Suspended frazil ice crystals below Filchner Ice Shelf

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1 Introduction

The Filchner Ice Shelf has its groundingline roughly between 1000 and 1500 m below the surface, and because the freezing point of sea water falls with increasing pressure, the water that flows in beneath the ice shelf is invariably warmer than the freezing point in situ. Melting at the ice-water contact cools and dilutes the sea water, creating Ice Shelf Water (ISW), a water mass colder than the surface freezing point. As the ISW rises it becomes supercooled in situ, and formation of ice starts. Observations suggest that the ice forms as frazil ice crystals, which are initially suspended in the water column, but are subsequently deposited as a slushy layer at the base of the ice shelf. Some of the frazil crystals remain in suspension and are transported out from underneath the Filchner Ice Shelf (Dieckmann et al. 1986).

Frazil ice is important to the sub-ice ocean dynamics and overall glacial ice mass balance through two processes: (i) frazil ice growth is a more effective sink for supercooling than is the growth of columnar ice directly onto the ice shelf base; (ii) the presence of suspended ice crystals makes the ISW more buoyant. The formation of frazil thus modifies the forcing on the overturning circulation, which, in combination with the process of crystal deposition, determines the location and rate of marine ice accumulation at the ice shelf base (Jenkins and Bombosch 1995).

We here describe results of the ISW plume model of Jenkins and Bombosch (1995), when dynamic growth of frazil ice is incorporated. The following new processes are considered: (i) a distribution of ice crystal sizes ranging from the μm to the mm scale; (ii) differential growth and rise of ice crystals based on the crystal radius; (iii) secondary nucleation of new crystals of the smallest size, taking the turbulent strength into account through the turbulent dissipation rate.

2 The Plume Model

The plume model was developed by Jenkins (1991) as a model of the ocean beneath an Antarctic ice shelf. The model treats the ocean as a two layer system, with the ambient water filling most of the cavity, and the plume as the upper mixed layer of ISW. Tides are assumed to be a source of turbulence for the plume, and help to keep the plume well mixed. A steady state solution for the plume is found along the (close to horizontal) ice shelf base. The plume starts at the grounding line, follows a prescribed path along an ice stream, and ends at the ice front. The plume is characterized by a thickness D, and

