MODELLING ANTARCTIC FLOWS

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The large rotating Coriolis platform was used to investigate oceanographic flows of particular importance in the Antarctic region. Topographic features (such as canyons and ridges) on continental slopes were found to direct dense overflows downslope and increase the entrainment of ambient water into the overflow, as compared to flows on smooth slopes. In cases where dense flows on slopes generate eddies in the overlying fluid, simulated ice shelves were found to present a substantial obstacle to the flow, diverting the eddies downslope and impeding the flow of dense water into the ice shelf cavity. However, if the ambient water was stratified (as is the case in the winter around Antarctica) the ice shelf may not obstruct the flow, leading to seasonal differences in the flow of dense water into the ice shelf cavities. The exchange of flow between ice shelf cavities and the open water, driven by the generation of dense High Salinity Shelf Water (HSSW) outside the cavity and relatively light meltwater within the cavity, was also modelled.

1. INTRODUCTION

The Antarctic is an important region for the generation of the densest water masses in the world's oceans. Strong surface cooling results in sea ice formation and brine rejection, with the brine sinking to form High Salinity Shelf Water (HSSW) on the continental shelves around Antarctica. Some of the HSSW flows along slopes and down into cavities beneath the floating ice shelves that surround the Antarctic continent. The undersides of the ice shelves melt, with the resulting fresher water rising up the undersides of the ice shelves and mixing with the waters in the ice shelf cavities to form dense cool waters. Finally Ice Shelf Water (ISW) leaves the cavities and flows down the continental slopes into the deep ocean, further mixing with the surrounding water to form Antarctic Deep and Bottom Waters. Large dense oceanographic flows on slopes tend to flow predominantly along the slope due to the effect of the Earth's rotation, with a friction-driven downslope component. Depending on the parameters of the flow, the flow may exhibit small-scale waves or break up into domes of dense fluid, with eddies generated in the overlying water. Here we use the large Coriolis platform to model some of the important aspects of the fluid flows in the Antarctic region.

Three sets of experiments were conducted. In the first set we examined the effect of topography on dense flows on slopes ("overflows"), especially the effect of the topography on the route taken by the overflow and the mixing of the flow with the surrounding water. The topography took the form of a single ridge or canyon, and a comprehensive set of parameter regimes was tested. It was found that both canyons and ridges tended to steer the flow downslope and increase mixing, compared to a slope without these features. In the next set of experiments, the effect of an ice shelf on a dense flow was modelled. We focused on flows which generated eddies in the overlying fluid and found that the step change in water depth caused by the simulated ice shelf blocked the eddies and arrested the underlying dense flow. However, if the ambient water was stratified the eddies could be limited to a deep layer that was not affected by the ice shelf and the flow could penetrate into the ice shelf cavity. Finally, we modelled the flow in the ice shelf cavity generated by meltwater rising up the underside of the ice shelf interacting with a source of simulated HSSW outside the cavity.

2. EXPERIMENTS

A straight, flat-topped ridge was constructed in the 13 m diameter circular tank on the Coriolis rotating platform. The ridge was 8 m long, 2 m wide and 0.25 m high, and was flanked by 1 in 10 slopes (see Figure 1). The ridge was bounded by walls perpendicular to the ridge-axis, while the ridge itself was off-centre, splitting the tank into a smaller and a larger sub-basin. The slope in the smaller sub-basin was painted white for dye experiments, while the other slope was black for particle tracking experiments. There was a removable panel on the white slope that could be replaced by a ridge or canyon running directly downslope. Both features were triangular in cross-section, with a width of 16 cm and a height or depth of 10 cm. Ice shelves were simulated by Perspex boxes, 2 m square in plan, which could be suspended above the slope in any desired location or orientation. They were used on either slope as desired. For the ice shelf cavity experiments the flow was confined by extra walls to a smaller part of the ridge and one slope (see Figure 1b), with the ice shelf occupying the full width of the domain, and sources of fresh and dense water.

