Precipitation of frazil from Ice Shelf Water plumes

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Introduction

If seawater at the local freezing temperature sinks, it has the potential to melt ice at depth due to the pressure decrease in the freezing temperature of seawater ($\approx -7.53 \times 10^{-3}$ °C bar^{-1}). Conversely, if meltwater released at depth rises, it may become supercooled and ice may form. These two processes together may form an 'ice pump', a heat engine which melts ice at depth and deposits it at a shallower location (Lewis and Perkin, 1986). The ice pump is thought to be particularly important in redistributing ice mass under large ice shelves; the rising meltwater forms a turbulent plume of relatively fresh Ice Shelf Water (ISW), which becomes supercooled as it rises, causing frazil ice formation that deposits on the ice shelf base.

Frazil ice formation in ISW plumes has so far only been modelled in the one-dimensional depth-averaged models of Jenkins and Bombosch (1995) and Smedsrud and Jenkins (2004) (hereafter referred to as JB and SJ respectively), who postulated the path taken by each plume. While their results are in good spatial agreement with basal melting and freezing rates inferred from observation (Joughin and Padman, 2003), the predicted deposition of basal ice seems to be systematically lower by up to 2 m year^{-1}.

It seems likely that the frazil formation and deposition predictions of these models would benefit from the inclusion of depth-variation, which permits the study of frazil rising within the plume and the effects of variation in supercooling over the depth of the plume as a result of the pressure decrease in freezing temperature.

In this report a multiple-size-class frazil model is modified in order to study depth-variation in the frazil deposition phase of the ice pump mechanism. Particular attention is paid to frazil ice precipitation and a model that explicitly features the near-shelf balance between crystal rising and turbulent mixing is formulated. The modelling study in this report is more fully described in Holland and Feltham (2004).

General model description

The ISW plume is considered to be a mixture of seawater and frazil ice crystals, with the frazil discs divided into size classes according to their radius. The governing equation for the concentration in each frazil size class (C_i) of our one-dimensional (vertical) model is

$$\frac{\partial C_i}{\partial t} = \frac{\partial}{\partial z}\left(\nu_T \frac{\partial C_i}{\partial z}\right) - w_i \frac{\partial C_i}{\partial z} + S_i \qquad (1)$$

where z is positive upwards from the plume base, ν_T is the turbulent diffusivity, w_i is a buoyant frazil rising velocity for each size class, and S_i represents interaction with other size classes through growth, melting, and secondary nucleation. We solve a coupled system comprised of one equation for each size class and a vertical diffusion equation for the temperature of the water fraction.

The vertical section was sited in the Foundation Ice Stream plume of SJ's results, 400 km from the grounding line at a point where the plume is neither supercooled nor superheated on depth-average. This area was intensively studied by SJ and has a deep plume and some of the most active refreezing beneath FRIS (Joughin and Padman, 2003). The latter study evaluated the basal accumulation rate to be 3 – 4 m year^{-1} there while SJ predicted a precipitation rate of 0.5 – 1 m year^{-1} in the vicinity of this location.

The plume section was 60 m deep and laid between the ambient seawater and an ice shelf extending to 470 m beneath sea level. We used 10 frazil size classes, a fixed salinity of 34.5 psu, and a small initial frazil concentration of $C_{in} = 4 \times 10^{-8}$ divided evenly between all size classes (SJ). The depth-mean velocity parallel to the ice shelf was $U = 0.055$ m s^{-1} (SJ), the tidal rms velocity was $U_T = 0.06$ m s^{-1} (SJ) and the vertical eddy diffusivity was taken to be $\nu_T = 10^{-3}$ m^2 s^{-1}. Since SJ predict zero depth-average supercooling at this location, a uniform initial temperature of $T_{in} = T_f|_{z=I/2}$ was used, resulting in a plume with maximum supercooling at the top and maximum superheating at the bottom (each with magnitude ≈ 0.02 °C). Apart from frazil precipitation at the ice shelf base, boundary conditions of zero flux are set for all variables on all boundaries, because direct melting or freezing at the base of the ice shelf is neglected in this study and the entrainment of frazil or heat is already modelled by SJ.