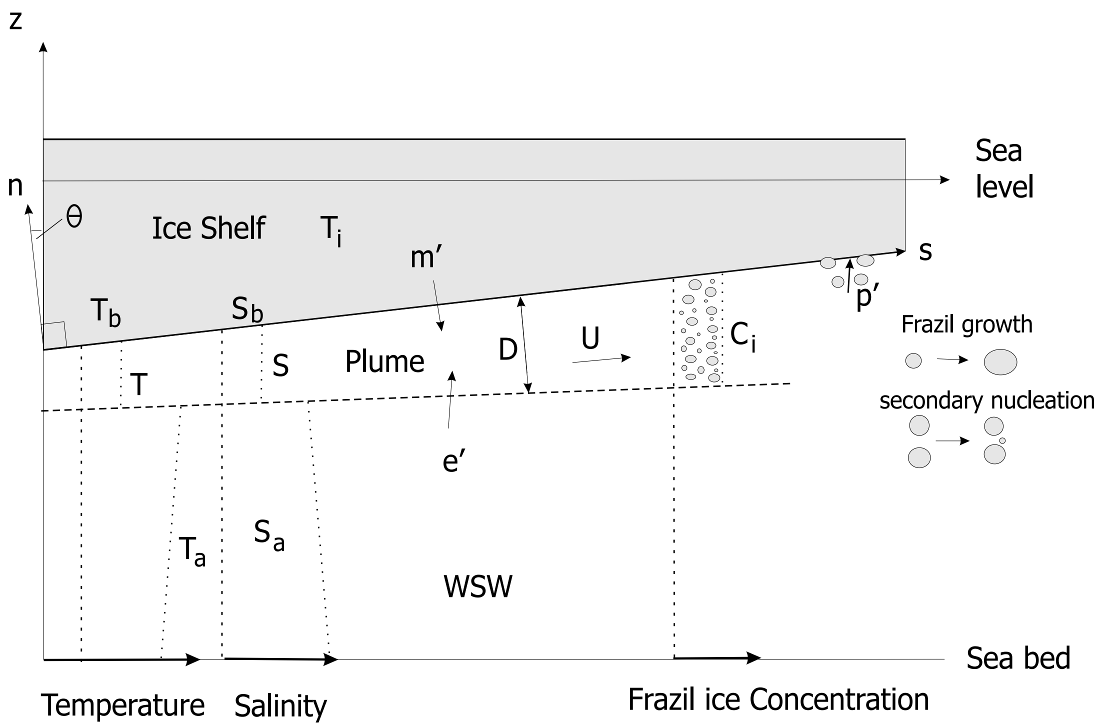

Figure 1: Sketch of the ISW plume model setup and parameters, as well as the two major frazil ice processes.

depth-averaged values of velocity U, temperature T, and salinity S. The ISW plume is initiated as a small flux (0.01 m^2/s) of water at the grounding line, and flows upwards along the ice shelf base as a turbulent gravity current driven by its positive buoyancy, entraining ambient water along the way, as well as melting basal ice and forming new ice (Figure 1).

Formation of frazil ice was added into the plume model by Jenkins and Bombosch (1995) using one size of crystals, and dynamic growth of frazil ice in the model is described by Smedsrud and Jenkins (2003). It is assumed that the first growth of ice will be downward growing platelet ice as well as "normal" congelation ice. Some of the platelet ice crystals are then assumed to be broken off by turbulent eddies, and will subsequently be suspended in the plume. The frazil ice crystals are assumed to be circular disks characterized by their radius and thickness. The size range used is 0.01 to 4.0 mm, and the approach used by Smedsrud (2002) is generally followed. The crystal is assumed only to grow at the edges.

The ISW plume is treated as being a well mixed upper layer, and consequently C_i is the mean frazil ice concentration over the plume depth D. The total rate of change of the frazil ice volume in the ISW plume is therefore a sum over all sizes. The frazil ice dynamics added to the plume model do not alter the early stages of the plume up to the point where the ISW becomes supercooled.

