The Dissolution of Polar Ice into a Stratified Ocean

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Abstract

We use laboratory experiments to investigate the effect of stratification on the dissolution of polar ice. The temperature at the ice-ocean interface, the ablation rate, and the plume velocity are measured as a function of height and of stratification. We observe that stratification reduces the interface temperature, the ablation velocity and plume velocity. To compare our results with geophysical ice shelves we propose a stratification parameter that describes where stratification will be important. We use the stratification parameter to predict that ocean stratification will have an important effect on the dissolution of ice shelves in the polar regions. Finally, we compare our experimental results to a common numerical parameterization of ice-ocean interactions and note some significant differences.

1 Introduction

An important component of global climate is the increasingly rapid decrease in the mass of the Antarctic and Greenland Ice Sheets (Rignot et al., 2011). This mass loss is occurring on the underside and fronts of ice shelves formed where glaciers reach the polar oceans and from the icebergs that calve from them. The polar oceans provide a source of heat and salt that controls the dissolution of ice shelves and icebergs. The transport of heat and salt to the ice-ocean interface is assisted by a turbulent wall plume that forms next to the ice face. Recent observations made in the cavity of Pine Island Glacier ice shelf show that the ocean is unstably stratified in temperature and stably stratified in salinity (Jenkins et al., 2010). This stratification will affect the turbulent wall plume and hence the transport of heat and salt to the ice-ocean interface. As such, the ambient stratification could have an important effect on the mass loss from the Antarctic and Greenland Ice Sheets.

Previously we have conducted experiments in a homogeneous ambient fluid over a range of far field conditions. It was observed that both the ablation rate and interface temperature are uniform with height (Kerr and McConnochie, 2015). In contrast, the maximum plume velocity increases like $z^{1/3}$ where z is the distance from the transition to turbulence (McConnochie and Kerr, 2016). This is inconsistent with the standard three-equation parameterization of ice shelf melting that typically predicts that the ablation rate and plume velocity are proportional to one another (Jenkins, 2011). It is important to assess whether this contradiction between laboratory observations and numerical parameterizations remains once stratification is included in the laboratory experiments.

2 Method

We have conducted experiments that investigate the dissolution of a vertical ice face in cold salty water with a stable salinity gradient. The experiments were conducted in a 1.2 m high, 1.5 m wide, and 0.2 m long tank that was kept in a temperature controlled room. The far field temperature was kept constant at 3.5°C and the mean far field salinity has been kept at 3.5 wt. % NaCl. The effect of stratification has been investigated up to a Brunt-Väisälä frequency, $N = \left(\frac{g}{\rho_o}\frac{\mathrm{d}\rho}{\mathrm{dz}}\right)^{1/2}$, of 0.287 rad/s where g is the acceleration due to gravity, ρ_o is a representative fluid density and $\mathrm{d}\rho/\mathrm{dz}$ is the ambient density gradient.

We have measured the ice ablation velocity, the temperature at the ice-ocean interface and the maximum plume velocity across this range of Brunt-Väisälä frequencies. Figure 1 shows two photographs of a typical experiment visualised using the shadowgraph method. The left image shows the ice from a height of 36 cm to a height of 76 cm and the right image shows the ice from a height of 72 cm to the free surface at 114 cm. The ice is on the right of each image and the ambient salt water is on the left. The turbulent plume can be seen next to the ice. During an experiment the plume outflow produced a growing layer that slowly propagated down the tank. All measurements were made above this outflow layer to ensure that the far field properties did not change while an experiment was being run. Throughout our experiments, double diffusive layers were observed with a layer height predicted by previous theoretical and experimental studies (Huppert and Josberger, 1980; Huppert and Turner, 1980).

