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# Melting driven convection at the ice-seawater interface

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## Abstract

We performed direct numerical simulations to investigate the interaction of a vertical ice interface with seawater, and particularly the small-scale convection generated when a wall of Antarctic ice melts in the salty and warmer seawater. The three coupled interface equations are used, along with the Boussinesq and non-hydrostatic governing equations of motion and equation of state for seawater, to solve for interface temperature, salinity and melt rate. Fluxes of both heat and salt to the interface play significant roles in rate of ice melting. The main focus is on the dissolving of ice (at ambient water temperatures between $-1^\circ$ $C$ and $6^\circ$ $C$ and salinity around 35 ‰) as characterizes many sites around Antarctica. Under these conditions the diffusion of salt to the ice-water interface depresses the freezing point and further enhances heat diffusion to the ice.

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*Keywords:* melting, convection, double-diffusive layers

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## 1. Introduction

Over the past decade, the Antarctic and Greenland Ice Sheets have been losing mass at an alarming rate. Satellite radar measurements during 1992 to 2006 showed that the loss rate of Antarctic ice mass has increased by 75%[1]. Antarctic ice-shelves are melting by turbulent transport of heat and salt to the ice face, predominantly under the influence of warmer and salty Circumpolar Deep Water entering ice shelf cavities from the surrounding Southern Ocean[5,1]. The water exiting ice shelf cavities contributes to Antarctic Bottom Water, providing a crucial component of the global thermohaline circulation. Both heat and salinity play a significant role in the melting process which takes place inside a boundary layer in proximity to the ice-shelf. Knowledge of these processes, and the feedbacks between them, is needed to predict melting rate and future rises in sea level.

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**Nomenclature**

| | |
|---|---|
| $x, y, z$ | co-ordinate system |
| $u, v, w$ | velocities in x,y and z directions respective |
| $m_i$ | melting rate |
| $T_w$ | far field water temperature |
| $S_w$ | far field water salinity |
| $S_b$ | imposed ambient salinity |
| $\rho_b$ | imposed ambient density |
| $T_i$ | interface temperature |
| $S_i$ | interface salinity |
| $Q^H$ | heat flux |
| $Q^S$ | salinity flux |
| $Gr$ | Grashof number |
| $Pr$ | Prandtl number |
| $Sc$ | Schmidt number |
| $l_\eta$ | thermohaline layer thickness |

The limited availability of field data regarding the thickness and velocity of the ice, and the position of the grounding line (where the ice shelf meets the ocean floor) make it difficult to determine the mass loss from the Antarctic ice-shelf and the mechanisms responsible. Recent field measurements by Jenkins *et al.* 2010[6] near Pine Island Glacier used an autonomous underwater vehicle to provide detailed measurements in close proximity to the melting ice sheet. These observations support the idea that the melting and retreat of the ice-shelf grounding line is occurring due to the uptake of heat from relatively warm and salty Antarctic Circumpolar Deep Water[5,1]. Seawater next to the Antarctic ice shelves is commonly observed to have a stable gradient in salinity and an unstable gradient in temperature[6]. However, the flow field near the ice water interface is very difficult to measure and large uncertainties lie in the accurate prediction of melting rate.

Modelling ice-shelf melting processes is a significant challenge and there are only limited data available from laboratory experiments on melting of ice under oceanic conditions. Groundbreaking experiments[12,13] showed formation of double-diffusive layers and efficient mixing of melt water from a vertical block of ice in warm water with a salinity gradient. Later, laboratory experiments by Josberger & Martin[7] examined melting of vertical ice-block of O(1)m of height in salt-water of uniform far-field temperature and salinity. Those experiments covered the wide range of surrounding water temperature and characterised the flow near the interface.

Depending on the temperature of the surrounding seawater, ice shelves may either melt or dissolve. Melting will occur when the seawater is sufficiently warm, and it is controlled only by heat transfer[11]. During melting, the interface salinity is zero, and the interface temperature is the melting point of ice (e.g. $0°C$ at atmospheric pressure). On the other hand when the sea temperature is close to or below the melting point of fresh ice, dissolution will take place and is governed by a combination of heat and mass transfer[7,11]. During dissolution, the interface salinity is non-zero, and the interface temperature is less than the melting point of ice and further enhances heat transfer. Recently, laboratory experiments[10] have studied the dissolving process and proposed a theoretical estimation for the scaling of melt rate. In many regions Antarctic seawater stays at temperatures close to $0°C$[4,5], thus dissolution might play a key role in those environments. The present study will also cover the dissolution dominated regime by maintaining low surrounding water temperature ($0°C < T_w < 6°C$).

The ice-ocean interaction problem is computationally challenging because the grid size must be sufficiently small that both the thermal ($\delta_H$) and salinity ($\delta_S$) boundary layers are resolved. In particular, $\delta_S$ is order of 1 mm, which is an order of magnitude smaller than $\delta_H$. At the micro-level the role of the diffusion of salt to the ice-ocean interface, which leads to dissolution of the ice plays, is very complex. Most global ocean models[8,14] and regional ocean modeling systems[15] describe the flow field at a much larger scale ($> O(1)$ km) and rely on parameterizations of the smaller unresolved scales, including the boundary layer against the ice interface. These parameterizations are not coupled