Laboratory experiments of eddy blocking by Ice shelves

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Laboratory simulations of eddy behaviour in the region of ice shelf edges

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Abstract :

Eddies have been identified in mooring records from along the front of the Ronne ice shelf, Antarctica. This is an area where dense High Salinity Shelf Water (HSSW) flows into the cavity beneath the Filchner Ronne Ice Shelf (FRIS). This work uses experiments conducted on a small 1.2 and a large 13 m diameter rotating table considering the effect that an ice shelf has on the propagation of eddies. The paper focuses on the behaviour of eddies in the region of the ice front and it aims to address whether eddies can propagate beyond the ice front into the ice shelf cavity. It is shown that a relatively small change in ice shelf thickness is required to impede the propagation of eddies into the cavity beneath the ice shelf. However, when stratification is present eddies appear to propagate into the ice shelf cavity.

Résumé :

When possible, write the abstract of the paper in French (150 words maximum)

Key-words :

Ice shelf; Downslope Flows; Eddies

1 Introduction

The Filchner-Ronne Ice Shelves and Weddell Sea are key areas related to the formation of deep oceanic water masses in Antarctica. High Salinity Shelf Water (HSSW) is formed as a by-product of sea ice formation. Some of this HSSW flows into the cavity beneath the Filchner-Ronne Ice Shelf system and eventually exits the cavity as supercooled Ice Shelf Water (ISW) (Nicholls et al., 2003, Nicholls et al., 2001, Nicholls et al., 1991, Nicholls and Jenkins, 1993, Nicholls, 2001, Nicholls, 1997, Nicholls, 1996). The processes that lead to the conversion from HSSW to ISW are the melting of the ice shelf base and the mixing with this melt water. One of the inflows of HSSW is on the western side of the Ronne Ice Shelf in the region of the Ronne Depression. Mooring records FR5 and FR6 from the ice front at the Ronne Depression show a strong boundary current which is rich in eddies. Seasonal stratification of the water column has been identified in the southern Weddell Sea in the region of the Ronne Depression (Makinson and Schroder, 2006). This paper aims to address the effect of the ice shelf on eddies in the inflowing HSSW and attempts to answer the question as to whether eddies can propagate from the open ocean (Weddell Sea) into the ice shelf cavity across the ice front. The work used laboratory experiments conducted at the School of Mechanical, Aerospace and Civil Engineering (MACE), University of Manchester on a 1.2 m diameter rotating table in addition to a shorter series of experiments using the 13 m diameter rotating table at LEGI-Coriolis, Grenoble, France. When the ice shelf is not present the experiments described in this work use similar configurations to previous work on dense flows down slopes by previous authors e.g. Cenedese et al. (2004), Lane-Serff and Baines (1998), Lane-Serff and Baines (2000), Etling et al. (2000). The simplified setup of the experiments is shown in Figure 1. More detailed descriptions of the experimental apparatus are described in Section 2.

