Development of Frazil Modelling in Ice Shelf Water plumes

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Abstract
Preliminary results are presented from a modelling study directed at the spatial variation of frazil ice formation and its effects on flow underneath large ice shelves. The chosen plume and frazil models are briefly introduced, and results from two simplified cases are outlined. It is found that growth and melting dominate the frazil model in the short term. Secondary nucleation converts larger crystals into several nuclei due to crystal collisions (microattrition) and fluid shear and therefore governs the ice crystal dynamics after the initial supercooling has been quenched. Frazil formation is found to have a significant depth-dependence in an idealised study of an Ice Shelf Water plume. Finally, plans for more extensive and realistic studies are discussed.

Introduction

Descending plumes of High Salinity Shelf Water (HSSW) are generated by seasonal pulses of brine rejected during sea-ice formation (figure 1). When this saline water encounters the grounding line of an ice shelf it will melt the ice, forming a plume of fresh Ice Shelf Water (ISW) which rises along the ice shelf base. This fresher water becomes supercooled as it rises due to the decrease in the freezing temperature (T_f) with depth, resulting in direct basal freezing and the production of frazil ice, <10mm platelets which form in a supercooled turbulent fluid and rise and precipitate onto the ice shelf under their own buoyancy.

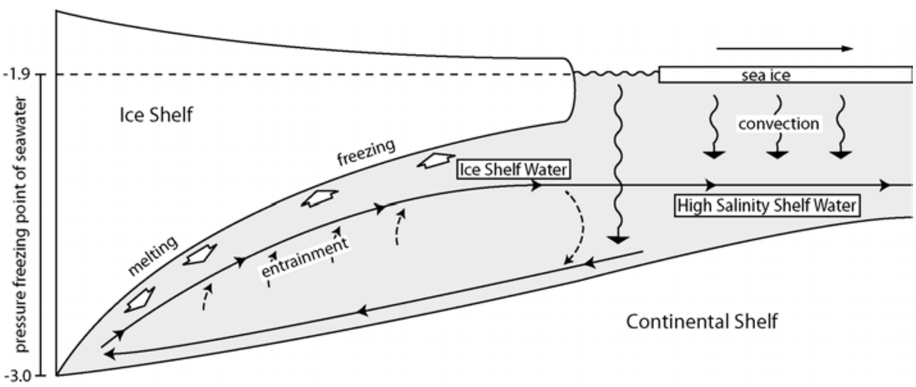

Figure 1: Schematic diagram of processes beneath an idealised ice shelf.

Study of the plume–ice-shelf interaction is potentially of great importance since HSSW and ISW are involved in the formation of Antarctic Bottom Water (Foldvik and Gammelsrød, 1988), the most prevalent water mass in the world's oceans and a primary component of the thermohaline circulation. In addition, a detailed understanding of ice formation beneath ice shelves is relevant to understanding the mass balance of the major Antarctic ice shelves.

The present study is the development of a high resolution model of ice-shelf–ocean interaction. It is part of the Autosub Under Ice programme, which intends to send an autonomous underwater vehicle underneath Filchner-Ronne ice shelf (FRIS) to extend our limited understanding of the environment beneath ice shelves. Modelling of the conjectured flows under FRIS in conjunction with this expedition will help explain Autosub's findings and verify the model.

Frazil modelling

Our model development is an extension of previous models. Jenkins (1991) presented a one-dimensional (depth-averaged) analysis of a generalised ISW plume, treating it as a turbulent gravity current. This study examined basal melting and freezing rates in the absence of any frazil ice. Jenkins and Bombosch (1995) developed this model further, adding a frazil model with fixed crystal size to the same depth-averaged plume dynamics. This study revealed that frazil formation is much more efficient at taking up plume supercooling than basal freezing alone, and presented an interesting dynamical feedback mechanism whereby plume acceleration increases frazil formation and decreases precipitation, raising the buoyancy of the plume and thus accelerating it further. Smedsrud and Jenkins (submitted, a & b) further developed this depth-averaged case by introducing a frazil ice model with multiple crystal size classes. This study elucidates the size of frazil crystals forming in ISW plumes under FRIS and removes some unphysical oscillations found in the single-size-class solution.

In our model development, we intend to adopt the multiple-size-class frazil model of Smedsrud and Jenkins (submitted, b) and develop the formulation of the dynamical model underlying previous studies. Firstly, we intend to remove the depth-averaging of plume properties in order to properly resolve supercooling, frazil rising, turbulent mixing and boundary-layer effects. Secondly, we will add a second horizontal coordinate and study the effects of Coriolis forces on the paths of ISW plumes, which are postulated in previous works. The modelling will make use of commercial Computational Fluid Dynamics software (PHOENICS) and will employ a high-order turbulence closure (e.g. the k-ε model) for the calculation of the Reynolds stresses.

Prior to the development of these advanced models, we have studied a series of simplified models, two of which are the focus of this discussion. In the remainder of this paper, we outline results from a well-mixed box, which elucidates the behaviour of the frazil model, and from a simple one-dimensional case in which depth-variation is included.

