Cold Regions Science and Technology 82 (2012) 94–109

Contents lists available at SciVerse ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

A comprehensive analysis of the morphology of first-year sea ice ridges

Lucie Strub-Klein [a,b,*], Denise Sudom [c]

[a] The University Centre on Svalbard (UNIS), Arctic Technology Department, PO Box 156, 9170 Longyearbyen, Norway
[b] The Norwegian University of Technology (NTNU), Department of Civil and Transport Engineering, Høgskoleringen 7a, 7034 Trondheim, Norway
[c] National Research Council Canada, 1200 Montreal Road, Ottawa Canada K1A 0R6

ARTICLE INFO

Article history:
Received 21 January 2012
Accepted 17 May 2012

Keywords:
First-year ridges
Ratios
Block dimensions
Macroporosity
Consolidated layer

ABSTRACT

A review of the morphological properties of over 300 full-scale floating first-year sea ice ridges has been made, including measurements from 1971 until the present time. Ridges were examined from the Bering and Chukchi Seas, Beaufort Sea, Svalbard waters, Barents Sea and Russian Arctic Ocean for the Arctic regions; and from the Canadian East Coast, Baltic Sea, Sea of Azov, Caspian Sea and Offshore Sakhalin for the Subarctic (or temperate) regions. Grounded ridges were excluded. A wide catalogue comprising the ridge thicknesses (sail, keel and consolidated layer), widths and angles as well as the macroporosity and the block dimensions is provided. The maximum sail height was found to be 8 m (offshore Sakhalin), and the mean peak sail height was 2.0 m, based on 356 profiles. The mean peak keel depth is 8.0 m, based on 321 profiles. The relationship between the maximum sail height, h_s, and the maximum keel depth, h_k, for all ridges is best described by the power equation $h_k = 5.11h_s^{0.69}$. The correlation differs depending on the region. For Arctic ridges a linear relationship was found to be the best fit ($h_k = 3.84h_s$), while for the Subarctic ridges a power relationship ($h_k = 6.14h_s^{0.53}$) best fit the data. The ratio of maximum keel to maximum sail is 5.17 on average (based on 308 values), and has also been calculated for each region mentioned above. Arctic ridges generally have a lower keel-to-sail ratio than those in Subarctic regions. The statistical distribution of keel-to-sail ratios is best represented by a gamma distribution. The average sail and keel widths were 12 and 36 m, respectively. The relationships between the sail and keel widths and other geometrical parameters were also determined. Variation of sail and keel thicknesses within individual ridges has been compared with the variability of all ridges. Ridge cross-sectional geometry can vary greatly along the length of a ridge, even over a short distance. A study was made on sail block thicknesses, and it was found that they correlate well with the sail height with a square root model. The typical macroporosity for a first-year ice ridge is 22% (based on 58 values) with an average sail macroporosity of 18% (based on 49 values) and average keel rubble macroporosity of 20% (based on 44 values). The average ridge consolidated layer thickness was 1.36 m based on 118 values. The variation of the consolidated layer was examined, and it was found that the layer tends to grow evenly with time over the width of the ridge cross section. A greater spacing between the measurements seemed to affect the variation, as it decreased with an increasing distance between each borehole. A statistical analysis based on 377 measurements of the consolidated layer of ridges in the Barents Sea showed that the gamma distribution well describes the distribution of the consolidated layer thicknesses in that area.

1. Introduction

Over large areas, sea ice is generally not flat and on average consists of 10–40% ridges by volume (Leppäranta, 2011). If the ice remains attached to the shore, it is called landfast ice. Floating ice is more dynamic and is often subjected to drift caused by winds and currents. Floating ice floes may collide, resulting in ice deformation by rafting, ridging or rubbling. A ridged ice feature may also become grounded (referred to as a stamukha). The World Meteorological Organization (WMO, 1970) defines an ice ridge as “a line or wall of broken ice forced up by pressure”. These can be “fresh” or “first-year” features, or “weathered” and “old” (WMO, 1970). The present study concerns only first-year ridged ice features that are not grounded. For the purposes of this paper, first-year ridges are defined as those which have not survived one summer's melt. First-year ridges may present very sharp sails with visible blocks, and their degree of consolidation is almost always much less advanced than the older multi-year ridges. Ridged multi-year ice may also reach greater thickness than first-year ridges—in the range of 40 to 50 m (Johnston et al., 2009). Observations on sea ice ridges are as old as the first polar explorations in the 16th century, but the scientific curiosity for sea ice ridges developed in the 19th century when Weyprecht (1879), Nansen (1897) or Malmgren (1927) devoted some chapters of their

