Interannual variability beneath Filchner-Ronne Ice Shelf, Antarctica

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Introduction

As a result of their importance in the production of Antarctic Bottom Water, processes over the Antarctic continental shelf have a strong impact on the global ocean. Some of the ice shelves that cover much of the continental shelf are thought to play a significant role in the production of AABW, particularly in the southern Weddell Sea [*Foldvik and Gammelsrød*, 1988]. The impact of the ocean on ice shelves is of interest from a glaciological perspective also, as ice shelves form the seaward boundary of much of the Antarctic Ice Sheet.

The Filchner-Ronne Ice Shelf in the southern Weddell Sea is the most massive

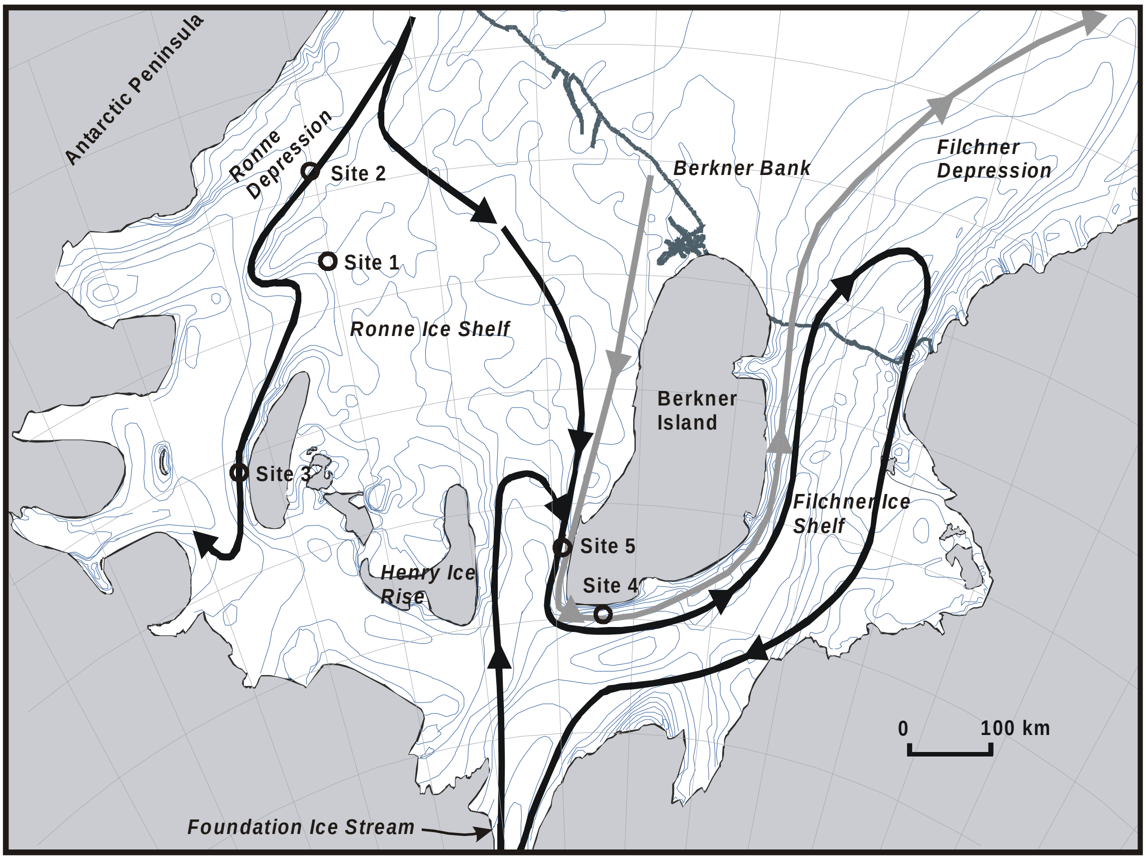

Figure 1. Map of Filchner-Ronne Ice Shelf showing locations of oceanographic sites (1 to 5). Heavy arrows show flows derived from HSSW from the Ronne Depression. Light arrow shows the flow from HSSW formed over Berkner Bank. The contours are of bathymetry, and have an interval of 100 m.

