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Thermodynamics of slush and snow–ice formation in the Antarctic sea-ice zone

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ABSTRACT

Snow over Antarctic sea ice is often flooded by brine or seawater, particularly in spring, forming slush and snow ice. Here, we evaluate the representation of the thermodynamics of slush and snow–ice formation in large-scale sea-ice models, using laboratory experiments (NaCl solutions poured into grated ice in an isolated container). Scaling analysis highlights latent heat as the main term of the energy budget. The temperature of the new sea ice immediately after flooding is found very close to the saltwater freezing point, whereas its bulk salinity is typically >20 g/kg. Large-scale sea-ice models faithfully represent such physics, yet the uncertainty on the origin of flooding saltwater impacts the calculated new ice temperature, because of the different salinities of seawater and brine. The laboratory experiments also suggest a potential limitation to the existing physical representations of flooding: for brine fractions $>60\%$, ice crystals start floating upon saltwater. Natural sea-ice observations suggest that the isolated system assumption holds for a few hours at most, after which rapid heat and salt exchanges mostly destroy the initial flooding signature on temperature and salinity. A small footprint on ice salinity remains however, natural snow ice is found 3–5 g/kg more saline than other forms of sea ice.

1. Introduction

The Antarctic sea-ice environment is highly dynamic, characterized by the frequent passage of storms (Worby et al., 1998), the influence of ocean waves (Squire, 2007) and substantial precipitation (Bromwich et al., 2004). Such conditions force the redistribution and mixing of pure ice, snow, seawater, brine and meltwater within the pack, as indicated by the diverse texture and isotopic signals in Antarctic compared to Arctic sea ice (Jeffries et al., 1997). The processes mixing ice, snow and water are mainly the flooding of snow by seawater and brine (e.g. Lytle and Ackley, 1996), the percolation of meltwater through the brine network with possible stagnation and refreezing within the ice (e.g. Kawamura et al., 1997), and ice ridging, which traps seawater among broken ice blocks (e.g. Leppäranta et al., 1995; Tin and Jeffries, 2003; Williams et al., 2014). In turn, the main Antarctic sea ice halo-thermodynamic regimes (Haas et al., 2001; Kawamura et al., 1997; Maksym and Jeffries, 2000; Saenz and Arrigo, 2012) are more diverse than the standard Arctic modeling view suggests (e.g. Maykut and Untersteiner, 1971).

In particular, flooding of the snow base is widespread in the Antarctic sea-ice zone, fostered by two specificities: relatively small ice thickness (Worby et al., 2008) and abundant snowfall, often exceeding 500 mm of water equivalent per year (Bromwich et al., 2004; Jeffries et al., 2001). As a result, the snow–ice interface is often pushed below sea level (negative freeboard), hydraulically forcing the infiltration of saltwater into snow, forming slush and snow ice (Eicken et al., 1994; Lytle and Ackley, 1996). The flooding water can be brine moving upwards, if the ice is permeable (Golden et al., 1998), or seawater moving laterally from cracks and floe edges (Massom et al., 2001). The snow–ice thickness is highest in late winter in coastal regions of the East Antarctic sector and of the Amundsen and Bellingshausen Seas (Maksym and Markus, 2008). In the Northern Hemisphere, there are much fewer reports of slush and snow ice, because of generally thicker ice and much lower precipitation, as confirmed in large-scale model sea ice hindcasts (e.g., Vancoppenolle et al., 2009). Yet snow ice has been reported near the coast of Svalbard (Høyland, 2009) and in the Baltic Sea (Leppäranta, 1983). Slush and snow ice contribute to about a third of the total Antarctic sea-ice mass production, as suggested by oxygen isotope analyses (Jeffries et al., 1997; Worby

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et al., 1998), satellite (Maksym and Markus, 2008) and model-based (Vancoppenolle et al., 2009) estimates.

Slush and snow–ice formation has long been represented in large-scale sea-ice models as a single process (e.g., Fichefet and Morales Maqueda, 1997; Hunke et al., 2015; Vancoppenolle et al., 2009). The rate of snow–ice growth is determined by the fraction of snow depth lying below sea level, as determined by isostasy (Leppäranta, 1983). The initial temperature and salinity of the newly formed slush/snow ice derive from salt and energy conservation as proposed by Schmidt et al. (2004). This model representation of snow–ice thermodynamics has not been evaluated with observations, however. Process studies with one-dimensional models have focused on the rate of snow–ice formation (e.g. Crocker and Wadhams, 1989; Leppäranta, 1983), on the impact of the brine flow on the salinity evolution (Maksym and Jeffries, 2000, 2001; Saenz and Arrigo, 2012), whereas Saenz and Arrigo (2012) also treat the impact of slush desalination on the growth of ice algae. Yet the energetic aspects of flooding events and their impact on the initial slush and snow–ice thermodynamic properties have not been investigated. In this context, the present study aims (i) to describe the energy and salt budget of slush and snow–ice formation; and (ii) to evaluate the thermodynamic computation of initial slush and snow–ice properties from large-scale sea-ice models, using laboratory experiments.