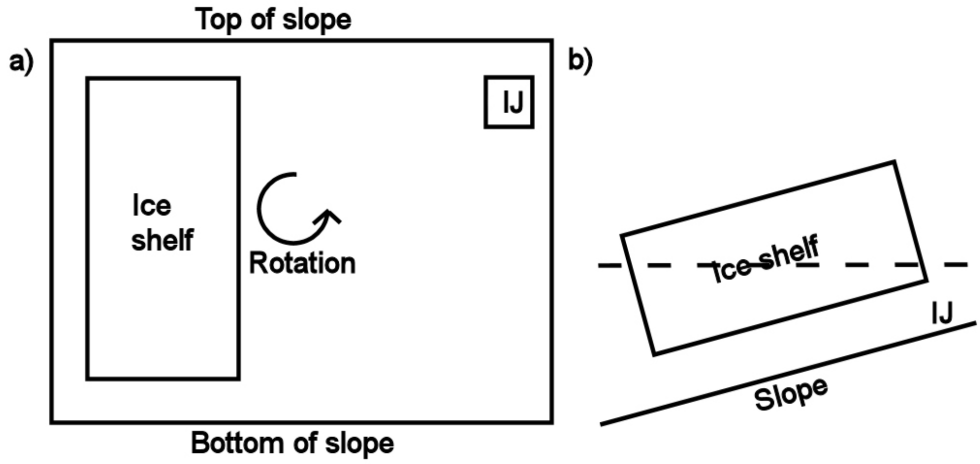

Figure 1 : The experimental setup for of the experiments shown from above (a) and from the side (b). The dense plume is either injected along the slope towards the ice shelf or down the slope depending on the experiment.

2.1 Methods - Small Scale Experiments

The small scale experiments were conducted at the School of MACE. These were run first and used a 1.2 m diameter rotating table with a Perspex tank (internal dimensions of 55x55x55 cm), a slope with a fixed angle of 1 in 10 and a gravity fed source. The source fluid densities were varied from 1010 to 1100 kg m^{-3} with an ambient density from 996 to 1000 kg m^{-3}. This produced density differences ranging from 1 to 10 %. The source injector was fixed 10 cm from the top of the slope facing down the slope and fluid exiting the source was dyed red for visualisation. The ambient fluid depth was either 2.5 or 5 cm at the top of the slope. Dye was also added to the surface of the ambient fluid during the experiments to visualise the flow in the upper layer. The ice shelf is simulated only through its physical effect on the water column height and these experiments all have an unstratified ambient fluid. The ice shelves used were built from Perspex sheet, suspended from above the tank with a space between the shelf and slope ranging from 1.25 to 5 cm. Images are recorded from a video camera mounted above the tank and a still camera at the side of the tank. The rotation period was set to 10s in all but 10 experiments. This arrangement consistently produced eddies which are largely barotropic and vortex stretching was the primary mechanism for their formation. The ice shelf and slope were setup in different configurations. The ice shelf front could be either perpendicular or parallel to the slope. A solid coast was included at the end of the slope for 25 of experiments and the total number of the experiments completed was 84. This paper will only consider the experiments where the shelf is perpendicular to the slope.

2.2 Methods - Large Scale Experiments

The large scale experiments were conducted at the LEGI-Coriolis facility in Grenoble France. These experiments used slopes that were 8 m wide (along-slope) by 2.5 m downslope and had a gradient of 1 in 10. One was painted black for use with PIV and the other white for red dye experiments. The ice shelf was constructed out of clear Perspex with dimensions of 2.0x2.0x0.4 m. This was placed so its front was either 4 or 4.5 m from the dense fluid injector. The ice shelf was setup such that the ice front was perpendicular to the slope as this configuration produced the most interesting results in the small scale experiments. The total depth of ambient fluid for all these experiments was 35 cm i.e. 10cm deeper than the top of the slope. The density difference between the ambient fluid and the dense source fluid was set to 0.4 % with a further offset of 0.4 % when two layer stratification was used in the ambient fluid. Two experiments were completed which had two layer stratification of the ambient fluid. One experiment had a 5 cm deep layer of fresh fluid at the surface and a second experiment with a 10 cm layer of fresh fluid at the surface. Red dye was used to visualise the flow within the dense plume when experiments were conducted on the white slope. Particles with sizes between 100 and 400 μm were added to the ambient and source fluid when experiments were conducted on the black slope. These were illuminated at different horizontal levels with a moving laser sheet so PIV processing of the results could be conducted. Images were recorded using a video camera on the white slope and two digital scientific still camera on the black slope. The rotation rate for these experiments was 60 s. As in the small scale experiments this arrangement consistently produced eddies which are largely barotropic.

