparently produced realistic ridge profiles. Continuum models that consider the deformation of bulk rubble (Sayed and Frederking 1986) as well as laboratory experiments (Timco and Sayed 1986) showed that the complex processes of ridge formation are not adequately described by the "averaged" idealized profiles. A better description of ridge geometries, particularly newly formed ridges, is still needed to guide the development of analytical models. One of the objectives of the present study was to clarify some of the above uncertainties. Detailed cross-section profiles and ice-block dimensions, as well as longitudinal variations along the ridges have been examined.

The present work also examined characteristics of newly formed ridges in the landfast ice of the Canadian Beaufort Sea. Only very limited and qualitative information about ridges in that region is currently available (Spedding 1982). Records from a number of seasons (Spedding and Hawkins 1985; Beaufort Sea – Mackenzie Delta Environmental Impact Statement 1982) indicate that the landfast ice edge coincides with the 20 m water depth contour, and that artificial islands do not appear to influence its location. The behaviour of landfast ice, however, remains poorly understood. There are no available models that can predict ice extent offshore or its interaction with artificial islands. Knowledge of ridge properties at various locations can lead to estimates of the magnitude of stresses and deformation and, consequently, guide the modelling of the ice cover.

The site

Measurements were conducted from 16 to 25 April 1986 before landfast ice breakup in the vicinity of Tuktoyaktuk. Ice edge location is shown in Fig. 1. The ice extended to approximately 60 km from shore and was mostly flat with ridges forming near the outer edge and around artificial island locations. Grounded rubble fields were established over the submerged berms of the islands, which were built as foundations for oil exploration caissons during previous winters. An open lead, approximately 30 km wide, was located adjacent to the landfast ice. Pack ice, consisting of numerous multi-year floes imbedded in first-year ice, drifted in a westerly direction beyond the lead.

Surveyed ridges were chosen near the outer edge at various distances from the grounded rubble fields. Measurements were

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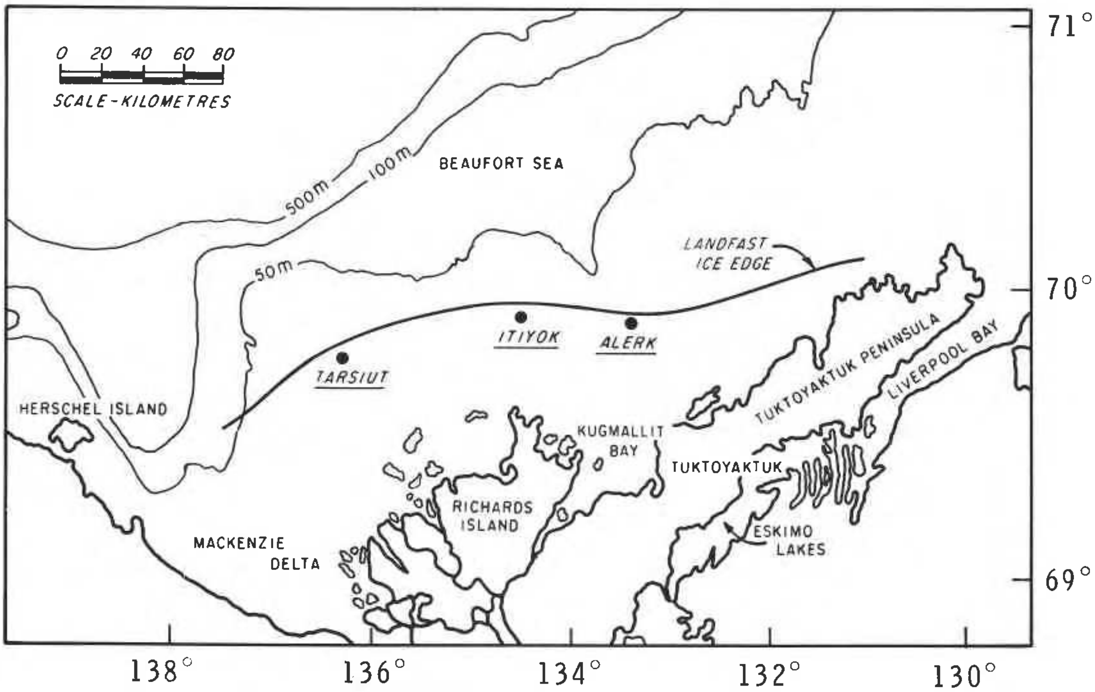

FIG. 1. The outer edge of landfast ice and some of the grounded rubble fields, April 1986.

conducted in the neighbourhood of Tarsiut, Itiyok, and Alerk (shown in Fig. 1) and along the ice edge, covering approximately a 200-km line. One ridge in the pack ice was also included for comparison.