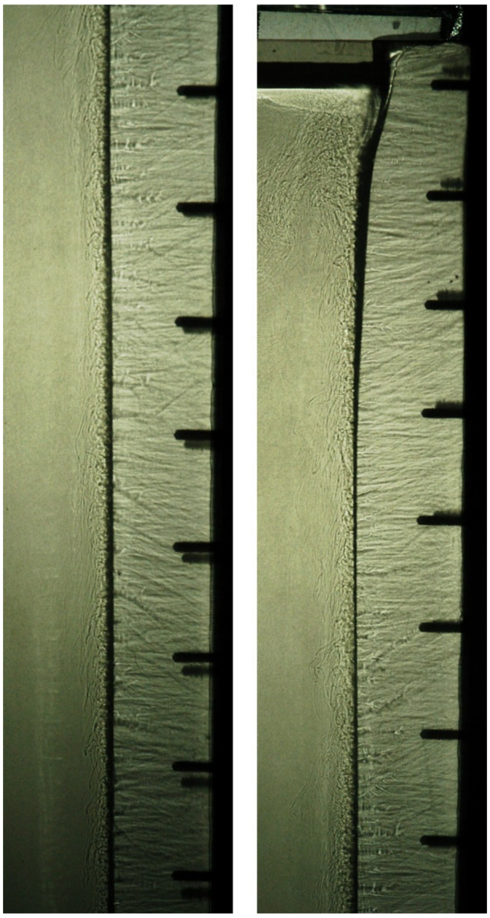

Figure 1: Photographs from a typical experiment visualised with the shadowgraph method. The vertical spacing between black screws is 6 cm.

3 Results

3.1 Interface Conditions

Figure 2 shows the measured interface temperature as a function of the Brunt-Väisälä frequency. Similarly to the experiments conducted in a homogeneous ambient (Kerr and McConnochie, 2015), we observed that the interface temperature did not depend on height. The data point at $N = 0$ rad/s is the theoretical value from a homogeneous ambient fluid (Kerr and McConnochie, 2015). It is clear from figure 2 that as the ambient fluid becomes more strongly stratified the interface temperature is reduced. However, there appears to be a lower limit beyond which the interface temperature becomes insensitive to further changes in stratification. This lower limit appears to be around -1.4°C. This is significantly above the liquidus temperature of the far field, which is approximately -2.1°C. A lower limit on interface temperature of -1.4°C implies an upper limit on interface salinity of 2.4 wt. % NaCl.

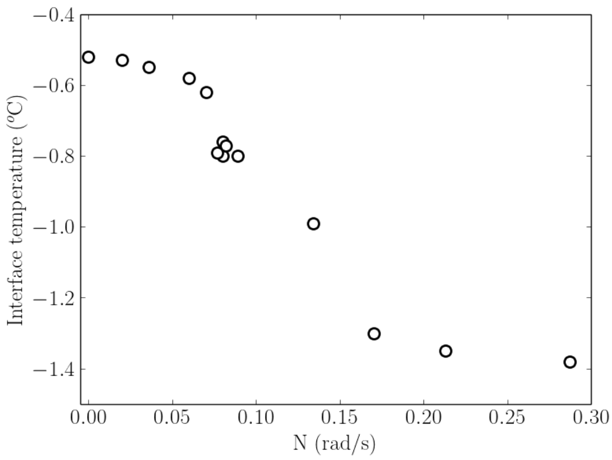

Figure 2: Measured interface temperature as a function of the Brunt-Väisälä frequency.

Similarly to the interface temperature, the ablation velocity is reduced by stratification. In addition to this, in the presence of a stratified ambient, the ablation velocity is not uniform with height as it was in the homogeneous experiments (Kerr and McConnochie, 2015) and instead reduces with height. Figure 3 shows the ablation velocity at three different heights as a function of the Brunt-Väisälä frequency. The three heights are named the bottom, middle and top of the tank and relate to 200 – 250 mm, 475 – 525 mm, and 750 – 800 mm from the base of the tank respectively. These definitions are such that the bottom region is immediately above the turbulent transition and the top region is below the first front of the plume outflow layer. The effect of stratification on the ablation velocity is more significant in the top region suggesting that there is a length scale over which stratification affects the flow.

