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The phase evolution of young sea ice

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Abstract. Sea ice forms as a porous matrix consisting of pure ice crystals in equilibrium with brine. We present an experimental and theoretical study that reveals that the brine expelled by growing sea ice initially remains trapped within the crystalline interstices but that drainage into the underlying water is ultimately triggered abruptly due to the onset of buoyancy-driven convection. The onset is quantified by a critical porous-medium Rayleigh number, and we present an empirical marginal stability diagram that defines the transition.

Introduction

The formation of sea ice in the polar oceans is an important factor influencing global ocean circulation and climate. For example, the annual export of fresh water in the form of sea ice from the North Polar Basin (2,800 km^3 yr^{-1}) [*Aagaard and Carmack*, 1994] is approximately twice the combined outflow of North America's four largest rivers. This fact has drawn attention recently to the role of oceanic solidification, the high-latitude distillation process, in global thermohaline circulation [*Aagaard and Carmack*, 1994; *Maykut*, 1986]. The seasonal difference in sea ice coverage is 8×10^6 km^2 in the Arctic and 18×10^6 km^2 in the Antarctic, and the dynamics of the brine rejection process that accompanies ice growth has a substantial impact on the stability of the oceanic mixed layer and hence the large-scale circulation of the ocean. Present day coupled ocean–atmosphere global climate models predict abrupt climate changes induced by the flux of freshwater into the North Atlantic Ocean, indicating that sea ice export is an important control in convective stability [*Rahmstorf*, 1995].

A primary motivation for unravelling the processes governing the formation of young sea ice is to understand how cracks in the perennial ice cover, known as leads, exert an influence on the large-scale processes described above. Recent field observations in the Arctic [*Morison et al.*, 1993] show that the heat loss through these fissures can be up to 300 W m^{-2}, or fifteen times that from the surrounding ice. Hence, although they occupy less than 10% of the surface area, leads can account for roughly half of the total oceanic heat loss. Depending upon environmental conditions, sea ice can reach a thickness of 15 cm in the first 24 hours of growth [*Wettlaufer*, 1997], a regime captured in the experiments described here. It is through such young sea ice that the heat flux is greatest, so the onset of brine drainage early in its life influences the phase evolution and thereby plays a significant role in determining the overall heat budget. Whereas frazil ice constitutes a significant proportion of the ice cover in the Southern Ocean, and in other seasonal ice zones, the overwhelming majority of sea ice growth in the Central Arctic Ocean occurs in leads and is columnar [*Weeks*, 1997]. In this letter we present a new model of ice formation which shows that the brine expelled by growing sea ice initially remains trapped between ice platelets but ultimately drains into the underlying water. Our laboratory experiments have elucidated the brine drainage dynamics and have quantified the conditions required for drainage to occur.

The detailed structural evolution of sea ice is dictated largely by its solid fraction, which provides a link between local ice properties and the fluxes driving large scale processes. The solid fraction exerts a controlling influence on the thermal, electromagnetic, acoustic and mechanical behaviour of sea ice [*Wettlaufer*, 1997]. The bulk thermal diffusivity dictates the growth and decay of the sea ice cover, and the electromagnetic properties control its scattering signature. For accurate monitoring of long-term trends, the remote detection of the areal fraction of thin ice is crucial and comprises a major effort in the remote sensing by satellite of the polar regions [*Winebrenner et al.*, 1995]. However, present approaches rely on a semiempirical description of the solid fraction, rather than the quantitative approach described here.

Sea Ice as a Mushy Layer

When a binary liquid mixture (such as a solution of salt in water) is cooled and solidified, the solid that forms (ice) typically has a composition different from that of the liquid. The liquid adjacent to the growing solid becomes enriched in the rejected component (salt). If the rejected component causes the density of the liquid to increase then both compositional and thermal convection may ensue when the cooling and solidification is from the top downward [*Huppert and Worster*, 1985]. The solid growing from such a liquid mixture usually forms a porous layer (called a mushy layer [*Worster*, 1992a]) in which concentrated liquid surrounds nearly pure solid crystals. The dense, enriched liquid can be trapped within the matrix if it has insufficient negative buoyancy to overcome dynamically the resistance provided by the solid crystals. To study this particular process, we conducted a series of laboratory experiments in which aqueous solutions of sodium chloride (NaCl) were cooled and solidified from above in a carefully insulated rectangular container ($20 \times 20 \times 40$ cm) enclosed in a specially built chamber with independent temperature control in order to minimize heat gains from the laboratory. We conducted similar ex-