Measurements

Sites of the surveys were chosen where floating ridge sails were prominent during helicopter reconnaissance. Rubble sails higher than 1 m were considered to be ridges and only the maximum heights from each location were measured. Thus, the data represent ridges of extreme sail heights rather than an "unbiased" population of all ridges.

A chain and level survey instrument was used to determine sail cross-section profiles. The instrument consists of a liquid-filled hose and a pressure sensor calibrated to convert pressure difference between cable ends to elevation. Sail cross sections were surveyed by recording the inclined distance and elevation difference between pairs of points along each section. Elevation difference readings were accurate to within ± 0.01 m (for a range of 5 m), and length readings along the cable to within ± 0.05 m. This accuracy is adequate since variations in sail dimensions are much larger due to the relatively large block sizes (with the minimum dimension usually larger than 0.3 m). The use of this instrument proved to be considerably faster than the usual level and rod survey method.

For most ridges, two to four sections that appeared representative of its sail were surveyed. In addition, a few ridges were profiled in more detail, taking about 10 sections along the sail's length to examine the longitudinal variation of geometry. Dimensions of several ice blocks were measured at each cross section. A total of 19 ridges was surveyed. This included 76 cross-section profiles and dimensions of 165 ice blocks.

Results

Longitudinal variation of sail geometry

Variations in sail height, width, and shape of cross section along the length of three ridges were examined. Cross-section profiles were spaced at 20–40 m intervals. The first ridge (Itiyok 1) was approximately 600 m long and adjacent to Itiyok rubble field. The second ridge (Itiyok 2), located 8 km west of Itiyok rubble field, traversed 300 m along a meandering path with waves of approximately 60 m length and 30 m amplitude. The third ridge formed in first-year pack ice during two ice failure events along the boundary of a multi-year floe and had a total length of approximately 4 km. Cross sections covering a 2 km length of that ridge were surveyed.

Examples of 10 sail profiles from the ridge "Itiyok 2" are shown in Fig. 2. These profiles clearly show the variability in height, width, and shape along the length of the ridge. Irregularity of the shapes is likely caused by the relatively large size of blocks compared to sail size.

The cross sections were surveyed between the intact, and nearly flat, ice sheets on both sides of the sail. Elevation of those ice sheets were usually different at the opposite sides of the sail (see Fig. 2). The direction of such an elevation difference (up or down) was maintained along the length of all ridges. The ice sheets probably tended to deflect upwards on one side of the ridge and downwards on the other side during ridge formation. Local modes of failure (e.g., bending or buckling), however, varied considerably along the length of a ridge.

Summary statistics of sail height and width for each ridge are given in Table 1. Height values were relatively clustered around the average while width values showed more scatter. The heights may fit normal probability distributions as shown in Fig. 3. The number of points is too small, however, to obtain valid quantitative measures of goodness of fit. The widths do not appear to fit such distributions.

It should be emphasized that observed sail geometries were not two-dimensional. In addition to changes of cross-section profiles, ridges usually followed irregular and sometimes meandering paths. Only a few ridges had axes that followed nearly straight lines.

TABLE 1. Statistics of the longitudinal variation of ridge cross-section geometry

		Sail height				Sail width			
Ridge site	Number of cross sections	Maximum (m)	Average (m)	Range (m)	Standard deviation (m)	Maximum (m)	Average (m)	Range (m)	Standard deviation (m)
Itiyok 1	9	2.3	1.8	1.0	0.4	21.5	12.1	14.8	4.7
Itiyok 2	10	5.1	2.9	3.9	1.3	13.8	11.0	9.6	3.0
Pack ice	18	4.4	2.5	3.3	0.9	17.9	7.9	14.3	3.5

