Physical oceanography studies in the Weddell Sea during the Norwegian Antarctic Research Expedition 1978/79

ARNE FOLDVIK, TOR GAMMELSRØD AND TOR TØRRESEN

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Hydrographic and current measurements obtained during the Norwegian Antarctic Research Expedition 1978/79 to the southern Weddell Sea are presented. Cold, dense Ice Shelf Water circulating under the floating ice shelves is observed to leave the shelf as a concentrated bottom flow. From moored current metres this discharge is estimated at $0.7 \cdot 10^6$ m^3/s at −2.0°C (one year average) and with no appreciable seasonal variation. This contribution to the Weddell Sea Bottom Water is clearly identified through extreme temperature gradients at our deepest stations (below 2500 m). The core of Weddell Deep Water shows a considerable ($T \sim 0.5$°C) warming up since 1977, presumably due to the lack of polynya activity in the intervening period. Measurements in the coastal current at the ice shelf (70°S, 2°W) show step structures which are probably due to cooling and melting at the vertical ice barrier. Slight supercooling due to circulation under the ice shelf is also seen. The net effect of the ice shelf boundary seems to be a deep reaching cooling and freshening of the coastal current providing the low salinity, freezing point Eastern Shelf Water. This process is considered a preconditioning which enhances production of the saline Western Shelf Water which in turn is transformed to Ice Shelf Water.

Arne Foldvik, Tor Gammelsrød and Tor Tørresen, University of Bergen, Institute of Geophysics, Department of Oceanography, N-5000 Bergen, Norway; July 1984 (revised July 1985).

The Norwegian Antarctic Research Expedition 1978/79 (NARE-79) to the Weddell Sea with the icebreaker R/V 'Polarsirkel' was a direct follow-up of the Norwegian Antarctic Research Expedition 1976/77 (NARE-77). Most of the observations were obtained in the southern Weddell Sea, but on the transects some work was done near Bouvetöya (see Foldvik et al. 1981)

One of the main objectives of the physical oceanography programme was to study deep and bottom water formation processes near the shelf region in the southern Weddell Sea. Four current meter moorings, deployed near the continental shelf break in 1977, were successfully recovered. Some results of the current meter registrations, those relating to the formation of bottom water, are presented here. Other results, those relating to shelf waves, have been published by Middleton et al. (1982). We also repeated some of the CTD sections taken in 1977 (see Foldvik et al. 1985, henceforth referred to as POL-77), and obtained additional sections which further improve our knowledge of the distribution of cold bottom water. The positions of the CTD stations and of the current meter moorings are shown in Fig. 1. CTD observations in the coastal current near the floating ice shelf are discussed in the context of watermass transformation.

For a general description of the bathymetry, hydrography and circulation in the survey area we refer to POL-77.

Methods

During this cruise, 81 stations were obtained with a Neil Brown CTD sonde. The computed salinities were calibrated against water samples analysed at the Geophysical Institute, University of Bergen, and showed a r.m.s. error of 0.01 units. Most of the results presented here are 2 m averages of the original data. The data handling was carried out using the University of Bergen computer facilities. The CTD programme package by Røyset & Bjerke (1982) was applied.

For current measurements we used subsurface anchored moorings which were deployed in 1977 and recovered during this cruise. Data were recorded every 60 minutes with Aanderaa current meters.

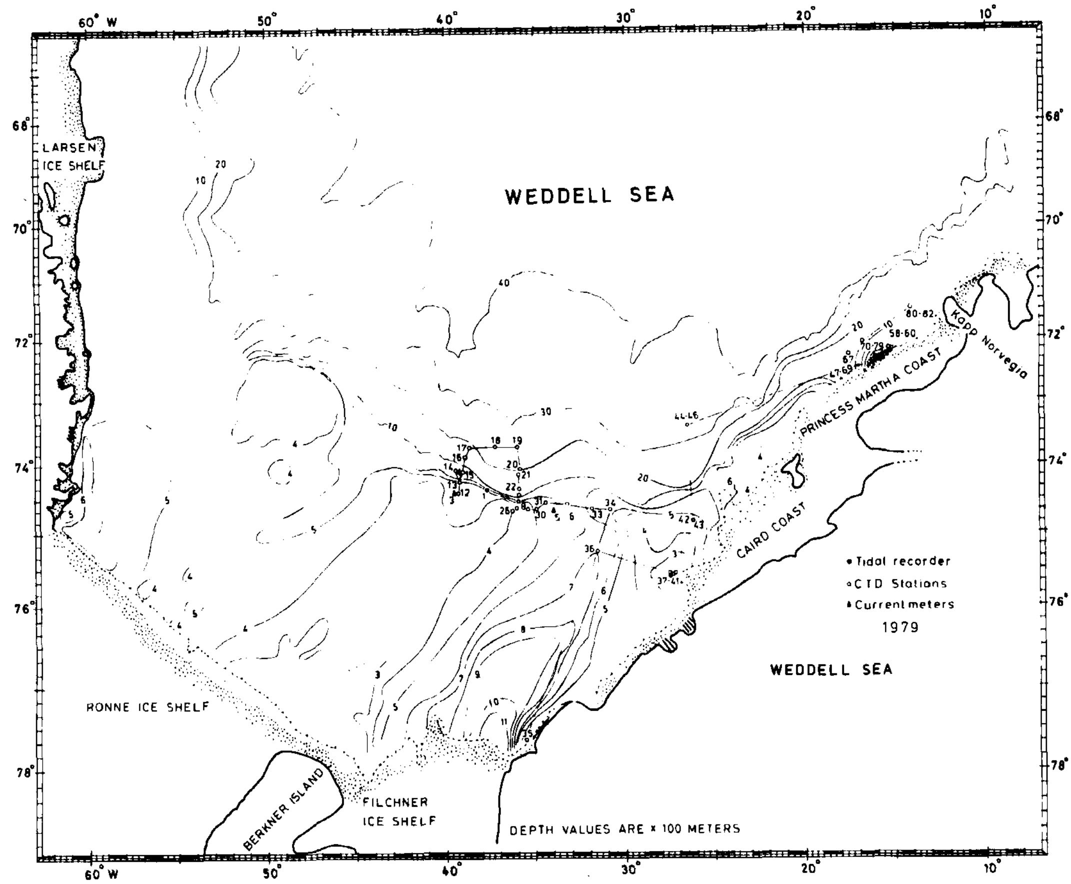


Fig. 1. Map of the southern Weddell Sea. The floating ice shelves are shaded. The CTD stations are marked with open circles and the moorings with solid triangles. Sections are indicated with solid lines.

