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Rotating Ice Shelf Water plumes

Paul R. Holland and Daniel L. Feltham
Centre for Polar Observation and Modelling, University College London, UK

Introduction

Seawater's freezing temperature decreases with increasing pressure and therefore depth, so water at the surface freezing temperature (such as High Salinity Shelf Water, HSSW) becomes superheated as it descends and intrudes into a sub-shelf cavity, gaining the potential to melt the ice shelf base. The meltwater released cools and freshens the ambient seawater to form a water mass which is colder than the surface freezing temperature, known as Ice Shelf Water (ISW). This ISW subsequently flows along the base of the ice shelf under the influence of buoyancy, frictional and Coriolis forces, continually entraining the ambient seawater. If the ISW plume rises then the increase in local freezing temperature may cause it to become supercooled and start to freeze, both directly at the ice shelf base and (more efficiently) through the formation of frazil, tiny disc-shaped ice crystals. These crystals may precipitate out of the plume onto the ice shelf and, in combination with direct freezing and consolidation, this causes the accretion of marine ice to the base of the ice shelf.

The dynamics of ISW plumes have been the subject of many modeling studies (MacAyeal 1985, Hellmer & Olbers 1989, Jenkins & Bombosch 1995, Smedsrud & Jenkins 2004), although the majority are limited in that the path taken by each plume must be chosen beforehand. Payne et al. (in preparation) employ a simplified version of the model used here to examine melt rates beneath the floating section of Pine Island Glacier; no supercooling or frazil formation is predicted in that case. The aim of this study is to examine in detail the effects of Coriolis force on ISW plumes representative of flow under Filchner-Ronne Ice Shelf (FRIS), which has thick deposits of marine ice at the base of shallower areas of the shelf (Sandhäger et al. 2004). This is accomplished by incorporating frazil ice dynamics and ocean–ice shelf interaction into an unsteady plume model which is two-dimensional in the horizontal plane. We therefore consider transient effects and the full horizontal momentum balance governing ISW flow for the first time. We discuss the implications of our findings for the flow of meltwater under the rest of FRIS.

Model description

The ISW plume is simulated by combining a parameterisation of ice shelf basal interaction and a multiple-size-class frazil dynamics model with an unsteady, depth-averaged reduced-gravity plume model. In the model an active region of ISW evolves above and within an expanse of stagnant ambient fluid, which is considered to be ice-free and has fixed profiles of temperature and salinity. Figure 1 illustrates the processes governing the plume flow. The horizontal extent of the active plume is determined by a simple 'wetting and drying' scheme based on the slope of the interface between the plume and ambient

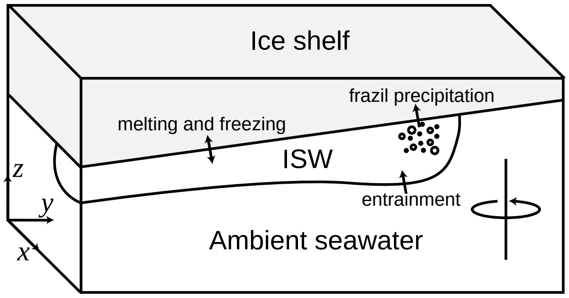

Figure 1: Definition of coordinates and schematic of relevant processes.

fluid (Jungclaus & Backhaus 1994). To initiate the plume, we assume that basal melting at the ice shelf's grounding line generates a mixed layer of ISW with a fixed depth of $D_{in} = 5$ m. This mixed layer has the properties of equal parts of the ambient seawater and the meltwater, which itself has properties calculated according to Gade (1979).

ISW is treated as a mixture of seawater and frazil ice crystals. The frazil ice concentration is distributed between size classes defined by a fixed crystal radius, so that growth or melting results in a transfer of mass between classes. In addition to frazil growth, melting, and precipitation, we model the process of secondary nucleation, whereby new frazil nuclei form from existing ice crystals.