Well-mixed scenario

'Well-mixed' refers to an effectively zero-dimensional case in which there is no spatial variation in any of the model variables. In addition we consider salinity to be constant, S = 34.6psu, and assume a fixed freezing temperature of T_f = -2°C. Under these assumptions there are no transport terms or frazil rising or precipitation and the only equations to be solved are the governing equations for temperature and the interaction between individual frazil size classes.

For simplicity, we assume that the frazil has three size classes with radii $r(1)$ = 0.1mm, $r(2)$ = 1mm and $r(3)$ = 4mm. The model has a 'seed' population of $C(i)$ =1.3×10^{-8} in each size class, where *C(i)* is the volume frazil concentration per unit volume of frazil-water mixture. An initial supercooling of 1×10^{-4} °C is imposed and the model proceeds until it achieves equilibrium, with $T = T_f$ and negligible frazil transfer terms. These assumptions are all based upon the modelling study of Smedsrud and Jenkins (submitted, b).

Figure 2 shows the evolution of each model component over the first day of simulation. In the first three hours supercooling is quenched by frazil growth, which results in a volume increase in frazil classes 2 and 3. This causes a net decrease in class 1 as growth of 0.1mm crystals moves ice into the 1mm class, implying that more crystal volume is transferred into class 2 than is returned to class 1 by secondary nucleation. Class 2 has the largest volume increase in the first day because the smallest crystals (in class 1) have the highest growth rate due to their larger surface area for the given initial volume.

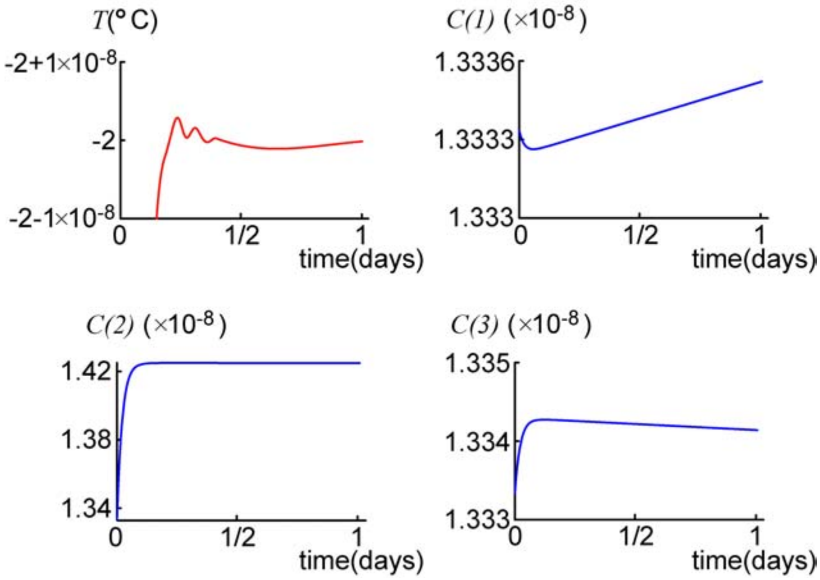

Figure 2: Results of well-mixed case over the first day of simulation

After a longer simulation time, secondary nucleation becomes dominant once the growth and melting of frazil subsides due to the lack of supercooling or superheating. The high concentrations of frazil in classes 2 and 3 are slowly transferred to class 1 as the process of secondary nucleation continues, so that the steady state has $T = T_f$ and all frazil in class 1.

Depth-varying scenario

In order to illustrate some basic effects of depth-variation in an ISW plume, a simple case is studied in which the plume temperature is held at the average value of T_f over the plume depth throughout the simulation. If depth-variation were not considered, the plume would therefore have a temperature equal to T_f, but in fact the decrease in T_f with depth means that the top half of the plume is supercooled while the bottom half is superheated (figure 3). This scenario is similar to the depth-averaged ISW plume of Smedsrud and Jenkins (submitted, b) beneath a linear ice shelf, where supercooling is negligible in a 100m-deep plume after a 500km journey.

Horizontal gradients are neglected in the model due to the small aspect ratio of the plume, and vertical advection other than the frazil's own buoyant rising is also negligible. A constant turbulent diffusion coefficient of $\nu_T = 1\times10^{-3}\text{m}^2/\text{s}$ is adopted and the same values of salinity, crystal radii and seed population are used as before. The ambient water at the base of the plume is considered frazil-free and Neumann boundary conditions for frazil are ascribed at the plume-ice shelf interface. Frazil crystals in each size class have a rising velocity proportional to their size and crystals entering a narrow region beneath the ice shelf may be precipitated out of the plume.

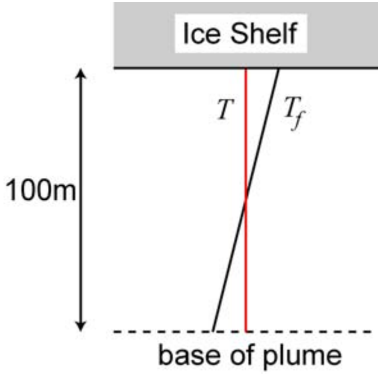

Figure 3: T_f and plume temperature.