Investigations on the shelf-break in the southern Weddell Sea

Ice shelf water and bottom water formation

According to Carmack & Foster (1975b) there is a cyclonic circulation at all depths in the Filchner Depression. Dense Western Shelf Water (WSW) formed on the continental shelf north of the Berkner Island drains into the depression where it appears as a saline bottom layer (Carmack & Foster 1975b; POL-77). The WSW then flows underneath the Filchner Ice Shelf where it is cooled to the in situ freezing point (T <-2.2°C) and diluted by melting to form Ice Shelf Water (ISW) (Carmack & Foster 1975b; POL-77). The ISW flows north along the western slope of the Filchner Depression and is seen at station 36 (Fig. 2) as a temperature minimum above the denser and more saline WSW (see also Fig. 12 in POL-77). At the sill of the Filchner Depression ISW is observed as a 150–250 m thick bottom layer (Fig. 3).

The ISW observed on the sill flows down the slope towards the deep ocean (POL-77). Because of its high density and high compressibility (due to its low temperature) the ISW is confined to the bottom, being deflected towards the west under the influence of the coriolis-, gravity- and frictional forces. In the section at 36°W (Fig. 4) we observe the ISW plume at 1500 m depth near station 22, where the potential temperature is as low as -1.93°C. The very strong vertical gradients associated with the plume interface are clearly seen in Fig. 5. At this same section a plume

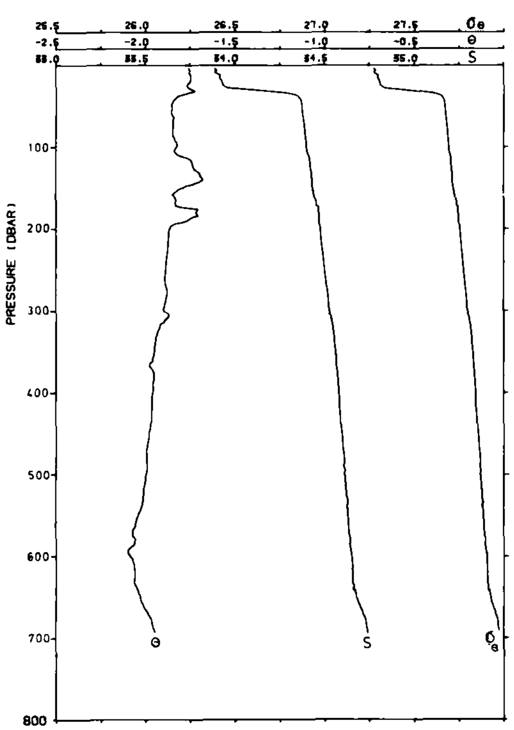


Fig. 2. Vertical profiles of potential temperature (θ), salinity (S), and potential density (σ_θ) for station 36.

was observed in 1977 (Fig. 15 in POL-77) with practically the same core temperature.

The ice prevented us from extending the section at 39°W (Fig. 6) sufficiently northwards to hit the ISW. A temperature minimum (T ~ −1.25°C) near the bottom at station 18 (Fig. 7) indicates that the ISW crosses the 2000 m isobath at about 37°W, in accordance with earlier observations (POL-77).

Fig. 8 shows the position, mean currents and mean temperatures for the current meters recovered on the cruise. One of the moorings (Site 5) was positioned on the sill between stations 31 and 32 (see Fig. 3) and with two instruments located at 25 m and 100 m above the bottom. The mean temperatures for the lower and upper instruments were −2.0°C and −1.9°C, respectively, and except for a few warm events (Fig. 9a, b) the temperature was consistently below the surface freezing point. Thus the instruments monitored ISW flow for more than one year.

The plots of the current components (Fig. 9a, b) show an oscillation in the current speed with a period of about 12 days. This oscillation is not present in the current direction, which is northwesterly most of the time (Fig. 10). Fig. 9b indi-