Applying the Boussinesq approximation and integrating over the plume depth, we formulate conservation of mass equations for the mixture, water fraction and each ice class respectively (Smedsrud & Jenkins 2004). We use the depth-integrated Boussinesq Navier-Stokes equations of Jungclaus & Backhaus (1994) and extend the heat and salt transport equations of Smedsrud & Jenkins (2004) to our two-dimensional case, introducing unsteady and horizontal turbulent diffusion terms.

We follow Jungclaus & Backhaus (1994) in using an entrainment formulation which explicitly represents the relative strengths of shear production and stability suppression of turbulence at the interface between the plume and ambient fluid. The choice of drag coefficient is very important because in this model friction is the only force which breaks geostrophy and causes flow across isobaths. Unfortunately, the basal roughness of ice shelves is currently an unknown quantity. Despite basal crevassing, ice shelf bases are generally thought to be smooth due to the effects of melting and ice pumping, so the value of 1.5×10^{-3} adopted by Holland & Feltham (2005) is used here.

Melting and freezing at the ice shelf base is treated by extending the 3-equation formulation used by Jenkins & Bombosch (1995) to two horizontal dimensions, and the frazil dynamics model is a two-dimensional version of that used by Smedsrud & Jenkins (2004). We are unable to adopt their initial frazil nucleation strategy because our model is unsteady and multi-dimensional, so our frazil nucleation logic is as follows: If a model cell is newly supercooled, we set the concentration in each frazil size class in that cell to 10^{-7} unless it already exceeds that value.

Results

To elucidate the basic two-dimensional behavior of ISW plumes, we initially use a wedge-shaped ice shelf. The plume starts from an initial mixed layer of width $W_{in} = 10$ km under an ice shelf which rises from 1100 m depth at the grounding line to 500 m depth at a distance of 200 km downstream. This geometry is chosen to roughly resemble the base of the Evans Ice Stream section of FRIS. All boundaries are considered to be open apart from on the inflow side, where solid walls represent the grounding line. In this section we show 'snapshots' of results after 30 days of simulation.