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periments using sea water, and there was no discernible difference from the experiments using solutions of NaCl. The temperature of the upper surface of the cell was controlled with a cryostatic system. The experiments covered a wide range of concentrations and surface temperatures including those encompassing typical polar situations. In the early stages of our experiments, we find that although weak compositional convection is evident from shadowgraph images (figure 1a), our measurements in the liquid region indicate that the composition remains essentially constant (figure 2a), which signifies that there is little transport of salt out of the mushy layer. This occurs despite the liquid within the mushy layer being more dense than that below it. However, once the mushy layer has reached a critical thickness h_c, the concentration of salt in the liquid region suddenly begins to increase (figure 2a). The increase is associated with the appearance of strong convective plumes (figure 1b), which emanate from channels within the mushy layer (figure 1c). Visual inspection during a *post mortem* of the mushy layer revealed that these brine channels, which have been observed previously both in the laboratory [*Eide and Martin*, 1975] and in the field [*Malmgren*, 1927; *Bennington*, 1963; *Lake and Lewis*, 1970], occupy the full thickness of the mushy layer.

The brine draining from the mushy layer is replaced by a weak return flow of relatively fresh water from the liquid region below it, which partially freezes within the pores of the mushy layer to increase its solid fraction. We present here the first *in situ* measurements of the mean solid fraction of sea ice as it evolves in time. Water expands as it solidifies to form ice. We measured the expansion and the thickness of the mushy layer and deduced the mean solid fraction from a simple mass balance. Alternatively, given the assumptions that the vertical temperature field in the mushy layer is approximately linear and that the interstitial liquid is in local equilibrium [*Worster*, 1992a], it is possible to deduce the mean solid fraction from the measurements of the concentration of the liquid region using a solute balance [*Tait and Jaupart*, 1992; *Huppert and Hallworth*, 1993]. The two estimates agree to within 3%. The mean solid fraction estimated in the latter way is shown in figure 2b. We see that the solid fraction increases significantly once the thickness of the mushy layer has exceeded the critical value h_c and brine