3.1 Results – Small Scale Experiments

This paper will concentrate on the results covering eddy behaviour at the ice front. Eddy behaviour at the ice front is summarised in Figure 2. The parameters Y/L and the stretching parameter are the same as those used in Lane-Serff and Baines (1998) where Y is the along-slope draining scale, L is the internal Rossby radius of deformation and the stretching parameter is a measure of the relative stretching of fluid if it propagates down-slope from the source. There is no indication that Y/L affects the behaviour of eddies at the shelf front. The stretching parameter, which is a measure of the strength of the eddies, does have an effect. The only eddies that enter the cavity are formed when the stretching parameter is greater than 0.12. Eddies propagate up and down slope throughout the domain of the stretching parameter. The quantity d/h (where d is the ambient fluid depth at the source and h is the height of the ice shelf above the slope) also has an effect. Eddies propagate upslope when d/h is greater than 4 and down slope when d/h is less than or equal to 4. Eddies were observed to break up at the shelf front throughout all the domains discussed. Many of the behaviours observed may be related to the small size of the experimental setup which will be discussed further in the next section.

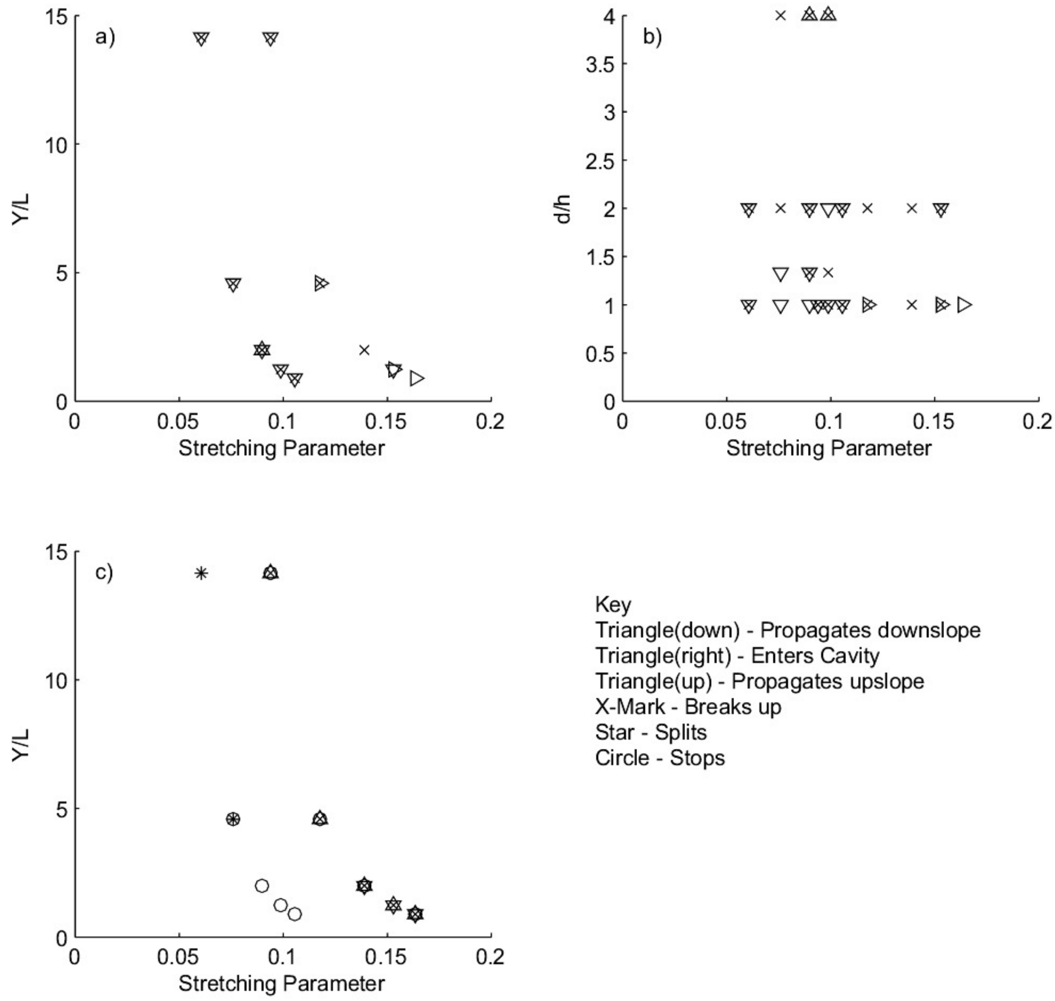

Figure 2 : Plots of the eddy behaviour observed at the ice front in the small scale experiments. The non-dimensional parameter Y/L which is the along slope draining scale divided by the internal Rossby radius and the stretching parameter are the same as those in Lane-Serff and Baines (1998). The dimensionless parameter d/h is the depth of ambient fluid at the source divided by the height of the ice shelf above the slope.

3.2 Results – Large Scale Experiments

The large scale experiments cover a small parameter space and allow more detailed observations to be recorded. The stretching parameter was fixed at 0.03 for all experiments which is less than in any of the small scale experiments. They also include stratification of the ambient fluid for two experiments and the use of a surface injector for one experiment. The raw tracks that eddies follow are shown in Figure 3**.**

