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Ronne Inflow Experiment - Fieldwork

Keith Nicholls, Keith Makinson
British Antarctic Survey, Natural Environment Research Council, High Cross Madingley Road Cambridge CB3 0ET, U.K.
Svein Østerhus
Bjerknes Centre for Climatic Research, University of Bergen, Allegaten 70 N-5007 Bergen, Norway

Introduction

From work carried out over the last 15 years, we know that much of the circulation beneath the Filchner-Ronne Ice Shelf is driven by dense water production north of the ice front [*Nicholls*, 1996]. Winds and tidal action maintain a semi-permanent shorelead throughout the winter, enabling large heat loss to the atmosphere [*Renfrew et al.*, 2002]. As soon as the water column has reached the surface freezing point, sea-ice formation increases its salinity and the resulting high salinity shelf water (HSSW) is then available to drain beneath the ice shelf. Once in the sub-ice shelf cavity, HSSW can melt ice at the depth of the ice base where the freezing point is lowered by the effect of pressure [*Millero*, 1978]. In this way HSSW is converted into slightly less saline, but significantly colder Ice Shelf Water (ISW).

Nicholls et al [2001] outline the major flows beneath the ice shelf (Figure 1), as determined by a combination of glaciology, conventional ship-based measurements at the ice front, and moorings deployed beneath the ice shelf via hot-water drilled access holes. The densest HSSW flows into the Ronne Depression (RD), ventilating the western side of the cavity. Flow into the RD also passes through a gap in the ridge delineating the eastern boundary of the depression, and heads east. A modified version of this water is observed at sites 4 and 5, south and west of Berkner Island. Although the flow picks up buoyant meltwater by interacting with the ice shelf, by the time the water reaches the Filchner Ice Front it is still too dense to escape the Filchner Depression (FD). The flow therefore returns beneath the ice shelf to execute another full circuit of the FD, presumably powering melting at the deep grounding lines *en route*. The second main externally driven flow beneath the ice shelf comprises a lower salinity version of HSSW, which is formed over Berkner Bank (BB). After flowing around Berkner Island this lower density water mass is light enough to exit the Filchner Depression at its northern end without recirculating within the Filchner Depression.

The step-change in water column thickness at the ice front presents a dynamic barrier to the HSSW, impeding its flow into the sub-ice shelf cavity [*Gerdes et al.*, 1999]. How and when the water flows beneath the ice front remains an open question, as does an accurate assessment of the flux of associated heat. Attempts to estimate influx of HSSW using moorings at the ice front are fraught with difficulties. The practical issues are connected with the highly variable summer sea-ice conditions over the southern Weddell Sea continental shelf: it is difficult to predict when a ship can access the ice front to deploy and recover the moorings. Another danger is presented by the possibility of moorings being dragged by icebergs.

Although some records have been obtained [*Foldvik et al.*, 2001; *Nicholls et al.*, 2003], making accurate estimates of HSSW inflow from a limited number of moorings, before the HSSW has coalesced under Coriolis into an organised flow is problematic. The flow is strongly modified by the presence of the ice front, a topographic barrier that itself moves at a speed in excess of 1 km per year. An additional problem is that current meter moorings are unable to measure directly the component of flow resulting from tidal rectification, an effect that is particularly strong near major topographic features such as the ice front [*Makinson and Nicholls*, 1999].

The aim of the fieldwork described here is to monitor the flow into the RD of the dense version of HSSW. We wish to determine the seasonally averaged flux of the inflow, and the controls on the inflow. Our approach is to deploy a line of moorings across the RD, some tens of kilometres south of the ice front. The moorings are far enough from the ice front both to avoid its direct influence, and for the flow to have been gathered by the effects of topography and the Coriolis force. The line of moorings was positioned to capture the entire inflow: the element that routes through the gap in the ridge, and also the element that ventilates the RD itself.