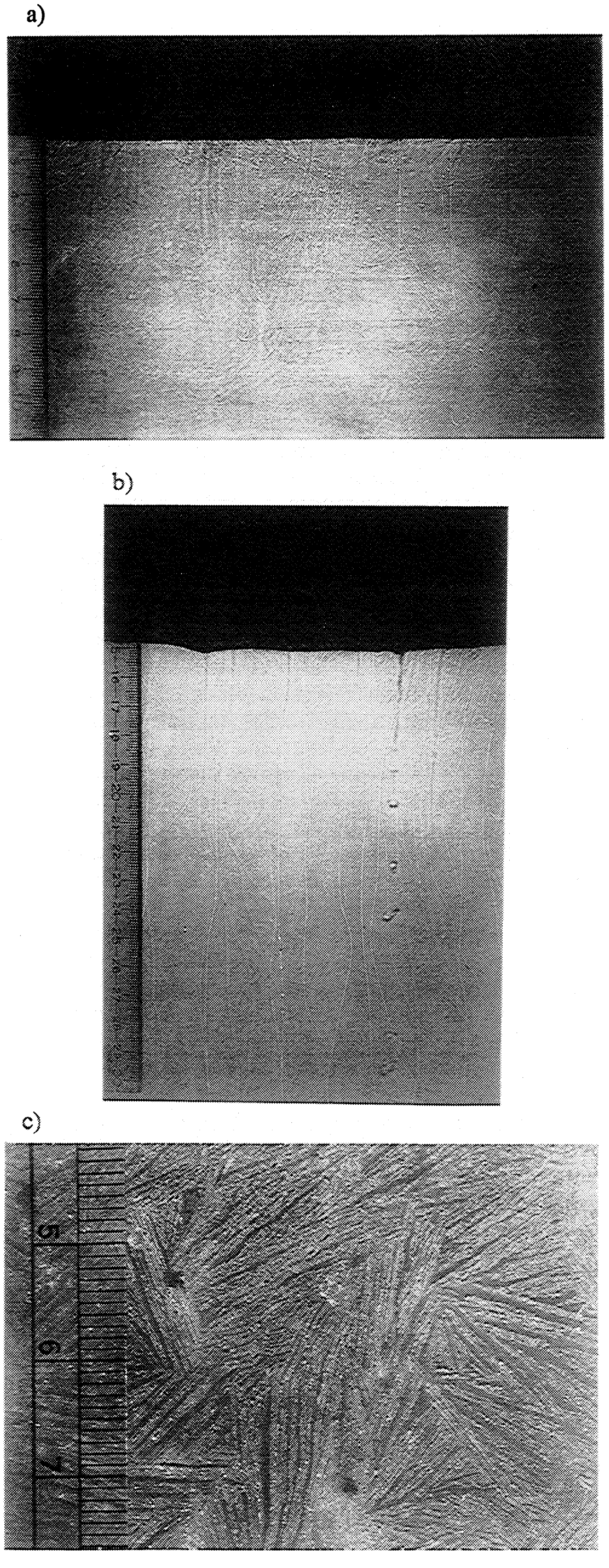

Figure 1. Photographs taken during an experiment in which an aqueous solution of sodium chloride (3.55 wt.%; approximately Arctic Ocean mixed layer concentration) was cooled and solidified from above. A centimeter scale is shown on the left. The black region at the top of pictures (a) and (b) is the mushy layer, whose structure can be seen in photograph (c). (a) Early in the experiment, when the mushy layer has a thickness of 2.4 cm, weak compositional convection is evident in the form of very thin streamers. These emanate from the interfacial region between the mushy layer and the liquid and do not carry a significant flux of salt (see figure 2). (b) Later in the experiment, when the thickness of the mushy layer is about 15 cm, which is greater than the critical thickness (see figure 2), strong plumes of brine emanate from deep within the mushy layer and emerge from brine channels within the layer. These plumes carry a significant salt flux. (c) The underside of the mushy layer showing the crystal structure and two clear brine-drainage channels. The crystal shape and orientation is typical of that found throughout the mushy layer. In particular, the c-axes of the ice crystals are oriented principally horizontally, displaying the columnar stucture of natural sea ice. Visual inspection of the mushy layer during a *post mortem* revealed that these brine channels extend through its full thickness.

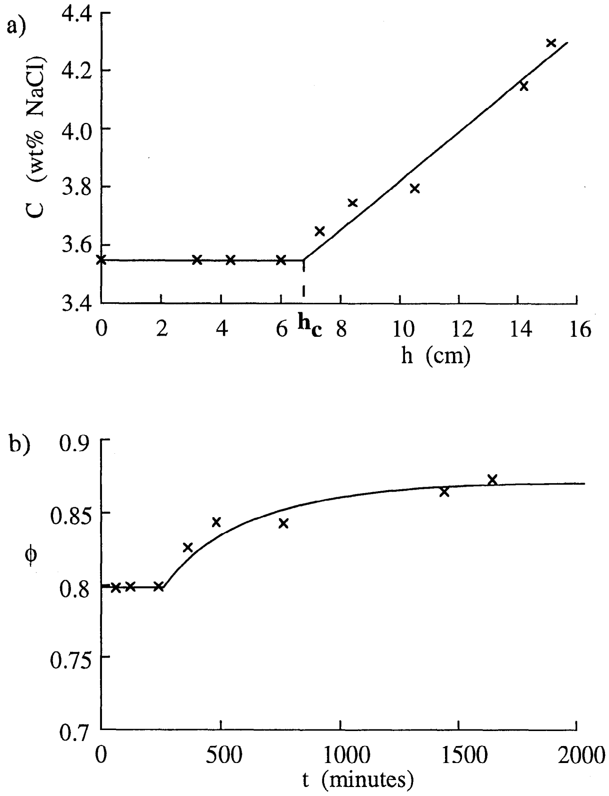

Figure 2. Results for an experiment with initial concentration $C_0 = 3.55$ wt.% NaCl and temperature at the upper surface $T_B = -20°\text{C}$. (a) The measured concentration of the liquid region as a function of thickness of the mushy layer and a curve drawn to fit the measurements. The concentration remains constant initially, indicating that brine rejected by the growing ice remains in the mushy layer. Once the thickness of the mushy layer exceeds a critical value h_c, brine drains into the underlying liquid region. (b) The evaluated solid fraction of the mushy layer as a function of time. The mushy layer begins to grow more slowly once the critical thickness has been exceeded since the increased solid fraction requires the removal of additional latent heat.

is draining from the layer. The additional solidification within the mushy layer requires the removal of additional latent heat, which retards the growth of the mushy layer [*Wettlaufer et al.*, 1997].

Critical Condition for Brine Drainage

The onset of brine drainage has important consequences for the evolution of sea ice and for convection of the ocean beneath it. In oceanographic modelling, the salt flux from sea ice is commonly treated as being proportional to the thermal driving (i.e. the difference in temperature across the layer of sea ice, between the air and the ocean) [*Smith and Morison*, 1993]. Our experiments, with different surface temperatures, have shown that the salt flux does indeed increase with the thermal driving once the critical thickness h_c has been exceeded. However, the flux and the driving are not directly proportional since the flux is influenced in a nonlinear fashion by the changing permeability of the mushy layer. What is even more remarkable is that the critical thickness *increases* with the thermal driving so that the salt flux is essentially zero for longer. This is a consequence of the fact that, when the thermal driving is greater, the resultant solid fraction of the mushy layer is larger. Hence its permeability is lower; its resistance to flow is greater.