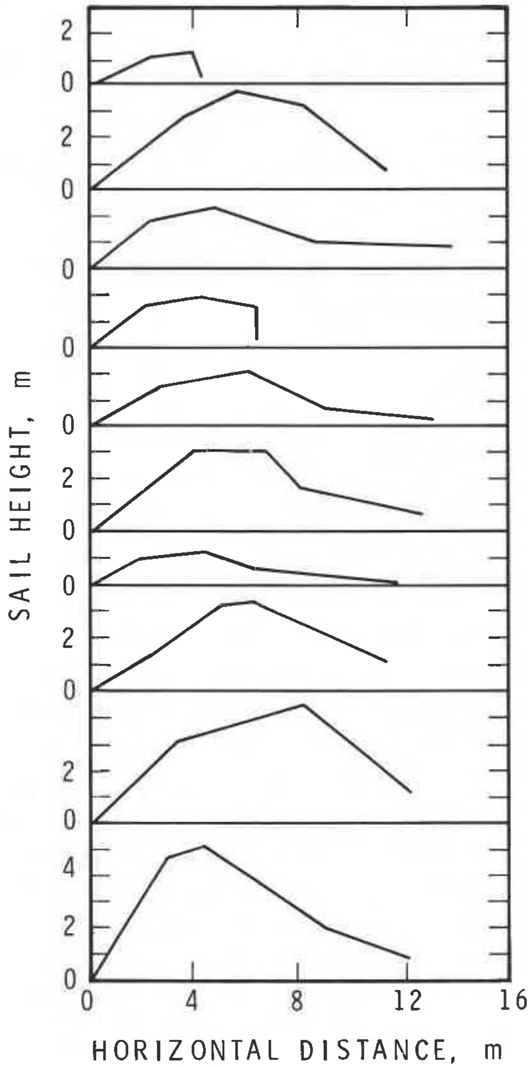

FIG. 2. Sail cross-section profiles of the ridge "Itiyok 2," spacing of the sections varies form 20 to 40 m.

Sail cross-section geometry

Two approaches are used to characterize sail geometries. The first examines the height and width measured at each surveyed cross section. For relatively long ridges, cross-section geometry can vary appreciably along the ridge's length as illustrated above. This variation permits the use of a large number of profiles (although more weight would be given to ridges that were surveyed in detail). The second approach employs the average values of height and width for each ridge and thus gives equal weight to all ridges.

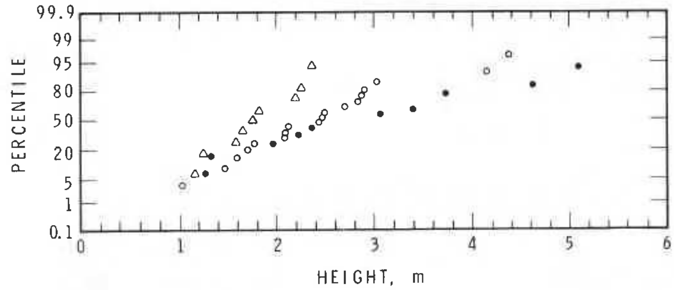

FIG. 3. Normal probability plot of sail height for three ridges: Itiyok 1 (△), Itiyok 2 (●), and pack ice (○).

Heights are plotted versus widths using average ridge values (Fig. 4*a*) and ridge values from all measured profiles (Fig. 4*b*). The scatter increases when all profiles are considered. A regression of the average values in Fig. 4*a* gives the relationship

[1] $h = 0.91 + 0.18w$

where h and w represent the height and width in meters, and the correlation coefficient is 0.85. The same relationship is also close to the best fit of data from all cross sections (Fig. 4*b*) but with a lower correlation coefficient of 0.47. An average slope defined as $\tan^{-1}(2h/w)$ varies, according to [1], from 20° for $w = 10$ m to 28° for $w = 5$ m. It is evident, however, from Fig. 2 that the maximum width and height do not define the detailed shape. The side slopes vary considerably across a ridge and in some cases even exceed 45°.

Plots of sail height and width against average, maximum, and minimum ice-block thickness showed considerable scatter. As an example, height is plotted versus average ice-block thickness in Fig. 5. No reasonable fit for the data in Fig. 5 could be obtained. The formula of Tucker *et al.* (1984), which fits their data with a correlation coefficient of 0.77, is also plotted in Fig. 5.

A motivation for relating sail dimensions to ice-block thickness has been the hypothesis that ridge height should be proportional to the force in the ice cover during the ridging process. The force in turn can be related to ice thickness. Thus, sail height would depend on the thickness if the driving forces act on the ice cover for relatively long periods. Since the forces on the ice cover may act intermittently or over relatively short periods, many ridges may not attain the maximum possible dimensions. Ice blocks also had several thicknesses in most sail cross sections, indicating that blocks originated from a number of ice sheets. Ice of the original sheets may have different mechanical properties. Therefore, a simple dependence of force on ice thickness may not exist. Failure modes during ridge formation are complex, which may contribute to the lack of a clear dependence of sail dimensions on ice thickness.

