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Seasonal changes in the properties of first-year, second-year and multi-year ice

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ABSTRACT

To date, too few measurements have been available to document the seasonal change in the strength for different types of sea ice. The situation is remedied here with nearly 1300 borehole measurements on first-year ice (FYI), second-year ice (SYI) and multi-year ice (MYI) in the Canadian Arctic from the past 15 years. The thickness, temperature, salinity and borehole strength are given for five categories of sea ice: FYI, SYI, young multi-year ice (yMYI), thick level multi-year ice (TkMYI) and hummocked multi-year ice (hMYI). Results show that the deterioration of FYI and SYI is offset by about one month in summer, yMYI is more similar to TkMYI than SYI, and deteriorated MYI floes can have strengths comparable to more competent looking MYI floes in summer. The seasonal reduction in strength for different ice types is expressed here as an 'equivalent floe strength', which is the depth-averaged strength of all boreholes on a floe normalized by the maximum depth-averaged strength of FYI in winter (32 MPa). Seasonal trends in strength show SYI and MYI floes to be stronger than FYI floes in all seasons. The strength of FYI floes decreases from 61% (May) to 9% (July), relative to its 32 MPa winter maximum, whereas the equivalent floe strength of SYI decreases from 69% (May) to 16% (August), relative to 32 MPa. The equivalent floe strength of the combined category of yMYI & TkMYI decreases from 78% or more (May) to 40% (September). The equivalent floe strength of hMYI decreases from 102% (May) to 51% (September).

1. Introduction

Satellite-derived observations from 1980 to 2015 reveal decreasing trends in the maximum extent (February or March) and minimum extent (September) of Arctic sea ice, with a steeper trend in the latter.[1] The overall decreasing trend of minimum ice extent is punctuated by one or more years of substantial increases, prompting use of the term 'recovery mechanism' (Tietsche et al., 2011), which is not well understood at present. The increasingly dramatic fluctuations in minimum ice extent that have occurred in recent years may indicate that the ice regime is shifting, environmental changes affecting thin first-year ice (FYI) and second-year ice (SYI) more than thick multi-year ice (MYI). Indeed, today the Arctic Basin is characterized by a thinner ice regime than in the past, as the declining extent of MYI is replaced by FYI (Kwok and Untersteiner, 2011). Evidence of this comes from combined submarine and ICESat records showing the average winter thickness of sea ice in the Arctic Basin to have decreased from 3.5 m, to less than 2 m over the past three decades (Kwok and Untersteiner, 2011) and analyses showing an increased presence of SYI (Comiso, 2006, 2011).

Today, Arctic operations take place mostly from mid-July to mid-September, although there is interest in extending operations into the shoulder seasons (*i.e.* earlier in summer and later in fall) and possibly conducting year-round shipping beyond areas where it already occurs. The decrease in overall thickness and extent of sea ice provides greater opportunities for marine traffic and offshore oil exploration (National Petroleum Council, 2015), but that does not necessarily make ice conditions less difficult for marine operations (Arctic Council, 2009). Instead, it brings new challenges. An ice regime that includes more SYI and young multi-year ice (yMYI) places greater demands on operators to reliably distinguish between two, similar looking ice types – which is not straightforward. While experienced personnel sometimes find it difficult to distinguish FYI from SYI or MYI, it is more often the case that SYI cannot be distinguished from relatively thin MYI (see Johnston and Timco, 2008a, 2008b). Classifying sea ice becomes even more difficult during the shoulder seasons and in winter, when melt ponds freeze, the ice is snow-covered and light is low or non-existent. Equally important is the fact that sea ice is deteriorating in summer, whereas its competency increases in fall and winter. That said, MYI can present a

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[1] http://nsidc.org/arcticseaicenews/files/

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serious impediment to ships at any time of year, so even the most powerful icebreakers are advised to avoid it, where possible (Canadian Coast Guard, 2012).

Two cornerstones of safely operating in the Arctic require understanding the challenges that different types of sea ice pose and being able to classify different ice types reliably. Here, measurements made over the past 15 years are used to show how FYI, SYI and MYI differ in thickness, temperature, salinity and strength throughout the year. The study has several objectives. The first objective is to show why it is important to classify sea ice correctly. The second objective is to quantify the differences between FYI, SYI and MYI, which are not clear at present, especially where SYI is concerned. The third objective uses existing measurements to determine whether there is a sound basis for developing different categories of MYI, as has been done for FYI (see WMO, 1985). All three objectives relate to operations across the Arctic, where 2 to 3 m thick sea ice can be encountered in late summer (Johnston and Timco, 2008a). The International Maritime Organization's (IMO) Polar Code, which is due to come into effect for new ships in January 2017, increases the relevance of the subject: two of the three Polar Ship categories will be able to transit regions of FYI that may contain old ice inclusions, provided the ship has the appropriate ice class and has an approved methodology for determining the ship's operational limitations in ice (ABS, 2016).