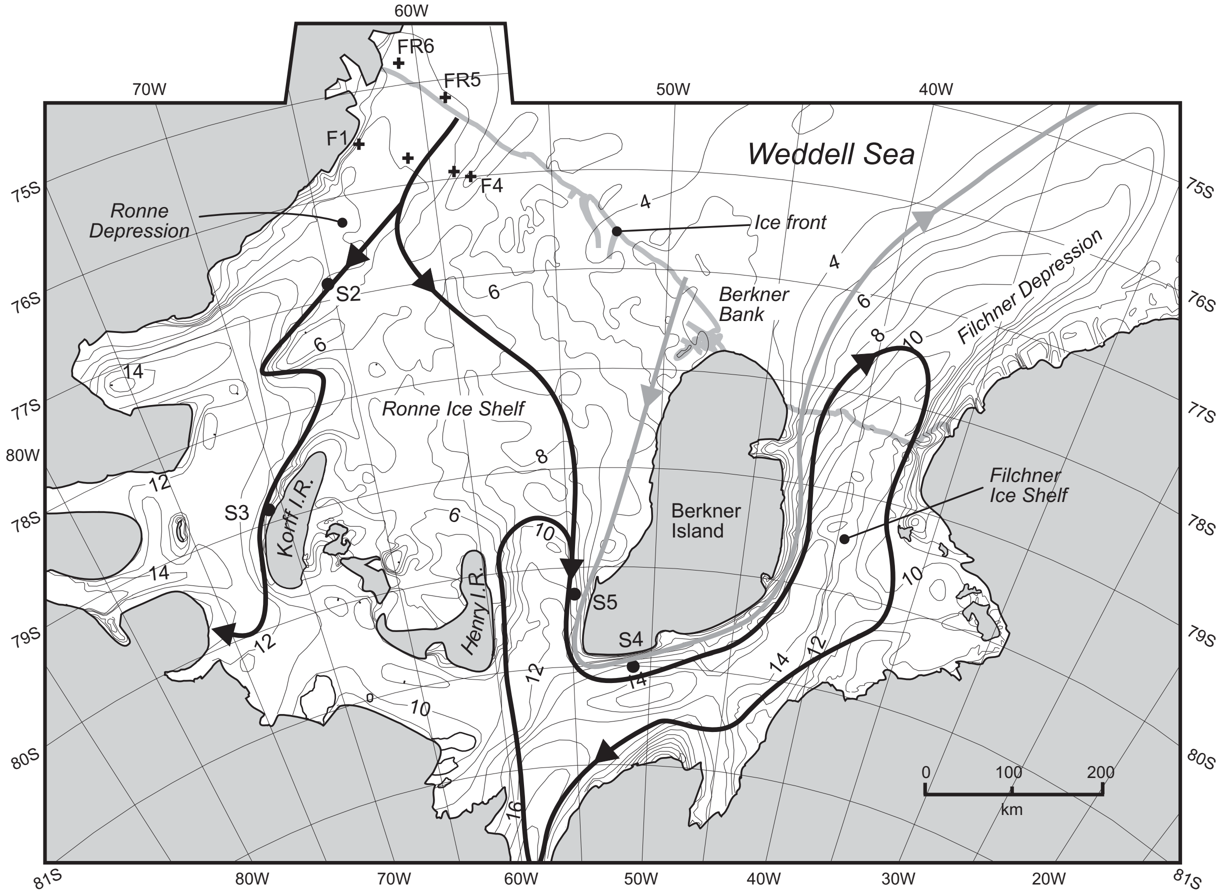

Figure 1. Map of Filchner-Ronne Ice Shelf. Contours show seabed depth in 100s of metres. The arrows indicate simplified circulation in cavity beneath ice shelf. The sites occupied during 2002-03 are indicated (F1-4).

Moorings

Drilling at the four sites took place between December 2002 and January 2003. The sites are named Fox 1 to 4, Fox 1 being at the western end of the line. The first task at each site was to drill an access hole through the ice shelf. A sequence of CTD profiles were then obtained, before re-widening the hole and deploying an oceanographic mooring. Fox 3 was the first site to be drilled, and was revisited at the end of the season, when time allowed another drilling and the deployment of an additional mooring.