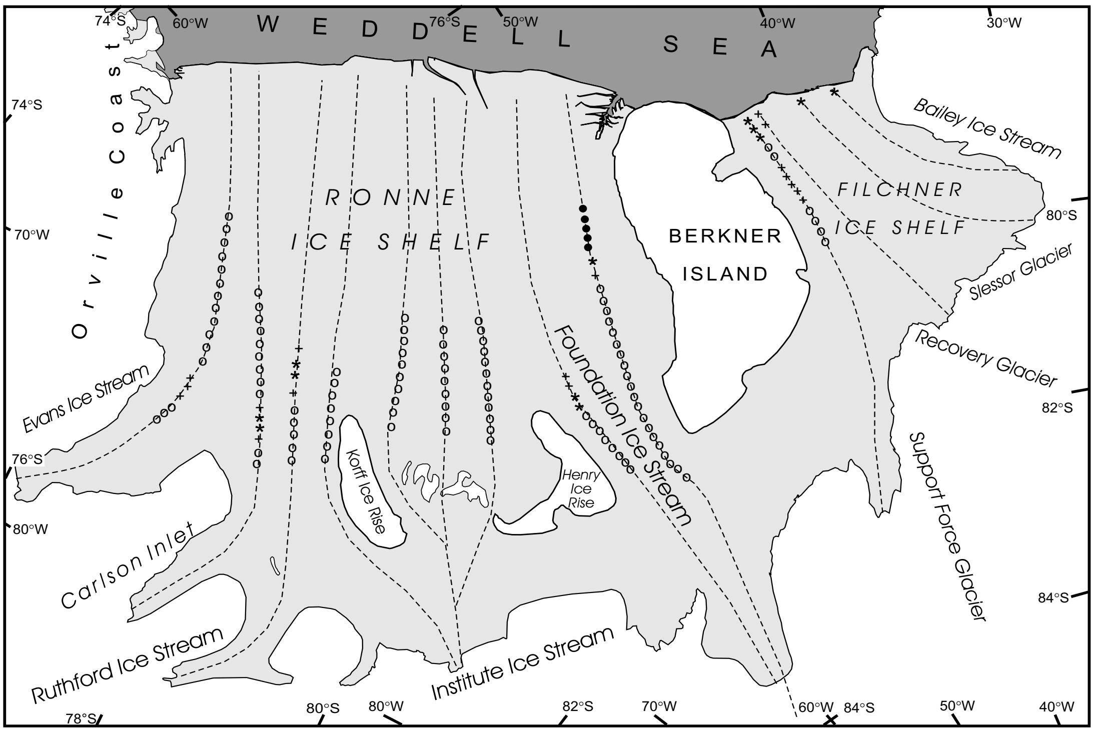

Figure 2: Map of the Filchner Ronne ice shelf, with proposed plume paths indicated. Only paths below the Filchner Ice Shelf are discussed in this paper. Calculated precipitation rates are indicated along the plume paths (o) 0-0.5 m/year, (+) 0.5-1 m/year, ($*$) 1-2 m/year, and (•) more than 2 m year..

3 Model results

We have chosen to present results from a proposed path below the Support Force Glacier shown in figure 2. Results from the other paths below the Filchner Ice Shelf (Slessor and Recovery Glaciers, and Bailey Ice Stream) are similar, but there is less frazil ice growth and precipitation. Differences are discussed briefly in section 5.

The Support Force Glacier plume is initiated at 1400 m depth, and ascends 430 km northwards to the ice front at 285 m depth as shown in figure 3 a). The ambient water has simplified linear profiles of both temperature, T_a=-1.9 to -2.18 °C, and salinity S_a=34.5 to 34.71 psu, from the surface to 1400 m depth.

The in situ freezing point at 1400 m depth is -3.0 °C, and the ambient water that is mixed into the plume close to the groundingline is 0.8 °C warmer. This leads to efficient melting shown in figure 3 b), with close to 5 m/y over 15 km. Melting ceases around 250 km, when the cooling from the vertical rise starts to dominate over entrainment of warmer ambient water.

Frazil ice formation in the ISW plume takes place between 260 km and the ice front. Levels of supercooling typically reach 0.5 $\times 10^{-3}$ °C, but show no indication of oscillations like those discussed in Jenkins and Bombosch (1995). The plume reaches maximum supercooling below the ice shelf shortly after it has become supercooled, before much growth of frazil ice has taken place. The total frazil ice growth shown as negative meltrates in figure 3 b) reaches a maximum below the ice shelf of 1 m/y around 400 km. Most of this ice precipitates (0.7 m/y), and the rest stays suspended in the plume until it reaches