We first describe (Section 2) two approaches for the energy budget of slush and snow–ice formation. The first one simplifies the energy budget but is not fully energy-conserving. The second one is based on energy and salt conservation (Schmidt et al., 2004) and used in large-scale sea ice models. The realism of both approaches is investigated through laboratory experiments. In these experiments, described in Section 3, a NaCl solution is poured within grated ice (a lab analog for snow) in a cryogenic container, varying the physical input conditions (the temperature of both snow and saltwater, the saltwater salinity, and the grated ice density). Both theoretical approaches suggest that the temperature of the initial slush is very close to the freezing point of the flooding saltwater, which is confirmed experimentally (Section 4). Yet we find a significant limit in the validity of both representations of the process: if the liquid fraction exceeds 60%, the ice crystals start to float, stratifying the system into two layers with distinct properties. In Section 5, results are put in the context of natural sea-ice observations. In Section 6, we provide elements of discussion and conclude this paper.

2. Theoretical background

As assumed in large-scale sea-ice models, freshly formed slush and snow ice are not explicitly distinguished: both are considered as sea ice, characterized by temperature (T, in °C) and bulk salinity (S, in g/kg) (Bitz and Lipscomb, 1999; Vancoppenolle et al., 2010). Hence, and unless otherwise stated, we will hereafter use *snow ice* both for *slush* and *snow ice*. The transformation of a mixture of snow and saltwater into sea ice is considered (see illustrations of the process as occurring in the field in Fig. 1a and as conceptualized in Fig. 1b). The initial state of the system is characterized by a snow mass m_s, with temperature T_s, zero salinity, and density ρ_s, homogeneously flooded by saltwater with mass m_w, temperature T_w and salinity S_w. The final state is a mass of sea ice m_i with temperature T_i, salinity S_i and density ρ_i. Note that we neither consider the neighboring dry snow above or sea ice below (see Fig. 1a), nor the pathway, nor the origin of the flooding water.

2.1. The freezing-point approach

The first approach to derive the snow–ice temperature shortly after formation is based on physical reasoning. For the snow temperatures [−10 °C, 0 °C] and saltwater temperatures [−2 °C, 2 °C] encountered in nature, the Stefan number cT/L is generally small (<0.05). Therefore, the sensible heat stored in saltwater and snow is generally much smaller than the latent heat released (absorbed) due to internal freezing (melting). Hence, only a small amount of internal freezing (melting) is required to compensate for the sensible heat of the two initial phases. Because of the small internal melting or freezing, the salinity of the brine incorporated in new snow ice is close to the flooding saltwater salinity S_w. Assuming thermal equilibrium and linear liquidus, one finds that the temperature of the new snow ice is simply:

$$T \approx T^{fr} = -\mu S_w, \qquad (1)$$

where μ gives the linear dependence of the freezing temperature as a function of water salinity and differs for seawater and NaCl solutions (see Table 1). In this view, the new snow–ice temperature is the freezing point of the flooding saltwater T^{fr}. Whereas this *freezing point approach* seems suitable for a physical description of the process, it may not be valid in all conditions. In addition, because sensible heat is neglected, the freezing point approach is not energy-conserving, and hence not appropriate for large-scale models.

2.2. The fully energy- and salt-conserving approach

In most sea-ice models, the temperature and salinity of solid and liquid mixtures right after formation derive from mass, salt and energy conservation equations (Schmidt et al., 2004). Following this generic approach, hereafter referred to as *fully-conserving*, the enthalpy of snow ice is computed as the sum of the enthalpies of snow and flooding saltwater (Hunke et al., 2015; Vancoppenolle et al., 2009). From enthalpy, the ice temperature can be retrieved. The new snow–ice salinity (on which enthalpy

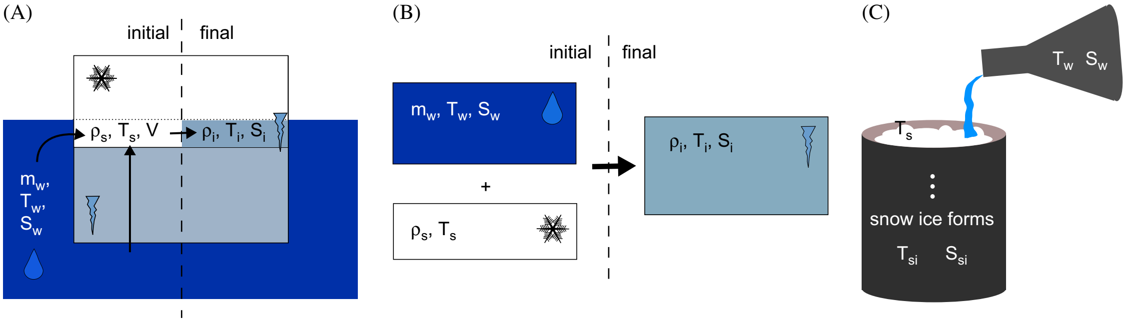

Fig. 1. Schematics of a flooding event (a) in the field, (b) as viewed in sea-ice models, and (c) in the laboratory experiments described in this paper. ρ represents density, m mass, V volume, T temperature and S salinity. The subscript w stands for water, i for ice and s for snow.

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