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# Formation and discharge of deep and bottom water in the northwestern Weddell Sea

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## ABSTRACT

Deep and bottom water formation in the Weddell Sea is the major source of the bottom water of the world ocean. Measurements made in the northwestern Weddell Sea between 1989 and 1993 during the 'Weddell Gyre Study' indicate that the outflow of young bottom water with the western boundary current of the Weddell Gyre is dominated by a rather fresh water mass which obtains its thermohaline characteristics by mixing of deep water with a flow from the shelf in front of the Larsen Ice Shelf. The more saline source water mass, which is necessary to maintain the thermohaline properties of the Weddell Sea Deep Water, is less prominent in the bottom water outflow. The transport of bottom water with the western boundary current of the Weddell Gyre ranges from 1 to 4 $10^6$ $m^3s^{-1}$. The outflow is subject to a seasonal cycle with minimum temperatures and maximum velocities in early austral winter.

## 1. Introduction

Renewal of the abyssal waters in vast areas of the global ocean comes about through the formation of Antarctic Bottom Water, representing the densest of the major oceanic water masses (e.g. Wüst, 1935; Deacon, 1937; Lynn and Reid, 1968; Mantyla and Reid, 1983). From its source regions around Antarctica, the Antarctic Bottom Water spreads along the bottom, and can be traced as far northward as to about 50N in the eastern Atlantic by its thermohaline characteristics and other chemical constituents (e.g. Broecker and Peng, 1982). The volume flux of Antarctic

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Bottom Water from the Southern Ocean to the north is estimated (Stommel and Arons, 1960; Gill, 1973) to be of about 20 Sv (1 Sv = $10^6$ $m^3$ $s^{-1}$), taking into account the entrainment of overlying water masses.

The main formation area of those dense source water masses which determine the uniqueness of the Antarctic Bottom Water is the Weddell Sea where 50 to 90% of the total Antarctic Bottom Water obtain their characteristics (Carmack, 1977; Foldvik and Gammelsrød, 1988). Formation in the Weddell Sea is favored by the large-scale cyclonic Weddell gyre circulation (for the most recent descriptions see Orsi *et al.,* 1993; Fahrbach, 1993; Fahrbach *et al.,* 1994b). It carries relatively warm and saline water masses from the Antarctic Circumpolar Current southward into cold polar regions where they loose heat and gain density. Transformed dense water masses are transported back to the north in a western boundary current clinging to the continental slope off the Antarctic Peninsula. At the northern tip of the Antarctic Peninsula the flow turns eastward into the northern periphery of the Weddell Gyre. The newly formed dense water masses follow this eastward turn of the flow (e.g. Foster and Carmack, 1976a; Orsi *et al.,* 1993), and may then escape from the northern periphery of the gyre through topographic clefts (e.g. Carmack and Foster, 1975b; Nowlin and Zenk, 1988; Locarnini *et al.,* 1993) to the more northern deep ocean basins (Reid *et al.,* 1977; Reid, 1989; Whitworth *et al.,* 1991). Partly they may spread to the south, descending to the Weddell Abyssal Plain (e.g. Carmack and Foster, 1975b; Orsi *et al.,* 1993).

Production of dense water is supposed to occur preferably on the broad continental shelf in the southwestern part of the Weddell Sea where water not only is cooled to its freezing point by contact with the atmosphere, but also increases its salinity due to the accumulation of brine rejected during freezing of sea ice (Brennecke, 1921; Mosby, 1934; Gill, 1973). Once the water on the shelf has become dense enough by cooling and brine release, it may spill over the shelf edge and, entraining overlying water masses, flow down the continental slope until being deflected to the left by the Coriolis force and being incorporated to the gyre circulation (Killworth, 1977). Water drawn underneath the ice shelves may cool down to the *in-situ* freezing point at increased pressure, i.e. to below the freezing temperature at surface pressure and emanate as a supercooled plume as observed in front of the Filchner-Ronne Ice Shelf (Carmack and Foster, 1975a; Foster and Carmack, 1976b; Foldvik *et al.,* 1985; Foster *et al.,* 1987).

The plume descending the continental slope which finally provides new Weddell Sea Bottom Water consists of a mixture of the dense shelf water, notably the Western Shelf Water, with different other water masses: with relatively warm and saline Warm Deep Water advected from the north at intermediate depths and cold and rather fresh Winter Water on its top which meet and mix with shelf water at the shelf edge (Gill, 1973; Foster and Carmack, 1976b; Foster *et al.,* 1987), and with Weddell Sea Deep Water or Antarctic Bottom Water occupying the strata below the Warm

Deep Water through which the plume has to descend to ultimately reach the deep basin floor. The Weddell Sea Bottom Water occurring at abyssal depths then represents one end member of the mixing line with Warm Deep Water along which the thermohaline properties of the Antarctic Bottom Water are distributed (Gill, 1973; Foster and Carmack, 1976a). The term 'Antarctic Bottom Water' is thus somewhat confusing in the Weddell Sea (as pointed out before by Reid *et al.*, 1977) as it is not a bottom water mass and the use of the term Weddell Sea Deep Water is more appropriate.

The present study is based on data collected between 1989 and 1993 during the Weddell Gyre Study undertaken with RV *Polarstern*, consisting of CTD (conductivity-temperature-depth) sections and measurements of current velocity and temperature obtained from moored instruments. The CTD sections cross the tongue of dense bottom water at different latitudes along its downstream motion along the continental slope off the Antarctic Peninsula, partly in regions rarely sampled before because access by ship usually is hindered by severe ice cover. The analysis of these measurements reveals two types of dense bottom water which can be related to different formation processes or areas on the shelf, and contributes to a better understanding of the modifications these source water masses undergo while descending down the continental slope and being carried downstream until they come in contact with the world ocean at the northern periphery of the Weddell Gyre.

## 2. The data set

The data set collected during the Weddell Gyre Study contains three sections which cross the outflow tongue by extending from the shelf off the Antarctic Peninsula into the deep basin (Fig. 1a). The southernmost transect reaches the shelf edge at 68° 55′ S, 56° 17′ W in front of the Larsen Shelf Ice, the middle transect at 63° 25′ S, 52° 32′ W off Joinville Island and the northernmost transect at 61° 54′ S, 43° 07′ W off the South Orkney Islands. The distances between these transects, measured along the shelf edge, are 630 km from the Larsen-Ice-Shelf section to the Joinville-Island section and 510 km from the Joinville-Island section to the South-Orkney-Islands section. The Joinville-Island section which runs from the Antarctic Peninsula across the Weddell Sea toward its eastern margin off Kapp Norvegia was occupied three times, first during the "Winter Weddell Gyre Study" in September and October 1989 (Augstein *et al.*, 1991), second during the "Summer Weddell Gyre Study" in November and December 1990 (Fahrbach *et al.*, 1992), and third during the "Sommer Weddell Wirbel Studie" in December 1992/January 1993 (Fahrbach *et al.*, 1994a).

Distributed along the transects, full-depth vertical profiles of temperature and conductivity were measured with CTD (Conductivity-Temperature-Depth) probes of type NBIS Mark IIIb. The spacing between these hydrographic stations was 40 to 70 km in the interior of the basin and 10 km over the continental slopes. The probes