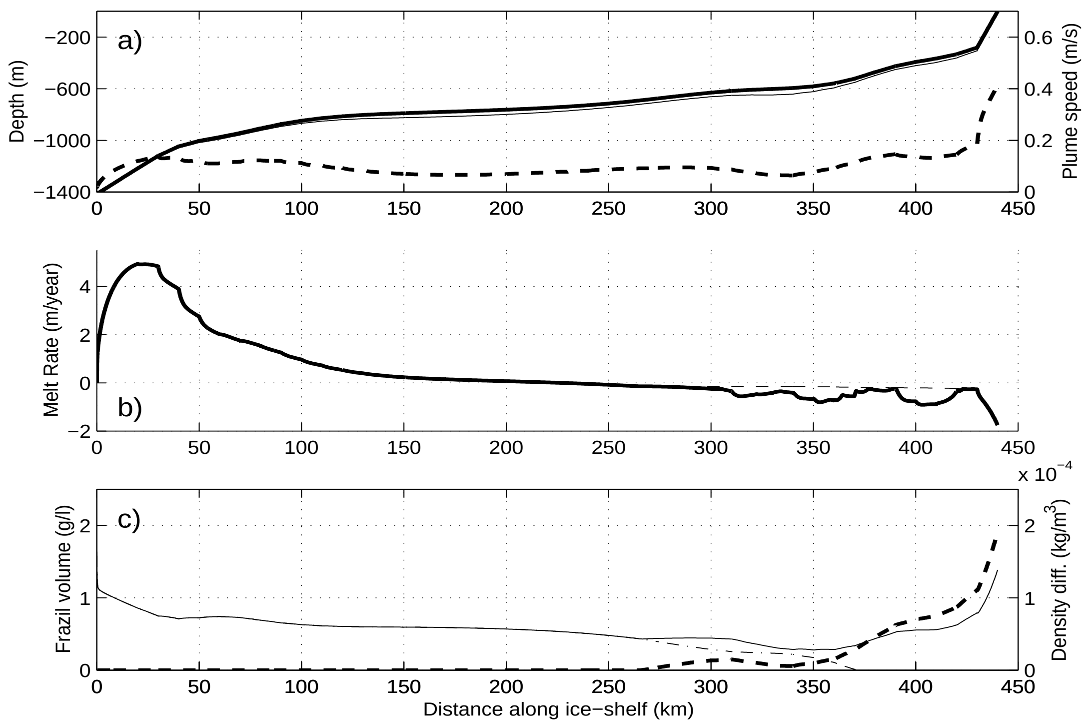

Figure 3: Model results for the Support Force Glacier ISW plume. a) Depth of the ice shelf base depth with plume depth (D) and plume speed (U) dashed line. b) Melt rate, and ice growth (negative melt rate). c) Volume of suspended frazil ice (dashed line) and density difference between the ambient water and the plume. The density difference with no frazil ice in the plume is also shown (dash dotted line).

the ice front. At the ice front the plume becomes 21 $\times 10^{-3}$ °C supercooled due to the rapid vertical rise, and ice growth peaks at 2 m/y.

The plume speed U increases after 300 km due to the suspended frazil ice as the frazil adds buoyancy to the water (figure 3 c). At the ice front the plume rises near vertically with an average speed of 30 cm/s and close to 2 g/l of frazil ice. The ascent from 285 m depth to the surface takes about 9 hours, and the maximum density deficit created by frazil ice is 0.15 $\times 10^{-3}$.

4 Model sensitivity

In general we find that the model is less sensitive to changes in the parameterization of frazil processes than was the earlier version of Jenkins and Bombosch (1995). This is a result of the addition of an evolving spectrum of crystal sizes, which means that the size classes favored for growth (smaller) and precipitation (larger) are present or can be developed.

The stability of the model is well illustrated by its response to changing the Nusselt number, N_u. Although N_u analytically has a lower bound of 1.0, we use lower values here to mimic the effect of the slower (molecular) diffusion of salt, compared with heat, for the case when turbulent conditions in the plume are not fully developed. Changing N_u alters the supercooling of the plume, but the crystal spectrum and the total growth and precipitation of frazil ice is close to constant in N_u=0.2 and N_u=8.0 cases. A difference in $\bar{U}$ and $\bar{D}$ is caused by the quicker start of the frazil formation process with high N_u, giving a slightly higher $\bar{U}$ and thus a higher entrainment increasing $\bar{D}$.

In contrast, a smaller range of N_u in the Jenkins and Bombosch (1995) model could induce a complete range of model behavior from one where the single, fixed crystal size class experienced rapid growth and zero precipitation, to one where the ice growth was neglectable, and precipitation of the seed crystals almost instantaneous.

Even with the full spectrum of crystal sizes, the ease with which the ice can be retained in suspension remains an important influence on model behavior. If a significant volume of frazil is suspended, then U increases, and the plume stays fairly thin. This leads to a high rate of cooling for the plume as it ascends, and thus more frazil ice is produced in a feed-back loop.

As there are no observations of the initiating crystals breaking off from the base to guide us towards the size, the initial flux of frazil has up to now been set equally between the 10 sizes used. The effect of partitioning this flux unevenly in favor of the small side of the frazil spectrum is done by giving the 5 smallest sizes 19 % of the initial flux each, while the 5 largest sizes have 1 % each. This leads to the highest levels of frazil ice and precipitation, as well as the highest $\bar{U}$. The supercooling is low as there are so many small crystals that grow fast.

With mostly large crystals in the initial frazil flux, the opposite effect is seen; less frazil ice and precipitation, a larger supercooling, and a lower $\bar{U}$. This has approximately the same effect as a lower initial flux, where the similarity is caused by the lower initial concentration of the smaller crystals in both cases.