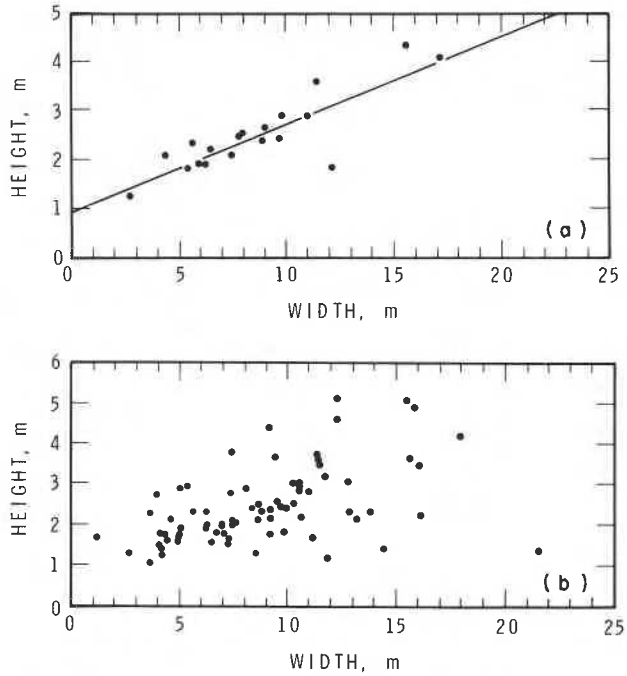

FIG. 4. Height versus width: (*a*) average values of ridges and showing the best linear fit; (*b*) values measured at all cross sections.

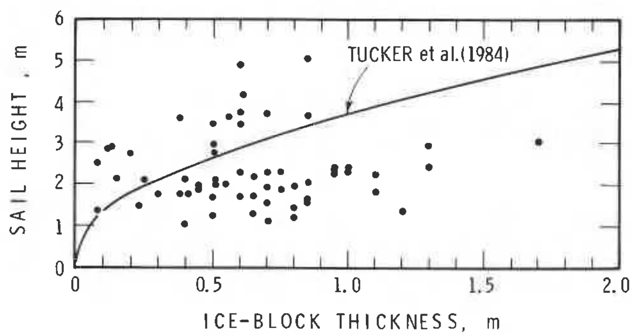

FIG. 5. Sail height versus average block thickness. The curve-fit equation of Tucker *et al.* (1984) is also plotted ($h = 3.71\sqrt{t}$).

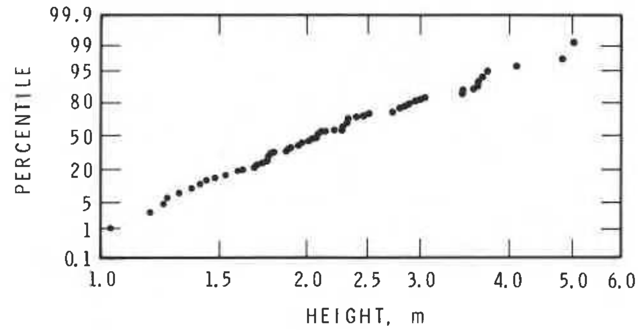

FIG. 6. Lognormal plot of sail heights.

Statistics of sail dimensions

Heights (measured at all surveyed cross sections) in landfast and pack ice follow a lognormal distribution as shown in Fig. 6. The mean height is 2.43 m, the standard deviation is 0.94 m, and the maximum is 5.09 m. In spite of the reasonable correlation between height and width, attempts to fit width measurements to a number of statistical distributions were unsuccessful. The widths have an average of 8.87 m, a standard deviation of 3.93 m, and a maximum of 22 m. The standard values of the skewness and kurtosis coefficients are 3.3 and 0.6 respectively. A few large values near the maximum, as confirmed by the positive skewness coefficient, caused the deviation from normal and lognormal distributions. The small value of the kurtosis coefficient (a value of 3 corresponds to a normal distribution) indicates that the width probability distribution is relatively flat (of low "peakedness" compared to a normal distribution).

Although the ratios of mean to standard deviation are close for height and width values, the range of widths is relatively large (owing to a few large values). This observation may be explained by considering the following possible, albeit speculative, scenario of ridge formation. An early or "primary" stage of ridging may correspond to a steady force acting on the ice cover and relatively uniform failure. The central part of a cross section, which usually includes the maximum height, will form during such a stage. Another "final" stage that corresponds to a decreasing force and nonuniform (or sporadic) failure of ice may follow. This later stage would not affect the maximum heights of a ridge, but may increase the width values at some locations, thus increasing their scatter.