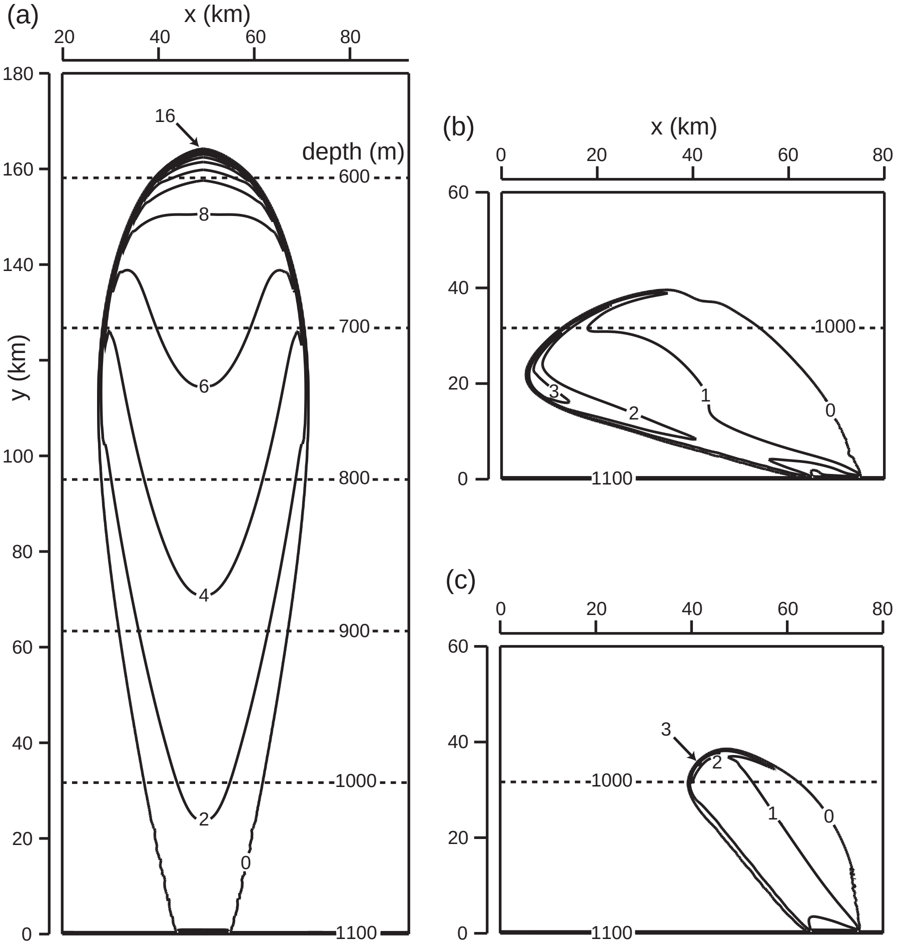

Figure 2: Contours of plume thickness (m) in the various cases after 30 days of simulation. (a) No rotation, (b) rotation, (c) rotation and high basal drag ($c_d = 1.5 \times 10^{-2}$).

Figure 2a shows the plume thickness in the non-rotating case. The plume flows directly up the shelf with a speed of approximately 8 cm s^{-1} and tapers from a thick head at the propagating plume front to a shallow plume near the inflow. Figure 2b demonstrates the effect of adding Coriolis terms to the momentum balance; the flow is nearly geostrophic because basal drag is so low, so Coriolis forces immediately deflect the plume until it flows almost parallel to isobaths of the ice shelf base. The plume flows much more slowly under this new balance (approximately 2 cm s^{-1}) and it does not propagate far upslope from the inflow region. If ISW plumes do not flow upslope they will not become supercooled or produce any marine ice.

This tendency for a model plume to flow alongslope is in contradiction to observations (when a reasonable drag coefficient is used) and is partly due to the neglect of realistic bathymetric features in the model domain (Jungclaus & Backhaus 1994). In addition, this depth-averaged model neglects the details of flow in an Ekman layer next to the ice shelf in which viscous forces are important and upslope 'draining' of fluid should occur. These effects can be partly reproduced by increasing the drag coefficient to $c_d = 1.5 \times 10^{-2}$, and Fig. 2c shows that this does indeed make the plume flow further up the slope than before.

We now adapt the domain in an attempt to explain the origin of the region of marine ice located near Cape Zumberge (Sandhäger et al. 2004). The domain is the same as before apart from a wall running perpendicular to the grounding line and a corner, which represents the boundary between Evans Ice Stream inlet and Cape Zumberge. The topography of the ice shelf base is set such that its isobaths are perpendicular to the wall everywhere, a situation roughly approximating the real bathymetry in this location.