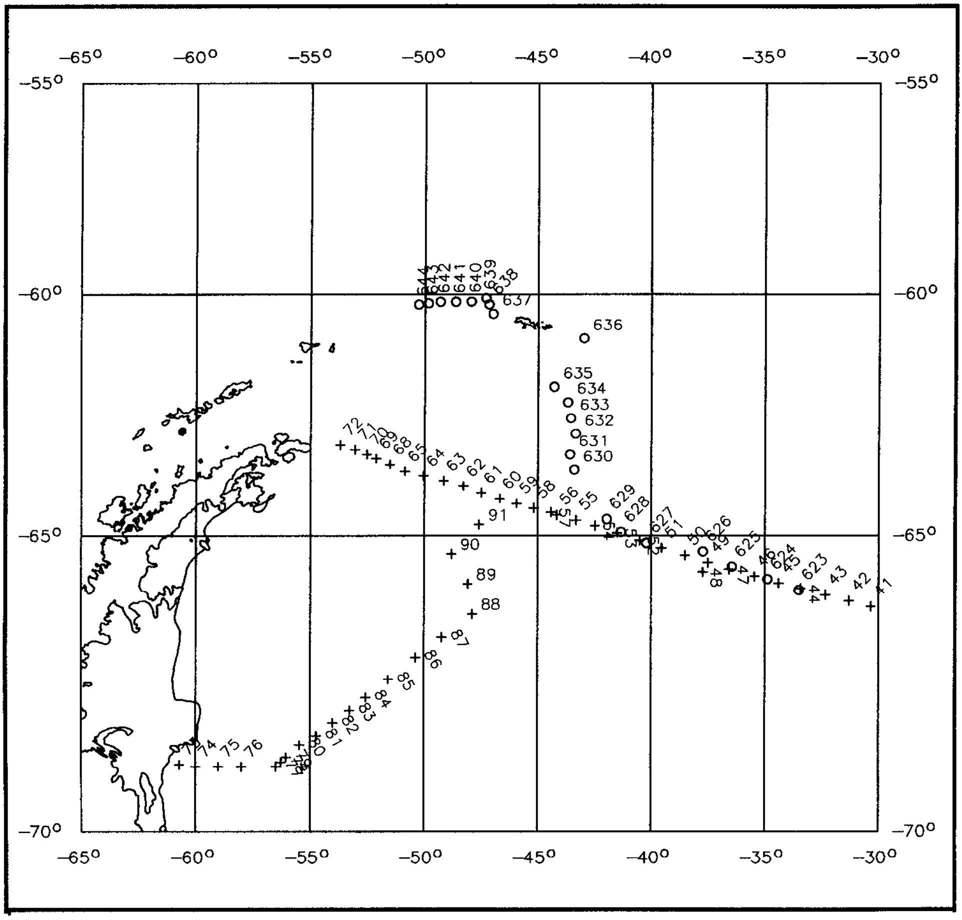

Figure 1. Location of the CTD-profiles on the transects off Joinville Island, the Larsen Ice Shelf and the South Orkney Islands (a), the location of the CTD-transect and the current meter moorings between Joinville Island and Kapp Norvegia (b) and the location of the instruments in the moorings from December 1990 to December 1992 (c). Aanderaa current meters (dots), ACM-2 (squares), Aanderaa thermistor cables (bars), Aanderaa water level recorder (triangle), upward looking sonars (rhombs), sediment traps (open triangles), ADCP (open circle). The depth contours are taken from GEBCO 5.18 and modified according the soundings obtained during Ice Station Weddell 1 and 'Polarstern'-cruise ANT X/7 (H. Hinze pers. com.).

were calibrated before and after the cruises by the Scripps Institution of Oceanography for temperature and pressure. During the cruise the performance of the instruments was controlled through simultaneous measurements with digital thermometers and pressure meters as well as with protected and unprotected mercury thermometers. Furthermore, water samples were taken at up to 24 depths at each station for salinity determinations with a salinometer type Guildline Autosal 8400A.

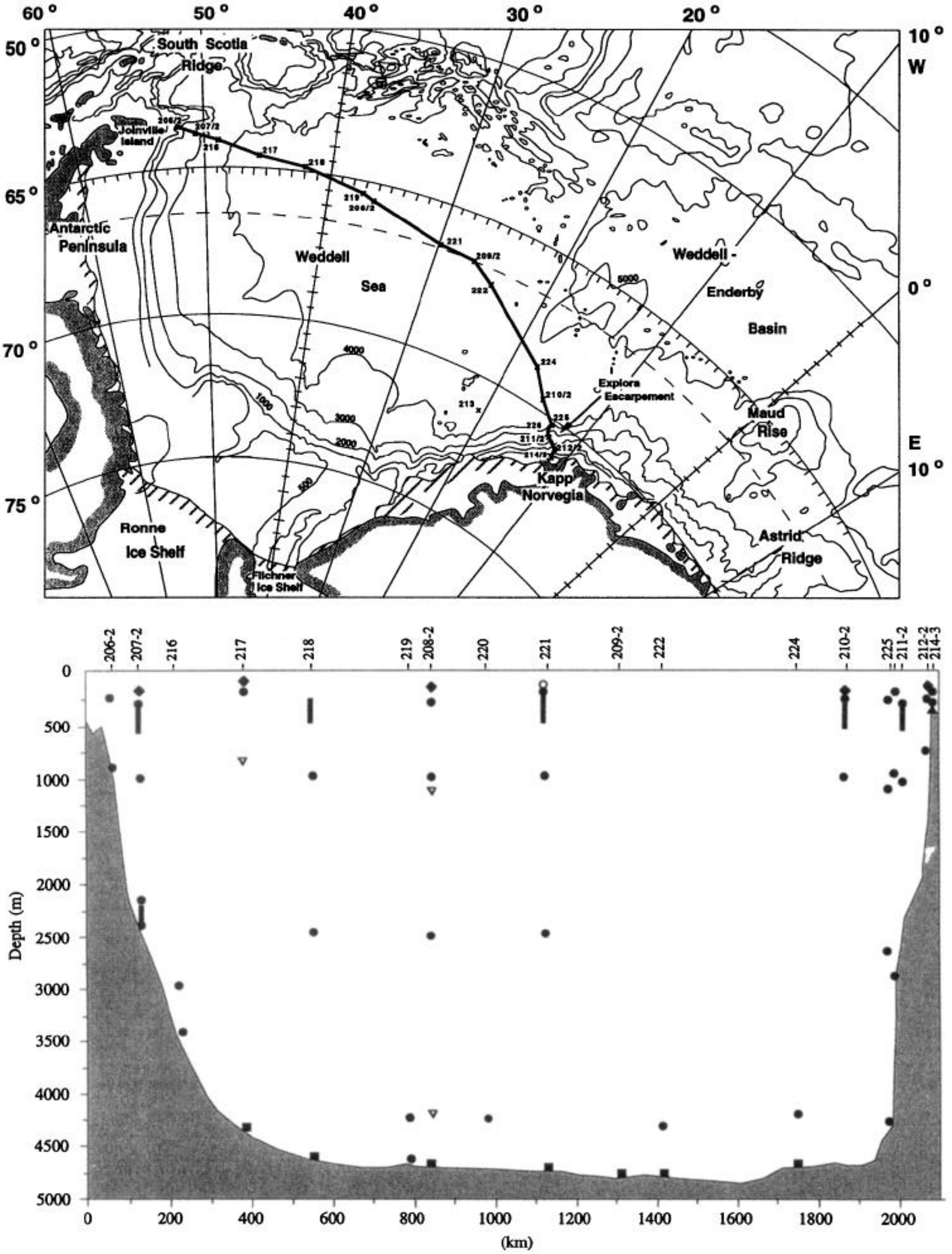

Figure 1. (Continued)

The salinity profiles calculated from the CTD measurements were adjusted to fit the salinity values determined from the water samples. After application of all corrections, the accuracy of the CTD data from below the thermocline is better than 0.003 in salinity, 3 mK in temperature, and 3 db in pressure. The salinities are given by use of the Practical Salinity Scale.

$^{18}O/^{16}O$ ratios ($\delta^{18}O$) of all sea water samples were determined at the Alfred-Wegener-Institut in Bremerhaven. For the oxygen isotope preparation of $H_2O$ 7 ml water were equilibrated with 0.26 mmol $CO_2$ by using a self constructed automated preparation system. Isotope equilibrium in the $CO_2$-$H_2O$ system was attained by intensive shaking the $CO_2/H_2O$-mixture over 400 minutes at 21.0°C. The equilibrated $CO_2$-gas was purified in a cooling trap (−90°C) and subsequently transferred to an on-line connected Finnigan Delta-S mass spectrometer. Isotope preparation and stable isotope measurement were calibrated twice against V-SMOW and V-SLAP standard waters. The total accuracy for the $\delta^{18}O$ determinations of all water samples is better than 0.03 per mil. In order to facilitate a better comparison all bottom water samples were remeasured in one single batch. These double determinations confirmed the first results and assured the precision of the measurements.

During the first *Polarstern* survey in September and October 1989 8 moorings with 26 current meters were deployed along the 2100 km long transect between the Joinville Island on the northern tip of the Antarctic Peninsula and Kapp Norvegia (Augstein *et al.*, 1991). These moorings were recovered in November and December 1990, when a new set of 21 moorings was also laid (Fahrbach *et al.*, 1992). From the second set, 18 moorings were recovered in December 1992 and January 1993 (Fahrbach *et al.*, 1994a). The distribution of the moorings along the transect and the placement of the instruments are indicated in Figures 1b and c. Due to problems with the power consumption of the Aanderaa current meters most instruments have not recorded for the whole period of two years of the second deployment, but only for one year. Additional data were obtained from three moorings with eight current meters which were deployed during the European Polarstern Study (EPOS) in February 1989 (Arntz *et al.*, 1990) and recovered in February 1990. One mooring (213) was deployed south of the main transect from February 1990 to February 1991.

The full data set collected during the three years comprises the measurements of 61 current meters, 54 of which were RCM4/RCM5 and RCM7/RCM8 type current meters from Aanderaa Instruments. The Aanderaa current meters were serviced and calibrated by the manufacturer before deployment. The remaining seven current meters were acoustically operating devices, type ACM-2 from EG&G. They were used during the second deployment period at the deepest level of the moorings. The near bottom current meters were placed 50 m above the sea floor, to be outside the bottom boundary layer. The uppermost current meters of those moorings which span over the full water column were situated in the depth range between 200 and 300 m in order to stay clear of passing icebergs. Details of the data processing and more information on the performance of the instruments are documented in a technical report of Rohardt *et al.* (1992).