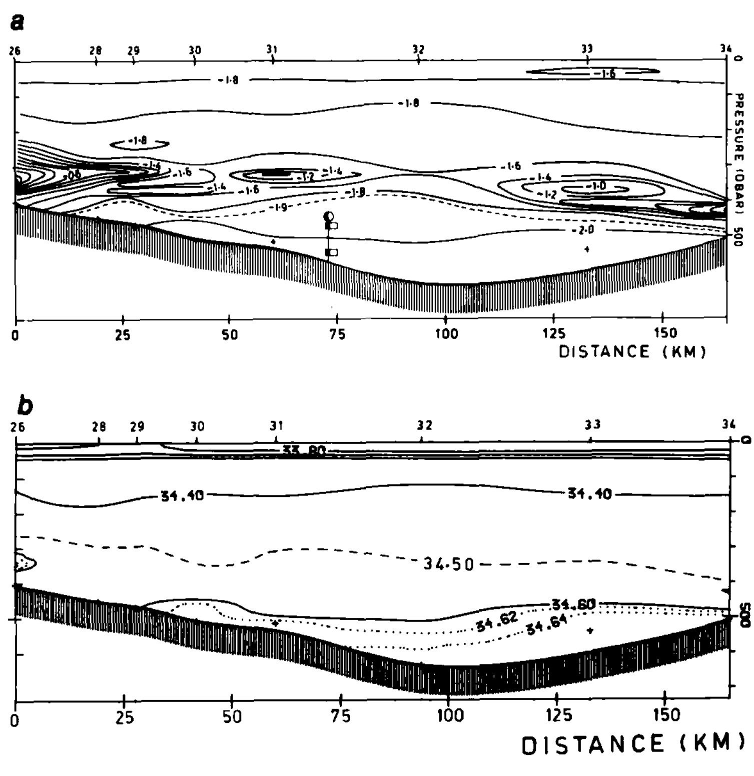
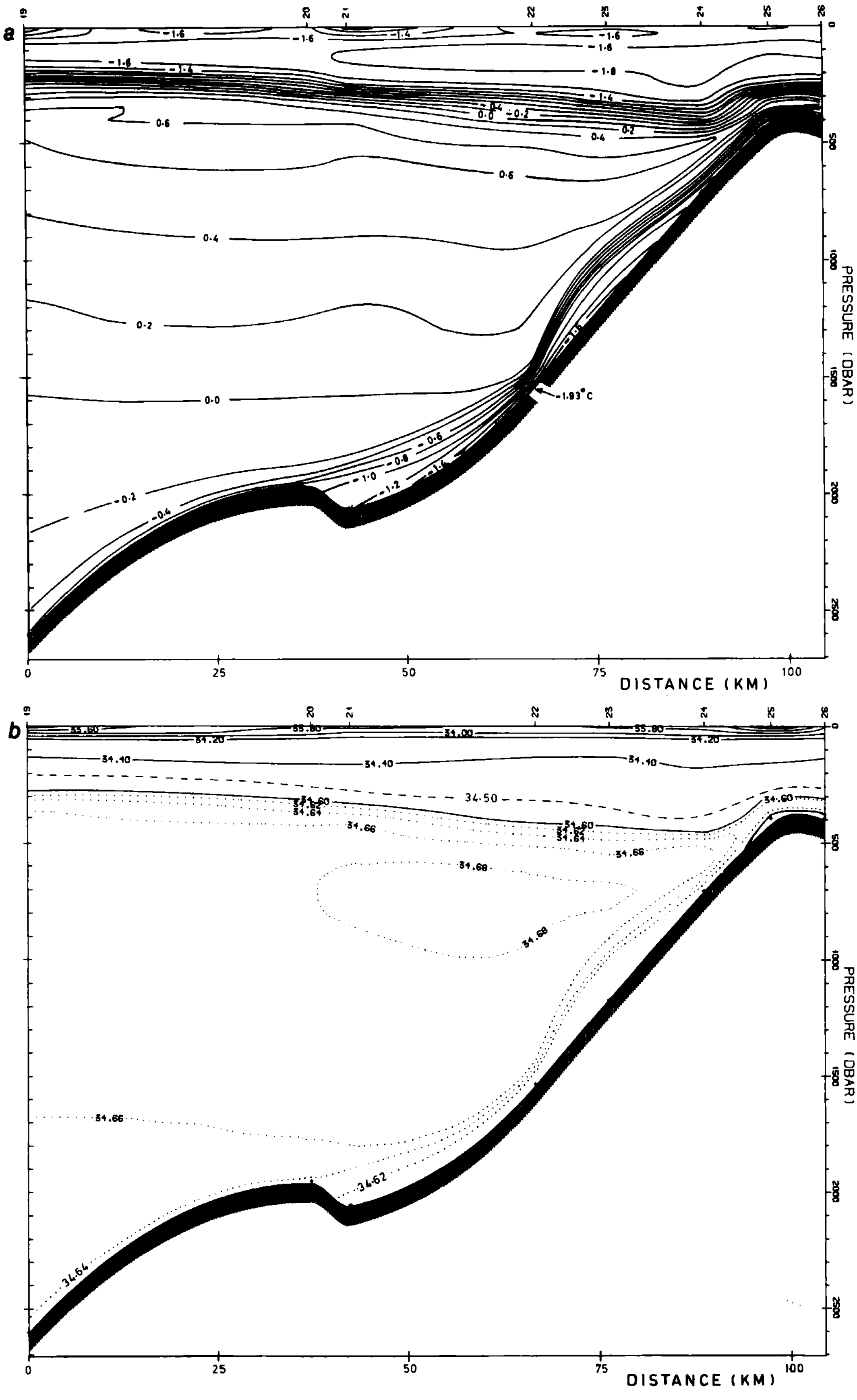


Fig. 3. Section along the sill of the Filchner Depression from west to east (stations 26 and 28–34). a. Potential temperature (°C); b. Salinity. The current meter mooring at Site 5 is marked in the potential temperature section.



a
-1.93°C
PRESSURE (DBAR)
DISTANCE (KM)
b
34.50
34.60
34.66
34.68
34.62
34.64
PRESSURE (DBAR)
DISTANCE (KM)

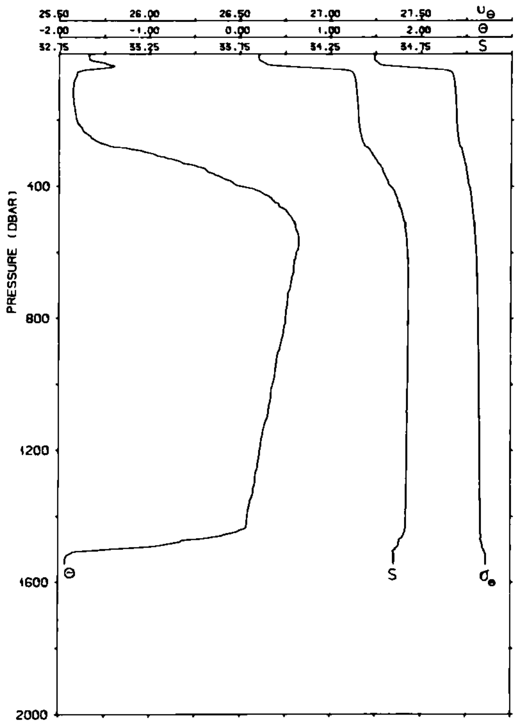


Fig. 5. Vertical profiles of potential temperature (θ), salinity (S) and potential density (σ_θ) for station 22.

cates that these variations are smaller in the winter and spring than in the summer and autumn, but it is difficult to see any seasonal variations in the monthly averages (Fig. 10). A rough estimate of the internal eigen frequencies of the Filchner Depression accords well with the assumption that the observed 12-day period is related to internal seiches.

From Fig. 3 the cross-section area of ISW is about 15 km^2. Assuming that this is representative for the yearly average and adopting the mean current speed normal to the section as 0.05 m/s, we find that ISW leaves the shelf-break at the rate $0.7 \cdot 10^6$ m^3/s.

The amount of Weddell Sea Bottom Water produced due to mixing of the ISW plume with the overlying WDW depends on the detailed processes of entrainment. A very conservative estimate of WSBW formation is obtained by mixing approximately equal parts of ISW and core WDW (at 0.5°C), thus producing $1.4 \cdot 10^6$ m^3/s of Weddell Sea Bottom Water. However, the temperature of entrained WDW is lower than its core value (see Fig. 4), and the resultant production of WSBW may well be comparable to the $2\text{-}5 \cdot 10^6$ m^3/s estimated by Carmack & Foster (1975a).

The relative importance of this direct process of bottom water formation to other processes, viz. shelf-break mixing (Foster & Carmack 1976) is not clear. Also, additional sources of ISW may be located at the western part of the Weddell Sea continental shelf.

Weddell Deep Water

The core of warm, saline Weddell Deep Water (WDW) is found around 400–500 m at stations 17-19 (Fig. 7). At 39°W (stations 12-17, Fig. 6) the high temperature WDW is observed on the deep stations only, but at 36°W (stations 19-26, Fig. 4) this water intrudes on the shelf. Even on the southernmost station (station 26) at 36°W the temperature is as high as 0.5°C at 340 m depth. In the east–west section on the sill (Fig. 3) a temperature maximum is found on most stations at 300–400 m depth, but the temperature never exceeds 0°C east of station 26. The POL-77 sections at 36°W, 37° 30′W and 39°W also show that the preferred location for intrusion of WDW upon the shelf is at 36°W. Further west Foster & Carmack (1976) observed a similar intrusion of WDW at 40°W.