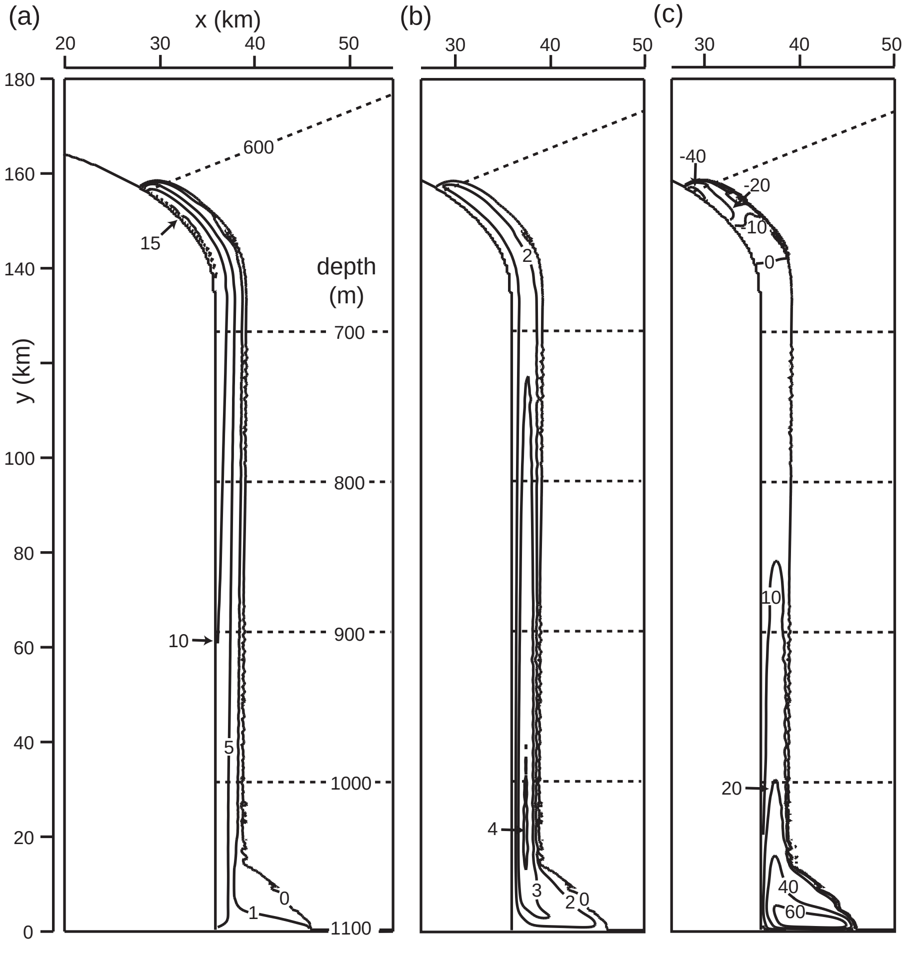

Figure 3: Results of the Evans Ice Stream case (a rotating plume constrained by a wall) after 80 days. (a) Plume thickness (m), (b) plume speed (cm s^{-1}), (c) total basal mass transfer (cm $year^{-1}$). Note that all plots are stretched in the x direction.

The modeled ISW plume does not separate from the shelf, so we examine its properties after 80 days of simulation. The plume immediately turns left from the grounding line under the influence of Coriolis forces, but is impeded by the wall and forced to propagate upslope instead, becoming a very narrow boundary current with the ISW banked up against the wall (Fig. 3a). The plume moves slightly more quickly than the geostrophic plume (Fig. 2b) but is still much slower than a non-rotating plume due to the retarding influence of drag from the no-slip wall.

Figure 3c shows that we predict a basal melting of up to 60 cm year^{-1}, a frazil precipitation rate of up to 50 cm year^{-1}, and a direct freezing rate of up to 1 cm year^{-1}; according to our model, frazil overwhelmingly dominates direct freezing as a source of marine ice. Comparing these results to maps of marine ice thickness (Sandhäger et al. 2004), the deposition area of marine ice off Cape Zumberge is reproduced rather well considering our simplified bathymetry. However, it is important to note the transient behavior of the model. Frazil forms in the head of the plume when it becomes supercooled on first approaching the corner in the wall, after traveling 130 km in 65 days, and the plume continues to flow and precipitate along the wall after traversing Cape Zumberge. This means that we do not find a steady state in which significant precipitation occurs in any fixed location. Supercooling and frazil formation continue at the corner of Cape Zumberge once the plume head has passed, but with a maximum precipitation rate of only 2 cm year^{-1}.

Discussion

Our model of a wall-bounded rotating plume predicts ice deposition patterns which generally account for the observed distribution of marine ice on Filchner-Ronne Ice Shelf near Cape Zumberge (Sandhäger et al. 2004). These results also qualitatively match basal melting and freezing rates inferred from satellite observation (Joughin & Padman 2003). Our plume's deposition zone is narrower than these observations, but we would have to adopt the full shelf base profile to test whether our simplified shelf bathymetry is responsible for this. The model predicts melt, precipitation, and freeze rates of 60 cm year^{-1}, 50 cm year^{-1}, and 1 cm year^{-1} respectively. These rates agree well with other modelling studies, but are under-predicted by an order of magnitude according to Joughin & Padman (2003). Joughin & Padman (2003) concede that their radar altimeter shelf thicknesses might be less accurate near the grounding line, so it is possible that they overestimate melt there. Marine ice is thought to form from consolidation of the layers of frazil slush observed near the ice shelf base, the rate of which is probably governed by the rate of brine rejection from the slush. Frazil precipitation rates are therefore not directly comparable to marine ice accretion rates. To truly compare models to observed basal accretion rates we require a better understanding of the process of marine ice consolidation.