## 3. Results

*a. The water mass characteristics in the northwestern Weddell Sea.* The general hydrographic situation, as revealed by all our sections in the western Weddell Sea, is determined by the presence of four major water masses (Fig. 2). Cold (temperature below 0°C) and fresh Winter Water is found in the top hundred metres in the interior. In front of the shelf edge the layer thickness increases to more than 600 m. At the shelf edge the Winter Water meets with the more saline shelf water. During summer the Winter Water is capped by a surface layer of a few tens of meters which is warmer and fresher. Below the Winter-Water layer Warm Deep Water forms a temperature and salinity maximum at intermediate depths which deepens from the interior toward the continental slope by several hundred meters within a few hundred kilometers off the shelf edge. However, above the upper part of the slope, the inclination of the axis of the Warm-Deep-Water core reverses and points upward toward the shelf. Off the shelf edge the Warm Deep Water forms a front with the shelf water. The largest part of the water column is occupied by Weddell Sea Deep Water, also termed Antarctic Bottom Water by other authors. It is superimposed to a cold (temperature below −0.7°C) and relatively fresh layer of Weddell Sea Bottom Water. The coldest temperatures and lowest salinities of the Weddell Sea Bottom Water are found at intermediate depths on the slope.

Whereas the general hydrographic situation is common to the three sections (Fig. 2), the thermohaline properties of the water masses and their volumes are changing from south to north. In particular, the water found close to the bottom on the shelf decreases in salinity from 34.61 to 34.53 between the Larsen-Ice-Shelf and the Joinville-Island sections, and increases in potential temperature from −1.8 to −1.2°C. The presence of the most saline and coldest shelf water at the Larsen-Ice-Shelf section may in part be related to the bottom topography, namely a depression on the shelf which may favor the accumulation of cold and brine-enriched water formed during periods of sea ice formation. Due to the northward salinity decrease and temperature increase of the shelf water the gradient across the front between shelf water and Warm Deep Water weakens from south to north. The depth of the Weddell-Sea-Bottom-Water core increases from the south to the north consistent with a slight downslope component superimposed on the generally long slope bottom water flow.

The temperature/salinity ($\theta/S$) relations of the water masses found in our sections below the surface layer (Fig. 3) are distributed within a triangle the edge points of which are determined by the thermohaline properties of the Winter Water (salinities between 34.45 and 34.50 and potential temperatures between −1.8 and −0.8°C), of

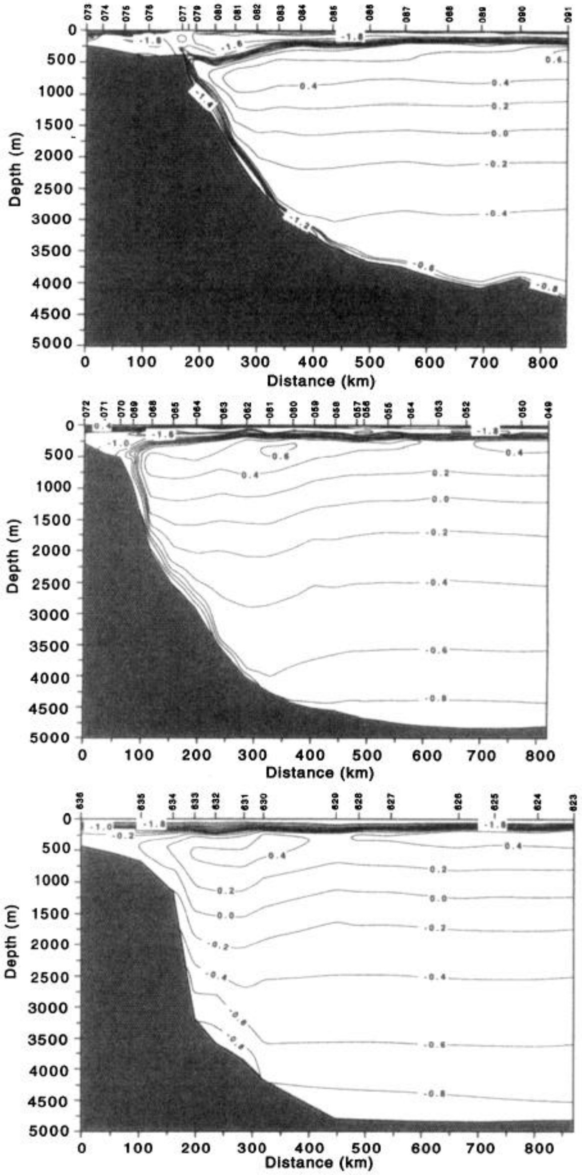

Figure 2. Potential temperature (a) and salinity (b) transects which extend toward the interior of the Weddell Gyre from the Larsen Ice Shelf (top), Joinville Island (middle) and from the South Orkney Islands (bottom). The Larsen-Ice-Shelf and the Joinville-Island sections were done in January 1993, the South-Orkney-Islands section in July 1992.

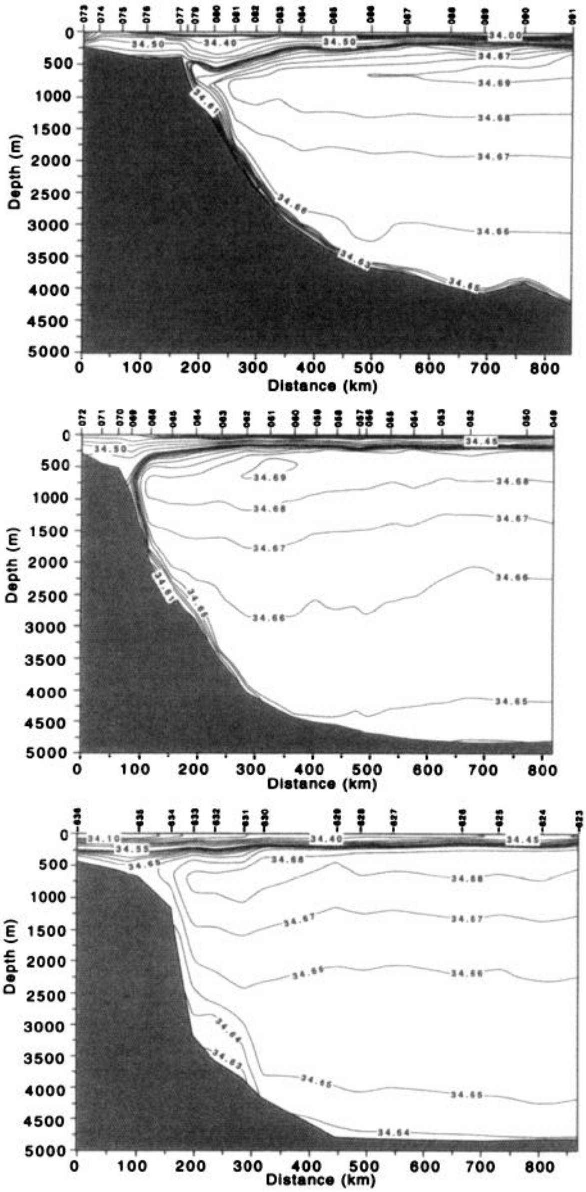

Figure 2. (Continued)

the densest fraction of the shelf water (34.61 and −1.8°C), and of the Warm Deep Water (34.69 and 0.7°C).

The $\theta/S$ diagram from the Larsen-Ice-Shelf section (Figs. 3, left and 4, left) indicates Warm Deep Water of quasi constant density penetrating on the shelf. The

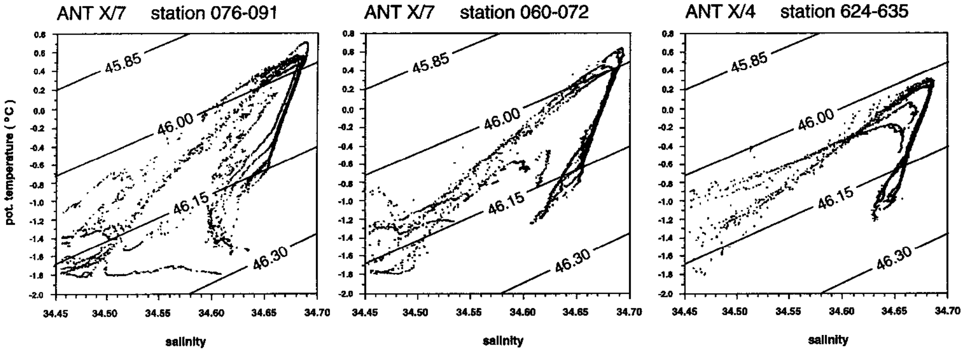

Figure 3. $\theta/S$ diagrams obtained from CTD measurements made along the transects off the Larsen Ice Shelf (left), off Joinville Island (middle), off the South Orkney Islands (right). Lines of constant density are given as $\sigma_4$ in order to better estimate the spreading of the bottom water.

temperature maxima of the different $\theta/S$ profiles are aligned along a line of constant density related to a pressure between 0 and 500 dbar, namely along $\sigma_\theta = 27.81$ or $\sigma_{0.5} = 30.18$. As the modified Warm Deep Water is found at the shelf edge at almost sill depth of about 500 m, the isopycnal lines of $\sigma_\theta = 27.81$ or $\sigma_{0.5} = 30.18$ specify the minimum density above which the mixing product of the modified Warm Deep Water with the shelf water is dense enough to spill over the shelf edge and to sink down the continental slope. This applies when the salinity of the shelf water (which has a temperature of close to $-1.8$°C) exceeds 34.54 (determined by $\sigma_\theta = 27.81$). It is seen from Figure 3 (left) that such a dense water mass indeed is present in front of the Larsen Ice Shelf. The process of generation of a denser water mass by mixing modified Warm Deep Water with brine-enriched shelf water and subsequent sinking is comparable to the one described by Foster and Carmack (1976b) at the southern Weddell continental slope, however with different water mass properties. After the initial density gain the thermobaric effect tends to increase the down slope motion.