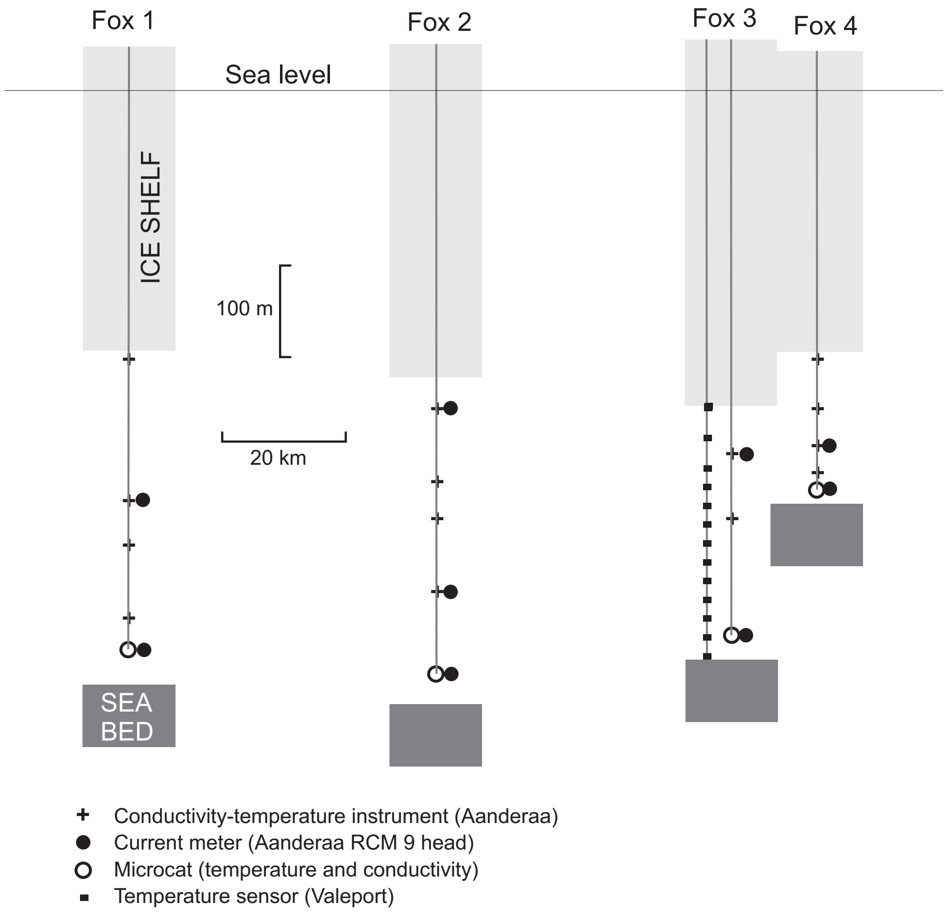

Figure 2. Diagram showing moorings deployed during 2002-03. Thermistor cables deployed at Fox 3 and Fox 4 are not shown.

Figure 2 shows the disposition of instruments on the moorings. The moorings generally consisted of two current meters (three at Fox 2), four Aanderaa-style temperature/conductivity instruments (two at Fox 3), and one Seabird Microcat. Not shown in the figure are two thermistor cables, one on the Fox 3 mooring, where it reaches down into the top-most few metres of the water column, and the other at Fox 4, where it is monitoring the temperature of the ice shelf. The second mooring at Fox 3 consists of a string of fifteen high precision temperature sensors. The data from all instruments are being logged locally, while data from the current meters, CT instruments and a subset of the thermistors are being transmitted via Argos datalink.

Results from CTD profiles

The graphs in Figure 3 show examples of the potential temperature (θ) (top panel) and salinity profiles (lower panel) obtained from the four sites. Also shown in the top panel are the upper portions of the freezing point profiles. These are *in situ* freezing points, but adjusted to potential temperatures so that they are comparable with the potential temperature profiles.

During the 2001-02 season Craig Stewart used a combination of phase-sensitive radio-echo sounding (pRES) and GPS ice strain measurements to derive meltrates for the three Fox sites for which unambiguous basal returns could be obtained (Fox 2, 3 and 4). The derived meltrates are shown on the profiles in the upper panel (C. Stewart, Personal communication, 2003), and are clearly consistent with the superheat available in the water column. At around 0.053°C the *in situ* freezing point at Fox 4 is very large, and there is a correspondingly large measured meltrate (1.4 m a^{-1}). The superheat at Fox 2 is small (0.002°C), and the meltrate is rather low, at only 0.1 m a^{-1}. The water near the ice shelf base at Fox 3 is actually at the freezing point, and the measured meltrate is zero.

