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Hydrographic and Current Measurements in the Southern Weddell Sea 1979/80

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Summary: During the 1979—1980 expediton with the icebreaker POLARSIRKEL we had an excellent opportunity to study the physical oceanography of the inner part of the Weddell Sea. The ship followed the ice shelf barrier from Cape Norwegia at about 15 °W, and due to favourable ice conditions, it was able to penetrate all the way to the Antarctic Peninsula (60 °W). In this preliminary report we give a review of the physical oceanography programme which mostly consists of hydrographic (CTD) stations near the barrier, and also some current and water level measurements. The different water masses observed are described and the possibility for a tidal-driven upwelling near the ice shelf barrier is indicated.

Zusammenfassung: Während der Expedition 1979/80 mit dem Forschungseisbrecher POLARSIRKEL ergab sich die Möglichkeit, die physikalisch-ozeanographischen Bedingungen der inneren Weddell-See zu untersuchen. Wegen der ausgezeichneten Eisbedingungen konnte das Schiff der Schelfeisfront von Kap Norwegia (15 °W) bis zur Antarktischen Halbinsel (60 °W) folgen. In diesem Beitrag wird ein Überblick über die ozeanographischen Arbeiten gegeben, die im wesentlichen aus hydrographischen Stationen (CTD) vor der Eisfront bestanden. Zusätzlich wurden einige Strömungs- und Gezeitenmessungen durchgeführt. Die verschiedenen Wassermassen, die entlang der Eisfront beobachtet wurden, werden beschrieben. Die Möglichkeit einer gezeitenbedingten Vertikalbewegung an der Eisfront wird aufgezeigt.

1. INTRODUCTION

The Weddell Sea is considered as the most important region for formation of Antarctic Bottom Water. Freezing of ice at the surface will increase the salinity of the water and thus increase the density. According to MOSBY (1934) the water on the continental shelf (see map in Fig. 1) may sink down the continental slope when it obtains a salinity of 34.62‰. This heavy shelf water mixed with the Warm Deep Water at intermediate depth will form the Antarctic Bottom Water. More recent work by FOSTER & CARMACK (1976) shows that some modified water masses are important in the mixing processes that take place. They also point out that the flow down the continental slope turns to the west and follows the contours. The final product, the Antarctic Bottom Water, follows the general clockwise circulation of the oceanic basin of the Weddell Sea and leaves the basin in the northern part when flowing towards the east. From here it penetrates into the deeper parts of the World Oceans.

In the Filchner depression there have been observed very low temperatures (-2.2 to -2.3 °C) at depths below the lower edge of the ice shelf (LUSQUINOS, 1962; CARMACK & FOSTER, 1975; FOLDVIK & GADE, 1978). The freezing point at the sea surface is about -1.9 °C (for the salinities usually present in Antarctic water) and decrease with about 0.08 °C pr. 100 m depth due to increase of pressure. The very cold water in the depression, denoted Ice Shelf Water, must therefore have been cooled down at great depth. As mentioned by FOLDVIK & GADE (1978) is it reasonable to assume that this water forms by heat transfer to the ice at the lower edge of the ice shelf, and is later transported out of the region. They traced the Ice Shelf Water to the north along the western slope of the depression and concluded that this water also participates in the Antarctic Bottom Water formation.

A part of our CTD (conductivity, temperature, depth) observations were within the depression area, Fig. 1. CARMACK & FOSTER (1975) point out that in spite of the low temperatures in the Ice Shelf Water the high salinity water on the western shelf is generally denser. This region is therefore of special interest in the study of the processes for bottom water formation.

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During our five-week stay at the shelf area (mainly around 50 °W) we took more than 150 CTD stations (Fig. 1) and also made some current and water level measurements.

The main aim of our investigations was to throw some light on the circulation of the inner part of the