5 Validation of results

Thin crystal plates have been trawled from about 250 m depth just north of the Filchner Ice Shelf (Dieckmann et al. 1986). These crystals were probably flowing northwards from beneath the ice shelf within a neutrally buoyant ISW plume (Foldvik and Kvinge 1974), and provide the only “in situ” data on crystal sizes available to validate model results. The ice crystals were observed on an echo sounder and when trawled, turned out to be thin plates ($\sim$ 0.5 mm thick) with a rough outer edges, and radii of about 10 mm. It is worth noting that the trawl net had a mesh size of 10 mm, so that any crystals smaller than 5 mm in radius may have escaped the trawl.

Weather the ISW plume reaches the ice front or not depends on the ambient salinity profile, controlling the density of the ambient water. As soon as the plume reaches neutral buoyancy it detaches from the ice base, and this is more likely to take place in summer when the surface layer is freshened by (sea ice) melt water. Using a salinity profile from just north of the ice front from February (station 60, Foldvik et al. 985a) makes the plume neutrally buoyant at 350 m depth.

In winter surface salinities in the Weddell Sea are higher due to sea ice growth, and it is likely that the ISW plume will be buoyant all the way to the surface as with the simplified linear profile used here. The frazil crystals and water are assumed to move together as a bulk volume, and the crystals thus “lift” the ISW upwards to the surface as in the “conditional instability” described by Foldvik and Kvinge (1974). Once the ISW plume has reached the surface the integration stops, but in reality the suspended frazil

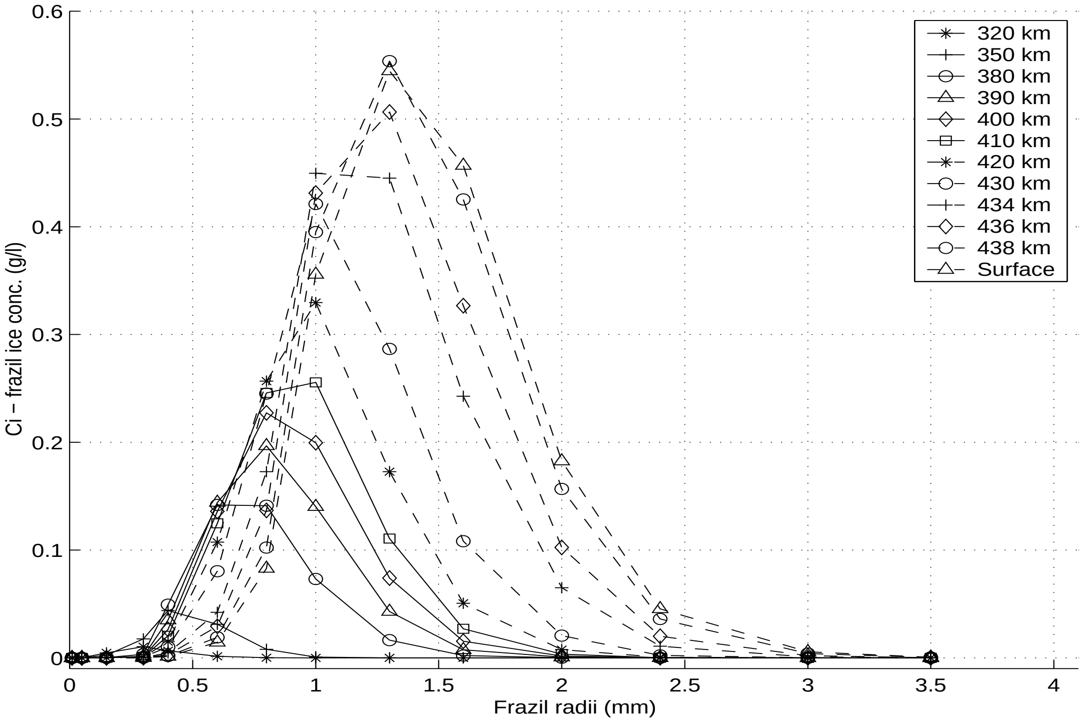

Figure 4: Frazil ice size spectrum for the Support Force Glacier ISW plume, which rises vertically at the ice front at around 430 km.

crystals and plume water would separate. With the ISW losing its frazil ice, it would be 2.25×10^{-4} kg/m^3 denser than the surrounding water, and sink. The water remains 0.02 °C supercooled, so the crystals could continue to grow while at the surface.