The thermohaline structure of the bottom layer on the continental slope and in the deep basin of the northwestern Weddell Sea can be explained as originating from a plume of dense water which runs off from the shelf superimposed to a strong along-slope motion and mixes at its top with the various water masses in the strata through which it sinks to ultimately reach the abyssal depths. All the $\theta/S$ profiles collected in the northwestern Weddell Sea off the shelf edge display, approaching the sea floor, a sharp bend toward lower salinities (Fig. 3). This sharp bend marks the top of the bottom water layer, and typically occurs a few hundred meters above the sea floor. Just below the sharp bend the thermohaline properties follow an almost linear $\theta/S$ relationship. The linear segments of the $\theta/S$ profiles point toward a common intersection with the shelf water profile at a density of approximately $\sigma_\theta = 27.81$ as indicated by the broken lines in Figure 4 (middle). The intersection point indicates

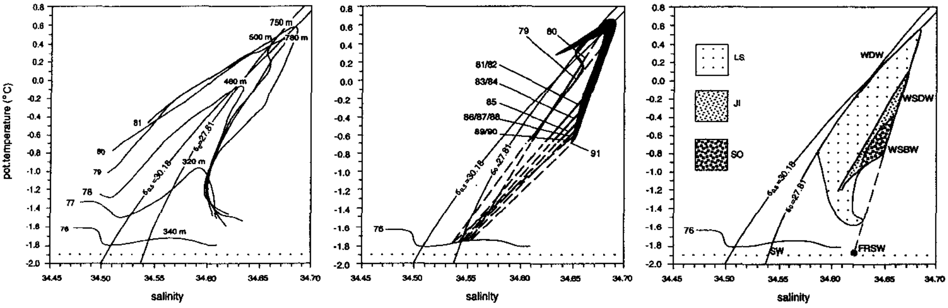

Figure 4. Schematic representation of the processes in $\theta/S$ diagrams which lead to bottom water formation on the western continental slope in the Weddell Sea: 1. Spreading of the Warm-Deep-Water core from the deep sea on to the shelf and its modification (left). 2. Mixing of the newly formed plume of descending bottom water with Weddell Sea Deep Water. The broken lines extend the linear segments of the $\theta/S$ curves toward the lightest fraction of shelf water which is able to form a descending plume through mixing with modified Warm Deep Water (middle) and 3. $\theta/S$ range of newly formed bottom water occupied by the on the 3 transects (right). FRSW = Filchner-Ronne Slope Water as observed by Foldvik *et al.* (1985), JI = Joinville-Island section, LS = Larsen-Ice-Shelf section, SO = South-Orkney-Islands section, WDW = Warm Deep Water, WSDW = Weddell Sea Deep Water, WSBW = Weddell Sea Bottom Water, SW = shelf water.

the lightest fraction of shelf water which can, through mixing of modified Warm Deep Water, form a descending plume which is only slightly more dense than the adjacent deep water and mixes most efficiently with the water masses through which it sinks. The shift of the bend toward greater depths with increasing distance from shelf reflects the increasing amount of Weddell Sea Deep Water entrained into the descending plume.

On the continental slope off the Larsen Ice Shelf the salinities tend to increase again within the bottom water layer toward the bottom (stations 79 through 83, Fig. 3, left). Where the near-bottom salinity increase is strongest (station 81) it occurs at almost constant temperature of approximately −1.6°C. The characteristics of this high salinity water mass are close to values observed on the shelf, although the temperature on the slope is somewhat higher than on the shelf. The lower part of the Weddell-Sea-Bottom-Water layer displaying the highest salinity represents that part of the plume with the densest water which would be least affected by mixing during its descent.

While on the western slope the high-saline bottom water is only observed at a few stations, the bottom water in Weddell basin west of 17W is marked by a rather low salinity, obvious in the $\theta/S$ profiles by a bend toward low salinites (Figs. 3 and 5). The dominance of a low salinity water mass in the bottom layer is evident in any repetition of the Joinville-Island section made during the 'Weddell Gyre Study', independent of the year and season. The low salinity of the Weddell Sea Bottom Water is consistent with the view that its thermohaline signatures originate from the water of the northwestern shelves in particular off the Larsen Ice Shelf which, on average, is rather fresh in comparison with the Western Shelf Water from the Ronne Shelf area. In particular, the denser fraction of that water which is able to sink down the continental slope is in general less saline than the dense water mass observed in the southern plume by Foldvik *et al.* (1985) and denoted as Filchner-Ronne Slope Water (FRSW) in Figure 4 (right). However, water with properties of the Filchner-Ronne Slope water must be formed in considerable quantity to maintain the thermohaline properties of the Weddell Sea Deep Water which are distributed along an almost straight line running from the Warm-Deep-Water core properties to a salinity of about 34.62 at freezing temperature. However, even if the plume observed on the southern slope is in general more saline than the one in the west as confirmed by three independant observations (A. Foldvik, pers. com.), we cannot rule out that at least at occasions less saline plumes might be formed in the south as well and low saline bottom water being advected along the slope to the west.

During downstream travel with the northeastward-heading western boundary current, the thermohaline variety of the Weddell Sea Bottom Water decreases from the Larsen-Ice-Shelf to the South-Orkney-Islands section (Figs. 3 and 4, right), due to mixing within the bottom water layer and with the lower Weddell Sea Deep Water. However, its low salinity and temperature retains prominence. The densest of the water masses carried downstream toward the northern periphery of the Weddell Gyre hence has a low salinity signature which can be traced back to the transect in front of the Larsen Ice Shelf. It should be noted that—even at the northern periphery of the Weddell Gyre—the densest water still is found at intermediate depths on the continental slope from where it may escape to the north through the Powell Basin, the Orkney Passage and the South Sandwhich Trench. A discharge of the cold and low saline slope water to the north is corroborated by the observation that its influence on the thermohaline structure of the deep interior of the Weddell Sea is restricted to the water masses denser than $\sigma_4 = 46.17$ (Fig. 3) which have vanishing isopycnic contact with the open ocean (Orsi *et al.*, 1993). Within the bottom layer of the deep Weddell Basin the influence of the low-saline source water extends eastward along the Joinville-Island section over about 1600 km up to that point where the bottom starts to ascend again in approach of the eastern continental slope. Further east the most dense bottom water, and the low-salinity signature, are missing (Fig. 5).

*b. Mean structure and the temporal variability of the outflow.* During the flow from the Larsen-Ice-Shelf to the South-Orkney-Island section the extrema of thermohaline characteristics of the bottom layer weaken (i.e. its minimum temperature and salinity rise from −1.6 to −1.0°C and 34.60 to 34.62, respectively), the volume of Weddell Sea Bottom Water with temperatures below −0.7°C increases and the gradients from the Warm Deep Water to the bottom water and to the shelf water decrease

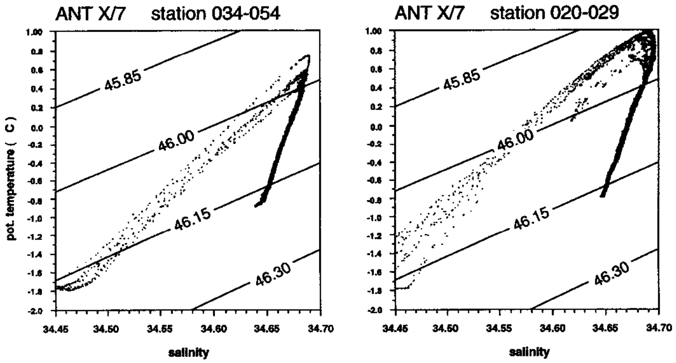

Figure 5. θ/$S$ diagrams on the transect between Joinville Island and Kapp Norvegia (see Fig. 1b) in the center of the Weddell basin between 22 and 43W (left) and the eastern part between 13 and 19W (right).

remarkably (Figs. 6 and 7). The northward discharge of near bottom water seems to occur in several cores. The depth of the deeper core increases from 2000 m off the Larsen Ice Shelf to 3750 m off the South Orkney Islands.