Figure 3a) shows the tracks followed by eddies as they approach the ice shelf front taken from eddy centres identified from the velocity field after PIV processing. The tracks all start at the top of the plot (y~90cm). It is clear that the eddies turn downslope as they approach the ice shelf for all values of h. This agrees with the small scale experimental results for a low value of the stretching parameter. When stratification of the ambient fluid is included (Figure 3b, experiments 24 and 25) the tracks stop prior to the ice shelf with the early turning of the pathway not visible. There are several possible explanations for this. The first is that the eddies are entering the cavity beneath the ice shelf and direct observation during experiment 25 supports this, although no tracks are plotted from this experiment. Another physical explanation is that the eddies may also be breaking up at the ice shelf. The loss of tracks could also be because of the data quality. The inclusion of stratification in the experiments caused several difficulties because the ambient fluid could not be mixed prior to the experiment start. This meant that many of the particles will have either settled on the bottom or at the interface between the dense and fresh ambient fluid. The stratification also causes refraction of the laser sheet causing the laser sheet to curve towards the slope and the surface depending on the level. This was most pronounced in experiment 25 where the interface between the two layers of fluid was more diffuse than it was in experiment 24. A more detailed analysis with more visual inspection of the raw images is needed to confirm if eddies are entering the cavity in experiment 25. The main difference between the results of the small and large scale experiments is the amount of kinds of behaviour observed. The small scale experiments shows eddies propagate upslope, propagate down slope, split, stop or break up. In the large scale experiments the eddies did not propagate upslope or split. This is attributed to lower mean background currents so a "more natural" behaviour is observed.