As only sails higher than 1 m were measured, the measurements represent ridges of extreme heights in the region under study. An unbiased sample of all ridges might follow a different distribution. A large number of small ridges in such a case may lead to an exponential distribution of heights.

The only published data on landfast ice ridges for the present location were given by Spedding (1982). Heights were not fitted to statistical distributions, but the maximum values are in agreement with the present measurements. Kreider and Thor (1981) examined ridge height statistics in the neighbouring nearshore Alaskan Beaufort Sea. The heights followed a negative exponential distribution and the measured maximums were close to the present values.

Geographical distribution of ridges

Some qualitative observations regarding the geographical distribution of ridges can be made, although no measurements of ridge spacing or density were performed. Most of the ridges were located near the edge of landfast ice. The ice cover surface was flat, with no ridges and only a few cracks, closer to shore. The number of ridges seemed to increase near grounded rubble fields that were close to the landfast ice edge.

Average sail height and width at various locations are given in Table 2. Heights showed a small increase towards the west along the outer edge of the landfast ice. There is no definitive explanation for this trend.

Ice-block dimensions

Dimensions of representative ice blocks were measured at all cross sections. The frequency histogram of the thickness values is shown in Fig. 7. The average is 0.57 m, the standard deviation is 0.36 m, and the maximum is 1.70 m. The standard coefficients of skewness and kurtosis are 4.28 and 0.87 respectively, which indicates that some relatively large thicknesses were present and that the distribution is flat (compared to a normal distribution). Since ice cover thickness usually ranges from 1.75 to 2 m at that time of year, it can be concluded that ridges formed either in the thinner ice of frozen leads or earlier in the winter.

Attempts to determine the statistical distribution of thickness values did not lead to a satisfactory result. For example, testing the goodness of fit of a normal distribution gave a χ^2 value of

TABLE 2. Geographical distribution of sail dimensions

Location (listed from west to east)	Average height (m)	Average width (m)
1.5 km west of Tarsiut	4.3	15.6
300 m west of Tarsiut	4.1	17.1
At Tarsiut	2.6	9.0
15 km east of Tarsiut	2.2	6.5
65 km east of Tarsiut	3.6	11.4
	1.9	6.3
11 km west of Itiyok	2.4	9.6
8 km west of Itiyok	2.9	11.0
At Itiyok	1.8	12.1
20 km west of Alerk	2.4	8.8
3 km west of Alerk	2.1	7.4
At Alerk (near ice edge)	1.4	4.2
	2.3	5.6
	1.9	5.4
	1.9	6.0
At Alerk (near the grounded rubble)	2.5	7.9
	2.9	9.8
Pack ice	2.5	7.9

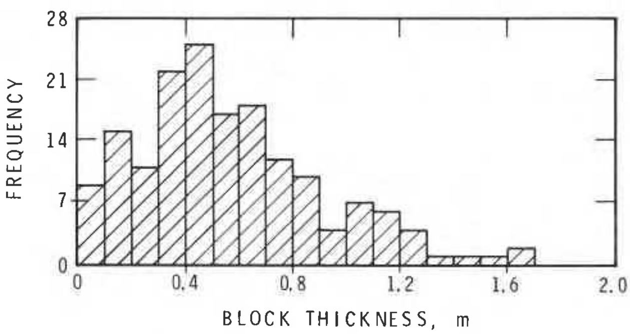

FIG. 7. Histogram of ice-block thickness.

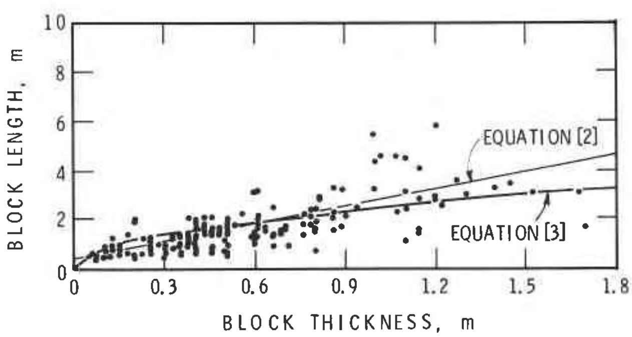

FIG. 8. Block length versus block thickness. Best linear fit (eq. [2]) and cantilever failure values (eq. [3]) are also shown.

35.3, with 15 degrees of freedom. The corresponding probability is 0.002, i.e., the fit is poor.