The annual mean currents measured 50 m above the bottom with moored instruments in the cold water tongue are weakest with 2 cm/s in the temperature and salinity minima at 2470 m water depth (between km 100 and km 150 in Fig. 6, middle) and increase to shallow and deeper levels with 12 cm/s at 950 m and 5 cm/s in 3480 m (Fig. 8). This current pattern results from two reasons. First, in areas of weak stratification ocean currents are strongly determined by the bottom topography. In the Weddell Sea the vertically averaged current speed is linearly correlated with the bottom slope (Fahrbach *et al.,* 1994b), and the minimum current in 2470 m depth is related to a plateau in that depth range. Second, the baroclinicity is strongest above the upper slope and decreases toward the interior of the gyre due to the front between the shelf water and the Warm Deep Water. The geostrophic current associated with that front gives rise to the horizontal current maximum in 950 m depth.

The monthly means of the current component perpendicular to the Joinville-Island section and the temperatures of the three near bottom instruments at 950 m, 2470 m, and 3480 m water depth reveal a seasonal signal with strongest currents and lowest temperatures approximately in the period from April to June (Fig. 8). During periods of minimum bottom temperature the bottom water layer's thickness (i.e. the thickness of the layer in which the temperature is below −0.7°C) is increased, while the vertical temperature gradient does not change significantly (Fig. 9, bottom).

The seasonal variation of bottom water temperature, however, is superimposed by a trend with decreasing temperatures from 1991 to 1992. The trend of temperature in the Weddell-Sea-Bottom-Water layer correlates with a change of the temperature of the Warm Deep Water at the western edge of its core (Fig. 9, top) where it meets in a

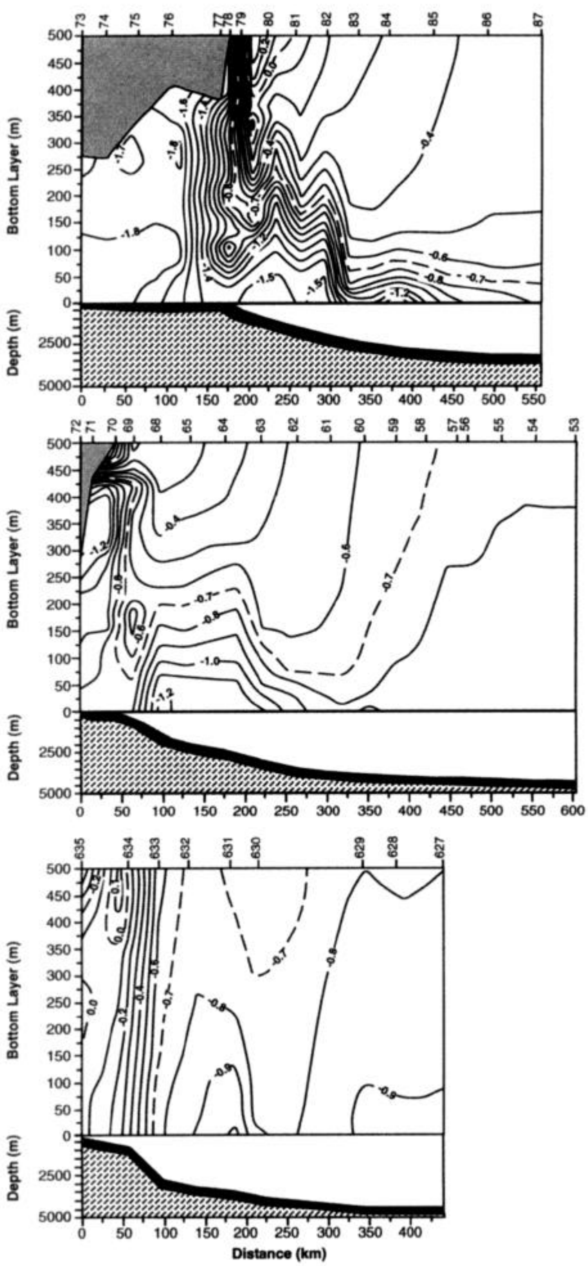

Figure 6. Potential temperature in 500 m thick layer at the bottom of the transects off the Larsen Ice Shelf (top) and Joinville Island (middle) measured in January 1993, and off the South Orkney Islands measured in July 1992 (bottom). The upper parts of the graphs show the temperature distributions in that layer. The grey area in the upper left corner indicate water depth of less than 500 m. The lower part of the graphs gives the bottom profiles. There, the layer shown in the upper graphs is indicated in dark grey.

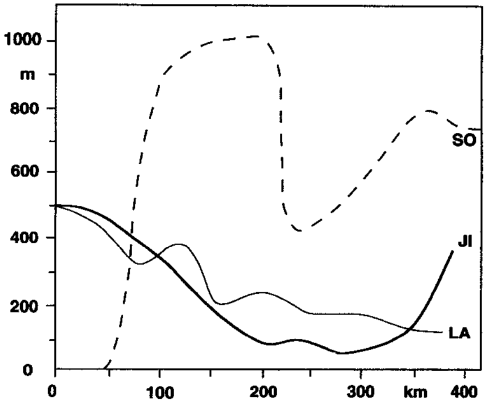

Figure 7. Thickness of the near bottom layer on the transects off the Larsen Ice Shelf (LA) and Joinville Island (JI) measured in January 1993, and off the South Orkney Islands measured in July 1992 (SO) defined by the −0.7°C isotherm.

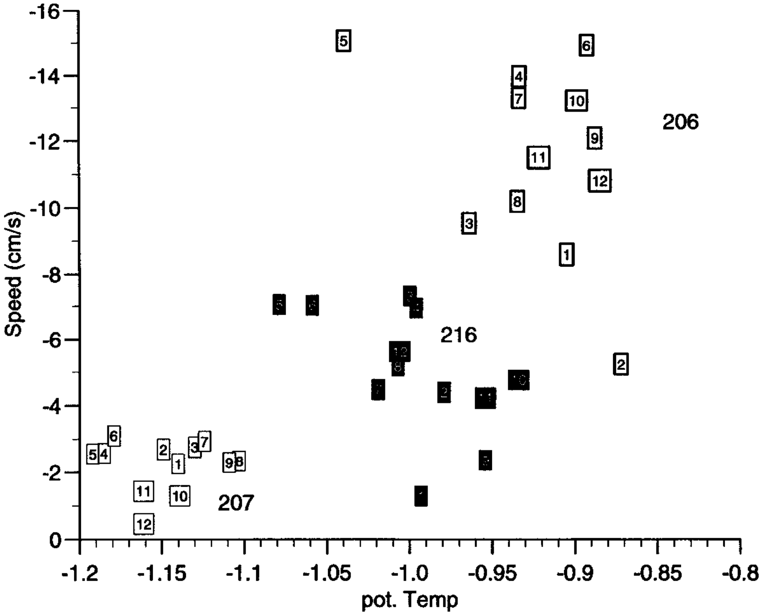

Figure 8. Monthly averages for 1991 of potential temperature and current speed at mooring 206 in 950 m depth, mooring 207 in 2470 m depth and mooring 216 in 3480 m depth. Each combination of current speed and potential temperature is shown by a small box. The numbers in the boxes give the month of the year 1991. The large numbers indicate the mooring code.