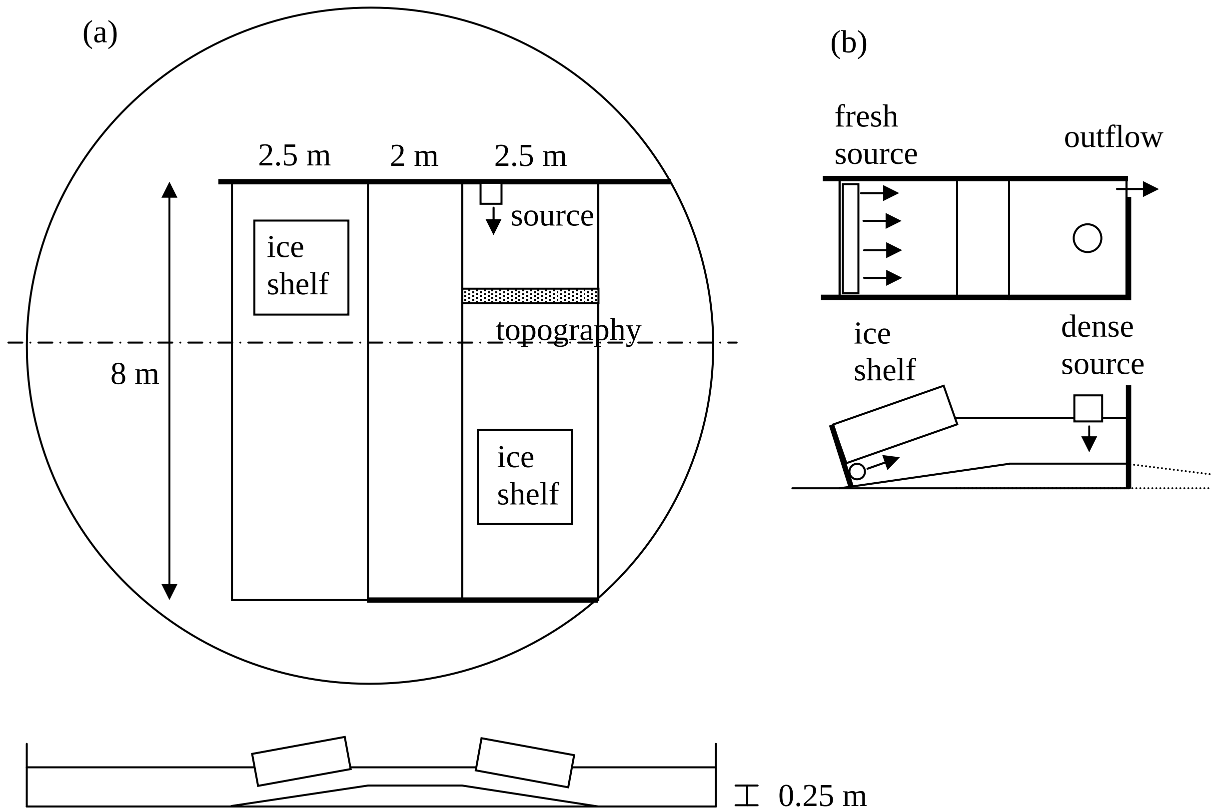

Figure 1. (a) Plan and section of the experimental arrangement used on the Coriolis platform. The topography (canyon or ridge) could be inserted in the position shown shaded as required, while the ice shelf (not used for the same experiments) could be placed in any location on either slope. (b) Enlarged plan and section of the smaller region used for the ice shelf cavity experiments, using just a 2 m wide section of the ridge (flat top and one slope) only. There was a small outlet to the main tank in one corner of the domain (as shown).

Three different sources were used. For the topography experiments and most of the dense flow/ice shelf interaction experiments a source was mounted directly on the slope, with dense fluid flowing out along the slope though an opening 20 cm wide and 2.5 cm high. For some ice shelf experiments and the ice shelf cavity experiments a source was used at the free surface, with dense water flowing down through a sponge, simulating HSSW generated by surface freezing and brine rejection. Finally, for the ice shelf cavity experiments, the meltwater under the ice shelf was simulated using a distributed source of fresh water running the width of the ice shelf

For the mixing experiments the dense source mounted on the slope was used, with the topography placed about 2.5 m downstream from the source. The parameters were altered to give various flow regimes (laminar, roll waves, or eddies – see Cenedese et al., 2004), while the mixing was measured by monitoring the developing density structure in the sub-basin. For the ice shelf experiments, the ice shelf was generally placed 4 to 6 m from the dense source, and tilted so that it was parallel to the slope. The vertical position of the shelf was adjusted to cover a range of relative depth changes at the ice shelf. Most experiments were conducted with an unstratified ambient fluid, but for some experiments an approximately two-layer ambient stratification was used. Both dyes and particle tracking were used. In the ice shelf cavity experiments, the surface dense source was used outside the cavity over the top of the ridge (simulating a source of HSSW), while fresh water was introduced close to the “grounding line” of the ice shelf to simulate meltwater. Laser induced fluorescence (LIF) and particle tracking were used to find high resolution density and velocity fields.

3. RESULTS

For the flows with ridges or canyons, the topography directed the dense flow downslope, with the dense water leaning against the ridge or filling the canyon. For cases where there were strong eddies in the overlying water, the eddies halted at the topographic barrier and tended to move upslope, apparently now detached from the dense flow dynamics. By examining the developing density profile in the basin, the entrainment into the overflow can be calculated. An average entrainment constant based on the total area of the overflow and a typical velocity can be estimated (Table 1). While the absolute values of the results need to be treated with caution, it is clear that topography has a substantial effect on mixing of overflows, with canyons having a bigger effect than ridges (more details in Wåhlin et al., 2008).