3.2 Plume Velocity

The maximum velocity of the plume has been measured using the shadowgraph PTV method (McConnochie and Kerr, 2016). Figure 4 shows the measured maximum velocities as a function of height for four different values of the Brunt-Väisälä frequency. The solid lines are power-law fits of the experimental data of the form $w = A(N)z^{x(N)}$, where $A(N)$ and $x(N)$ are unknown functions of the Brunt-Väisälä frequency. The results for $N = 0.036$ rad/s have the same 1/3 power-law dependence on height that was observed in a homogeneous ambient fluid (McConnochie and Kerr, 2016). Values of both the velocity power, $x(N)$, and the velocity coefficient, $A(N)$, are observed to decrease with increasing stratification. This could be partially caused by the ablation rate, and hence the buoyancy

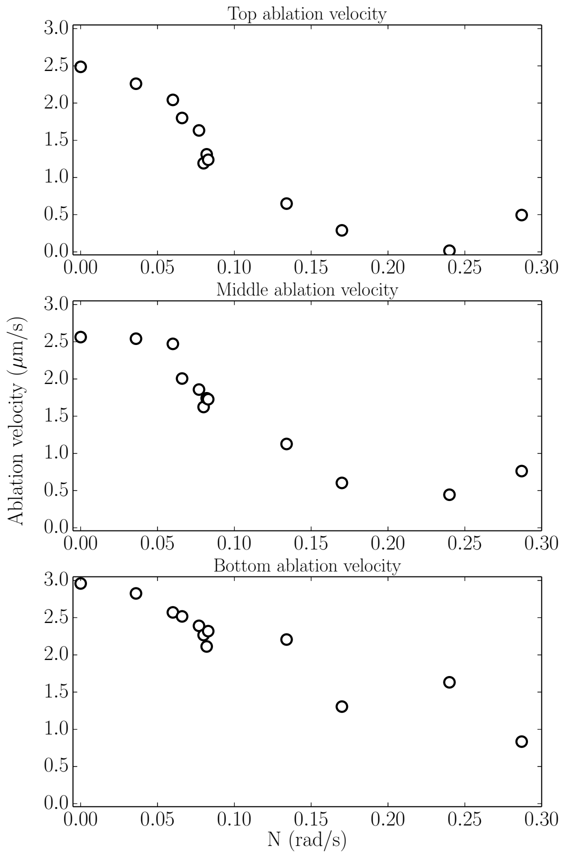

Figure 3: Measured ablation velocity as a function of the Brunt-Väisälä frequency for three different vertical positions on the ice.

flux, reducing with height but it is also consistent with fluid detraining from the plume into double-diffusive layers. Such detrainment would reduce the plumes buoyancy, which will in turn, reduce its acceleration.

4 Geophysical Scaling

Given the significant effects of stratification on the dissolution of ice in our laboratory experiments it is important to consider the possible effects of stratification on a geophysical scale. The ocean next to polar ice shelves is typically weakly stratified with a Brunt-Väisälä frequency of around 0.002 − 0.005 rad/s (Jenkins et al., 2010). Although this is much weaker than any of our laboratory experiments, such ice shelves are frequently more than 500 m high (Jenkins et al., 2010), which could lead to the weak ocean stratification having a significant effect.

We suggest a method for scaling the stratification from the laboratory to the geophysical scale of icebergs and ice shelves. Our scaling argument is based around a top-hat turbulent plume model for a homogeneous ambient fluid (McConnochie and Kerr, 2016). The plume buoyancy flux, F, can be described by

$$\frac{\mathrm{dF}}{\mathrm{dz}} = \Phi - QN^2, \tag{1}$$

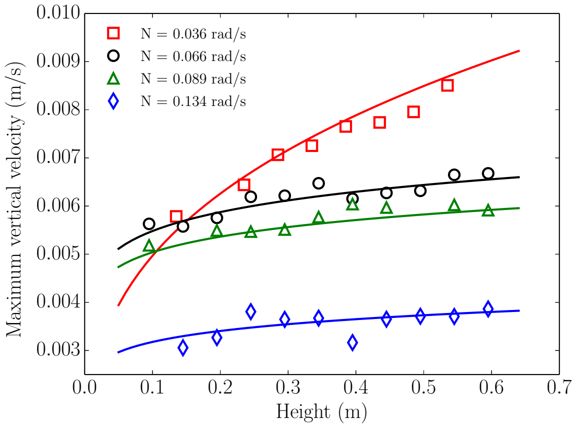

Figure 4: Measured maximum vertical velocities as a function of height for four typical experiments at different Brunt-Väisälä frequencies. The solid lines are power-law fits of the experimental data.

where Φ is the buoyancy flux per unit area into the plume and Q is the plume volume flux.

