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ANALYSIS OF FIRST-YEAR AND OLD ICE RIDGE CHARACTERISTICS

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ABSTRACT

A study has been carried out on the morphological characteristics of arctic and subarctic ice ridges, with an emphasis on the differences between first-year and second- or multi-year ice ridges. This work builds on the catalogue of ridge shapes created by Timco and Burden in 1995. Sail height, keel depth, and total ridge thickness are investigated, focussing on the differences between first-year and old ridges, and considering the effect of grounding. The consolidated layer thickness and width and overall dimensions of ridges are also examined. Comparisons are made for arctic and temperate ridges. The arctic regions include the Barents and Norwegian Seas, and the Beaufort Sea and Canadian/American Arctic. Temperate regions include the Baltic Sea, Gulf of Bothnia, Gulf of Finland, Bering Sea, Sea of Okhotsk, Labrador Coast, and Canadian Maritimes. Relationships between sail height and keel depth are developed, and the findings of this study are evaluated against existing statistics and formulae.

INTRODUCTION

Deformed ice features such as ridges often pose hazards to offshore operations in arctic and subarctic regions. An ice ridge refers to a line or wall of broken ice pieces (rubble) that are forced up by pressure, with a submerged keel consisting of broken ice that is forced downward (WMO, 2011). In many cases, ice ridges govern the design of offshore petroleum exploration and production structures. Ridges also hinder navigation and can scour the seabed and damage subsea installations. Various ridge characteristics are important for offshore engineering problems, including ridge dimensions, consolidated layer thickness, age of the ridge, and ice strength. Ridge spacing or frequency is also important. While this paper concentrates on discrete ridges, ridges can also form as part of a larger rubble field or hummock field.

The general components of a ridge are shown in Figure 1. The sail is the portion of the ridge protruding above the surrounding level ice; sail height is given as H_s and sail width W_s. The keel extends below the lower surface of the surrounding ice; keel depth is given as H_k and keel width W_k. In this paper, unless otherwise noted, the values of H_s and H_k are the peak values for the ridge, and are measured from sea level. The consolidated region of the ridge is generally present as a layer of rubble or rafted ice, bonded by refrozen slush or water that has filled the voids. The consolidated layer thickness is important since it may exert the highest forces if a ridge impacts a structure.

There are some general differences between first-year and old (second- or multi-year) ice ridges. Over time, the protruding ridge sail melts away and the surface of a ridge becomes smoother – ice observers use the degree of smoothness to estimate the age of a ridge (Weeks 2010). Old ice ridges often have broader keels than first-year ridges (Timco and Burden 1997), and keels that are slightly less deep relative to the sail height. While the keels of first-year ice ridges are mostly loose or unconsolidated, old ice ridge keels can be (and perhaps often are) almost completely consolidated.

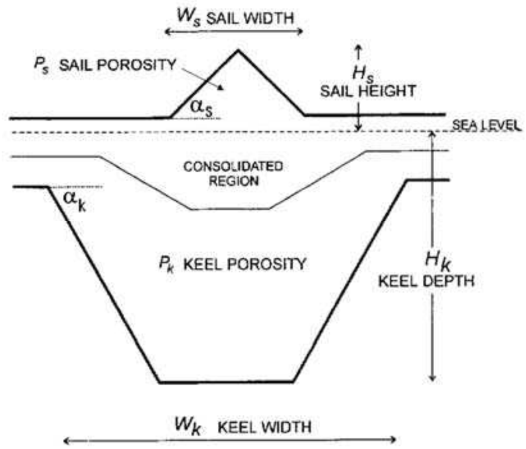

Figure 1. General components of a ridge (Timco and Burden, 1997)

RIDGE DATA SOURCES

A compilation of ice ridge properties and morphologies has been made. The focus is on discrete ridges for which physical and mechanical characteristics have been studied, especially ridges whose shapes have been profiled. A catalogue of ridge shapes was created in 1995 (Burden and Timco, 1995), and the analysis was published by Timco and Burden (1997). Building on this catalogue, a literature search has been performed of data published since 1995 as well as earlier studies not included in the Timco and Burden work. The current study also includes some data from the Timco and Burden data sources which were not not analysed in Timco and Burden (1997). Information has been obtained on a total of 262 first-year ice ridges and 85 second- or multi-year ice ridges. The present study is not complete, but all data available to the authors at the time of publication is analysed.