We analyse this idea quantitatively by making the hypothesis that the critical thickness is determined by the criterion that a porous-medium Rayleigh number

$$Ra = g\beta\Delta C\Pi(\phi)h/\kappa\nu, \qquad (1)$$

which measures the driving buoyancy of the enriched brine relative to the resistance of the solid matrix [*Phillips*, 1991], must exceed a critical value before significant drainage of interstitial brine can occur [*Worster*, 1992b]. In this definition, g is the acceleration due to gravity, $\beta\Delta C = \beta(C_0 - C_B)$ is the difference in the liquid density across the mushy layer, where C_0 is the initial concentration of the liquid region and C_B is the liquidus concentration corresponding to the imposed surface temperature, h is the thickness of the layer, κ and ν are the thermal diffusivity and kinematic viscosity of the liquid and Π is the permeability of the layer, which is a function of the solid fraction ϕ. This hypothesis indicates that

$$(h_c\Delta C)^{-1} \propto \Pi(\phi_c), \qquad (2)$$

where h_c is the critical thickness and ϕ_c is the value of the solid fraction measured at the critical time. In figure 3 we plot $(h_c\Delta C)^{-1}$ against the critical liquid fraction $(1 - \phi_c)$ for all the experiments. We observe that this provides a good collapse of all the data from thirteen experiments conducted with a wide range of initial concentrations and surface temperatures, which gives confidence to our hypothesis. Additionally, the trend of the function is consistent with the expected form of the permeability function, namely that the permeability increases with the liquid fraction and has positive curvature, increasing rapidly as the liquid fraction approaches unity.

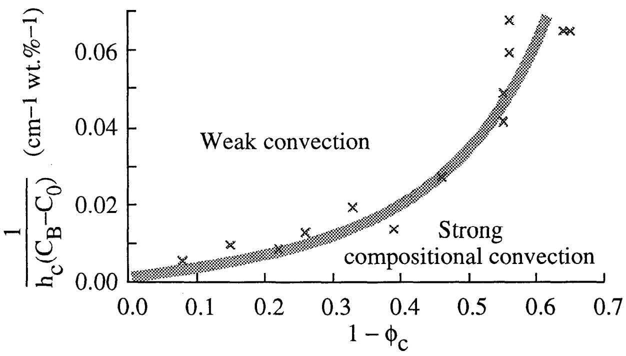

Figure 3. Critical conditions for the onset of a significant brine flux from the mushy layer. Crosses show when the brine flux began in each experiment. The initial concentration in the experiments ranged between 1 and 14 wt.% NaCl. The surface temperature ranged between −10 and −20°C. When the conditions of the mushy layer lie above the marginal curve drawn through the data, most of the salt rejected by the growing ice remains trapped in the mushy layer. Once the conditions of the mushy layer lie below the marginal curve then brine will be convected out of the mushy layer.

Discussion

To connect our results to field conditions we note that the maximum brine flux from a single lead occurs within about 6 hours of its formation [*Morison and McPhee*, 1997]. After sea ice reaches approximately 20 cm, there is very little discernible difference in its brine flux from that of the background. As mentioned above, the main, large scale, scientific hypothesis driving the study of leads is that the very uniform mixed layer structure observed in the Arctic is created entirely from a relatively small area of leads. Therefore these events, whose timescales are short relative to seasonal timescales, and which occur throughout the Arctic, may be responsible for the creation and maintenance of the large scale hydrography. Thus, a major conclusion is that our observed delay in the brine flux (of about 5 hours) is actually very significant on the timescale of the evolution of a single lead and hence has important implications for the link between leads and large scale hydrography. Furthermore, by influencing the solid fraction in the mushy layer, brine drainage slowed the growth of the layer by up to 15% in this same time period [*Wettlaufer et al.*, 1997].

Finally we point out that our results bear directly on the sea-ice ecosystem [*Arrigo et al.,* 1993]. The mobility of interstitial liquid is important for ice-borne algae communities and for the cycling of pollutants, which enter the sea-ice system through both the atmosphere and the ocean. In the Arctic, the atmospheric route includes the emission and subsequent fallout onto sea ice of harmful metals (e.g. Cu, Zn, Pb, Cd, Hg) [*Donchenko*, 1993], and the oceanic route involves the release of radionuclides into the major Russian rivers; primarily the Ob and the Yenisy [*Weeks*, 1994]. While in the water column, these constituents may adversely affect various components of the ecosystem locally, and once these chemicals make their way into the ice cover via solute or soil particle trapping, wind driven drift transports them to other regions where they eventually fall out into the water column. Hence, an important ingredient to the large scale problem of pollutant transport is the local mechanism by which the bulk sea water, containing these harmful elements, is trapped within the sea ice.

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