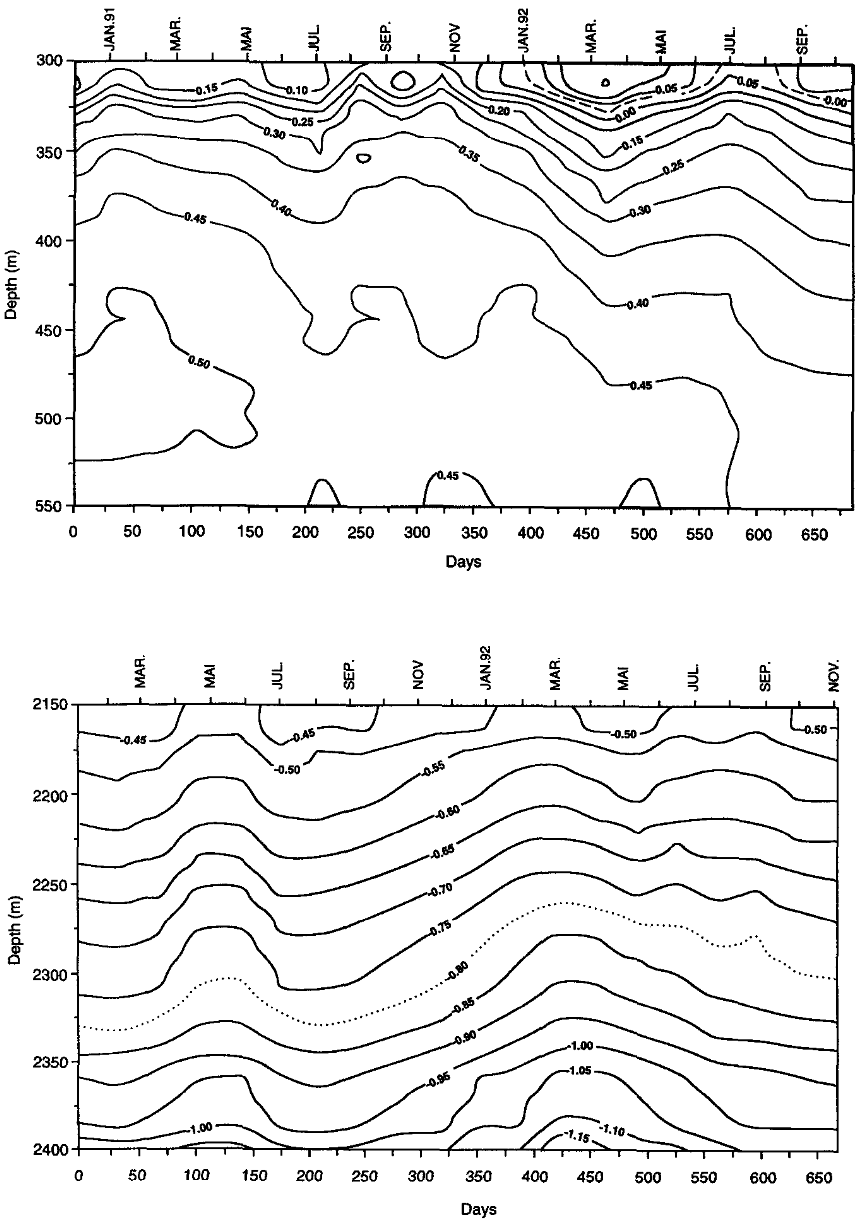

Figure 9. Isotherms in the level of the Warm Deep Water (top) and near the bottom (bottom) in the western outflow of the Weddell Sea from December 1990 to November 1992.

front with the shelf water; the Weddell Sea Bottom Water as well as the Warm Deep Water are by somewhat less than 0.1°C colder in 1992 than in 1991. This documents a direct influence of the Warm Deep Water on the thermohaline properties of the Weddell Sea Bottom Water and suggests that a rather constant amount of Warm Deep Water is involved in the mixing with dense shelf water to form the Weddell Sea Bottom Water.

Whereas the trend of the Warm-Deep-Water temperature at its western margin correlates with the one of the bottom water temperature, the seasonal signal is much less prominent in the Warm Deep Water than in the bottom water. This requires that the seasonal signal observed in the bottom water has to be introduced through the contribution of shelf water. If the trend of the bottom water temperature is removed from the time series shown in Figure 9 (bottom), the strongest seasonal decrease of temperature occurs approximately from February/March to April/May, and the strongest subsequent warming takes place from May/June to July/August. The decrease of temperature in the bottom layer follows the atmospheric cooling at the western rim of the Weddell Sea with a phase lag of about 1–2 months. The phase relation between changes in the atmospheric forcing and those of the water mass properties in the bottom layer fits into a scenario in which the heat loss of the water column during the cooling phase of the atmosphere in austral autumn and early winter enhances water mass formation on the shelf by cooling and brine release during sea ice formation. During the further progression of winter this process is inhibited by the already formed sea ice cover. With this scenario, the seasonal changes of temperature in the bottom layer are interpreted as evidence of pulses of cold and dense water which drain off the shelf during phases of maximum formation rate.

The observation that the temperature in 950 m depth (mooring 206) is never as low (Fig. 8) as in 2470 m (mooring 207) indicates that the formation area of the cold dense water must be upstream of the mooring site. The phase lag between the cooling phase of the atmosphere and the occurrence of the cold water pulses at the locations of the moored instruments allows for a rough estimate of the distance to the formation area. At the moorings 206 and 216 the strongest cooling occurs from April to May (Fig. 8), about 1 to 2 months after the strongest atmospheric drop of temperature; the typical current speeds during the months of March to May are 12 and 4 cm $s^{-1}$ at the two locations. The most pronounced decrease of temperature at mooring 207 takes place between March and April, about a month after the cooling of the atmosphere, and is associated with a current speed of approximately 2.5 cm $s^{-1}$. The estimates of distance based on these figures range from 65 to 630 km. The broad shelf off the Larsen Ice Shelf extends from roughly 100 to 700 km upstream of the mooring sites. A distance of merely a few hundred kilometers to the formation area is also implied by the nearly simultaneous arrival time of the

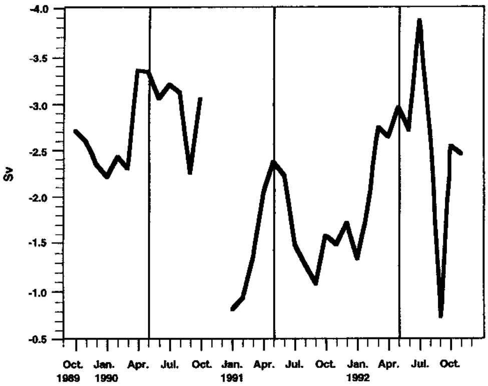

Figure 10. Time series of monthly average transport of Weddell Sea Bottom Water across the transect off Joinville Island, obtained from moorings 206, 207, and 216 from October 1989 to November 1992.

temperature signal (with a lag of about a month) at the different mooring locations at the slope among which the advection velocities vary significantly.

c. *Bottom water transports.* During 1991 the mean flow of bottom water colder than −0.7°C approximates 1.7 Sv, as determined on the basis of the annual mean currents and the CTD survey carried out in December 1990. The transports show a seasonal cycle and a longer term trend with a maximum outflow of 2.4 Sv in May 1991 and a minimum of less than 0.8 Sv in January 1991 (Fig. 10). To calculate this time series of the Weddell-Sea-Bottom-Water transport it was assumed that the shape of the cold water core remains constant but that the core changes in size.

The extension of the time series to the years 1990 and 1992 required additional assumptions because during those years current meter data are available only in the center of the bottom water core. To derive the transport of the plume it was assumed that the relation of the currents in 950 and 3480 m depths to the current in bottom water core which has been determined from the measurements during 1991 was valid for 1990 and 1992 as well. The maximum (monthly mean) transport determined from the extended time series equals 3.9 Sv and occurred in July 1992 (Fig. 10).

The above figures apply to the outflow of bottom water in the western boundary current of the Weddell Gyre. In addition to the bottom water layer clinging to the western continental slope, Weddell Sea Bottom Water is also observed on the transect from Joinville Island to Kapp Norvegia farther east up to 17W. The mean transport of bottom water colder than −0.7°C over that extent of approximately 1800 km is 4.2 Sv to the north and 0.37 Sv to the south (Fig. 11), as determined from 15 current meters in 50 m distance above the bottom. Approximately 70% of the Weddell Sea Bottom Water leaves the southern Weddell Sea at the western boundary. Whereas the outflow in the west is dominated from low salinity bottom

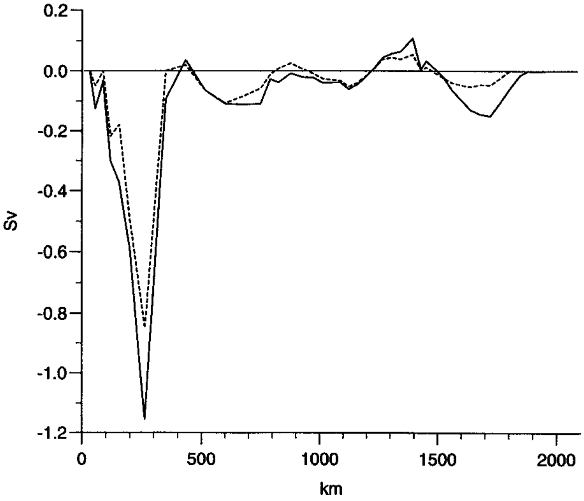

Figure 11. Transport in $10^6$ $m^3s^{-1}$ (Sv) of bottom water between two adjacent CTD-stations (on average in 40 km distance) across the transect between Joinville Island and Kapp Norvegia observed from current meter moorings deployed from November/December 1990 to December 1992/January 1993. Negative flow leaves the southern Weddell Sea to the north. The solid line indicates transport colder than −0.7°C, the broken line the one of water colder than −0.8°C. The distance in km on the horizontal axis is counted from the western shelf according to Figure 1c.

water, the $\theta/S$ diagrams in the center show only a small remnant of the low salinity part (Fig. 5).