Ridges were analysed from the Canadian, American, Russian and European Arctic as well as from more temperate regions. The number of first-year and old ice ridges per region is shown in Table 1. Available information was studied for each ridge; extensive data is not available in most cases. Key items include date or season of measurement, age of ridge, ridge length, sail morphology (height, width, angle), keel morphology (depth, width, angle), consolidated layer thickness, surrounding level ice thickness, and thickness of blocks within the ridge.

Sources of data for all ridges are also given in Table 1. For those ridges that are part of the Timco and Burden compilation, the original data sources are listed in Timco and Burden (1997). Sources are listed by type of ice measured – first-year (FY) ice, or old ice which includes both second-year (SY) and multi-year (MY) ice.

Table 1. Number of ridges per region, with sources of data.

Region	Number of ridges	Data sources
Barents Sea and Norwegian Sea	FY ice: 18	Hoyland (2007), Shafrova and Hoyland (2008), Krupina et al (2009), Strub-Klein et al (2009)
	Old ice: 21	Hoyland et al (2008), Strub-Klein et al (2009)
Baltic Sea, Gulf of Bothnia, and Gulf of Finland	FY ice: 20	Leppäranta (1995), Timco and Burden (1997)
Beaufort Sea and Canadian/American Arctic	FY ice: 76	Tucker and Govoni (1981), Timco and Burden (1997)
	Old ice: 64	Timco and Burden (1997)
Bering Sea	FY ice: 39	Timco and Burden (1997)
Sea of Okhotsk	FY ice: 90	Truscov (n.d.), Surkov and Truskov (1995), Beketsky et al (1996)
Labrador Coast, Canada	FY ice: 14	Timco and Burden (1997), Johnston (1999), Croasdale (1999)
Maritimes region, Canada	FY ice: 5	Timco and Burden (1997)
Total	*347*	

DISCUSSION

Ridge grounding

For the ridges in this study, ridge grounding did not have a significant effect on the reported total ridge thickness values. Figure 2 shows the total average thickness and total maximum thickness of ridges grouped by ridge age, first-year ice or old ice (second- or multi-year). Note that the maximum ridge thickness may be somewhat conservative (high), since for some ridges the maximum thickness used is the sum of maximum sail height and maximum keel depth. These peaks may not always occur at the same location.

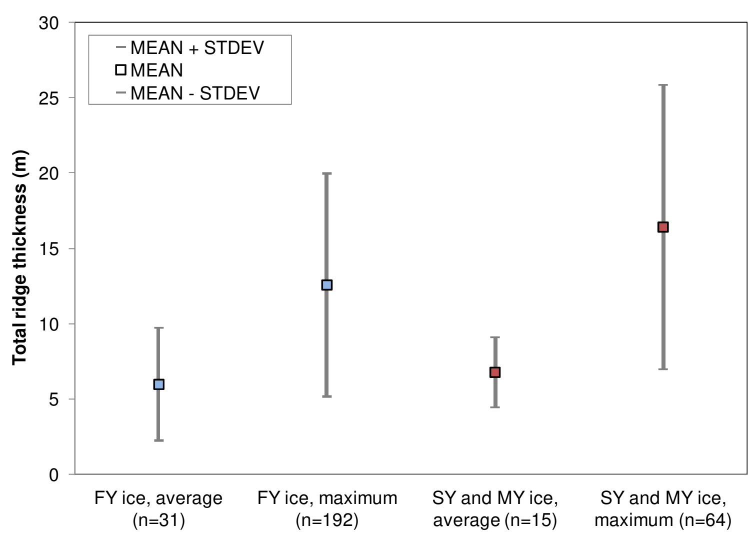

Figure 2. Total average and maximum ridge thicknesses grouped by first-year and old ice ridges. Means, standard deviations, and number of ridges (n) are shown.