Antarctic ice shelf, and its interaction with the Southern Ocean is of much interest. Measurements made during the 1990s have significantly advanced our knowledge of the circulation of ocean waters in the cavity beneath the ice shelf [*Nicholls and Makinson*, 1998]. A key finding was a strong seasonal signal in the thickness of the warmer water in the lower part of the water column, showing that the conditions beneath the ice shelf were sensitive to the climatic regime seaward of the ice front [*Nicholls*, 1997].

Here we report on further measurements that indicate a strong interannual variability at the eastern side of Ronne Ice Shelf, and we show how the timing of the interannual signal can be used to estimate the flushing period for the sub-ice shelf cavity.

Observations

Five oceanographic stations were occupied over Ronne Ice Shelf during the 1990s (Figure 1). Access was gained using a hot-water drill, oceanographic profiles (CTD) were obtained and a variety of different moorings left in the holes for long-term measurements. The time series of temperature from Site 3 shown in Figure 2 shows a strong and regular seasonal variability. This has been interpreted as a seasonal variation in the thickness of the warm deep layer of water flowing in from the ice front [*Nicholls and Jenkins*, 1993]. Sea-ice production seaward of the ice front generates High Salinity Shelf Water (HSSW) that ultimately descends beneath the ice shelf, creating an externally driven circulation. As the sea-ice production is seasonal, so will be the external forcing on the sub-ice shelf flow.

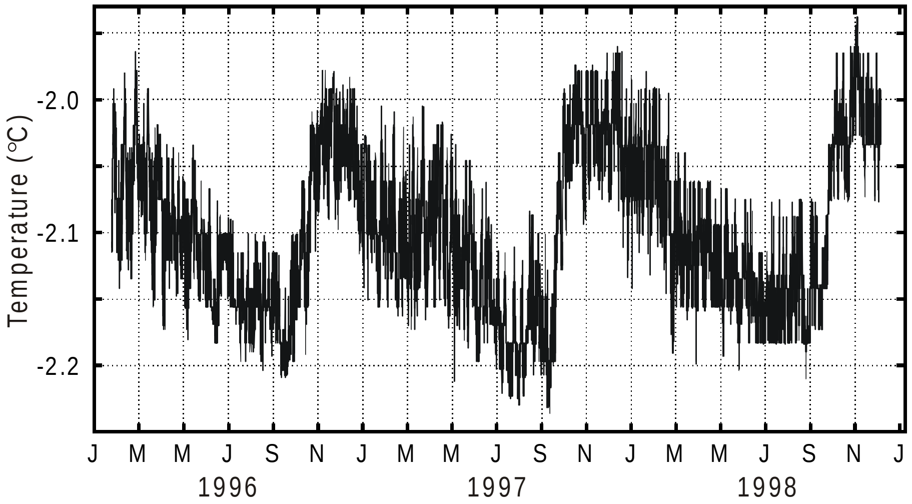

Figure 2. Temperatures recorded from a thermistor in the water column at Site 3 (see Figure 1). The strong seasonal variability is ascribed to seasonal changes in thickness of the deep, inflowing, warmer water.

A strong seasonal signal was also observed in the temperatures from Site 2. These results lead us to believe that the long-term variability in conditions beneath the western Ronne Ice Shelf is dominated by the seasonal signal. We now focus on data from Site 5, located on the eastern margin of Ronne Ice Shelf, near the south western coast of Berkner Island.