An alternative route for the bottom water outflow originating from the Filchner-Ronne Ice Shelf other than the western boundary current is suggested by measurements of northward flow in the bottom layer east of the western boundary current (Fig. 11). A northward transport 0.80 Sv of bottom water colder than −0.7°C between 1500 and 1900 km east from the western shelf edge exceeds significantly the southward recirculation of 0.34 Sv across the transect between 1200 and 1500 km from the western boundary. The northward outflow in the southeastern Weddell Sea is consistent with current meter records from mooring 213 located 275 km south of the main mooring line (Fig. 1b). The annual means obtained from 3 current meters placed within 500 m above the bottom (Rohardt *et al.*, 1992) show a persistent northward flow of 1.5 cm $s^{-1}$. The northward flow could be supplied from two sources. Either, it represents the recirculation of the southwestward inflow of the Weddell Gyre along the eastern continental slope or it is fed by a bottom water outflow originating from the southern continental slope. In the latter case the rather high potential temperature of approximately −0.8°C in comparison to −1.9°C observed on the slope (Foldvik *et al.*, 1985) of this northward flow indicates intensive mixing upstream with the Weddell Sea Deep Water.

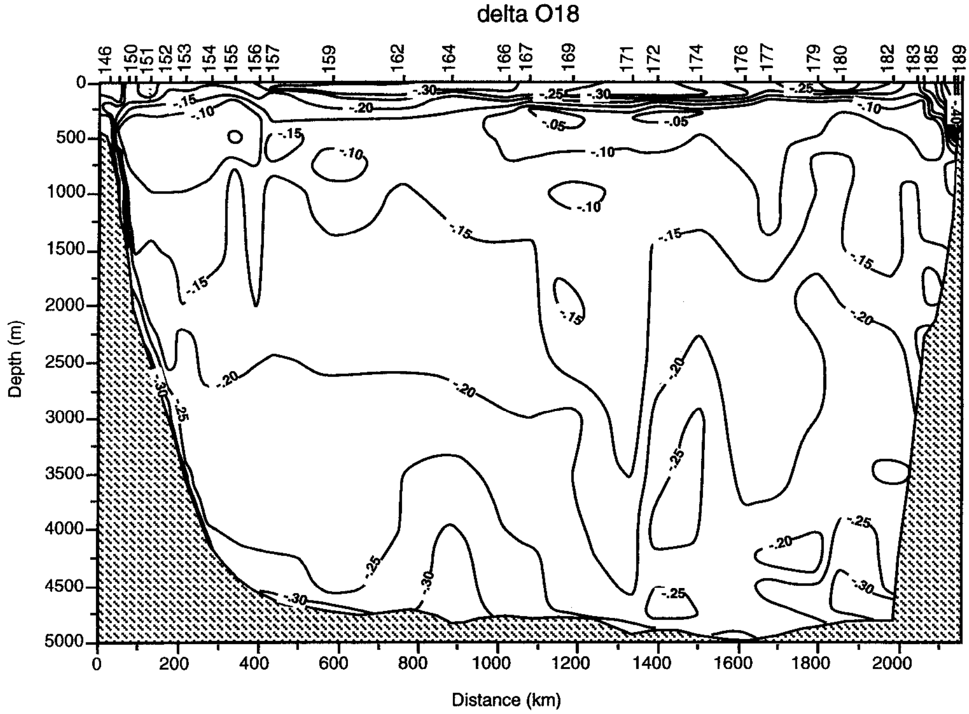

Figure 12. Transect of the anomaly of the stable oxygen isotope $\delta^{18}O$ between Joinville Island and Kapp Norvegia observed in September/October 1989.

A northward discharge of recently ventilated bottom water in the eastern part of the Weddell Basin besides the main outflow in the western boundary current is also suggested by the distribution of the stable oxygen isotope $^{18}O$ (Fig. 12). Whereas the water column in the gyre interior achieves $\delta^{18}O$ values above $-0.3‰$, the values in the surface and the western boundary layers are below that level. Low values of $\delta^{18}O$ are indicative of input from precipitation, melted snow or melted shelf ice. The isolated patch of $\delta^{18}O$ values below $-0.3‰$ in the eastern basin in the area of northward flow hence supports the view that water emanating from the Filchner-Ronne Ice Shelf makes a significant contribution to that flow.

## 4. Discussion and conclusions

Our hydrographic measurements in the tongue of the bottom water outflow in the northwestern Weddell Sea confirmed that the outflow is dominated by cold water of rather low salinity and high oxygen content. This layer is present in all of the hydrographic sections made so far across the slope of the continental shelf downstream of the Filchner Depression (Seabrooke *et al.*, 1971; Carmack, 1973; Carmack and Foster, 1975b; Foster and Middleton, 1979; Foster and Middleton, 1980; Foldvik *et al.*, 1985; Foster *et al.*, 1987; Gordon *et al.*, 1993) although it does not always appear as being continuous between the shelf edge and the floor of the deep basin. The prominence of a low-saline source water mass appears as a feature which is independent of the season, though our summer and winter hydrographic surveys have been made in different years. The conclusion on the persistency of the dominance of a rather fresh water mass in the outflow is corroborated by observations made in austral winter 1992 by Gordon *et al.* (1993), i.e. in the same year as one of our summer surveys, which also showed the significance of a low-saline water mass.

In spite of the persistence of the general structure, the outflowing volume of dense bottom water varies considerably between the seasons and different years. Our time series of current and temperature indicate an early winter maximum of the volume of the bottom water outflow, which is associated with the lowest temperatures. The volume transport was determined from our direct current meter measurements to vary between 0.8 and 3.9 Sv with an average of 2.2 Sv. These figures are at the lower end of the range specified by earlier determinations (Gill, 1973; Carmack and Foster, 1975b; Foster and Carmack 1976b; Weiss *et al.*, 1979; Gordon *et al.*, 1993).

As a possible source region of the dominant water mass in the outflow of dense bottom water we identified the broad shelf off the Larsen Ice Shelf. The water mass characteristics found on that shelf show that the near bottom water—while mainly formed during early winter—even in summer is dense enough to cascade down the slope. The salinities of the water off the Larsen Ice Shelf which is sufficiently dense for sinking span the range from 34.55 to 34.62. When descending down the continental slope this water can form the low-saline fraction of the Weddell Sea's Deep and Bottom Water by mixing with the various water masses found in the strata through which it sinks to ultimately reach the Weddell abyss.

The identification of the area off the Larsen Ice shelf as a formation area of bottom water in addition to the well known Filchner-Ronne Shelf Ice area is in agreement with measurements of the anthropogenic carbon dioxide content which imply that there is at least one other important source of new bottom water between the Filchner Depression and the northern tip of the Antarctic Peninsula (Anderson *et al.*, 1991). However, we cannot rule out contributions from other shelf areas which might be superceded by the run off from the Larsen area.

The formation of Weddell Sea Bottom Water by mixing of Warm Deep Water at the shelf edge with water from the area off the Larsen Ice Shelf represents a further pathway of bottom water formation. The modification of the Warm Deep Water as an intermediate step is less dramatic in the Larsen area than on the southern slopes, where according to Foster and Carmack (1976b) the highly saline Western Shelf Water, mainly found in the Ronne Trough, is the one source water mass of the Weddell Sea Bottom Water. If the most saline water off the Larsen Ice Shelf which we observed (station 76) mixes with Warm Deep Water, the resulting water mass fits perfectly on the $\theta/S$-line characteristic of the Weddell Sea Deep Water in the Weddell Gyre interior. The observation of a cold and saline bottom water mass with salinities higher than 34.61 at stations 81 and 82 can be due to that process (Fig. 3, left). However, this layer might as well be the remnant of a water mass advected from the Filchner-Ronne Ice Shelf area where a temperature of −1.9°C and a salinity as high as 34.62 have been observed (Foldvik *et al.*, 1985). It is indicated as Filchner-Ronne Slope Water (FRSW) in Figure 4 (right). However, as the saline type of the newly formed water is much less frequently observed in the northwestern Weddell Sea than the fresh type, it is most likely not formed off the Larsen Ice Shelf at a rate sufficiently high to compensate for the fresh water type. In order to maintain the linear $\theta/S$ relationship of the Weddell Sea Deep Water in the interior either the major part of the low saline bottom water type has to exit the Weddell Sea relatively fast or a second source of the high saline bottom water has to drain into the interior of the gyre apart from the western boundary current.