While ridge grounding may not always affect the total thickness of the ridge, it does significantly influence the ratio of keel depth to sail height as would be expected when a ridge is forced upward from its floating position. As seen in Figure 3, sail height and keel depth are correlated for floating ridges, while grounded ridges do not exhibit this relationship.

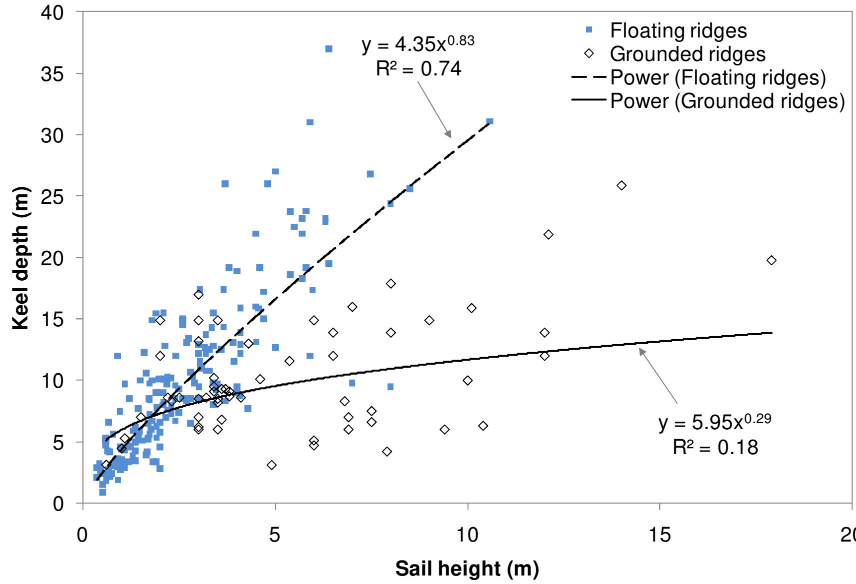

Figure 3. Maximum sail height vs. maximum keel depth for grounded and floating ridges.

Ridge age

The relationship between the ridge sail height and keel depth was investigated, omitting all grounded ridges. Maximum ridge keel depth and sail height are plotted in Figure 4.

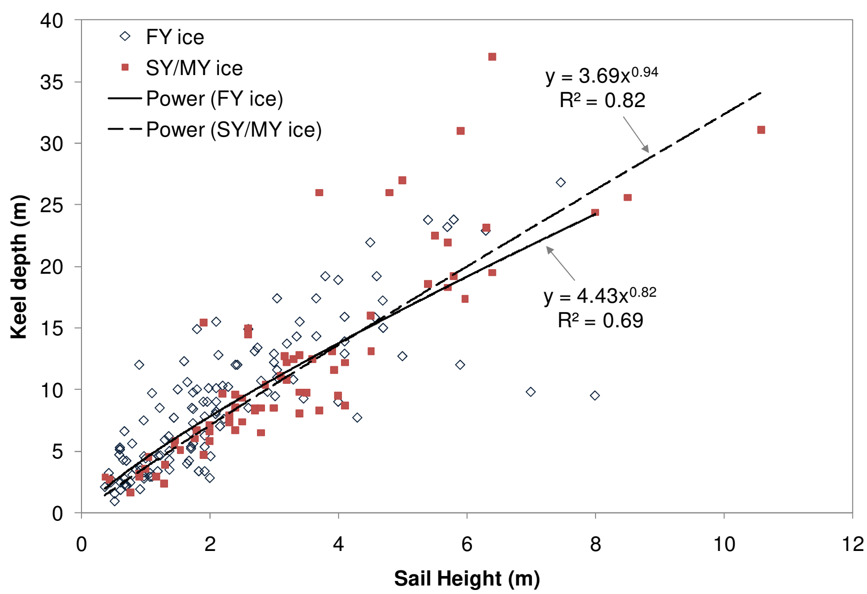

Figure 4. Maximum sail height vs. maximum keel depth for floating first-year and old ice ridges.

