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The consolidation of saline ice blocks in water of varying freezing points: Laboratory experiments and computer simulations

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ABSTRACT

The thermodynamic consolidation of ice rubble in the ridge keel is an important mechanism both in global heat balance and when it comes to offshore structure interaction. Classically, it is considered that consolidation in the keel occurs due to reserved cold at the stage of formation and due to further atmospheric cooling. Such scenario brings consolidation layer thickness to a value of about two times only thicker than the level ice around the ridge, while in-situ observations after summer season show that many ice ridges are almost fully consolidated. The authors propose a thermodynamic process inside ridge keels during the summer season, which may cause the keel to become more consolidated. They assume that fresh water can flow through the keel increasing the freezing point of fluid in the caves, which allows extracting additional cold from the solid ice of the keel and, as a consequence, freezing fluid inside caves. The physical mechanism of possible keel summer transformation in water with varying freezing points was investigated in the laboratory and numerically.

Two types of experiments were performed to investigate mass and salinity development of saline ice samples. In the first type of experiment we used samples with an opening of 2 cm, cut off from the sample in the middle part of it. This was made to illustrate visually the process of rubble consolidation and macro-porosity reduction. In the second type of experiment the samples of same dimensions, but without the gap, were used. In both experiments, samples were periodically moved between water reservoirs of different salinities (0 and 35 ppt), held at their freezing points. The mass, salinity and shape of the samples were observed. The experiments demonstrated a gradual increase in the total mass of the samples and significant variations of the salinity of the ice samples during stages at different reservoirs. We demonstrate that such salinity variations are very important for the accumulation of ice mass. Numerical simulations performed using the finite element method in Comsol Multiphysics 4.3a confirm the experimental results.

1. Introduction

The ice ridges are often under close consideration in the development of the Arctic offshore projects (see e.g. Barrette, 2011). The thermodynamic consolidation of the ridge keel is one of the main concerns when it comes to the ridge structure interaction. The degree of ridge keel consolidation governs the strength of keel and may define the scenario of an interaction of ridge keel with seabed or structure. For example in ice gouging process it may define whether keel will be destroyed or seabed soil will be deformed. It is believed 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., Høyland, 2002; Leppäranta and Hakala, 1992; Marchenko, 2008; Shestov and Marchenko, 2009). While, field observations (Shestov et al., 2012; Strub-Klein et al., 2010) of the ridge keels after summer season show that many of them are almost fully consolidated. This brought us to the discussion that summer transformation mechanism is of importance for ridge keel consolidation.

In our previous work (Shestov and Marchenko, 2016) possible physical mechanism of summer keel transformation was proposed. The mechanism requires the penetration of less saline water, which has a higher freezing temperature, into caves between submerged ice blocks. Replacement of the original colder water brings the system of a cave and surrounding sea ice out of the thermodynamic equilibrium. Further thermodynamic processes request new ice to form in the caves and old ice to melt on the walls of the brine pockets. Macro-porosity is reduced while micro-porosity is increased. The theoretical consideration in the work, mentioned above, is based on two scenarios: 1) the ice

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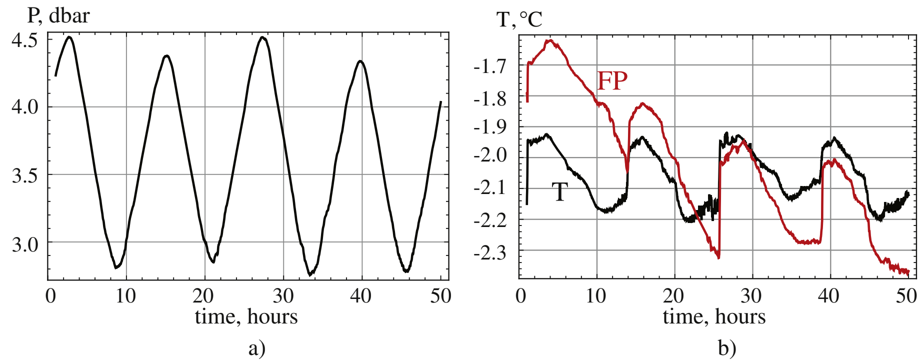

Fig. 1. The recorded water pressure, sea water temperature (T) and freezing point (FP) over several cycles of the semidiurnal tide, at the bottom.

and the water are insulated from the surroundings or 2) the water in the rubble is continually flushed so that it remains at its freezing point. From the results of the first scenario, for example, we may expect 50% reduction in macro-porosity if we choose initial macro-porosity of 0.2 and replace original water at the freezing point of temperature −2 °C with water at the freezing point of temperature −0.4 °C.

