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Thermodynamic consolidation of ice ridge keels in water at varying freezing points

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ABSTRACT

The permeability of sea ice ridge keels to surrounding seawater was investigated using data from field measurements in the Barents Sea. Two models that describe the consolidation of ice rubble due to the penetration of low salinity water at freezing point inside the rubble were formulated and analyzed when the water salinity decreases with time. The sea ice enthalpy depends on the temperature and salinity with considerable increase towards the 0 °C. It is shown that this dependence significantly influences the amount of newly formed ice around the rubble. The presence of brine pockets in the sea ice explains such dependence. When sea ice is heated brine solution should adjust its salinity to stay in thermodynamic equilibrium with pure ice. Reduction of salinity in the closed pocket is possible due to melting of ice on the wall of the pocket. This latent heat of fusion defines so high specific heat capacity of sea ice and as a result allows extracting enough coldness from sea ice rubble to reach high values of its consolidation. It was shown that in both models a key role in consolidation is played by the process of interchange between microporosity of sea ice and macroporosity of rubble field.

1. Introduction

Ice ridges are important features of the sea ice cover in the Arctic Basin and the adjacent shelf seas. Ice ridges are formed from the pressing-out of broken ice blocks below and on the surface of the level ice. Numerous reports estimate that ridged ice occupies between 10 and 40% of the ice-covered areas in different regions of the Arctic Basin (see, e.g. Flato and Hibler (1995)). The mean vertical lengths of ice ridges reach 10–15 m, with maximum values of approximately 30 m (Strub-Klein and Sudom, 2012; Timco and Burden, 1997). The vertical size of the ice ridges is considerably larger than the thickness of the level ice formed by the thermal freezing of seawater. Therefore, the influence of ice ridges on the ice loads on offshore constructions cannot be ignored. The initial strength of ice ridges is not very high because they are composed of unfrozen ice blocks. The formation of freeze-bonds between the blocks and further consolidation of the ridge keels are the most important processes that increase the ridge strength with time.

Grounded ice ridges may serve as anchoring points for landfast ice. Landfast ice becomes stable offshore when the necessary amount of grounded ice ridges is formed. The influence of ridge keels on the seabed in shallow water regions (ice gouging) can cause damage to underwater pipelines and communications lines (Barrette, 2011). This effect is of great importance for the Sakhalin shelf, Kara Sea, Barents Sea and Northern Caspian Sea shelf. The depth of ice gouging is a design parameter used to determine the burial depth for underwater pipelines. This work was initiated specifically because the authors were involved in the investigations of the ice gouging process in the Baydaratskaya Bay of the Kara Sea. Since the 1990s, numerous gouges on the seabed have been registered in the Baydaratskaya Bay at depths of up to 20 m. The length and depth of some gouges observed at depths greater than 15 m exceeded 2 km and 1.5 m, respectively (see, e.g., Marchenko et al. (2007)). Such gouges could be produced by ice ridge keels if they are consolidated.

Numerical estimates have revealed that the thickness of consolidated layers formed due to atmospheric cooling in the upper parts of ridge keels cannot exceed the thickness of level ice formed under the same weather conditions by more than two-fold (see, e.g., Leppäranta and Hakala (1992), Høyland (2002)). The local effects caused by a high concentration of ice blocks inside the ridge keels might explain the extension of the consolidated parts of the ridge keel to greater depths. Numerical simulations performed for realistic configurations of ridge keels and based on typical weather conditions in the Baydaratskaya Bay show that such extension may be of up to 5–6 m depths (Marchenko, 2008; Shestov and Marchenko, 2009). The ice rubble

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below the consolidated layer is destroyed under the interaction with the seabed soils (Shestov and Marchenko, 2009). Therefore long and deep gouges observed in the Baydaratskaya bay probably were formed by the impact of fully consolidated ridge keels into the seabed. Field studies of second-year and multiyear ridges demonstrated that their keels can be completely consolidated (see, e.g., Shestov et al. (2012)). The primary goal of the present study was the investigation of the physical mechanisms that could provide thermodynamic consolidation of ridge keels below the bottom of the consolidated layer that is formed due to atmospheric cooling.

This study was devoted to investigating the thermodynamic consolidation of submerged ice rubble that occurs due to the interaction of the rubble with surrounding water that is at its freezing point, which is higher than the temperature of the ice. The appearance of water with low salinity around the ridge keels can be explained by the penetration of melt waters into the surface layers of seawater from the ice surface and ridge keels. In coastal zones, the fresh water penetrates into the sea from rivers and from spring water run-off. All of these factors, including summer ice melting, ice drift and sea currents, influence the spatial and temporal distribution of water salinity in the upper water layer in the Arctic. In the Arctic seas, the water salinity varies from a mean value of approximately 35 g kg^{-1} to 0 g kg^{-1} near the mouths of rivers (Dobrovolskii and Zalogin, 1982). The freezing point of such waters varies from −1.9 °C to 0 °C.