The relationships fitted to the data are given in Equations (1) and (2), below. Although the equations differ slightly, the range of ridge keel and sail thickness measurements are not significantly different for first-year and old ridges. A power relationship between the maximum sail height and keel depth was found to best fit the data for both first-year and old ice, and is shown in Figure 4. The linear fit equations are also given below although correlation was lower.

For first-year ice, the power and linear relationships are:

$$H_k = 4.43H_s^{0.82} \quad \text{or} \quad H_k = 3.54H_s \qquad (1)$$

For second-year and multi-year ice, the power and linear relationships are:

$$H_k = 3.69H_s^{0.94} \quad \text{or} \quad H_k = 3.55H_s \qquad (2)$$

The mean ratios of keel to sail (H_k:H_s) for the present study are 4.35 for first-year ridges and 3.60 for old ice ridges. Table 2 shows the mean, minimum and maximum keel to sail ratios along with standard deviation and number of data points. The ratios are similar to those determined in earlier work. Overall, first-year ridge keels tend to be larger than old ice keels, relative to a given sail height. Tucker (1989) proposed approximate ratios of H_k:H_s of 4.5 for a first-year ridge and 3.2 for a multi-year ridge. Timco and Burden (1997) reported mean ratios of 4.46 for first-year ice and 3.34 for multi-year Beaufort ice (excluding ridges in the Queen Elizabeth Islands, which had an average ratio of 4.7). The present work includes all available data on the ridges in Tucker (1989) and Timco and Burden (1997). Twenty-one old ice ridges were added, but complete keel/sail data was available for only 11 of these. More new information was available on first-year ridges; the present study adds over 150 new first-year ridges to the Timco and Burden work, 87 of which have measurements of both keel depth and sail height.

Table 2. Keel depth to sail height ratios for first-year and second-/multi-year ice ridges

	First-year ice	Old ice
Mean ratio	4.35	3.60
Minimum	1.19	1.82
Maximum	13.33	8.13
Standard deviation	1.89	1.16
Number of data points	126	71

Ridge length and width

The ridge dimensions in the plane of the ice surface – ridge width and length – are important for offshore operations planning. Overall ridge length was measured for 38 ridges in this study. The average length was 80 m, but ridge lengths varied greatly – from 15 m to 0.5 km. Old ice ridges had average measured lengths of 120 m, which is about twice that of first-year ridges, but due to the small sample size this may not commonly be the case.

The ridge width is also important. It is important to note that this study focused on discrete ridges, not on the generally much wider rubble fields. The ridge width is measured as the widest point of the keel or sail, which is usually near the waterline (see Figure 1). The maximum measured sail widths for first-year ridges in this study averaged 13 m; very few sail widths were over 40 m. Insufficient data was found on sail widths of old ice ridges. The keel width is more useful for estimating loads on offshore structures, since the keel contains the consolidated, stronger ice. Maximum keel width for first-year ridges averaged 37 m, with a large standard deviation of ±30 m. For old ice ridges, very few data were available on keel widths; the maximum measurements ranged from 35 m to 79 m.

There is a general trend of increasing ridge keel width with keel depth. Timco and Burden (1997) found that the keel width is related to keel depth and to sail height: $W_k \approx 3.9H_k$ and $W_k \approx 15H_s$. This trend was not examined in the current paper since little new data on keel widths were obtained since the Timco and Burden study.