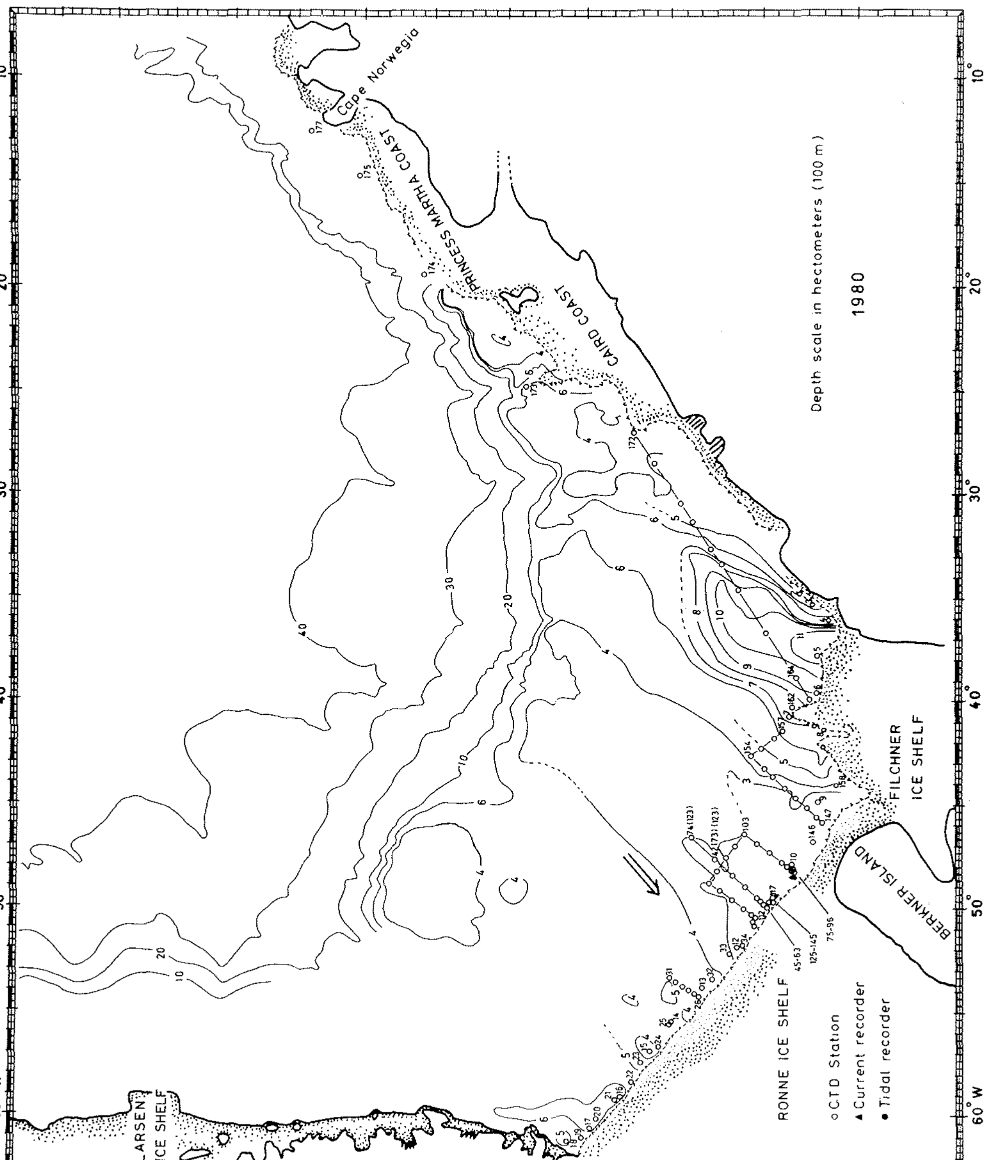

Fig. 1: Map of the southern Weddell Sea with depth contours and CTD-station grid.

Abb. 1: Karte der südlichen Weddell-See mit Tiefenlinien und CTD-Stationen.

Weddell Sea and to study processes close to the floating ice shelf. The favourable ice condition this year made it possible for R/V POLARSIRKEL to penetrate to the south-western part of the Weddell Sea (74° 42'S, 61° 19'W) which usually is inaccessible by ship. As far as we know only the U. S. Coast Guard icebreaker GLACIER has made oceanographic observations in this area before (in Austral summer 1968, according to SEABROOKE, HUFFORD & ELDER (1971)), but this ship did not follow the ice shelf.

In paragraph 2 we give a description of the hydrographic program and in paragraph 3 some preliminary results are presented.

2. OBSERVATIONS AND METHODS

2.1. *Hydrography*

Between 2 January and 17 February we obtained a total of 178 CTD stations, Fig. 1. The CTD measurements include conductivity, temperature, and pressure (depth) 30 times per sec.. With a lowering speed of 1 m/sec, which was the normal, this corresponds to an observation every 3 cm. The data were processed in real time to provide plots of salinity and temperature versus depth as the sonde was lowered.

A subset of the CTD stations (Fig. 1) defines a section close (about 1 nm) to the ice shelf from Cape Norwegia to the Antarctic Peninsula. We believe this is the most comprehensive set of hydrographic observations taken along the barrier in the Weddell Sea.

In order to study variations with distance from the ice shelf three sections were taken normal to the barrier (Fig. 1). One of the sections was repeated three times in a three week period to look for time variations. We also took four sections defining a box of 40x40 nm with the main aim of doing transport calculations based on conservation of some properties.