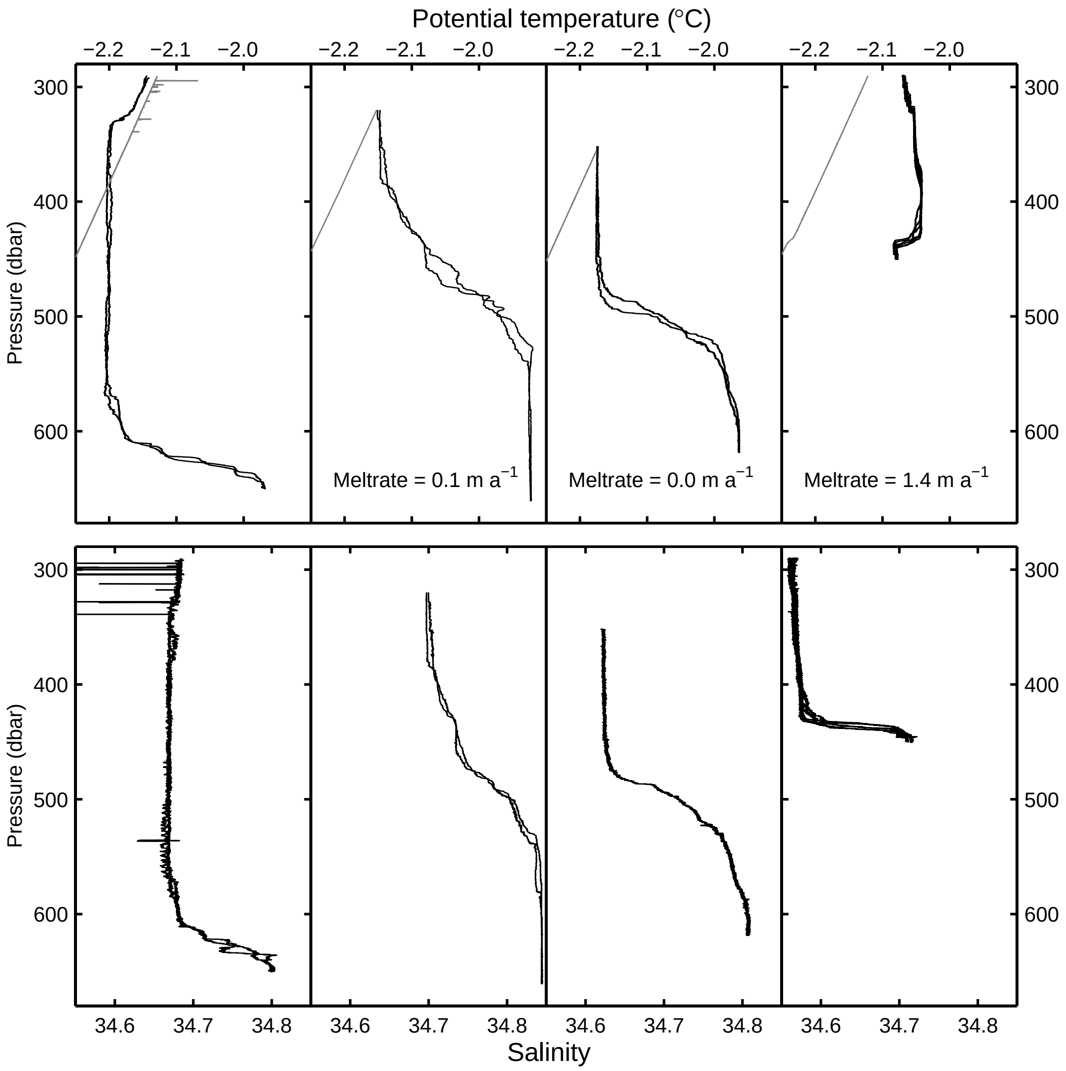

Figure 3. Profiles of potential temperature (upper panel) and salinity (lower panel) from Fox 1 (left) to Fox 4 (right). The light lines in the upper panel are the *in situ* freezing point profiles, corrected to potential temperature.

Fox 1 appears more complicated. During the drilling process, hydraulic connection was made with the sea when the nozzle depth was estimated to be around 310 m. However, radar-sounding at Fox 1 puts the depth of the ice shelf at around 355 m. The remainder of the ice thickness was made up of slushy ice, and that, together with the nature of the radar returns and the proximity of surface crevassing due to the nearby boundary between ice shelf and coast, suggests that we drilled into a slush-filled basal crevasse.

The salinity profile at Fox 1 shows several spikes in the top 40 m of the water column, which we ascribe to platelet ice passing through the conductivity sensors on the probe. The upper 90 m of the water column is *in situ* supercooled, the maximum cooling of 0.035°C occurring 40 m below the ice base. Above that depth, the water temperature remains 0.014°C below the *in situ* freezing point. The simplest explanation for this temperature profile is that 0.035°C is the highest degree of supercooling that is sustainable in this area before ice crystals form.