Two stations (27 and 28, Fig. 11) taken with only 15 minutes interval demonstrate how intense the intrusion activity is. During this short time-span the temperature at 375 m changed by more than 1.5°C. The abrupt front-like variability at the shelf-break is also seen in Fig. 12, where the hourly temperatures over a 6-week period at Site 5 are presented.

The 1979 data presented here show one striking difference over the 1977 data (POL-77), viz. the temperature of the WDW in the slope sections is some 0.5°C warmer in 1979 than in 1977. Investigations by Gordon (1982) indicate that this is not a local phenomenon near the shelf-break, but rather a major 'climatic' change in the warm Weddell Deep Water which may be related to the occurrence of the Weddell Polynya (Martinson et al. 1981). Thus 1977 was an anomalous cold WDW year.

Fig. 4. Section across the shelf at 36°W (stations 19–26). a. Potential temperature (°C); b. Salinity.

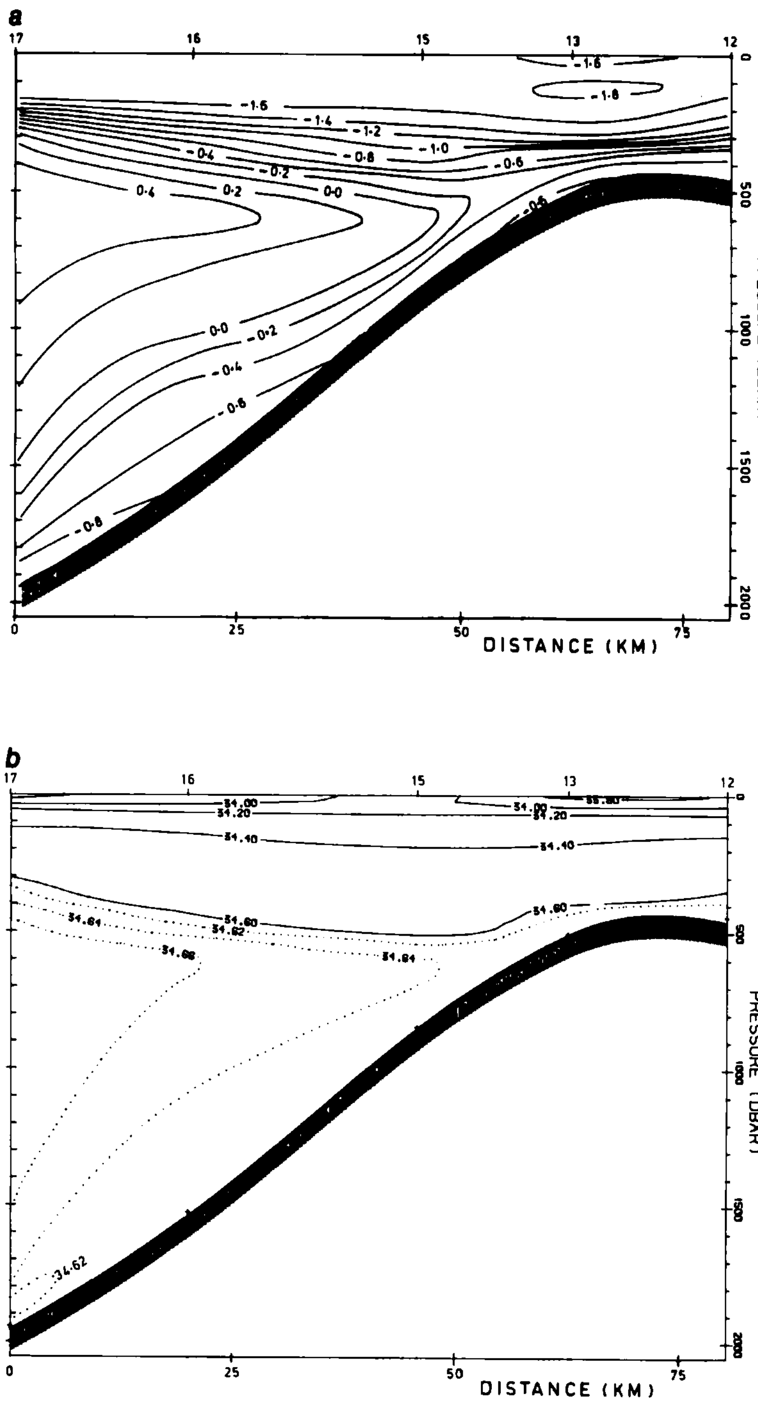


Fig. 6. Section across the shelf at 39°W (stations 12, 13 and 15–17). a. Potential temperature (°C); b. Salinity.