Contrary to previous studies, the model predicts that a high frazil deposition rate is a transient phenomenon which does not persist indefinitely. A small area of frazil deposition occurs off Cape Zumberge throughout the simulation but large precipitation rates only occur as the plume's head passes. This further exacerbates the problem of our low predicted refreezing rates, since the rates of Joughin & Padman (2003) are calculated in steady state. Our model suggests that ISW plumes are essentially a transient phenomena, which is supported by the idea that seasonal pulses of HSSW sink under the ice shelf and intermittently melt ice at the grounding line (Nicholls 1996).

We find that Coriolis forces are an important influence on ISW plumes, implying that they will only become supercooled if steered by an obstruction running perpendicular to isobaths of the ice shelf base. This concept explains the distribution of marine ice under FRIS; Cape Zumberge, Fowler Peninsula, Korff Ice Rise, Doake Ice Rumples, Henry Ice Rise, and Berkner Island all channel meltwater upslope and account for the nearby freezing zones. The model presented in this study is realistic enough for us to be confident in its emphasis of the important effects of rotation on ISW plumes.

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References

Gade, H. G. (1979), 'Melting of ice in sea water; a primitive model with application to the Antarctic ice shelf and icebergs', *J. Phys. Oceanogr.* **9**, 189–198.

Hellmer, H. H. & Olbers, D. J. (1989), 'A two-dimensional model for the thermohaline circulation under an ice shelf', *Antarc. Sci.* **1**, 325–336.

Holland, P. R. & Feltham, D. L. (2005), 'Frazil dynamics and precipitation in a water column with depth-dependent supercooling', *J. Fluid Mech.* **530**, 101–124. doi:10.1017/S002211200400285X.

Jenkins, A. & Bombosch, A. (1995), 'Modelling the effects of frazil ice crystals on the dynamics and thermodynamics of Ice Shelf Water plumes', *J. Geophys. Res.* **100**, 6967–6981.

Joughin, I. & Padman, L. (2003), 'Melting and freezing beneath Filchner-Ronne Ice Shelf, Antarctica', *Geophys. Res. Lett.* **30**, 1477. doi:10.1029/2003GL016941.

Jungclaus, J. H. & Backhaus, J. O. (1994), 'Application of a transient reduced gravity plume model to the Denmark Strait outflow', *J. Geophys. Res.* **99**, 12 375–12 396.

MacAyeal, D. R. (1985), Evolution of tidally triggered meltwater plumes below ice shelves, *in* S. S. Jacobs, ed., 'Oceanology of the Antarctic continental shelf', Vol. 43 of *Antarctic Research Series*, American Geophysical Union, Washington DC, pp. 133–143.

Nicholls, K. W. (1996), 'Temperature variability beneath Ronne Ice Shelf, Antarctica, from thermistor cables', *J. Geophys. Res.* **101**, 1199–1210.

Sandhäger, H., Vaughan, D. G. & Lambrecht, A. (2004), Meteoric, marine and total ice thickness maps of Filchner-Ronne-Schelfeis, Antarctica, *in* L. H. Smedsrud, ed., 'FRISP Report No. 15', Bjerknes Centre for Climate Research.

Smedsrud, L. H. & Jenkins, A. (2004), 'Frazil ice formation in an Ice Shelf Water plume', *J. Geophys. Res.* **109**, C03025. doi:10.1029/2003JC001851.