Block dimensions are correlated below to give a quantitative description of block geometry and some insight into failure modes. Block length (l), taken as the largest dimension, is plotted versus thickness (t) in Fig. 8. Linear regression gives the relationship

[2] $l = 0.32 + 2.328t$

where dimensions are in meters and the correlation coefficient is

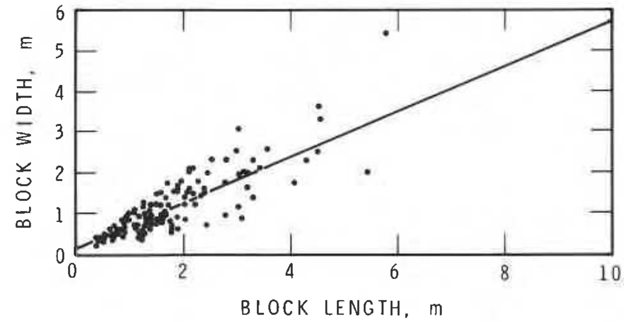

FIG. 9. Block width versus block length. Best linear fit is shown.

0.69. Tucker *et al.* (1984) observed comparable values. They calculated the characteristic length of the floating ice sheet and the length corresponding to maximum bending moment (considering the case of a beam on elastic foundation) and found them both larger than the measured block lengths. A possible reason for this discrepancy, proposed by Tucker *et al.* (1984), is that further breaking of the blocks took place after initial failure of the ice sheet.

Failure of a beam on an elastic foundation (representing a floating ice sheet) would result in block lengths proportional to $t^{0.75}$ (see, for example, Hetényi 1946). Since ice blocks apparently experienced further breaking, a simple scenario of block formation may be that of a cantilever beam failing under its own weight. In this case, block length would be proportional to $t^{0.5}$ and the flexural strength of ice. Considering a specific gravity of 0.9 and a flexural strength of 300 kPa for ice, the following relationship is obtained:

[3] $l = 2.38t^{0.5}$

where dimensions are in meters. The resulting values are close to those given by the linear fit in [2] for the present range of block dimensions. Therefore, block failure under its own weight may have occurred. This, however, does not exclude the possible occurrence of other more complex modes of block breakage inside the deforming bulk rubble.

Block width (b) is plotted versus length (l) in Fig. 9. Linear regression gives

[4] $b = 0.18 + 0.55l$

where dimensions are in meters and the correlation coefficient is 0.86. At present there is no hypothesis regarding the three-dimensional failure modes that can account for the above ice-block dimensions.

Conclusions

Ice ridging is a complex phenomenon that remains poorly understood. Only a few rudimentary analytical models of ridging are currently available. No theory thus far can adequately predict ridge geometry and ridging forces in the ice cover. The present study gives a detailed description of sail geometry statistics, although no physical or theoretical explanation for many of the empirical results is available.

The measurements were conducted in the southern Beaufort Sea. Sails of extreme heights were sampled along a 200-km length of the outer edge of the landfast ice, particularly near grounded rubble fields. Cross-section profiles and ice-block dimensions were measured along the sampled ridges.

Heights, measured at all ridges, followed a lognormal distribution with an average of 2.43 m. The maximum measured height was 5.09 m. Width values did not fit any distribution and had an average of 8.87 m and a maximum of 22 m. Sail heights appeared to increase near grounded rubble fields and there was a trend of slight height increase towards the west.

Geometry of cross-section profiles was irregular, and the maximum height at a cross section could not be correlated to block thickness. The height, however, can be correlated to the width.

Measurements along individual ridges showed that heights of a ridge followed a normal distribution, with little scatter around the average, but widths do not fit a statistical distribution and were more scattered.

Ice-block thicknesses (at an average of 0.57 m) were much smaller than the surrounding ice thickness (1.75–2 m). This indicates that ridges probably formed in ice from refrozen leads or in early winter. Block lengths were correlated to thicknesses and widths. The lengths were smaller than the values expected from initial ice sheet failure. Further breaking of the blocks, possibly under their own weight, must have occurred.

This study dealt only with sail geometry. Keels were not examined because of the difficulty and expense of conducting underwater measurements. Further study of keel properties is still needed. The observed geometries represent the final outcome of many complex processes of ice failure. They do not definitively reveal the manner in which ridges form or give direct estimates of forces in the ice cover. The preceding results can be used to verify the predictions of ridging models and as input for studies of ridge interaction with offshore structures and landfast ice cover behaviour.

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