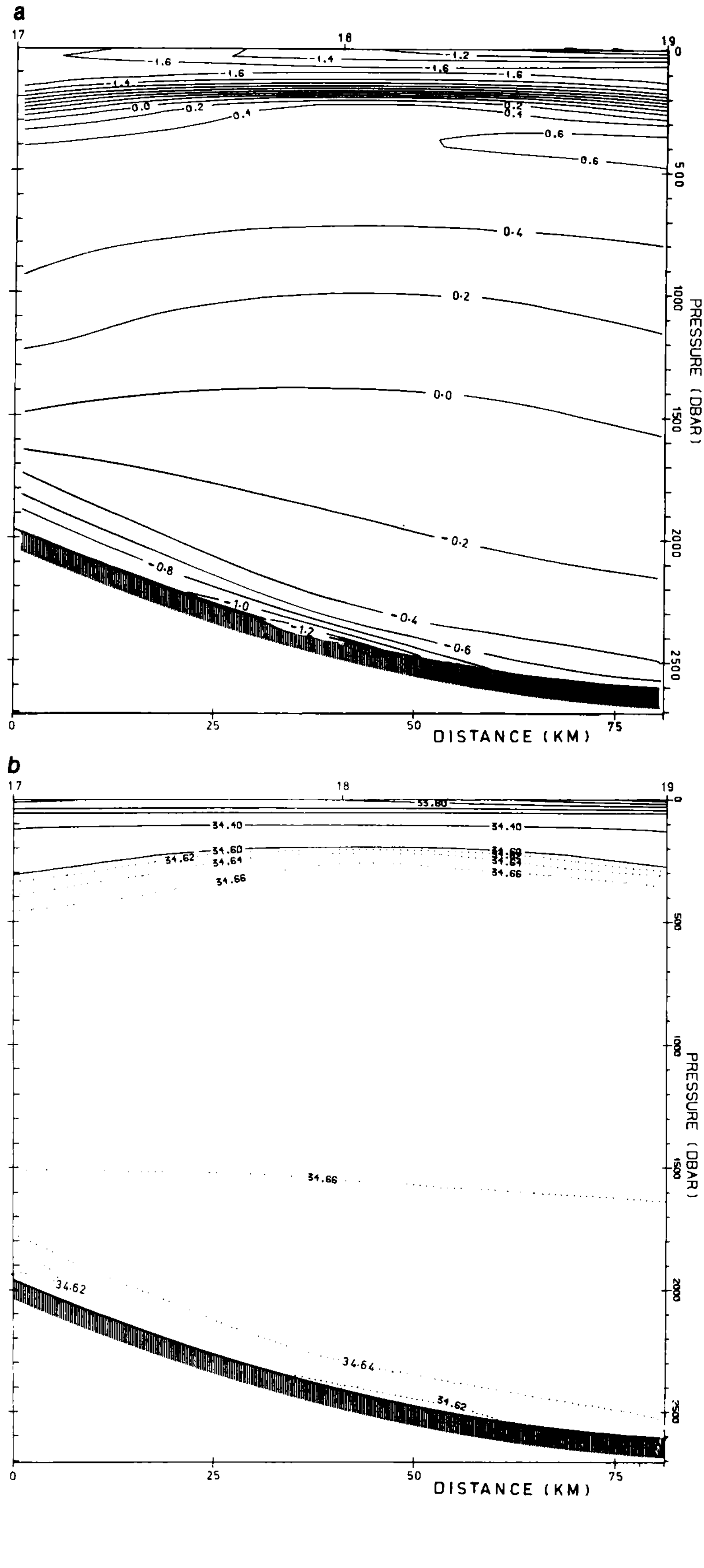


Fig. 7. Section parallel to the shelf-break at 2500 m depth from 36°W to 39°W (stations 17–19). a. Potential temperature (°C); b. Salinity.

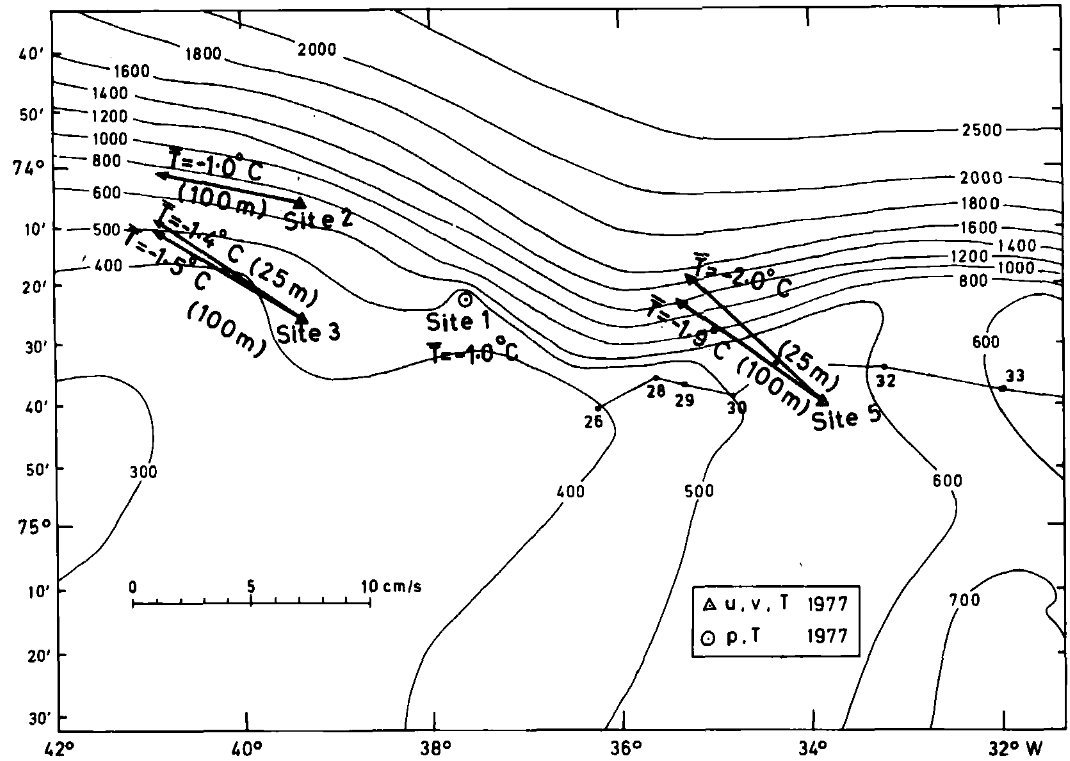
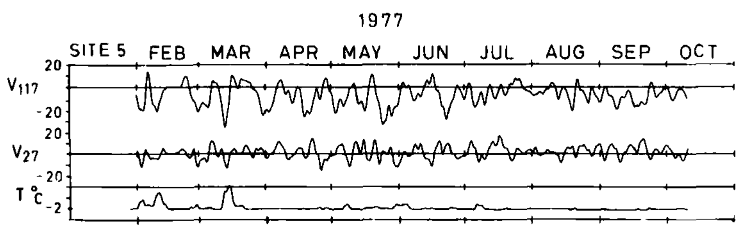


Fig. 8. The positions of the current meter moorings are marked with triangles and the positionings of the instruments above the bottom are given in parentheses. The mean current speed and direction are represented by arrows and the mean temperature is given. The section shown in Fig. 4 is marked with filled circles.



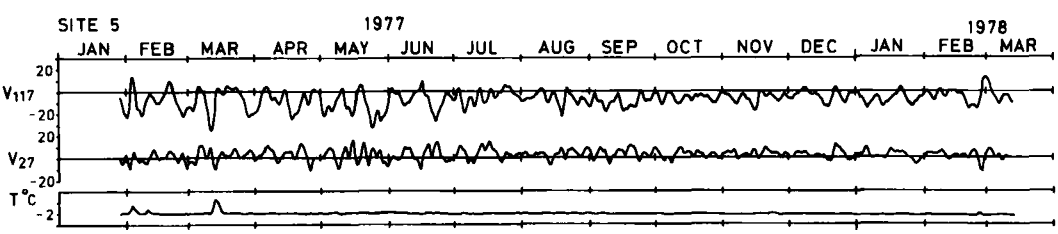


Fig. 9. Low pass filtered series of U, V and T from mooring site 5. The coordinate system is rotated +27° (clockwise). a. Instrument 2172 (100 m above the bottom); b. Instrument 2174 (25 m above the bottom).