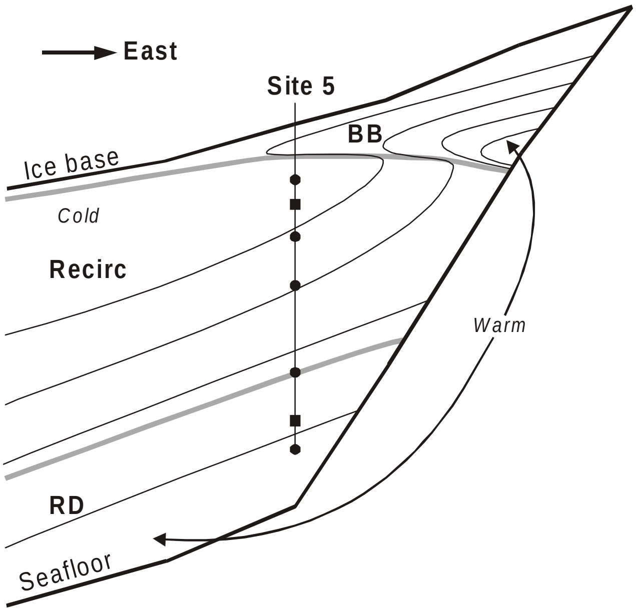

Figure 3. Schematic cross-section showing summer water properties at Site 5. The Berkner I. coast is to the right of the figure. BB represents water flowing south from the Berkner Bank. Recirc represents water recirculating from the east of Henry Ice Rise (see Figure 1). RD represents water flowing from the Ronne Depression. Light lines show plausible isotherms, while the grey, heavier lines suggest boundaries between the water masses, and therefore approximate isopycnals. The location of Site 5 is indicated, showing the locations of temperature sensors (●) and current meters (■). The deepest current meter worked for less than one year.

CTD measurements obtained from Site 5 (Figure 1), coupled with data from the moored current meters and temperature sensors [*Nicholls et al.*, 2001], yield the schematic cross-section of hydrographic properties shown in Figure 3. This schematic is a somewhat speculative representation of the local hydrography for the time the CTD measurements were made, during the austral summer. The arrows in Figure 1 indicate the paths of the water masses shown in Figure 3. The pathways were inferred from measurements made at the hot-water drill sites (1 to 5), from ship-based observations made over the open continental shelf to the north [*Nicholls et al.*, 2001], and from various glaciological measurements of the impact of basal melting and freezing on the ice shelf itself.

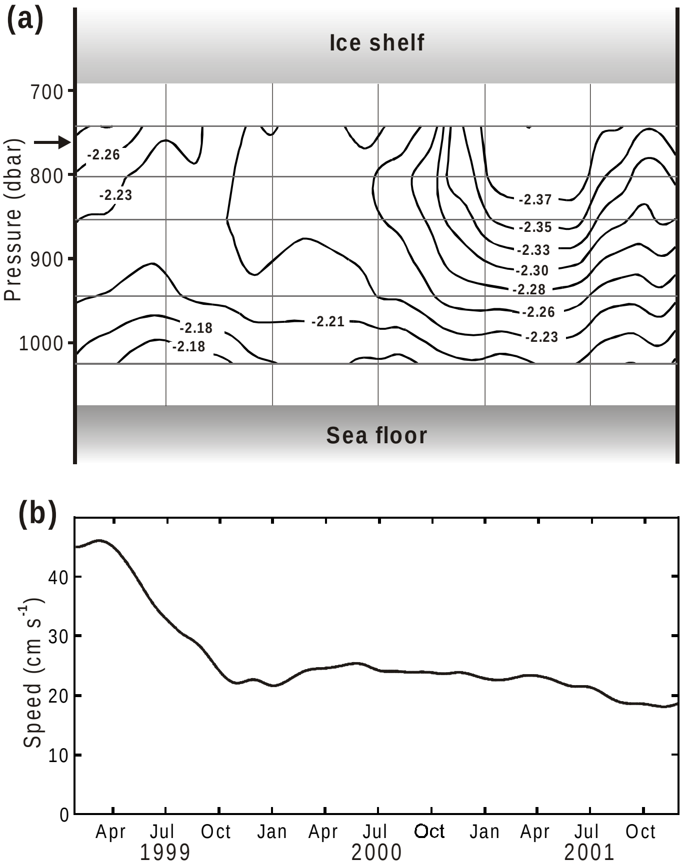

Figure 4. (a) Variation in the temperature of the water column at Site 5. Horizontal lines show the depths of the temperature sensors. (b) Speed along mean direction at the depth of the upper current meter at Site 5 (shown by arrow in (a)).

Records nearly three years in length are now available from the instruments moored at Site 5. Figure 4a shows a contour plot of temperature versus time through the water column. The strength of current along the mean flow direction as measured by the current meter is given in Figure 4b. The depths of the current meter and temperature sensors are indicated on the temperature contour plot.