Figure 4 shows the distribution of frazil in classes 1 and 2 throughout the depth of the plume over the first day and 10 days. Temperature is not plotted because it is held constant; supercooling and superheating are not altered by frazil formation in this case. Frazil immediately melts in the lower half of the plume (50-100m) due to the superheating there. In the supercooled region above 50m depth, it is clear that in the first three hours of simulation the frazil model behaves similarly to the well-mixed case, with a decreasing *C(1)* and a relatively large increase in *C(2)*. As before, *C(3)* (not shown) behaves like a scaled-down version of *C(2)*. It is interesting to note that the largest frazil growth occurs near the top of the plume (notwithstanding the precipitation band immediately beneath the ice shelf), where the supercooling is highest.

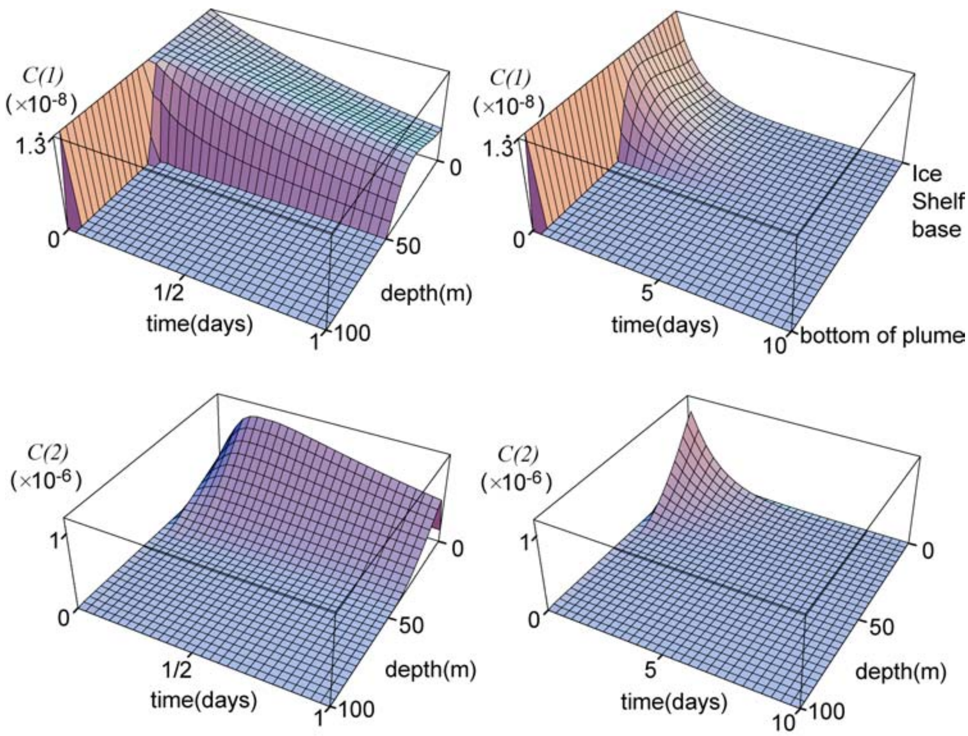

Figure 4: Results of depth-varying case in the first 10 days of simulation

After this short period of growth, the frazil concentration in all size classes decreases drastically, and the steady state solution has $C(i) = 0$ for all i. This occurs because the precipitation of frazil crystals onto the ice shelf outweighs in-situ production after the initial growth period. This analysis is confirmed by examining a control model in which frazil rising and precipitation are ignored (not shown). The growth of frazil ice beneath the ice shelf continues indefinitely in this case, since the supercooling in the top half of the plume is never taken up.

Current and future work

These preliminary studies are intended to provide a simplified view of the behaviour of the adopted multiple-size-class frazil model under a variety of conditions. After a thorough understanding of these basic cases has been gained, the aim of our project is to proceed to situations in which this frazil model is coupled to more complex hydrodynamics.

This advanced modelling will begin with a two-dimensional *x-z* model which takes account of depth variation in an ISW plume for the first time. This will be attempted by specifying boundary conditions at the turbulent base of the plume and thus avoiding the necessity of modelling the ambient HSSW. Using the theory of Baines (2001) it is possible to specify both entrainment and detrainment velocities through this boundary, so advection in both directions should be correctly modelled. These considerable assumptions will be tested against a full two-dimensional model of the sub-ice shelf cavity.

The depth-averaging assumption will then be restored so that a two-dimensional *x-y* model can be used to elucidate the effects of Coriolis forces on ISW plumes. This study will examine the relative strengths of Coriolis and topographic steering and will be used to predict plume paths from the deeper, plume-sourcing sections of the FRIS grounding line. When both of these studies are complete it will be appropriate to formulate a full three-dimensional model of an ISW plume rising along the base of an ice shelf.

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