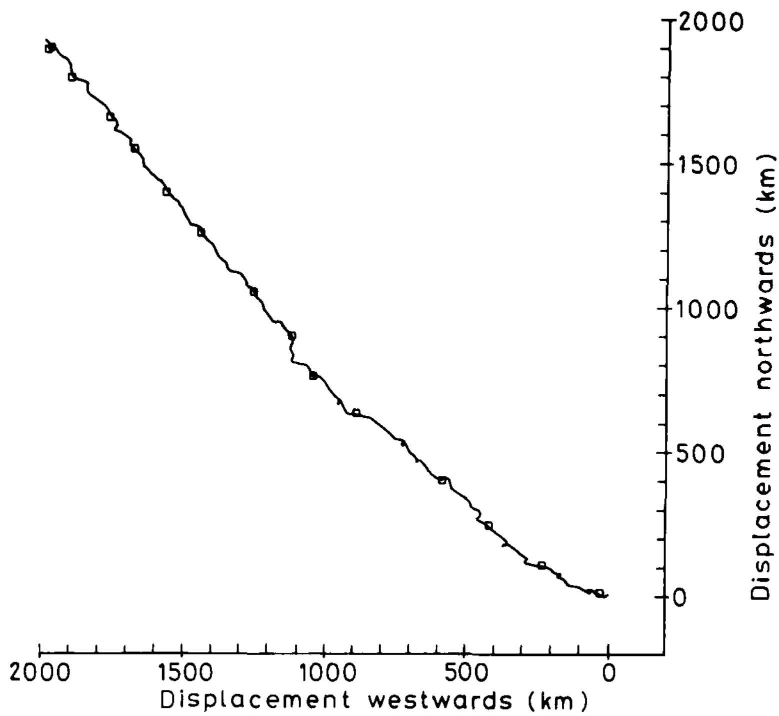


Fig. 10. Progressive vector diagram from instrument 2174, Site 5 (25 m above the bottom). The beginning of each month is indicated with a square, starting with February 1, 1977, in the lower right corner.

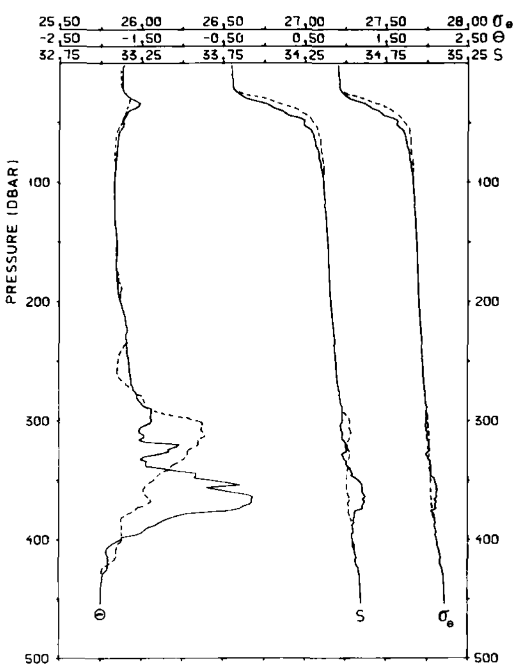


Fig. 11. Vertical profiles of potential temperature (θ), salinity (S), and potential density (σ_θ) for stations 27 (solid line) and 28 (broken line). The two profiles are from the same location with only 15 minutes time difference.

Interaction between the Antarctic Coastal Current and the floating Ice Shelf

The floating Antarctic Ice Shelf defines the southern boundary of the Weddell Sea surface circulation and exerts some influence on the surrounding waters, in particular on the westward flowing coastal current. An attempt was made to study the nature of this ice-ocean interaction near the Fimbul Ice Shelf (70°S, 2°W). An example of the water masses encountered in the area is given in Fig. 13. This CTD station was obtained in the coastal current some 2 km outside the ice shelf and shows a 100 m thick surface layer which is formed in summer due to heating, melting and mixing. Below the surface layer is a thick (~ 400 m), cold layer which has the temperature and salinity characteristics of Eastern Shelf Water (see Foster & Carmack 1976). This cold water in the westward flowing coastal current is probably Weddell Sea Winter Water (WW) which is being modified by melting and cooling at the ice shelf. A typical thickness of WW in the open ocean is 200 m, and the increased thickness observed here is due to the wedge form of the Antarctic Coastal

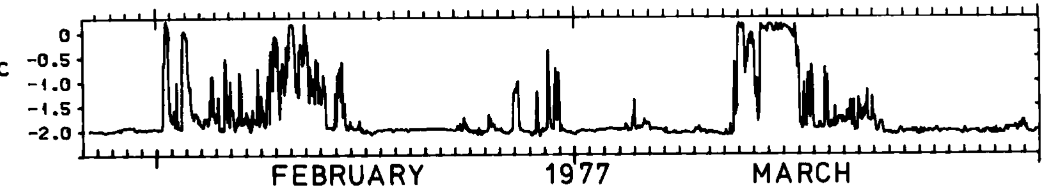


Fig. 12. Hourly observations of temperature at 100 m above the bottom, Site 5, Jan.-March, 1977.

Current (Sverdrup 1953; Gill 1973). Below the transition zone at 600 m there is the core of the warm Weddell Deep Water (WDW) which is found around this level over most of the Weddell Sea (Gordon 1982).

Station 10 (Fig. 14) was taken as close as possible to the ice shelf (we actually made the CTD sonde slide down the ice-foot). This station reveals a pronounced step structure in the upper 100 m. Since the general stratification here is stable in both temperature and salinity these steps are not produced by double diffusion. It is tempting to associate the steps with the mechanism of cooling at the nearly vertical ice wall. This explanation is supported by the observation that the layer thickness is approximately inversely proportional to the stability, in accordance with the experimental results of Huppert & Turner (1980).

Fig. 15 shows a section taken parallel to the ice shelf with all the stations within a few hundred metres from the shelf. It is seen that a step structure exists but that it is not equally well established at all stations. A section normal to the ice edge (Fig. 16) gives the impression that the step structure diminishes with increasing distance from the shelf.