At the time of deployment (and also of the CTD profiling) in January 1999 the current was nearing a peak of around 45 cm s^{-1}. Over the next 9 or 10 months the current decreased to around 23 cm s^{-1} and then stayed at or near that level for the remainder of the record. Any seasonal signal is dominated by a strong interannual component. During the initial decrease in current, the temperature recorded by every sensor increased. (Figure 4a). There was then a yearlong quiescent period in which the temperatures remained more or less stationary, except for a slight cooling near the sea floor. In November 2001, however, the upper half of the water column underwent a rapid and strong cooling to a temperature a little below the *in situ* freezing point at the ice base. This cold period lasted for about 6 months, before the temperature started to recover, up until the end of the record. There appears to be no obvious reflection of the November 2001 cooling in the current speed. A seasonal signal is just visible in the temperature records, particularly in the lower portion of the water column. Again, though, for most of the water column any seasonal signal is dominated by the strong interannual component described above.

Interpretation

The assertion that the conditions beneath the ice shelf are to an extent driven by sea-ice formation over the open continental shelf north of the ice front implies that they have a climatic sensitivity [*Nicholls*, 1997]. We would therefore expect interannual variability in the sea-ice production regime local to the ice shelf to be reflected in the conditions beneath the ice shelf. In particular, the area of open water available for freezing up at the start of the Austral winter determines whether there is the possibility of a large glut of HSSW available to sink beneath the ice shelf.

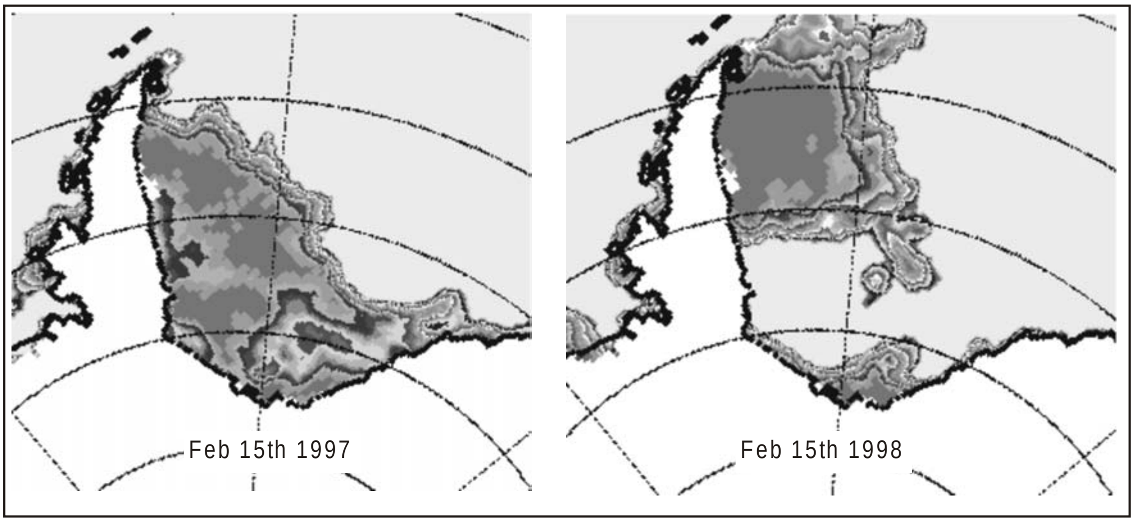

Figure 5. Near normal late summer sea ice conditions in the southern Weddell Sea in 1997, compared with the unprecedented conditions at the same time the following year.

Whether the glut is actually produced depends on whether the open water was generated by sea ice melting *in situ*, or if it has been exported from the continental shelf as a result of wind driving. In the former case, early winter sea-ice production will cause no net increase in salinity, as it must first compensate for the freshwater input from the summer melting.

Figure 5 shows the sea-ice conditions over the southern Weddell Sea in early1997 and in early 1998. The conditions shown in early 1997 are slightly heavier than average, but broadly typical, with most of the southern continental shelf covered in sea ice. The conditions in early 1998, however, were extraordinarily light, and were caused by the prevalence of southerly winds during the summer [*Hunke and Ackley*, 2001]. Such a large area of open water caused by sea-ice advection was likely to have caused an unusually large glut of HSSW entering the cavity beneath the western Ronne Ice Shelf.