Consolidated layer thickness

The consolidated layer is variable along the length of a ridge as well as throughout the ridge depth, and can be difficult to measure for large ridges. For the 22 first-year ridges with relevant measurements in the present analysis, the mean consolidated layer thickness is 1.46 m. On average, this represents 20% of the keel depth. The consolidated layer grows throughout the ridge's first winter, usually becoming 1.5 to 2 times the level ice thickness (Hoyland, 2008). For the present study, the consolidated layer to level ice thickness ratio is 1.8.

The consolidated layer grows as the ridge ages. Less data are available on the consolidated layer thicknesses in old ice ridges than first-year ridges. Although extensive data is not available, the keel portions of second-year and multi-year ice ridges generally seem to be mostly consolidated, at least for keels with depths of around 10 to 15 m or less. Hoyland (2008) examined several sources on old ridges with very deep keels and noted that ice was sampled only down to 10 m, not throughout the entire keel depth. Voelker et al (1981) measured seven multi-year ridges with keels ranging from 5.9 m to 15.4 m deep, and an average of 86% of the total keel depth was consolidated. Hoyland et al (2008) reported on 15 old, most likely second-year, ridges for which the macro-porosity was close to zero, i.e. the ridges had few or no large pores and were mostly consolidated. These ridges had keel depths ranging from 1.8 m to 7.1 m. Strub-Klein et al (2009) studied 5 second-year ridges with keel depths up to 8.2 m, and found that two ridges were almost completely consolidated, while more voids or soft ice were found in the other three ridges.

Ridge location

The sail heights and keel depths are plotted for ridges in the 6 regions listed in Table 1. Figure 5 and Figure 7 show the keel depth and sail height for first-year ice ridges and old ice ridges, respectively. Both floating and grounded ridges are included; grounded ridges are indicated in the plots. For several ridges studied by Hoyland et al (2008) and Strub-Klein et al (2009), complete information on the maximum keel depth or sail height was not available, and the average or one cross-section measurement was used. These data are plotted for interest only and were omitted from the keel-sail relationship analysis as this would skew the results. The largest first-year ridges measured have been in the Beaufort Sea, followed by ridges in the Sea of Okhotsk, Barents Sea and Norwegian Sea.

As previously discussed, the linear best-fit keel to sail relationship is $H_k = 3.54H_s$ for first-year ridges in all geographic regions. There is too little data and too much scatter to draw conclusions on keel to sail ratios for each geographic area, so the data was divided into arctic and temperate regions. "Arctic" is defined as north of the Arctic Circle (66° 33'N) and "temperate" below the Arctic Circle. Therefore the arctic regions include the Barents and Norwegian Seas, and the Beaufort Sea and surrounding Arctic area. Temperate regions are the Baltic Sea, Gulf of Bothnia and Gulf of Finland; Bering Sea; Sea of Okhotsk; Labrador Coast; and Canadian Maritimes.

Figure 6 shows the sail heights and keel depths for temperate and arctic first-year ice ridges. Grounded ridges were left out of the analysis. The best-fit lines to the data are plotted (forced through the origin) in Figure 6; correlation of keel to sail is very good (R^2=0.87) for the arctic ridges, but poor for the temperate ridges. The few temperate ridges with sail heights of greater than 5 m skew the best-fit line. A linear relationship, $H_k = 3.88H_s$, was found to best fit arctic ridges. The average keel to sail ratio is actually greater for temperate ridges than for arctic ridges; the ratios are given in Table 3.