Table 1. Entrainment constants for different flow regimes and topography (from Wåhlin et al., 2008).

$E / 10^{-4}$	Smooth	Ridge	Canyon
Laminar	2.6	5.9	7.4
Waves	3.0	6.4	7.2
Eddies	1.5	6.8	9.6

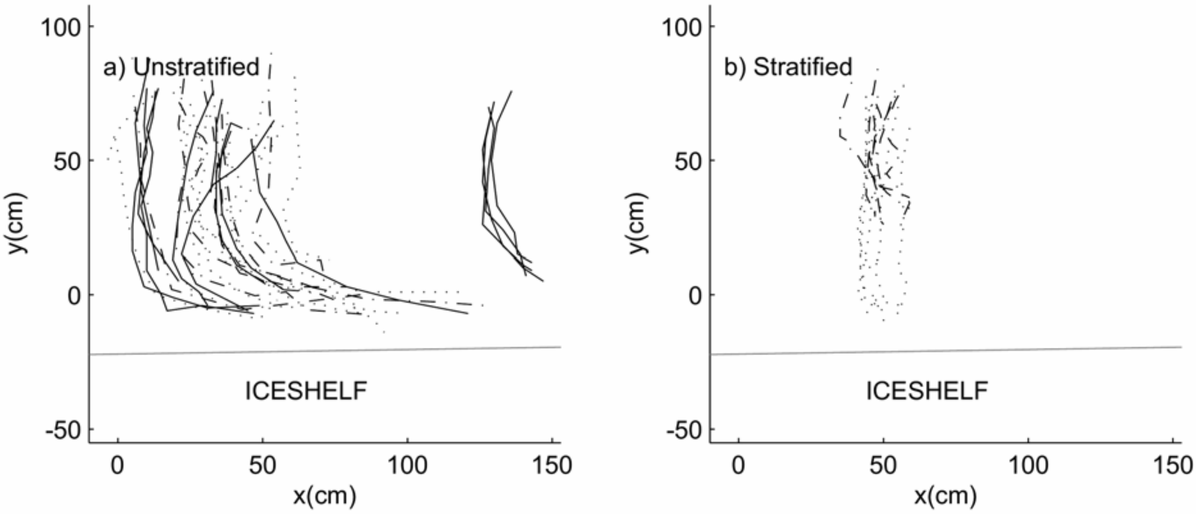

Figure 2. Paths of the centre of eddies where the ambient fluid is (a) unstratified and (b) stratified. The top of the slope is to the left (low values of x). (From Buck 2009.)

In the ice shelf experiments, parameters were chosen to give strong eddies in the overlying water. These progressed along the slope until reaching the ice shelf. The motion was measured either by following the dyed dense fluid, which breaks up into domes beneath the eddies, or by using particle tracking to follow the motion, with the centre of the rotating eddies identified from velocity plots. At the ice shelf, the eddies were arrested and deflected downslope, even where the ice shelf only gave a relative change in the water depth of ~10% (Figure 2). The domes of dense fluid then drained downslope at an angle under the ice shelf. For the cases where the ambient water was stratified, the eddies in the overlying fluid were confined to the lower ambient layer and the eddies appeared to be able to continue along the slope under the ice shelf (more details in Buck, 2009).

A sequence of eight ice shelf cavity experiments were carried out in order to illuminate various aspects of exchange between the ice shelf cavity and the open water. In one subset, the flow rates of the freshwater and saltwater sources were altered, and in another subset geometrical aspects of the ice shelf cavity were altered. The data is currently being analyzed, which first required a calibration and correction of the raw images to account for various geometrical and lighting distortions. The processed data is now being used to quantify the variation in ice shelf cavity - continental shelf exchange as a function of the experimental parameters.

4. CONCLUSIONS

We have shown that the presence of ridges and canyons has a strong effect on the route dense overflows take to the deep ocean, directing them downslope and increasing the amount of mixing with the overlying water. This has implications for overflows in many parts of the global ocean, such as the Filchner overflow, where there are substantial ridges and canyons on the slope just downstream of the point where the overflow leaves the Ronne Depression. Ice shelves are found to present a strong barrier to dense flows where these are coupled to the overlying fluid, but stratification may reduce this effect. This is significant as the waters on the Antarctic continental shelf are often strongly stratified in the summer and well mixed in the winter, so there would be seasonal difference in the way dense flows penetrate the ice shelf cavity. Finally we have been able to examine the complex exchange between the ice shelf cavity and open water, driven by sources of relatively dense and light water.

The unique Coriolis facility has allowed us to explore a range of flows with applications to oceanography around Antarctica and elsewhere. A wide ranging experimental progamme was successfully completed, with some results published in detail already (e.g. Wåhlin et al, 2008; Buck, 2009; Darelius, 2008) and further publications expected.

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