Periodic variations of sea ice salinity and temperature with the tidal frequency are observed on the Arctic shelf over a year. Near river mouths or during the summer ice melt and water run-off, such variations can be stronger. In the Arctic seas, the water salinity varies from a mean value of approximately 35 ppt to zero near the mouths of rivers (Dobrovolskii and Zalogin, 1982). The water freezing points vary from −1.9 to 0 °C, respectively. Typical examples of the time variations of the temperature and freezing point of sea water are shown in Fig. 1. The measurements were performed in Van Mijen Fjord, Spitsbergen, in March 2013 using a CTD recorder SBE 37 with a sampling interval of 6 s. The recorder was placed at the bottom, below the land fast ice. The freezing point was calculated using the approximation formula developed by Feistel and Hagen (1998). The amplitude of the temperature variations is approximately 0.2 °C. The salinity variations demonstrate that the water at the bottom can be supercooled.

In the second part of the present paper, we describe two laboratory experiments which were performed with saline ice samples. In both experiments, samples were systematically alternated between a bucket with salt water and a bucket with fresh water. In each bucket, the water temperature was different and held at the respective freezing point. In the first experiment, samples had an opening of 2 cm in the middle of the sample, and focus was placed on the sample's mass development and closing of the opening. While in the second experiment samples did not have an opening, and together with mass development changes in salinity of the samples were tracked. The mass and salinity of the ice samples were measured after each replacement. The experiment provides the possibility to estimate the increase in the ice mass when the sample was transferred from the salt water into the fresh water and demonstrates the thermodynamic consolidation of ice rubble in water with a periodically varying freezing point.

A mathematical model and the numerical simulations of the experiments are described in the third section of this paper. The numerical simulations were performed using the FEM software Comsol Multiphysics 4.3a. The mathematical model takes into account variations in the bulk salinity near the ice–water interface. The main results of the study are formulated in the conclusions section.

2. Laboratory experiment

2.1. Set-up

Experiments were performed in November 2011 in the cold lab of The University Centre in Svalbard. Saline ice samples were periodically moved between two buckets (Fig. 2a) containing fresh water from Lake Isdamen and salt water from Advent Fiord, which have salinities of 0.2 and 35 ppt, respectively. To maintain both waters at their respective freezing points of 0 °C and −1.9 °C, the air temperature in the laboratory was set to approximately −3 °C. Since there was a constant heat flux from the buckets to the cold room, ice formed on the sides of the buckets. When the sample is moving between different waters, each time it is surrounded with water at the freezing point of desired value, and heat and salt exchange between sample and water are allowed to happen.

Using a core barrel, the samples for experiments were cored from the ice which was in advance grown in the laboratory from the salt water. As a result, cylindrical samples of approximately 20 cm in length and 7 cm in diameter were used. Two different types of experiments were performed: Experiment 1 was focused, mainly, on the mass development of the sample, and Experiment 2 on the changes in salinity of the sample.

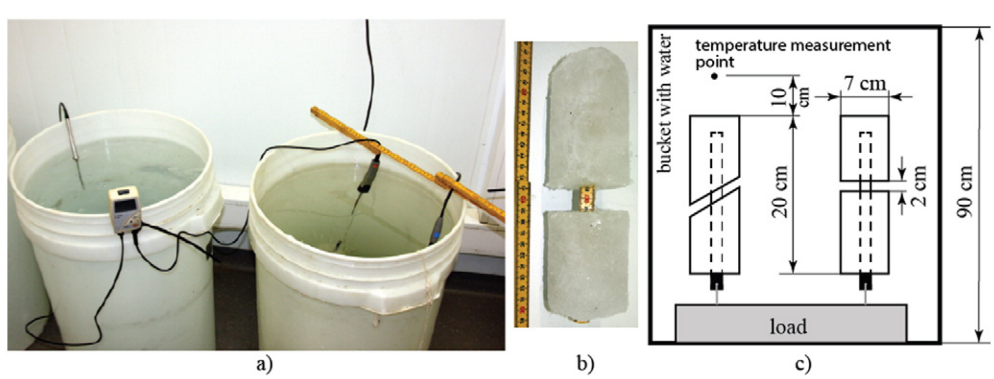

Fig. 2. The *fresh water* and *salt water* buckets at their respective freezing points (a), a sample prepared for the experiment (b) and a sketch of the sample positions (c) during the experiment.