When $N^2 > \Phi/Q$ stratification must be important, as the plume buoyancy flux would otherwise start to reduce. Using this condition we define a non-dimensional stratification parameter

$$S = \frac{N^2 Q}{\Phi} \tag{2}$$

that describes where stratification must be important. When $S \geq 1$ we would expect stratification to have an important effect on the wall plume and the ice. In our experiments $S = 1$ at a Brunt-Väisälä frequency of $N = 0.037$ rad/s. This value of the Brunt-Väisälä frequency closely corresponds to the location where stratification starts having a significant effect on the interface temperature and ablation velocity shown in figures 2 and 3 suggesting that the simple scaling argument is a useful test of the effect of stratification.

The stratification parameter, S, can be used with an expression for Q from the homogeneous plume model to obtain a critical height, z_c, for a given Brunt-Väisälä frequency where the ambient stratification will begin to influence the flow. This critical height is given by

$$z_c = 11\frac{\Phi^{1/2}}{N^{3/2}}. \tag{3}$$

We initially test the proposed scaling against our experimental results. The ablation velocity, V, and the plume velocity, w, are non-dimensionalized as

$$V^* = \frac{V}{Nz} \qquad\qquad w^* = \frac{w}{Nz}. \tag{4}$$

Figure 5 shows the non-dimensionalized ablation velocity and maximum plume velocity plotted against a modified stratification parameter, $S^* = S^{-3/4}$. The data plotted on figure 5 are the same as that plotted on figures 3 and 4. The solid line plotted on the right hand of figure 5 shows the $w^* \sim (S^*)^{2/3}$ scaling expected for high values of S^* (low N) (McConnochie and Kerr, 2016). The experimental data on figure 5 collapse towards a single curve suggesting that the proposed scaling is a valid method of extrapolating our results to a geophysical scale. However, the geophysically relevant scale is significantly

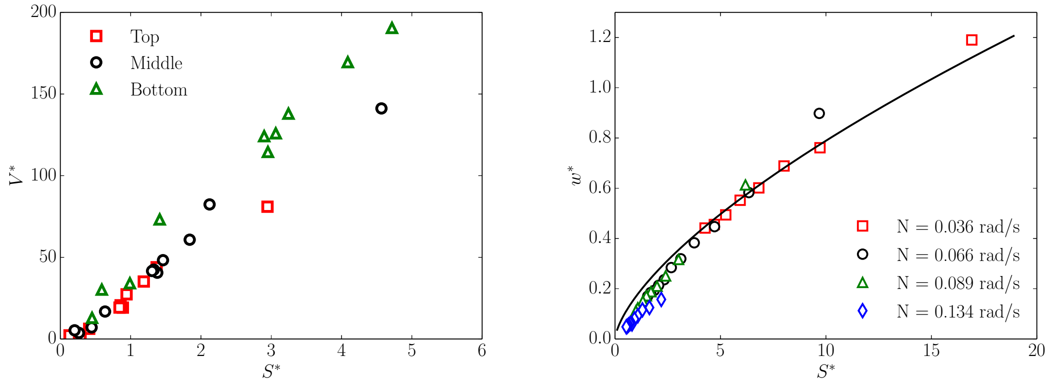

Figure 5: Non-dimensional ablation velocity (left) and plume velocity (right) plotted against S^*

different from our laboratory scale and field observations would be useful in further testing the validity of the scaling.

Field observations of several ice shelves and glaciers from Antarctica and Greenland are provided in table 1. The observed Brunt-Väisälä frequency and height, H, have been combined with an estimate of the buoyancy flux, $\Phi = 1.7 \times 10^{-7}$ m^{2}s^{-3} (McConnochie and Kerr, 2016), to evaluate the stratification parameter and a critical height above which stratification is expected to be important.