Precipitation formulation

Assuming that all net frazil transport into the viscous sublayer (VSL) immediately beneath the ice shelf is precipitated, the top of the active computational domain is defined to be a 'thin' layer ($z = I$) situated at the VSL's base. Considering a vertical balance of frazil processes in the thin layer, we arrive at

$$\frac{\partial C_i(I)}{\partial t} = w_i C_i(I) - \nu_T \frac{\partial C_i(I)}{\partial z} + S_i + p_i', \tag{2}$$

where the first three terms on the right-hand side represent rising into the thin layer, downwards diffusion out of it, and in-situ transfer between size classes, while p_i' is the actual upwards precipitation rate of frazil in the ith size class into the VSL, i.e. out of the domain (see figure 1).

The settling of particles into a VSL is regulated by turbulent structures in the outer boundary layer, with recent studies suggesting that vortices may be responsible for 'sweeps' and 'ejections' of sediment-laden fluid into and out of the VSL respectively (Robinson, 1991). Sedimentation in a boundary layer is therefore reduced as turbulence becomes more vigorous, because sweeps transport in lower concentrations of sediment than ejections carry out.

To represent the reduction of precipitation due to turbulence, JB parameterised frazil

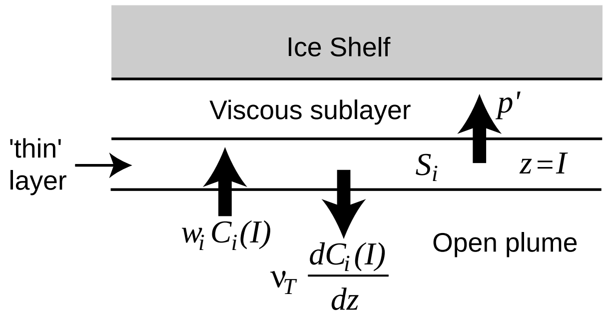

Figure 1: Schematic diagram of the frazil processes acting at the top of the domain.

deposition from an ISW plume as a function of plume speed, so

$$p'_{iT} = -w_i C_i(I)\left(1 - \frac{U^2 + U_T^2}{U_{Ci}^2}\right) \qquad (p'_{iT} \leqslant 0) \tag{3}$$

where U_{Ci} is a critical deposition velocity for each crystal size class above which precipitation cannot occur, calculated from the assumption that frazil deposition is suppressed when the fluid stress could theoretically erode particles from the boundary. No erosion is actually allowed to occur. An important weakness of this approach is that it is only valid for frazil volume concentrations of $C < 10^{-3}$; at higher concentrations frazil ice may suppress the turbulence enough to increase precipitation by increasing the viscosity of the mixture and/or by stabilising the boundary layer.

The relative importance of shear production to stability suppression of turbulence in this layer may be quantified through the gradient Richardson number, which is modified here to provide a single dimensionless quantity that represents the effects of viscosity, shear and stability on turbulence. Assuming that the shear stress exerted in a boundary layer by a steady externally-driven flow is unchanged by an increase in the fluid viscosity, the Richardson number becomes

$$Ri = -\frac{g\nu(C)^2}{\rho\nu_0^2}\frac{\partial\rho}{\partial z}\left(\frac{\partial u}{\partial z}\right)_{ref}^{-2}, \tag{4}$$

where ν_0 and ν are the viscosities of pure seawater and the frazil–seawater mixture respectively. In this study the reference velocity gradient is calculated by employing the seawater velocity profile predicted in the vicinity of the VSL by the law of the wall.

The precipitation rate switches from turbulence-impeded precipitation p'_{iT} for $Ri < 0.25$ to full precipitation of all increases in frazil concentration in the thin layer when bursting is suppressed, so that the precipitation rate is then

$$p'_{iL} = -w_i C_i(I) + \nu_T \frac{\partial C_i(I)}{\partial z} - S_i. \qquad (p'_{iL} \leqslant 0) \tag{5}$$

The transition of p'_i from p'_{iT} to p'_{iL} is smoothed using an error function.