The salinity input to the new thermodynamic equation of state of seawater (TEOS-10) Gibbs function requires knowledge of the absolute salinity of seawater (S_A), which is based upon the reference salinity of seawater (S_R) (Millero, 2010):

$$S_A = S_R + \delta S_A. \tag{1}$$

The reference salinity is the best estimate of absolute salinity based on the practical salinity scale (S_P):

$$S_R = S_P(35.16504/35.000)\ \mathrm{g\ kg}^{-1}. \tag{2}$$

The value δS_A can be estimated from the difference, $\Delta\rho/(\mathrm{kg\ m}^{-3})$, between the measured density and the value calculated from TEOS-10 at the S_R of the sample (Millero and Poisson, 1981):

$$\delta S_A = \Delta\rho / 0.75179\ \mathrm{kg\ m}^{-3}. \tag{3}$$

To avoid the presentation of unitless value of salinity, further through the paper we define salinity as g kg^{-1} in all cases. In the theoretical part, when salinity is given, we do mean absolute salinity (S_A), while all values related to experiments in the lab and field are measured in practical salinity scale (S_P).

The permeability of the ridge keels to seawater is very important for realizing the considered scenarios of the consolidation of ridge keels. Measurements of water velocities inside the ridge keels demonstrating their permeability by sea currents were performed and discussed in the papers by Gorbatsky and Marchenko (2007), Marchenko and Høyland (2008) and Shestov and Marchenko (2014). In the second section of the present paper, the permeability of the ridge keels to the surrounding waters is demonstrated by the analysis of temperature fluctuations inside the ridge keel. The field studies were performed on drifting ice in the north-west Barents Sea in May 2008.

In the third and fourth sections of this paper, two scenarios of ridge keel consolidation are considered. In the first scenario water in the ice rubble cavities is replaced with less saline water at the freezing point temperature, and new water remains within cavities. The first scenario can happen when fresh water from melt ponds drains down or when melt water from the keel lifts up into the rubble. In the second scenario, the rubble is constantly flushed with water at freezing point temperature, which continuously increasing. Suggested possibilities of this are spring run-off of fresh water and the currents in the mouths of rivers combined with the tidal currents. Mathematical models describing the consolidation according to the scenarios are formulated and numerical simulations are performed. Expressions for the thermodynamic Gibbs potentials of the seawater, ice and sea ice derived by Feistel and Hagen (1998) and classical thermodynamic considerations provide a background for the formulation of the mathematical models. The primary results of this work are formulated, discussed and summarized in the conclusion section.

2. Morphological structure and permeability of an ice ridge in the Barents Sea

Field investigations of an ice ridge were performed during the RV Lance cruise in the Barents Sea South-East of Svalbard during 5–15 May, 2008. The RV Lance was moored to the drifting floe 100 km to the East of the Hopen Island and drifted together with the floe for 5 days (Fig. 1a). The floe diameter was approximately 50 m, and it included an ice ridge. The floe was surrounded by drifting level ice that had a thickness of less than 1 m. The field investigations consisted of drilling studies of the ridge to identify its draft, thickness and macroporosity measurements of the consolidated layer, topographical studies of the ridge sail surface, visual observations with an underwater camera, salinity measurements of ice samples and temperature profiling of the ridge keel. The topographic mapping was conducted using a surveying instrument Total Station TCR 1205 (Leica Geosystems AG, Heerbrugg, Switzerland).

Fig. 1b shows a 3D model of the ridge sail based on measurement data. Ridge sail is composed of three localized hills with a maximum altitude that exceeds 4 m. Drilling was done using a 2-inch Kovacs auger along four profiles, A, B, C and D, which are shown in Fig. 1b with white lines. The distance between neighboring boreholes was approximately 1 m in profile A and 2 m in the other profiles. The results of the drilling studies are shown in Fig. 2, where only two fractions in the keel are distinguished: solid or soft ice (SF) and water or slush (LF). SF is shown by rectangles, and LF is located between them. It can be seen that in a few boreholes, the ice draft exceeds 9 m and the entire ridge keel is consolidated. Most of the consolidated part of the ridge keel lies in a region of about 8 m diameter in the horizontal plane between profiles B and C. The salinity of the ice samples collected from the ridge sail and keel varied from 2.9 to 5.9 g kg^{-1}, and the consolidated part of the ridge did not include blocks of fresh ice. The majority of the ice cores were collected from the consolidated layer of the ridge at depths of less than 2 m. The salinity of one ice core sampled from a depth exceeding 6 m was 4.5 g kg^{-1}. According to such values of salinities investigated ridge most probably is a first-year ridge.

Temperature profiling of the ridge keel was performed using a SBE-39 (Sea-Bird Electronics, Inc., Bellevue, Washington, USA) temperature and pressure recorder that was mounted on a rope. The sensor was moved downward inside preliminary produced boreholes in the ridge keel at locations 1 and 2 and from the side of the floe at locations 3 and 4. Locations 1–4 are shown in Fig. 1b as white circles. The boreholes were filled with seawater during the drilling process and were not disturbed for several hours before the temperature profiling was performed. Visual observations of the ridge keel were performed at the same locations using an underwater lens that was connected to a camera with a cable. Side photos of the ridge keel reveal that it consists of ice blocks and caves filled with seawater (Fig. 3a). The edges of the submerged ice blocks are smoothed, and the keel has a streamlined shape. Photos of the ridge keel from the inside (Fig. 3b) reveal that the interior of the ridge keel has a similar structure. The difference between the interior and the exterior of the ridge keel is that some caves between the ice blocks inside the keel were filled with a significant amount of slush.

During the temperature profiling, the SBE-39 recorder was gradually moved downward and maintained at different depths for 1 min and it took 30–40 min for each profile. The pressure was registered by the