The size spectrum for suspended frazil ice crystals at some chosen points along the Support Force Glacier flowline (figure 2) is shown in 4. In this model run the ambient water temperature is taken from field data (Dieckmann et al. 1986), and is about 0.2 °C warmer in the upper 100 m than the simplified linear profile. The radius of the frazil ice class having the largest concentration is called the significant frazil ice radius, r_{is}. This is the radius of the class constituting the peak in the frazil ice spectrum at any given position along the plume path. At the start of the formation process (320 km) $r_{is} = 0.4$ mm. When the plume reaches the ice front at 430 km r_{is} has increased to 1.0 mm, and $r_{is} = 1.3$ mm at the surface. The modeled frazil ice crystals grow to a maximum of 3 mm in radius, i.e. still well below the 10 mm observed by Dieckmann et al. (1986).

Precipitation in the Support Force Glacier plume starts at 300 km, and varies between 0.4 and 0.7 m/y up to the ice front. Precipitation starts with the 0.6 mm crystals (0.4 m/y at 300 km) and is followed by smaller crystals until 350 km. Because of the increase in speed after this point (figure 3 a) the smaller crystals all stay in suspension, and only the larger portions (0.8 mm - 2.4 mm) precipitate after this. Precipitation is smaller than the frazil ice growth shown in figure 3 b), at the maximum growth of 1 m/y after 400 km 0.7 m/y precipitate. The region of precipitation corresponds closely with the location of the marine ice area described by Sandhäger (1995) and found to be around 120 m thick, increasing northwards towards the ice front.

For the other plume paths on the Filchner Ice Shelf shown in figure 2 (Bailey, Slessor, and Recovery) the ISW plume becomes supercooled close to the ice front. This leads to low levels of precipitation. All plumes reach the ice front, and the frazil-laden water rises vertically to the surface, creating high supercooling and ice growth. Frazil concentrations reach 1.3 g/l, and r_{is}=1.3, so the crystals are generally smaller than in the Support Force Glacier plume.

6 Conclusion

Model results suggest that there are significant numbers of frazil ice crystals suspended in the ISW water plume below the Support Force Glacier of the Filchner Ice Shelf. The major proportions (by volume) of the crystals in suspension are usually around 1 mm, and total concentrations are up to 2 g/l. The suspended frazil ice adds buoyancy to the ISW by lowering the bulk density of the ice-water mixture by $\sim 5.0 \times 10^{-5}$ kg/m^3. This added buoyancy helps drive the sub ice shelf circulation, increasing the speed of the out-flowing ISW.

When the frazil ice crystals reach a critical size, they tend to leave the ISW by precipitating upwards onto the ice shelf base and forming marine ice. This takes place when the crystal radii have reached 0.6 mm. Precipitation is in the range 0.1 - 0.7 m/year, and compares well with observed areas of marine ice. The precipitation areas are controlled by the speed of the ISW plume, itself strongly influenced by the frazil concentrations, so the frazil ice size spectrum has a significant impact on the overall mass balance of the marine ice layer.

In general the ISW flow is controlled by the basal slope. Frazil ice formation acts as a positive feedback mechanism on the plume speed as more crystals in suspension speed up the plume, which increases the cooling rate, and produces yet more crystals.

Below the Filchner Ice Shelf the proposed ISW plume paths probably reach the ice front during winter, and a rapid vertical rise of the water and crystals is predicted. The cooling rate is then much higher than below the ice shelf, and crystals grow to 3 mm in radius. When the mixture reaches the surface, the water is $\sim 10.0 \times 10^{-5}$ kg/m^3 denser than the surrounding water and will tend to sink, leaving the crystals to from a surface ice cover. During summer the ISW plume probably leaves the ice shelf at depth.

7 Acknowledgment

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