* Corresponding author at: The University Centre on Svalbard (UNIS), Arctic Technology Department, PO Box 156, 9170 Longyearbyen, Norway. Tel.: +47 90829102; fax: +47 79023301.
E-mail address: lucie.sk@gmail.com (L. Strub-Klein).

0165-232X/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.coldregions.2012.05.014

scientific reports to these features. The interest for sea ice ridges grew considerably after 1950 and later in the 1970s, as the oil and gas potential of the Arctic regions began to surface. Austin Kovacs is one of the pioneers in the systematic investigations of sea ice ridges and published many reports and papers in the 1970s and early 1980s. However, his papers dealt mostly with multi-year ridges (Kovacs, 1976, 1977; Kovacs and Mellor, 1971, 1974; Kovacs et al., 1973, 1975) or in the case where he reported results on a first-year ice ridge, this feature was grounded (Kovacs and Mellor, 1971).

Ridges usually consist of three distinguishable parts:

– The sail, which is above the water line. It consists of blocks of ice piled up and frozen together by contact.
– The consolidated layer, which is below the water line. The blocks that initially pile up underwater form cavities which fill up with water. As the season progresses, the water freezes in these voids, contributing to the continuous consolidation of the ridge.
– The rubble, which is under the consolidated layer. It consists of loose blocks partially refrozen together, with water trapped in between.

The rubble and the consolidated layer form the keel. In general, the keel is wider than the sail and extends under the surrounding level ice.

Ridges are complex structures with a wide variability in shape and size. They are often modeled by triangles or trapezes (see Fig. 1) and characterized by their thicknesses, widths and angles. To our knowledge, a very simple model of the triangular shape for first-year ridges was introduced by Zubov (1945, Sections 104 and 105), as he developed the buoyancy of hummocks/ridges. In practice, the base of the keel is often irregular and not represented by a triangle. Although we do not investigate detailed ridge shapes in this paper, the ISO code (ISO, 19906, 2010) gives a range of values for the base or flat part of the keel (up to 5 times the sail height). Fig. 1 indicates the maximum dimensions for a typical ridge. However, not all the papers and reports present these dimensions the same way; for example, sometimes the sail and keel thicknesses are given as values averaged over a cross section.

It has been common to establish ratios between the maximum keel depth h_k and the maximum sail height h_s, the keel width w_k and the sail height h_s, or the keel width w_k and the keel depth h_k (these are reported in Timco and Burden, 1997; Sudom et al., 2011, and Strub-Klein, 2011, amongst others). These relationships have their use in the design of offshore structures and ships.

Indeed, sea ice ridges are often used to calculate the design load in Arctic marine regions in the absence of icebergs (Blanchet, 1998). In this case (and in theory), the ridge dimensions, macroporosity, and physical and mechanical properties are the necessary inputs for accurate modeling and calculations. In practice, these data are difficult to collect all at once, due to the lack of time and the difficult fieldwork conditions in cold regions.

Burden and Timco (1995) and Timco and Burden (1997) have presented and analyzed data collected on first-year sea ice ridges

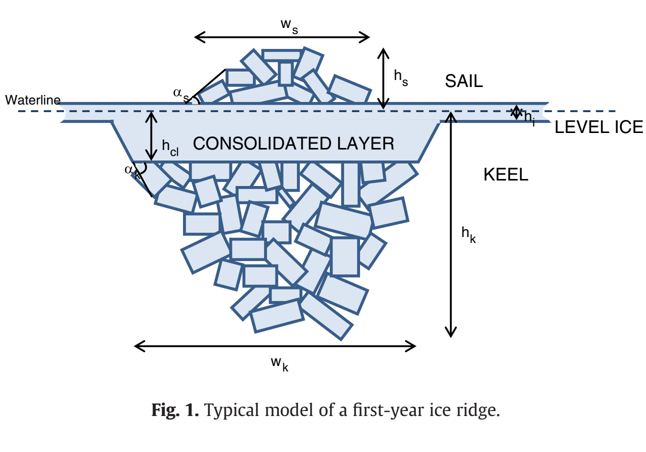

Fig. 1. Typical model of a first-year ice ridge.