Table 3. Keel depth to sail height ratios for arctic and temperate first-year ridges

	Arctic	Temperate
Mean ratio	3.85	5.21
Standard deviation	1.20	2.50
Number of data points	80	46

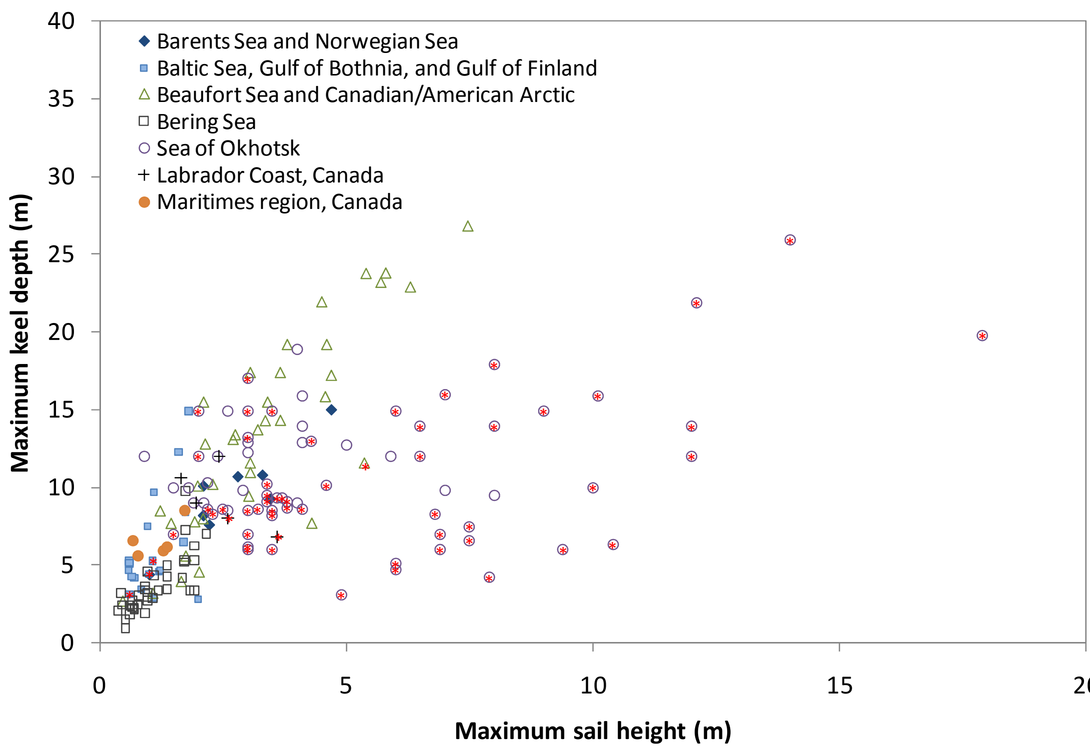

Figure 5. Maximum sail height vs. maximum keel depth for all first-year ridges, by location (red asterisks [*] indicate grounded ridges)