The paper proceeds as follows: We begin with a description of the sea ice nomenclature and sampling methodology. The properties of different categories of sea ice are then discussed, progressing from FYI, which is the least complicated type of sea ice, and ending with hummocked multi-year ice (hMYI), the thickest, most hazardous type of sea ice. Results include measurements from individual test depths in a borehole, the depth-averaged values for each borehole and the average properties of the floe overall. The concept of ‘equivalent floe strength’ is introduced to compare the seasonal percent reduction in strength for different categories of ice, whereby the average strength of all boreholes on any particular floe is normalized by the maximum depth-averaged strength of FYI in winter. Key findings from the study are used to revisit the objectives prior to formulating conclusions.

2. Nomenclature for sea ice types

We begin with some basic definitions, recognizing that the nomenclature in this paper does not adhere to the WMO convention. The WMO defines old ice as SYI, MYI and, more recently, residual FYI that survives summer to enter freeze-up (WMO, 1985, 2014). In this paper, the terms old ice and residual FYI will be avoided, as much as possible. Every effort will be made to distinguish SYI from MYI based upon its history of development or, since that is not usually possible, from its surface appearance and material properties. Although not explicitly stated by the WMO, the maximum thicknesses cited for FYI (up to 2.0 m), SYI (up to 2.5 m and sometimes more) and MYI (up to 3 m or more) refer to undeformed ice in spring. Applying these definitions is difficult at an operational level because most shipping occurs in summer, when the ice is thinning, and also because ice floes often are an aggregate of many ice types, thickened by mechanical deformation over time. Moreover, the overlapping thicknesses of SYI and MYI can lead to confusion. With that in mind, the sites examined during this study were subdivided as follows:

first-year ice (FYI) – sea ice of one winter's growth season. In this study, undeformed ice is shown to attain a maximum thickness of up to 2.2 m in spring in the high Arctic. The WMO (1985) cites the maximum thickness of FYI as 2.0 m.

second-year ice (SYI) – sea ice of two winter seasons. Undeformed ice attains a maximum thickness of 2.5 m in spring, sometimes more. In summer, greenish-blue melt ponds develop. *Bona fide* SYI has a known origin and history of development; unauthenticated SYI does not.

young multi-year ice (yMYI) – sea ice of three or more winter seasons; average thickness less than 4.5 m. Thickness may overlap with SYI, depending upon the time of year and geographic location. Melt ponds range from greenish-blue to turquoise blue. Ice appears thinner, has less freeboard and has undergone less weathering than the thicker forms of MYI described below. *Bona fide* yMYI refers to ice with a known origin and history of development; unauthenticated yMYI does not.

thick, relatively level multi-year ice (TkMYI) – sea ice of three or more winter seasons, with an average thickness of 4.5 m or more. Relatively level ice surface masks evidence of past mechanical deformation, having been smoothed by weathering over time. Typically has higher freeboard than yMYI. Melt ponds are usually turquoise blue.

hummocked multi-year ice (hMYI) – linear or sinuous region of broken sea ice of two or more winter seasons, forms mechanically due to pressure, weathers over time. Hummocks may occur as isolated features or may occupy substantial portions of a floe. Thickness ranges from 5 m to more than 42 m, as summarized in Johnston et al. (2009).

3. Methodology

Upwards of 40 sea ice floes have been sampled by the National Research Council over the past 15 years (Fig. 1), making this the longest running study to measure the engineering properties of sea ice using a standard approach. The early years of the study focussed upon documenting FYI, SYI and the uppermost few metres of MYI. Gradually, techniques and equipment were honed until, in later years, it was possible to sample 12 m thick MYI hummocks successfully. Measurements focussed upon the properties needed to design well-engineered structures for Arctic operations, including the thickness, strength, temperature and salinity of different types of sea ice (see Table 1). Up to five boreholes were made in the level and deformed areas of a floe. Typically, boreholes on undeformed FYI were separated by 1.5 to 2 m and boreholes on MYI were separated by 5 m or more, depending upon the ice features of interest. Vertical depth profiles of the ice temperature and ice salinity were measured from ice cores, after which a vertical strength profile was obtained by conducting *in situ* strength tests in the borehole itself. Boreholes were prepared with a variety of fibreglass ice corers and ice augers over the years, with diameters from 150 to 178 mm. Typically, the first borehole was made with an ice corer and additional boreholes were made with an ice auger, ice corer or a combination of the two. The ice auger allows work to proceed faster, but at the expense of measuring ice temperatures and salinities in the borehole, since cores are not obtained.

3.1. Ice thickness

The undisturbed snow depth at each borehole was measured before the ice thickness was measured with the drill-hole technique, whereby multiple lengths of 1 m long, 2″ (5 cm) diameter auger were used to penetrate ice up to 22 m thick. A rough measure of ice thickness was made by counting the auger flights as they were retrieved from the drill hole (± 0.5 m), then a more accurate measurement was made by lowering a weighted tape into the drill hole, hooking it on the underside of the ice and taking a reading (± 5 mm). For sites that were sampled more than once per season, drill-hole thicknesses were also used to estimate an ice ablation rate, recognizing that spatial variations in thickness limit the accuracy of that approach.

3.2. Ice temperature and ice salinity

Temperatures and salinities were measured on ice cores. Cores were extracted and processed in 1 m long segments until either the bottom of the ice was reached or the limit of the equipment was met. Over the