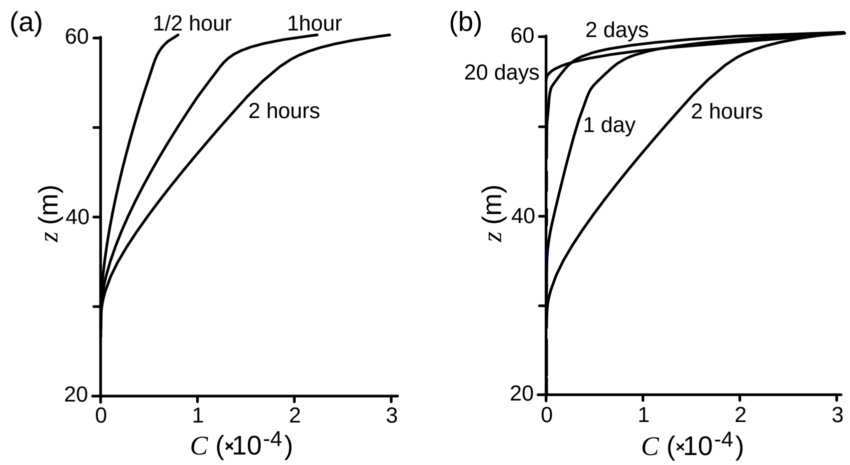

Figure 2: Total frazil concentration over the top 40 m of the plume for (a) the first two hours and (b) the first 20 days.

Results

For the purpose of this discussion, the results are arbitrarily divided into four periods: the initial growth phase, a transitional phase, a quasi-steady state and the true steady state. As shown in figure 2 (a), the initial growth period (the first two hours of simulation) is dominated by the growth of frazil ice in the upper half of the domain in response to the initial supercooling. This frazil forms a narrow layer immediately beneath the ice shelf, where the maximum supercooling is located and buoyant rising of crystals increases the in-situ population. The ice formation releases latent heat that tends to quench the supercooling. The initial ice volume is melted in the lower half of the plume, cooling it very slightly from its initially superheated state.

For the rest of the first two days of simulation there is a transition from this initial growth to a balanced state in which the majority of the plume is devoid of frazil; the end of this transitional phase marks the onset of the quasi-steady state (figure 2 b). Throughout this period frazil growth decreases and the importance of transport terms increases, as demonstrated by the relative magnitude of terms in the frazil governing equation in the thin layer at $z = I$ (see equation (2) and figure 3 a). The total ice concentration and stability at the top of the plume both increase until Ri exceeds its critical value (after approximately one hour) and subsequently precipitation reverts to its full laminar mode, suppressing any further increase in ice concentration. During this time the frazil growth becomes almost completely suppressed as the supercooling diminishes.

The quasi-steady state, which persists from day two onwards, is a period in which the frazil population maintains a vertical equilibrium and virtually all of the domain is warmer than the local freezing temperature. With a progressively-narrower area of supercooling remaining near the ice shelf, a situation is reached where the downwards diffusion and constant precipitation of ice out of the domain balance the rising of frazil and a small ice growth in the very top of the plume (figure 3 b). Since Ri is constant by this stage, precipitation of frazil ice remains steady throughout this period.