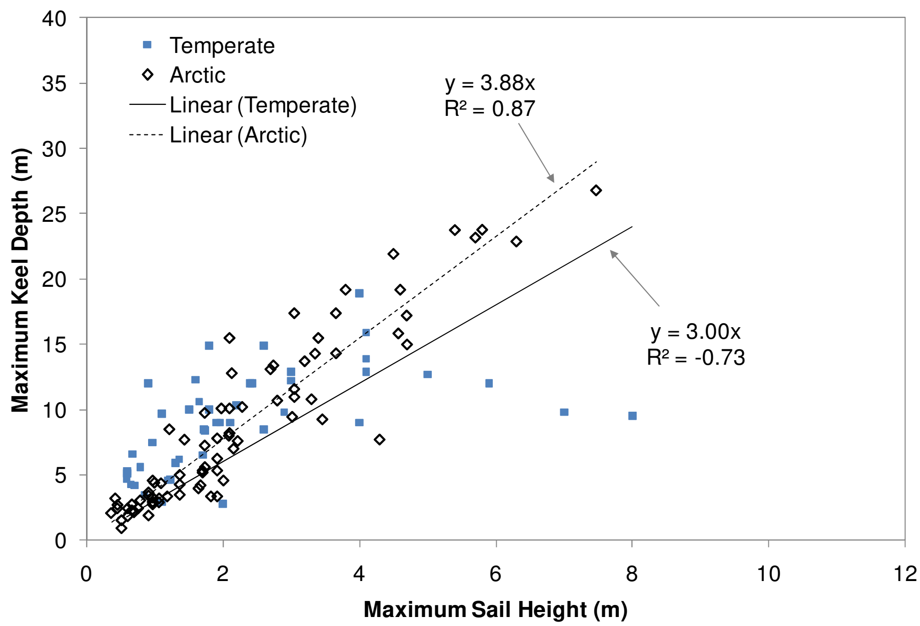

Figure 6. Maximum sail height vs. maximum keel depth for temperate and arctic first-year ridges.

The old ice ridges (Figure 7) were all in the Arctic and none were grounded. The linear fit line to the data is $H_k = 3.55H_s$, as presented in Equation (2). The keel to sail ratio is $H_k = 3.60H_s$, as given in Table 2.

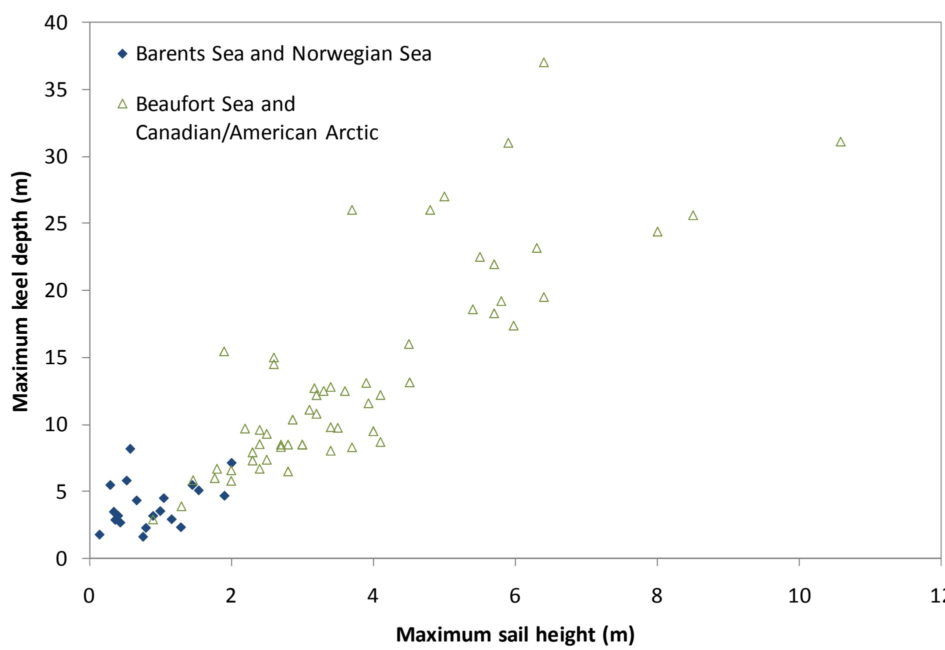

Figure 7. Maximum sail height vs. maximum keel depth for all second-year and multi-year ridges, by location