At three positions, when the ship was tied to the ice shelf, we made CTD time series of duration of 1, 1.5, and 2.5 days and a sampling interval of 1, 2 and 3 hours respectively. The purpose was to study the influence of the ice on the surrounding water on short time-scales, i. e. a few hours. Sporadic current observations were done with meters fastened to the CTD wire.

2.2 *Water level registrations*

With a high precision pressure recorder (Aanderaa WLR-l) placed on the bottom we obtained continuous water level measurements. Every recording consisted of a 10 min. mean value, which was stored on magnetic tape. The observed hydrostatic pressure was later on converted into tidal elevation, making use of the density from CTD observations. Due to changing ice conditions we had to recover the instrument after 4.5 days.

2.3 *Current measurements*

In the same 4.5 day period we also made current observations at two different depths (110 and 240 m) with Aanderaa RCM-4 meters. Later on we succeeded in supplementing these observations with series of about 10 days duration from two depths (25 m and 75 m). The instruments were adjusted to record the mean current speed over each 10 min. and the direction at the end of each sampling interval.

3. RESULTS

3.1 *Water masses and circulation*

Our investigations were mainly limited to the area close to the ice shelf. Fig. 2 shows the distribution of temperature, salinity and density in a section from the continental shelf east of the Filchner depression to

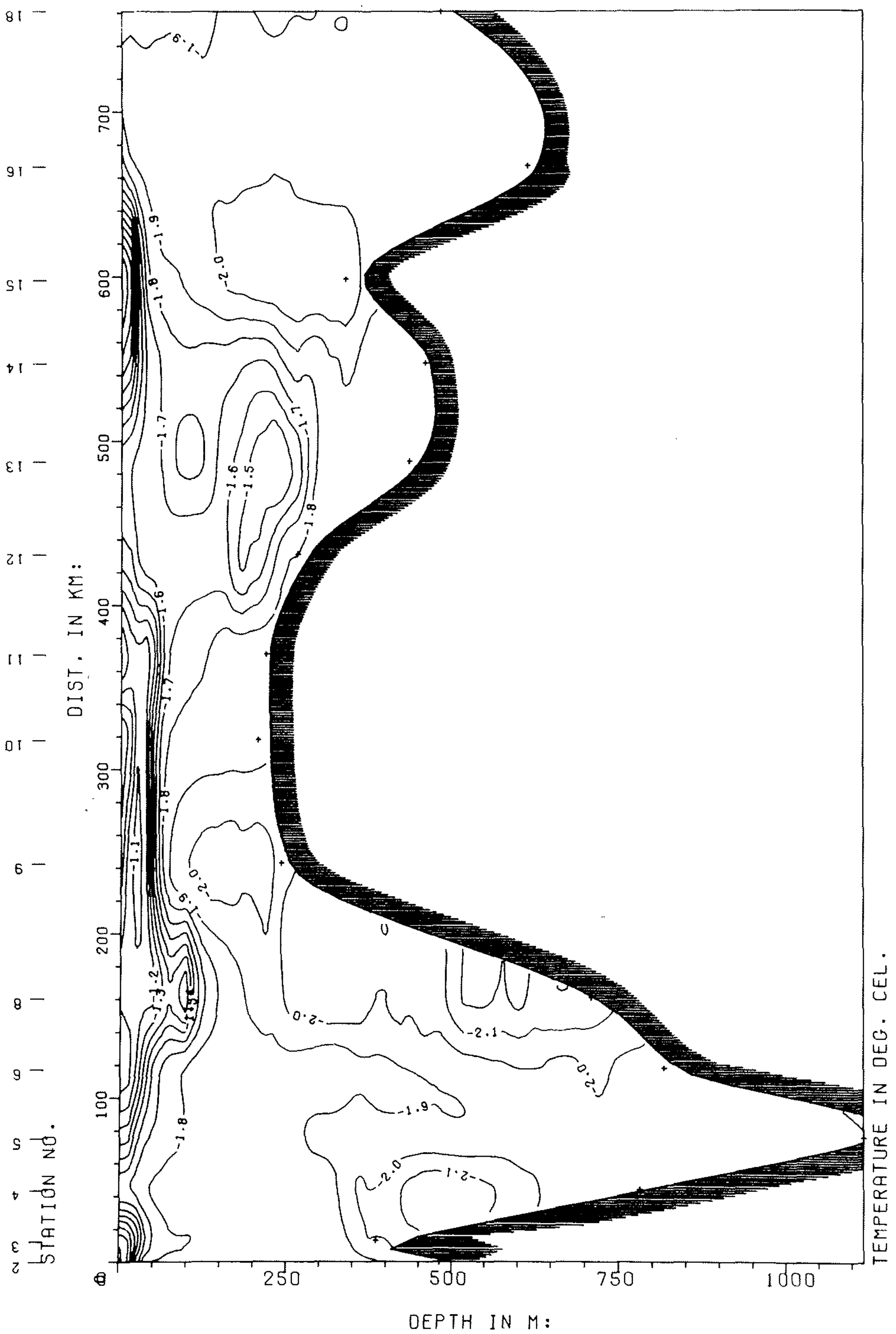

Fig. 2a: A vertical section along the barrier showing the distribution of temperature.