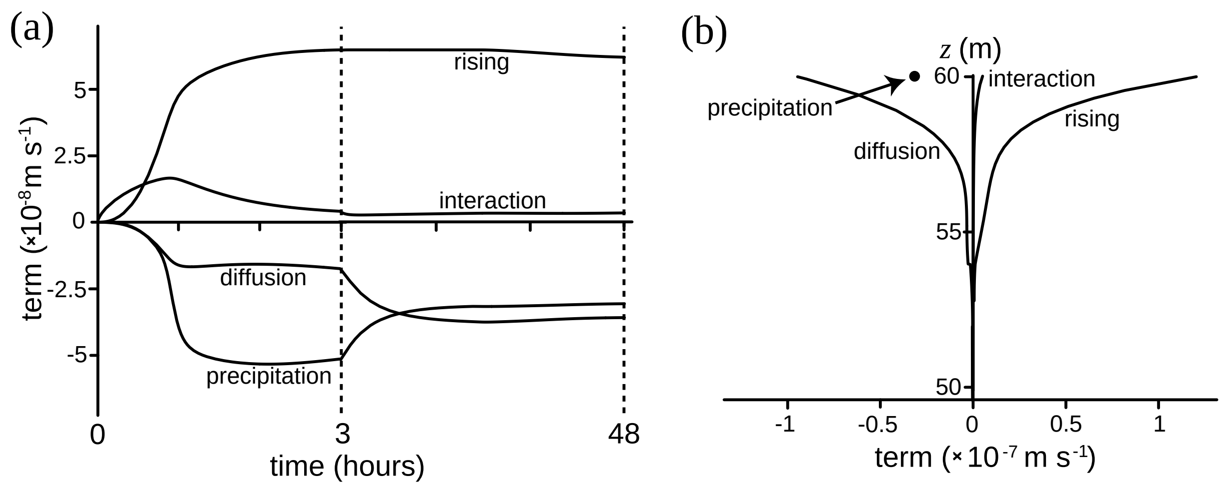

Figure 3: Balance of terms in the frazil governing equation: (a) in the thin layer ($z = I$) over the first two days of simulation, (b) over the top 10 m of the domain after two days of simulation.

The final steady state occurs at a much later time ($1 - 2$ months) when the whole plume is warmed to the equilibrium freezing temperature evaluated at the base of the ice shelf. All supercooling is then eliminated from the domain and no frazil ice is present.

Conclusions

Our model of a cross-section through an ISW plume shows that a considerable vertical variation can occur. Any vertically-uniform plume temperature less than the freezing temperature at the ice shelf base will produce a supercooling that decreases with depth, resulting in favourable conditions for frazil growth near the ice shelf, where populations are also enhanced by crystals rising from below under their own buoyancy. As frazil concentrations increase near the ice shelf, flow in the near-shelf boundary layer becomes laminar as a result of frazil-induced viscosity increases and stable stratification and our model predicts that a quasi-steady frazil distribution will form. In this state, frazil rising and a tiny ice growth balance precipitation onto the shelf and turbulent mixing of crystals back into the open plume.

The case study is deliberately chosen to illustrate the frazil growth which is neglected by a depth-averaged model. Since our initial conditions are of zero depth-average supercooling, the precipitation predicted here is additional to that predicted by depth-averaged models. Only multi-dimensional modelling will reveal whether this is important in determining the dynamics of an ISW plume.

The results from this modelling study imply that frazil ice should be preferentially located toward the top of ISW plumes, with volume concentrations increasing towards a narrow layer near the ice shelf base. The study also elucidates the balance between turbulence and frazil dynamics that govern the deposition rate of frazil ice into an overlying boundary layer. These are both advances in our understanding of factors limiting the mass transfer rate of the ice pump mechanism.

Future Work

We are currently involved in a modelling study which aims to examine the effect of Coriolis forces on ISW plumes. Using a two-dimensional depth-averaged model in the shelf-parallel plane, we have managed to reproduce the basic features of the one-dimensional along-shelf models in the non-rotating case using an idealised test domain.

Results from the rotating case show that the bulk behaviour of ISW plumes is critically dependent upon the basal roughness of the ice shelf. Through the formation of a viscous draining (Ekman) layer at the top of the plume, this roughness would break the current's geostrophic equilibrium and cause it to flow up the basal slope instead of parallel to basal elevation contours. We find that the basal roughness (drag coefficient) used by previous authors produces a flow which is almost entirely geostrophic, which may or may not be correct. We conclude that the lack of knowledge of ice shelf basal roughness appears to be significantly limiting our understanding of ISW plumes.

Acknowledgments

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