CURRENT RESEARCH ON RIDGE MORPHOLOGY

The catalogue of ridges compiled for the present study is not complete; some historic ridge data were unavailable at the time of publication, and new data will continue to become available as results are published on ridge measurement field programs. The University Centre in Svalbard (UNIS) and the Norwegian University of Science and Technology (NTNU) have conducted detailed ridge studies in the Barents Sea and Fram Strait for the past several years (see Table 1 for references to several publications). Field work has also recently been carried out off Svalbard as part of the ColdTech Sustainable Cold Climate Technology project (http://kaldtklima.net/ and http://www.norut.no/narvik_en/Norut-Narvik/Projects/Ongoing-projects/ColdTech-Sustainable-Cold-Climate-Technology). Some analysis of ridge data on the Norströmsgrund Lighthouse has been published (Bonnemaire and Bjerkås (2004), and Bjerkås and Bonnemaire (2004)) and more analysis is underway. In Canada's high Arctic, thickness measurements on deformed multi-year ice have been made for the past few years (M. Johnston, personal communication, May 2011). Some results from the 2009 measurement program are presented in Johnston and Haas (2011). Recent ridge observations have been made from the Canadian research icebreaker CCGS Amundsen in the Arctic Ocean (Capt. S. Julien, personal communication, April 2011). Upward looking sonar has been used to profile ridges in the Arctic (Melling and Riedel, 2008) and in the Northumberland Strait, Canada (Obert and Brown, 2011). It is possible that these data could also be used to study ridge shapes.

CONCLUSIONS AND RECOMMENDATIONS

Analysis has been performed on a compilation of ice ridge morphologies. For floating ridges, keel to sail relationships were analysed and found to be generally agreeable with previous studies. First-year ridges, on average, have slightly deeper keels for a given sail height. The ranges of keel and sail thickness measurements, however, are not significantly different for first-year and old ridges. For both first-year and old ice, a power relationship was found to best fit the data. The average ratio of keel depth (H_k) to sail height (H_s) was also calculated. For first-year ice ridges:

$$H_k = 4.43 H_s^{0.82} \qquad \textit{power relationship}$$
$$H_k = 4.35 H_s \qquad \textit{mean keel to sail ratio}$$

For old ice ridges (second-year and multi-year):

$$H_k = 3.69 H_s^{0.94} \qquad \textit{power relationship}$$
$$H_k = 3.60 H_s \qquad \textit{mean keel to sail ratio}$$

First-year ridge keels are often as deep as those of old ridges, with the main difference being that first-year ridge keels are mostly loose or unconsolidated. The mean consolidated layer thickness in first-year ridges in this study was 1.46 m, which on average represents 20% of the keel depth. Although extensive data is not available on the consolidation of second-year and multi-year ice ridges, the keel portions generally seem to be mostly consolidated, at least for keels with depths of around 10 to 15 m or less.

Ridge width and length are also important to offshore operators, but fewer data are available on these properties than on the vertical dimensions. In the present study, old ice ridges had an average length of 120 m, which is about twice that of first-year ridges. However, ridge lengths vary greatly for ridges of all ages. Maximum keel width for first-year ridges averaged 37 m, with a large standard deviation of ±30 m. For old ice ridges, very few data were available on keel widths; the maximum measurements ranged from 35 m to 79 m. There is a general trend of increasing ridge keel width with keel depth and sail height. It is important to note that this study focussed on discrete ridges, not on rubble fields which generally are much wider.

Ridge keel and sail thicknesses were analysed by region. The largest first-year ridges measured have been in the Beaufort Sea, followed by ridges in the Sea of Okhotsk, then Barents Sea and Norwegian Sea. Old ice ridges in the Beaufort Sea were also the largest. The first-year ice data were divided into arctic and temperate regions (all old ice data was within the Arctic Circle). Although the data is fairly scattered, first-year ridges in temperate regions generally had deeper keels in relation to the sail height. The ratios of keel depth to sail height measurements were 3.85 in the Arctic and 5.21 in temperate regions.

There are still gaps in the knowledge of sea ice ridge properties; a number of recent or ongoing field research programs will address some of these concerns. More data is needed on ridges in the Arctic, especially second- or multi-year ice ridges, and on first-year ridges in temperate regions. Information on consolidated layer thickness and the degree of consolidation of multi-year ridge keels would be valuable. Further data on ridge width would also be useful, especially that of the keel since it includes the consolidated layer. In the Beaufort Sea, most of the available ridge data is from the 1980s, but results are becoming available from recent studies. Research is also underway on ridges in the Barents and Norwegian Seas and the Gulf of Bothnia.

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