and multi-year ice ridges with a special focus on the keel-to-sail ratios (h_k/h_s) and relationships between the sail height and the keel depth. More recently, Sudom et al. (2011) and Strub-Klein (2011) have extended this existing database and while Sudom et al. (2011) focused on a comparison of the morphological properties between first- and multi-year ice ridges, Strub-Klein (2011) developed the relationship between the sail and the keel for first-year ridges and attempted to find a suitable statistical relationship for the keel-to-sail ratios.

The idea came to gather all the data and previous analyses on floating first-year sea ice ridges in one paper. Therefore we will first present the various data sources, compiling available data on the ridge dimensions and morphological properties. Next, we go deeper into the ridge geometry and morphology to improve the existing relationships and statistical models for ridge dimensions. We will also analyze the block thicknesses and the consolidation of first-year ridges with some considerations on the macroporosity and the variation of the consolidated layer thickness. In the last section of this paper we identify what is still lacking in ridge investigations.

2. Data sources

In total, 45 sources were used to compile the available data about floating first-year sea ice ridges. These papers presented ridges from the Bering and Chukchi Seas, Beaufort Sea, Svalbard waters, Barents Sea, Russian Arctic Ocean (considered Arctic regions); and from East Coasts of Canada, Baltic Sea, Sea of Azov, Caspian Sea and Offshore Sakhalin (considered Subarctic or temperate regions). These regions are shown in Fig. 2, except for the more southern Caspian Sea on the border of Europe and Asia, and the Sea of Azov to the south of Eastern Europe. The division for Arctic/Subarctic is at the Arctic Circle (generally defined as about 66°34′N). A precise location was not available for all ridges in the study—for example, profiles were available for some ridges in the Bering and Chukchi Seas without exact coordinates, so these ridges were grouped into "Bering and Chukchi" and considered to be Arctic. "Russian Arctic Ocean" is not an area as such, but with this term we refer to the part of the Arctic Ocean that is claimed by Russia. Most of the data sources for this study have been used by Burden and Timco (1995), Timco and Burden (1997), Sudom et al. (2011) or Strub-Klein (2011), with the addition of some data that was newly available or newly discovered by us. We aimed at presenting a catalogue that is as complete as possible. Diverse pieces of information were collected from at least 300 floating first-year ice ridges, and a summary of the data sources is given in Table 1. Raw data on keel and/or sail geometry was available for 251 distinct ridges, many having more than one profile. The 45 data sources are not the only ones existing on floating first-year sea ice ridges; other sources are discussed in Section 6. Some papers or reports which did not give precise enough data for us to use in the analysis are also listed in Table 1.

The dimensions that are typically reported by the authors of the various papers include: sail height h_s, keel depth h_k, sail width w_s, keel width w_k, consolidated layer thickness h_{cl}, sail angle α_s, keel angle α_k, length of the ridge l_r and/or the total width w_r. As one might expect, data were not collected and presented the same way by each author. The column "type of available data" indicates if the data given in the paper were the average ("avg") or maximum ("max") dimensions, or if the whole cross section ("whole") was available.

The data sources were selected such that at least one of the ridge dimensions amongst h_s, h_k, h_{cl} and h_b is reported (maximum or average). In most of the papers, some additional information such as the surrounding level ice thickness h_i, the porosity η, etc., is also presented. A summary of the additional properties (morphological, physical and mechanical) that each paper proposes as potentially useful to measure is given in Section 6 and in the Conclusions of this paper.

The ridge morphology can be investigated with the help of different techniques, which are: Drilling ("Dr"), Thermal Drilling ("Th Dr"), Diving ("Di"), Survey ("Su"), Sonar ("So"), or even Thermistor String