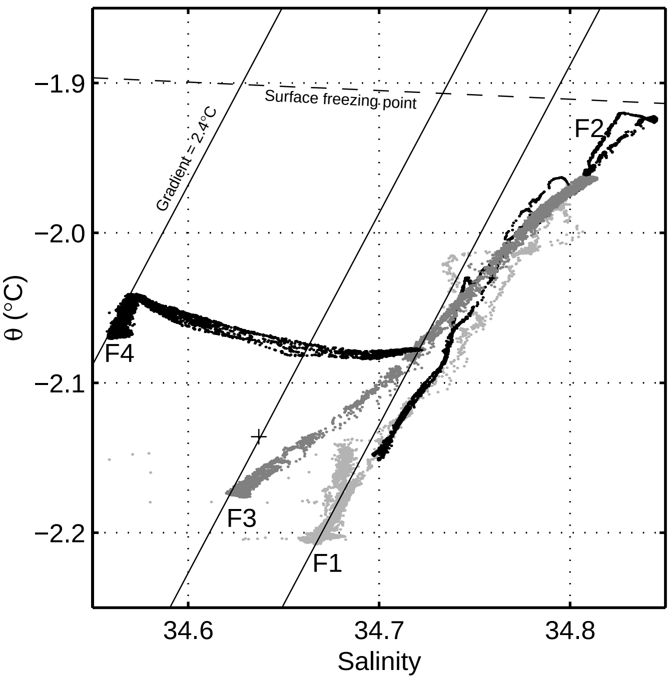

Figure 4. Potential temperature-salinity plots of profiles shown in Figure 3. Also included is the surface freezing line, and lines indicating the evolution of a water mass interacting with the ice shelf base. The characteristics of the ISW core observed at the ice front in 1998 are shown with a cross (+).

At Fox 2, the lower 130 m of the water column had θ-*S* properties of -1.92°C and 34.84. At only 0.07°C below the surface freezing point, this water mass is the closest to pure HSSW that was observed during the season, and is the highest salinity water ever observed beneath Ronne Ice Shelf.

The water columns at the four sites are most easily compared on a θ-*S* plot (Figure 4). The 2.4°C-gradient lines show how HSSW with an initial temperature at the surface freezing point (broken line) would be expected to evolve as it interacted with the base of the ice shelf [*Gade*, 1979]. Conversely, such a line can be used to indicate the salinity of the source HSSW for ISW observed beneath the ice shelf. The θ-*S* plot shows that, apart from the absence of the HSSW in the lower layer, the water columns at Fox 1 and 2 are very similar. Indeed for salinities higher than about 34.73, the water column at Fox 3 matches that seen at Fox 1 also.

The upper 130 m of the Fox 3 water column is occupied by a well-mixed water mass with a θ-*S* of –2.17°C and 34.62. As noted above, this is at the *in situ* temperature for the base of the ice shelf. Every year a ship has undertaken CTD casts at the ice front, a core of ISW has been seen in the Ronne Depression. *Nicholls et al* [2003] report that in 1998 the θ-*S* properties of the core were –2.136°C and 34.637. This point is plotted on Figure 4, and it is clear that it lies very near the 2.4°C gradient line that passes through the properties of the upper mixed layer at Fox 3. We conclude, therefore, that we see at Fox 3 the upstream version of the ice front ISW core.

Sited only 15 km east of Fox 3, the water column at Fox 4 has very different θ-*S* properties to those observed at the other sites. For the Ice Shelf Water in the upper 140 m of the cavity at Fox 4, the 2.4°C-gradient line shows that the source water must have a salinity of around 34.63. HSSW with such a low salinity is found only over Berkner Bank [*Gammelsrød et al.*, 1994], implying that most of the Fox 4 water column is under the influence of a circulation from the east. The water column within 20 m of the sea floor at Fox 4 is occupied by water that lies on the same θ-*S* characteristic as found at the other sites.

Summary

From the CTD profiles it seems that the four moorings are appropriately positioned to capture the HSSW inflow into the Ronne Depression. The meltrates deduced from the pRES studies at Fox 2, 3 and 4 are consistent with the amount of superheat in the water column near the ice shelf base, while the conditions measured near the base at Fox 1 suggest significant ice production in the water column. Fox 4 is being influenced by HSSW produced much further east, over Berkner Bank. The parent HSSW for the water masses observed at Fox 1 to 3, on the other hand, is more saline, and would most likely have been produced near the western end of the ice front. The upstream version of the core of ISW routinely observed at the ice front in the Ronne Depression is clearly visible at Fox 3.

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