In Fig. 16 we also note some warm and salty anomalies below 300 m depth. These are interpreted as intrusions of Weddell Deep Water. Note that in Fig. 16 the water is potentially

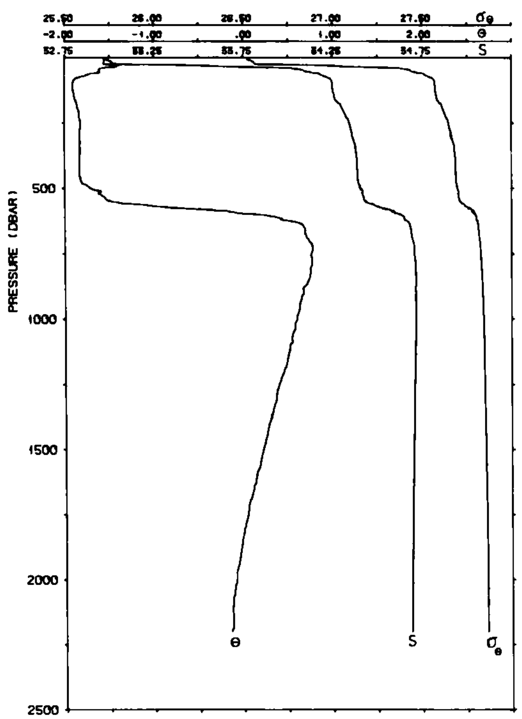


Fig. 13. Vertical profiles of potential temperature (θ), salinity (S), and potential density (σ_θ) for station 6.

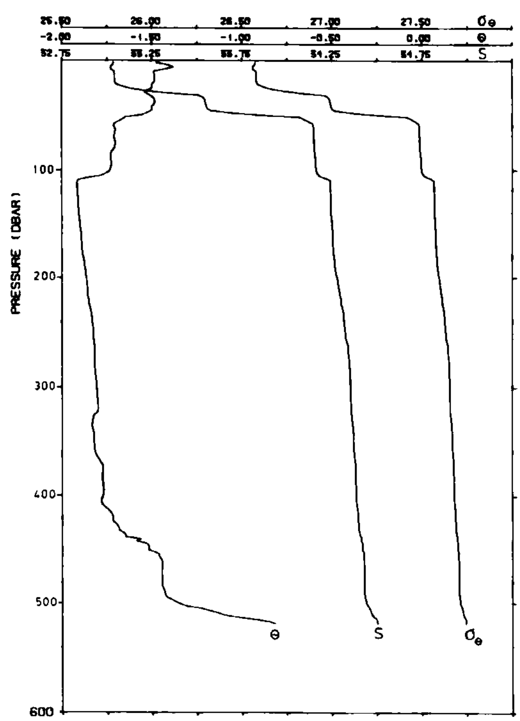


Fig. 14. Vertical profiles of potential temperature (θ), salinity (S), and potential density (σ_θ) for station 10.

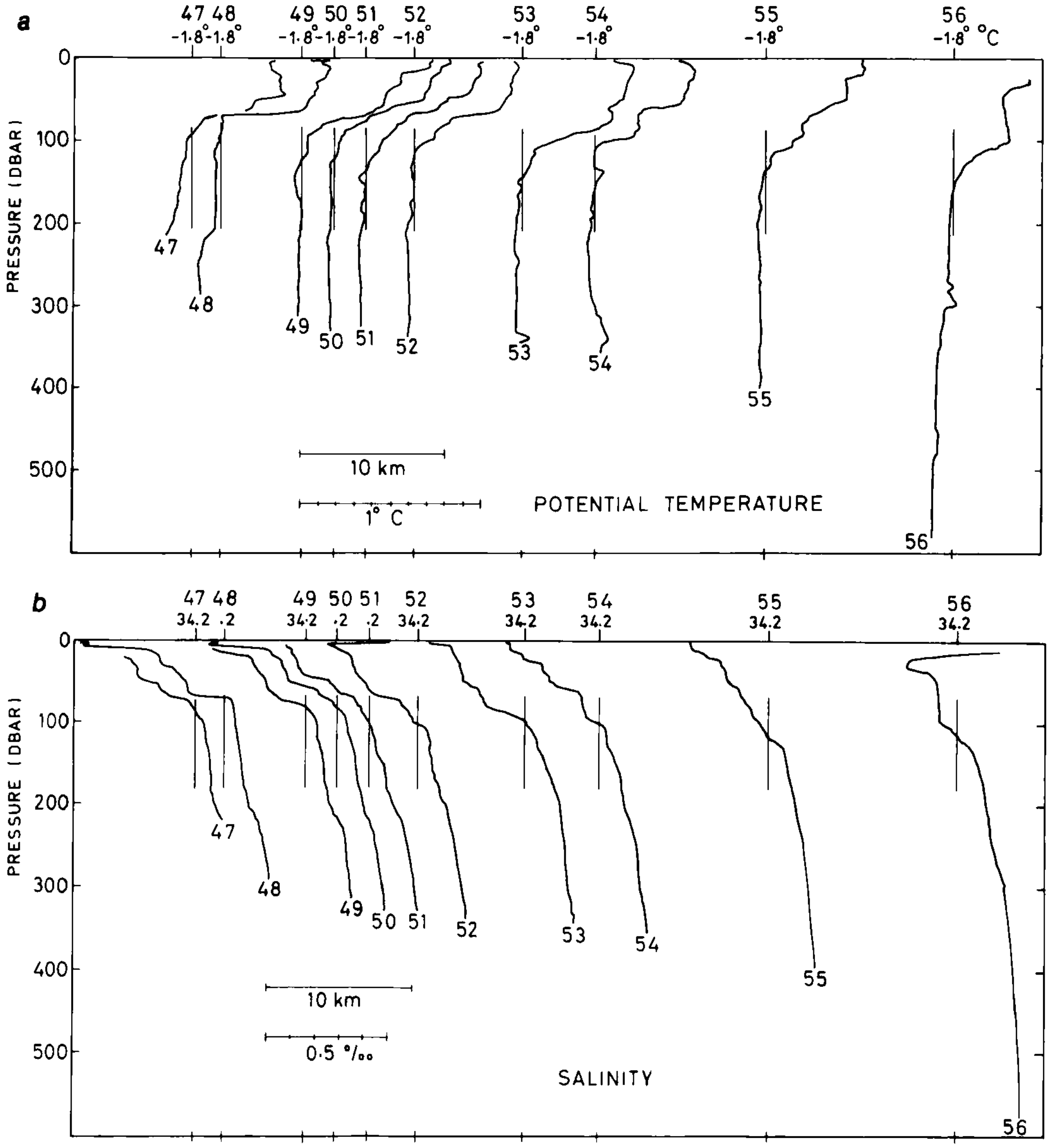


Fig. 15. Vertical profiles of potential temperature (a) and salinity (b) for stations 47–56, a section along the ice barrier from 16°W to 15°W. For each profile the −1.8°C isotherm and the 34.2 isohaline, respectively, are positioned according to the observed distance along the ice barrier.

supercooled below about 300 m depth which shows that the water has been cooled in contact with the underside of the floating ice shelf.