Referring to Figure 1, our interpretation of the high currents observed at Site 5 in early 1999 is that, by the time of the measurements, the HSSW glut following the eastern branch of the inflow had reached the Berkner Island coast. The relatively steep seafloor gradients along the coast will have caused the HSSW flow to accelerate past the Site 5 mooring.

As the glut passed the mooring and arrived at the deepest part of the cavity, the gravity forcing of the flow fell off, and the speed decreased. At the same time the inflow from the Berkner Shelf (Figure 1) was increasing in response to winter sea-ice formation. This inflow forms the warmer wedge shown in Figure 3. As the inflow increased the wedge expanded, ultimately enveloping the Site 5 mooring and explaining the gradual increase in temperature during the first half of 1999.

From October 1999 until November 2001 the HSSW glut circumnavigated the Filchner Depression (Figure 1). Its arrival at the deep ice in the vicinity of Foundation Ice Stream will have caused an increase in basal melting, and, therefore, an increase in Ice Shelf Water (ISW) production. The resulting glut of ISW arrived back at Site 5 in November 2000, causing the sudden and strong cooling in the upper half of the water column. The lowest temperatures that were recorded at this time are the same as the freezing point at the base of the ice shelf on the eastern coast of Henry Ice Rise, where high basal freezing rates have been inferred [*Thyssen et al.*, 1993]. The end of the ISW glut, as observed at Site 5, came at around August of 2001.

Inferred time scales for flushing

By using the anomalous glut of HSSW as a marker, it is possible to estimate the interval between HSSW entering the sub-ice shelf cavity on the western Ronne Ice Shelf, to the resulting ISW exiting at the Filchner Ice Front, having circulated once around the Filchner Depression. This yields a time scale for ventilation of the cavity.

It is not clear when HSSW originally enters the cavity. Measurements from moorings deployed at the ice front in the Ronne Depression suggest that inflow does not occur until late in the following summer. In that case the glut of HSSW must have traversed the cavity to the Berkner coast rather quickly, for its peak to arrive at Site 5 by April 1999. Another possibility is that the mooring in the Ronne Depression missed the main inflow of HSSW, deployed as it was very near the Antarctic Peninsula coast. If the main inflow occurs in the middle of the depression during the late winter, as suggested by a modelling study by *Jenkins et al* [submitted], the total time for the water to travel to the Berkner coast, around the Filchner Depression and return to Site 5 would be around 26 months.

The route around the Filchner Depression is about 2500 km in length. From Figure 4, the HSSW/ISW appears to complete the journey in around 20 months, suggesting an average speed of about 5 cm s^{-1}. If, after having returned to Site 5, the ISW glut travels back to the Filchner Ice Front at about the same speed, we would expect it to make the 700-km journey in about 5 or 6 months. The ventilation time for the cavity is therefore of the order of 2 to 2.5 years.

Clearly, we have not calculated a true flushing time. Flushing would require the entire content of the cavity to be replaced. Indeed, even as a transit time for HSSW, it is an underestimate, as the speed of propagation of the anomalous glut of HSSW around the cavity would be expected to be anomalously high. However, it provides for the first time a broad estimate that models might seek to reproduce.

It is of particular interest to note that there was no obvious response to the HSSW glut at the Site 3 mooring (Figure 1). The temperature record given in Figure 2 shows that the influx of HSSW recorded at the end of 1998 was not significantly different to previous years. Why this is so remains an open question.

Conclusions

Long-term measurements made beneath Ronne Ice Shelf show that, unlike in the west, the eastern side of the cavity responds strongly to interannual variability. We assuming the high currents measured at Site 5 in early 1999 to be the result of anomalously high HSSW production north of the ice front during the winter of 1998. Based on this assumption we estimate the time interval from HSSW entering the sub-ice shelf cavity in the west to its emerging from beneath Filchner Ice Front as ISW to be 2 to 2.5 years.

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