Table 1: Observed Brunt-Väisälä frequencies, N, and heights, H, from several ice shelves and glaciers from Antarctica and Greenland. Values of the stratifictaion parameter, S, and critical height, z_c, are evaluated based on our proposed scaling and an assumed buoyancy flux, $\Phi = 1.7 \times 10^{-7}$ m^{2}s^{-3}. Observational data comes from: a - Robinson et al. (2010), b - Williams et al. (2011), c - Rignot and Jacobs (2002), d - Venables and Meredith (2014), e - Sutherland et al. (2014).

Location	N (rad/s)	H (m)	S -	z_c (m)
McMurdo Ice Shelf, Antarctica[a]	0.0012	1000	20	104
Mertz Glacier, Antarctica[b]	0.0014	1300	39	83
Pine Island Glacier, Antarctica[c]	0.0024	450	28	37
Sheldons Glacier, Antarctica [d]	0.0048	500	130	13
Helheim Glacier, Greenland[e]	0.0032	600	73	24
Kangerdlugssuaq Glacier, Greenland[e]	0.0022	600	35	42

The observational data shown in table 1 suggest that stratification will have an important effect on the dissolution of polar ice into the ocean. The critical height, z_c, is much less than the total height, H, for all glaciers and ice shelves that were examined. This suggests that stratification needs to be considered when modelling the current mass loss from polar ice sheets and that any potential change in stratification will be an important contributor to the mass balance in the future.

5 Comparison with the Three-Equation Parameterization

When stratification is added to our experiments, the results remain inconsistent with the three-equation parameterization (Jenkins, 2011). In the case of a stratified ambient fluid the ablation velocity decreases with height while the plume velocity increases with height.

Use of the standard three-equation parameterization results in the two being proportional to one another.

The use of constant Stanton numbers to determine the heat and salt flux to the ice should be reconsidered, as a necessary result is that the ablation velocity is proportional to the plume velocity. The assumption of constant Stanton numbers originates from studies examining heat transfer in turbulent pipe flow and has not been justified in a dynamically relevant situation to ice-ocean interactions.

Field observations could be used to examine the transfer of heat and salt to the ice-ocean interface but at present this is not feasible as measurements cannot be made within the thermal and saline boundary layers adjacent to a dissolving ice face. Until this becomes possible and data is available within the boundary layer at a variety of heights up an ice face, it seems unlikely that field observations will be able to adequately test turbulent transfer parameterizations.

Direct numerical simulations have recently been used to model the ice-ocean interface in a similar geometry to our laboratory experiments (Gayen et al., 2016). The results of these simulations agree closely with our own results in the case of a homogeneous ambient fluid (Kerr and McConnochie, 2015; McConnochie and Kerr, 2016), however the effect of stratification is yet to be investigated. Nonetheless, direct numerical simulations are powerful tools that are able to provide many observations that would be difficult to measure in laboratory or field studies.

Due to the lack of prior testing and the difficulties in making sufficient field observations, it is vital that numerical parameterizations are tested against theoretical, laboratory and direct numerical simulation studies to ensure that they are consistent with physical data.

6 Conclusion

We have conducted experiments that investigate the dissolution of a vertical ice face in stratified, cold salty water. We have described significant changes to the temperature at the ice-ocean interface, the ablation velocity and the velocity of the turbulent wall plume as a result of stratification. A scaling argument has been used to suggest that ocean stratification in high latitudes will affect the Antarctic and Greenland ice sheets and the meltwater plume that forms next to them. A critical height at which several Antarctic and Greenland ice faces are affected by stratification has been calculated.

Finally, we have noted discrepancies between our laboratory observations and the standard three-equation parameterization of ice melting in both a homogeneous and a stratified ambient ocean. These discrepancies are concerning given the prevalence of the three-equation parameterization in numerical modelling of Antarctic mass balance. Although the parameterization may perform better on a geophysical scale, current field observations are not a sufficient means of validation. If the parameterization performs similarly poorly on a geophysical scale as it does on a laboratory scale then an improved parameterization is urgently needed in numerical modelling of ice-ocean interactions.

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