A substantial export of the newly formed low saline bottom water out of the Weddell Sea is indicated by the decreasing $\theta/S$ range in northwestward bottom water flow (Fig. 4). Despite their high density, the low salinity types of the Weddell Sea Deep and Bottom Water which are newly formed under the influence from water draining from the western shelves clinge to the continental slope as far downstream as to the South Orkney Islands. Because of their occurrence at intermediate depth at the northern periphery of the Weddell Gyre they have the potential to escape to the north through topographic clefts in the South Scotia Ridge system. Evidences of such an outflow of rather fresh and cold water to the north have been observed north of the Powell Basin (Nowlin and Zenk, 1985), in the South Orkney Trough and the South Sandwich Trench (Locarnini *et al.*, 1993), and have been traced northward into the Argentine Basin by Reid *et al.* (1977) and Whitworth *et al.* (1991). The direct path from the western formation area to circumpolar water belt implies a short residence time of the newly formed water in the Weddell Sea and consequently a fast link between the formation processes and the global ocean.

The above findings can be condensed into the following view of the formation and discharge of bottom water in the Weddell Sea. The outflow of dense bottom water with the western boundary current is dominated by a rather fresh water mass which obtains its characteristics to a large extent off the Larsen Ice Shelf by contact with the atmosphere. This outflow influences the abyssal waters of the open ocean, but does not contribute much to the thermohaline properties of the deep inner Weddell Basin. Characteristics of the bottom water originating from the Filchner Depression, on the other hand, are transported to the open ocean in a less unadulterated fashion, but determine the thermohaline structure of the deep interior of the Weddell Sea.

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## REFERENCES

Anderson, L. G., O. Holby, R. Lindegren and M. Ohlson. 1991. The transport of anthropogenic carbon dioxide into the Weddell Sea. J. Geophys. Res., *96,* 16,679–16,687.

Arntz, W., W. Ernst and I. Hempel, eds. 1990. The Expedition ANTARKTIS VII/4 (Epos leg 3) and VII/5 of RV *Polarstern* in 1989. Berichte zur Polarforschung, *68,* 214 pp.

Augstein, E., N. Bagriantsev and H. W. Schenke, eds. 1991. The Expedition ANTARKTIS VIII/1–2, 1989, with the Winter Weddell Gyre Study of the Research Vessels *Polarstern* and *Akademik Fedorov.* Berichte zur Polarforschung, *84,* 134 pp.

Brennecke, W. 1921. Die ozeanographischen Arbeiten der Deutschen Antarktischen Expedition 1911–1912. Aus dem Archiv der Deutschen Seewarte, *39,* 216 pp.

Broecker, W. S. and T. H. Peng. 1982. Tracers in the Ocean. Eldigio Press, Palisades, New York, 690 pp.

Carmack, E. 1973. Silicate and potential temperature in the deep and bottom waters of the western Weddell Sea. Deep-Sea Res., *20,* 927–932.

—— 1977. Water characteristics of the Southern Ocean south of the Polar Front, *in* A Voyage of Discovery, George Deacon 70th Anniversery Volume, M. Angel, ed., Pergamon Press, Oxford, 15–41.

Carmack, E. C. and T. D. Foster. 1975a. Circulation and distribution of oceanographic properties near the Filchner Ice Shelf. Deep-Sea Res., *22,* 77–90.

—— 1975b. On the flow of water out of the Weddell Sea. Deep-Sea Res., *22,* 711–724.

Deacon, G. E. R. 1937. The hydrography of the Southern Ocean. "Discovery" Reports, *15,* 124 pp.

Fahrbach, E. 1993. Zirkulation und Wassermassentransformation im Weddellmeer, Die Geowissenschaften, *11,* 246–253.

Fahrbach, E. with contributions of the participants. 1992. Cruise Report ANT X/2 *in* The Expeditions ANTARKTIS IX/1–4 of the Research Vessel *Polarstern* in 1990/91. U. Bathmann, M. Schulz-Baldes, E. Fahrbach, V. Smetacek and H.-W. Hubberten (eds.), Berichte zur Polarforschung 100, 31–94.

Fahrbach, E. with contributions of the participants. 1994a. Cruise Report ANT X/7 *in* The Expeditions ANTARKTIS X/8–9 of the Research Vessel *Polarstern* in 1992/93. U. Bathmann, V. Smetacek, H. de Baar, E. Fahrbach, G. Krause and (eds.) Berichte zur Polarforschung 135, 127–197.

Fahrbach, E., G. Rohardt, M. Schröder and V. Strass. 1994b. Transport and structure of the Weddell Gyre. Annales Geophysicae, *12,* 840–855.

Foldvik, A. and T. Gammelsrød. 1988. Notes on Southern Ocean hydrography, sea-ice and bottom water formation. Palaeogeo., Palaeoclima., Palaeoeco., *67,* 3–17.

Foldvik, A., T. Gammelsrød and T. Tørresen. 1985. Circulation and water masses on the southern Weddell Sea shelf. Oceanology of the Antarctic Continental Shelf, S. S. Jacobs, ed., Antarctic Res. Ser., *43,* American Geophys. Union, 5–20.

Foster, T. D. and E. Carmack. 1976a. Temperature and salinity structure in the Weddell Sea. J. Phys. Oceanogr., *6,* 36–44.

—— 1976b. Frontal zone mixing and Antarctic Bottom Water formation in the southern Weddell Sea. Deep-Sea Res., *23,* 301–317.

Foster, T. D., A. Foldvik and J. H. Middleton. 1987. Mixing and bottom water formation in the shelf break region of the southern Weddell Sea. Deep-Sea Res., *34,* 1771–1794.

Foster, T. D. and J. H. Middleton. 1979. Variability in the bottom water of the Weddell Sea. Deep-Sea Res., *26,* 743–762.

—— 1980. Bottom water formation in the western Weddell Sea. Deep-Sea Res., *27,* 367–381.

Gill, A. E. 1973. Circulation and bottom water formation in the Weddell Sea. Deep-Sea Res., *20,* 111–140.

Gordon, A. L., B. A. Huber, H. H. Hellmer and A. Ffield. 1993. Deep and bottom water of the Weddell Sea's western rim. Science, *262,* 95–97.

Killworth, P. D. 1977. Mixing on the Weddell Sea continental slope. Deep-Sea Res., *24,* 427–448.

Locarnini, R., T. Withworth III and W. D. Nowlin. 1993. The importance of the Scotia Sea on the outflow of Weddell Sea Deep Water. J. Mar. Res., *51,* 135–152.

Lynn, R. J. and Reid, J. L. 1968. Characteristics and circulation of deep and abyssal waters. Deep-Sea Res., *15,* 577–598.

Mantyla, A. W. and J. L. Reid. 1983. Abyssal characteristics of the World Oceans waters. Deep-Sea Res., *30,* 805–833.

Mosby, H. 1934. The waters of the Atlantic Antarctic Ocean. Scientific Results of the Norwegian Antarctic Expedition 1927–1928, 1(11), Norske Videnskaps-Akademi, Oslo, 1–131 pp.

Nowlin, W. D., Jr. and W. Zenk. 1988. Currents along the margin of the South Shetland Island Arc. Deep-Sea Res., *35,* 269–301.

Orsi, A. H., W. D. Nowlin Jr. and T. Whitworth III. 1993. On the circulation and stratification of the Weddell Gyre. Deep-Sea Res., *40,* 169–203.

Reid, J. L. 1989. On the total geostrophic circulation of the South Atlantic Ocean: Flow patterns, tracers, and transports. Prog. Oceanogr., *23,* 149–244.

Reid, J. L., W. D. Nowlin Jr. and W. C. Patzert. 1977. On the characteristics and circulation of the Southwestern Atlantic Ocean. J. Phys. Oceanogr., *7,* 62–91.

Rohardt, G., E. Fahrbach, G. Krause and V. H. Strass. 1992. Moored current meter and water level recorder measurements in the Weddell Sea 1986–1990, Berichte aus dem Fachbereich Physik, Alfred-Wegener-Institut für Polar- und Meeresforschung, 28, Bremerhaven, Germany.

Seabroke, J. M., G. L. Hufford and R. B. Elder. 1971. Formation of Antarctic Bottom Water in the Weddell Sea. J. Geophys. Res., *76,* 2164–2178.

Stommel, H. and A. B. Arons. 1960. On the abyssal circulation of the World Oceans. Deep-Sea Res., *6,* 140–154.

Weiss, R. F., H. G. Östlund and H. Craig. 1979. Geochemical studies of the Weddell Sea, Deep-Sea Res., *26,* 1093–1120.

Whitworth III, T., W. D. Nowlin, Jr., R. D. Pillsbury, M. I. Moore and R. F. Weiss. 1991. Observations of the Antarctic Circumpolar Current and deep boundary currents in the southwest Atlantic. J. Geophys. Res., *96,* 15.105–15118.

Wüst, G. 1935. Schichtung und Zirkulation des Atlantischen Ozeans. Das Bodenwasser und die Stratosphäre. Wissenschaftliche Ergebnisse der deutschen atlantischen Expedition *Meteor* 1925–1927, *6,* 1–288.

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