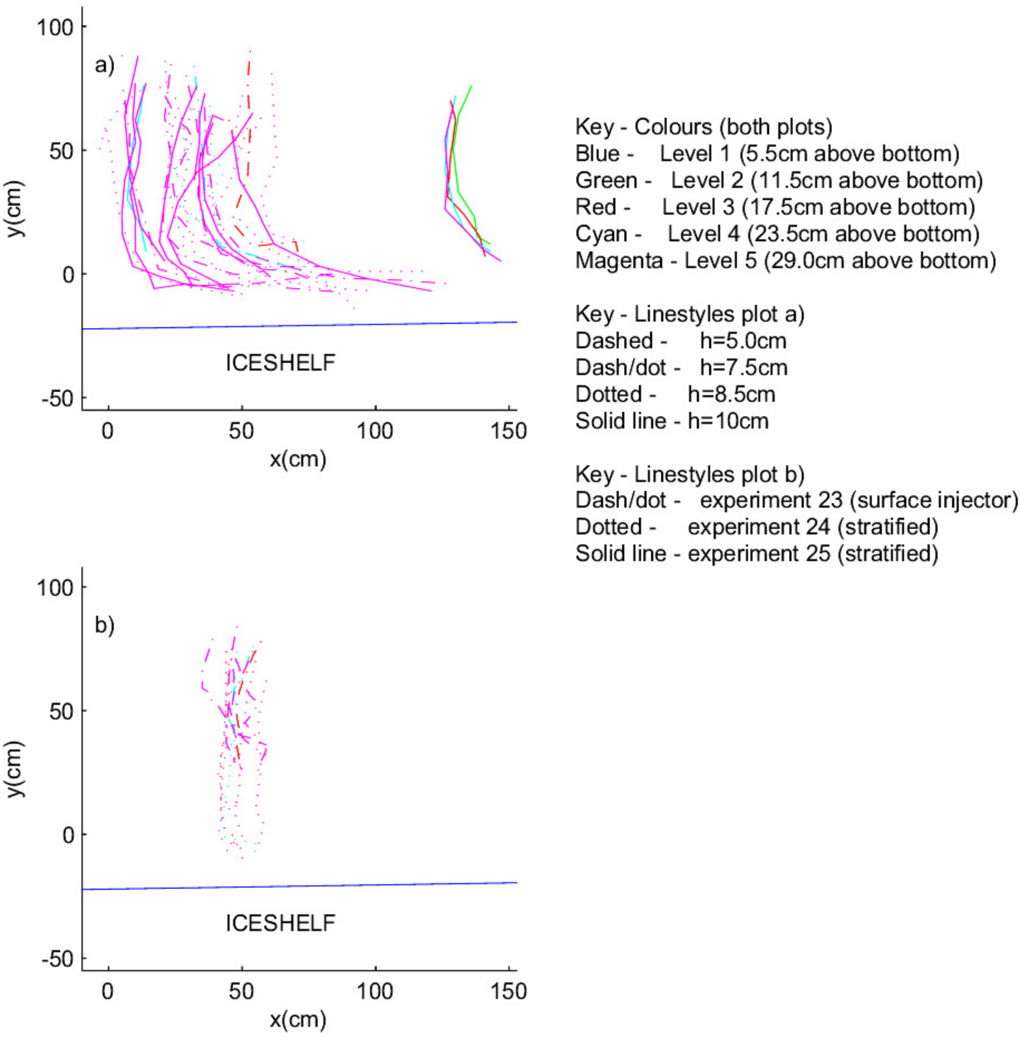

Figure 3 : Plots of the tracks of eddies from the large scale experiments. The ice shelf front is marked in blue and the y-axis corresponds to the top of the slope. Plot a) shows experiments 16 to 21. Plot b) shows experiments 23 to 25 where either a surface injector was used or stratification was present in the ambient fluid.

4 Conclusions

This paper has presented observations of the behaviour of eddies when they propagate into a step reduction of the water depth. It has been shown that is only takes a relatively small change in the water column height for the propagating of eddies to be interrupted or altered. The small scale experiments showed that unless the stretching parameter was greater than 0.13 then eddies could not propagate past the barrier the ice shelf creates. The large scale experiments showed eddy pathways that turn downslope when the ice front is reached. The amount of behaviours observed was less in the large scale experiments than in the small scale experiments. Eddies were not observed to propagate upslope or to split at the ice face so these behaviours have been attributed to the small size of the small scale experiments causing strong mean currents. The effect of stratification has also been studied and the deflection of eddies before reaching the ice shelf was not observed, indicating that eddies may be passing the ice front and entering the ice shelf cavity. A more detailed inspection of the raw images is necessary to confirm this.

The oceanographic implications of this work are that if eddies are passing beyond the ice front when stratification is present and not when the full water column is mixed then there will be a seasonal difference in the inflow into the cavity beneath FRIS. More specifically eddies will enter the cavity in summer when the water column is stratified but not in winter when the water column is mixed.

5 Acknowledgements

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