The new effect of these interactions between the ice shelf and the coastal water seems to be that of producing a deep (500-600 m) homogeneous layer near its freezing point. This so-called Eastern Shelf Water participates in the cyclonic circulation towards the Berkner Shelf where its transformation towards high salinity Western Shelf Water presumably takes place through the processes of surface freezing and sea-ice divergence (Gill 1973). This 'preconditioning' of the coastal water by the ice shelf provides for

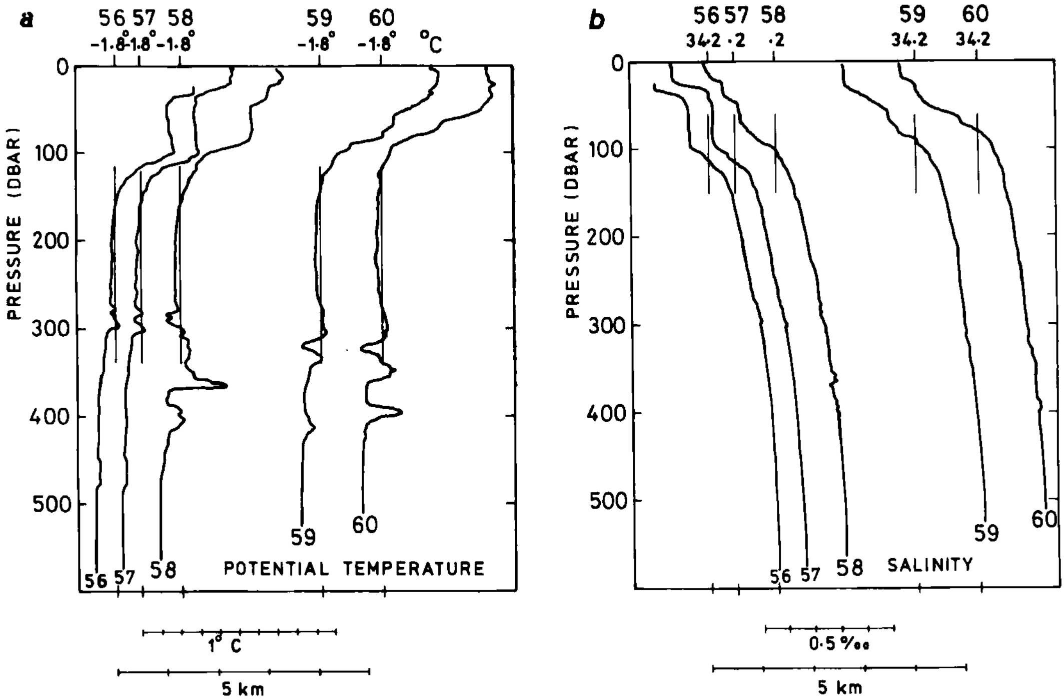


Fig. 16. Vertical profiles of potential temperature (a) and salinity (b) for stations 56–60, a section normal to the barrier at 15°W. For each profile the −1.8°C isotherm and the 34.2 isohaline, respectively, are positioned according to the observed distance from the ice barrier.

the most efficient use of the energy available for WSW production. As an example, consider a 300 m thick column of ESW at its freezing point and with salinity 34.4 (see Fig. 16). The freezing of 3 m of ice will liberate enough salt to produce WSW at salinity 34.7. On the other hand, the energy needed to cool a 300 m thick layer by, say,

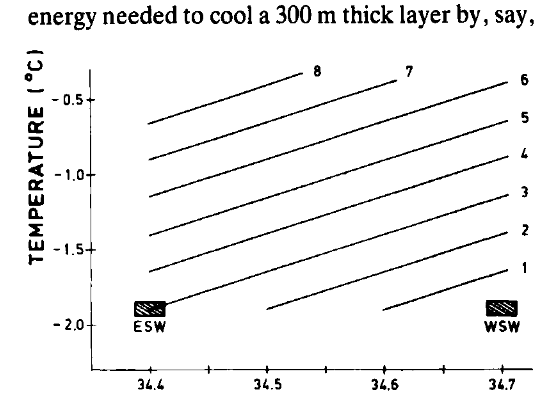


Fig. 17. The isolines indicate the amount of energy to be removed from a 300 m thick water column by freezing and/or cooling in order to obtain the θ, S characteristics of Western Shelf Water (WSW). Units are expressed in metres of ice frozen at the surface.

1°C, is equivalent to the freezing of 4 m ice at the surface. Thus, even relatively saline Modified Weddell Deep Water will require a higher surface energy loss than will ESW in order to produce WSW.

The preconditioning of the coastal water by the ice shelf may be looked at as the first important water transformation process in the chain of processes leading to the formation of Weddell Sea Bottom Water.

Summary

The cold, dense Ice Shelf Water which is formed from Western Shelf Water by cooling at the underside of the floating Filchner Ice Shelf, is found to overflow at the still of the Filchner Depression. One year of current meter observations at the sill show no appreciable seasonal signal, and the average discharge of ISW is estimated at $0.7 \cdot 10^6$ m^3/s at −2.0°C. Due to its high compressibility (low temperature) this water sinks towards the deep Weddell Sea basin continuously mixing with the surrounding warm WDW. At our deepest stations (2500 m) this cold water is observed as a bottom trapped lens with extreme temperature gradients. The resultant contribution to the newly formed Weddell Sea Bottom Water is presumably within the estimates of the total production of Weddell Sea Bottom Water (2-5 $\cdot 10^6$ m^3/s) given by Carmack & Foster (1975a).

The Weddell Deep Water was approximately 0.5°C warmer in 1979 than in 1977 (FGT-77). Comparisons with other observations (Carmack & Foster 1975a; Gordon 1982) show that this WDW was exceptionally cold in 1977, and thus the 1979 warming represents a return back to 'normal'. If the Weddell Polynya activity creates these large fluctuations then the apparent warming from 1977 to 1979 accords with the lack of observed polynyas in that period.

CTD casts near the floating Fimbul Ice Shelf revealed a step structure in temperature and salinity which is presumably due to cooling at the nearly vertical ice barrier. The observations also indicate cooling/melting at the underside of the ice shelf. The net result of these thermohaline processes in conjunction with mixing due to wind and tides near the barrier is the formation of a deep layer of freezing point, low salinity Eastern Shelf Water. This water is readily turned into Western Shelf Water by surface freezing.

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