Abb. 2a: Ein Vertikalschnitt entlang der Eisfront mit Temperaturverteilung.

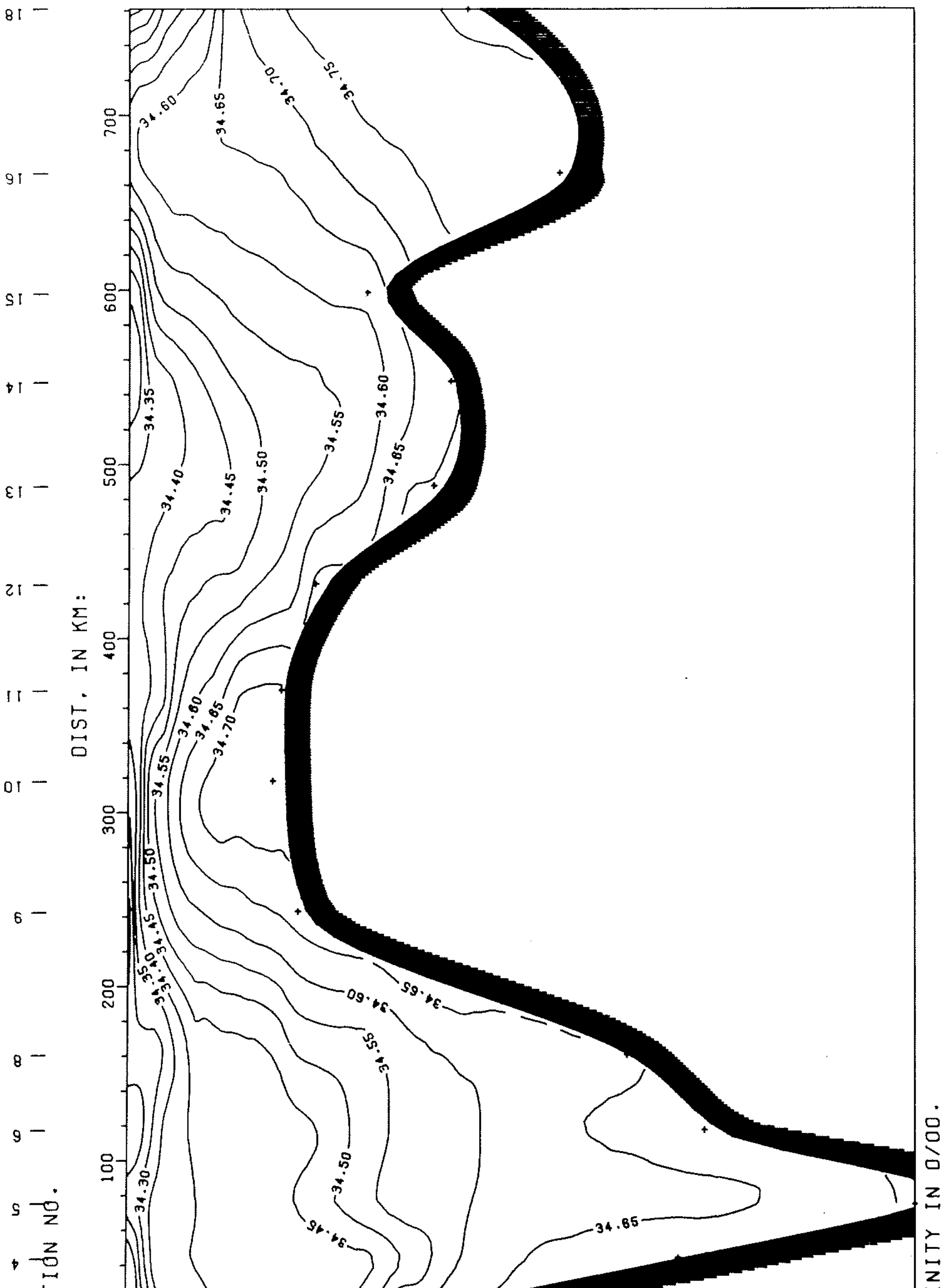

Fig. 2b: A vertical section along the barrier showing the distribution of salinity.

Abb. 2b: Ein Vertikalschnitt entlang der Eisfront mit Salinitätsverteilung.

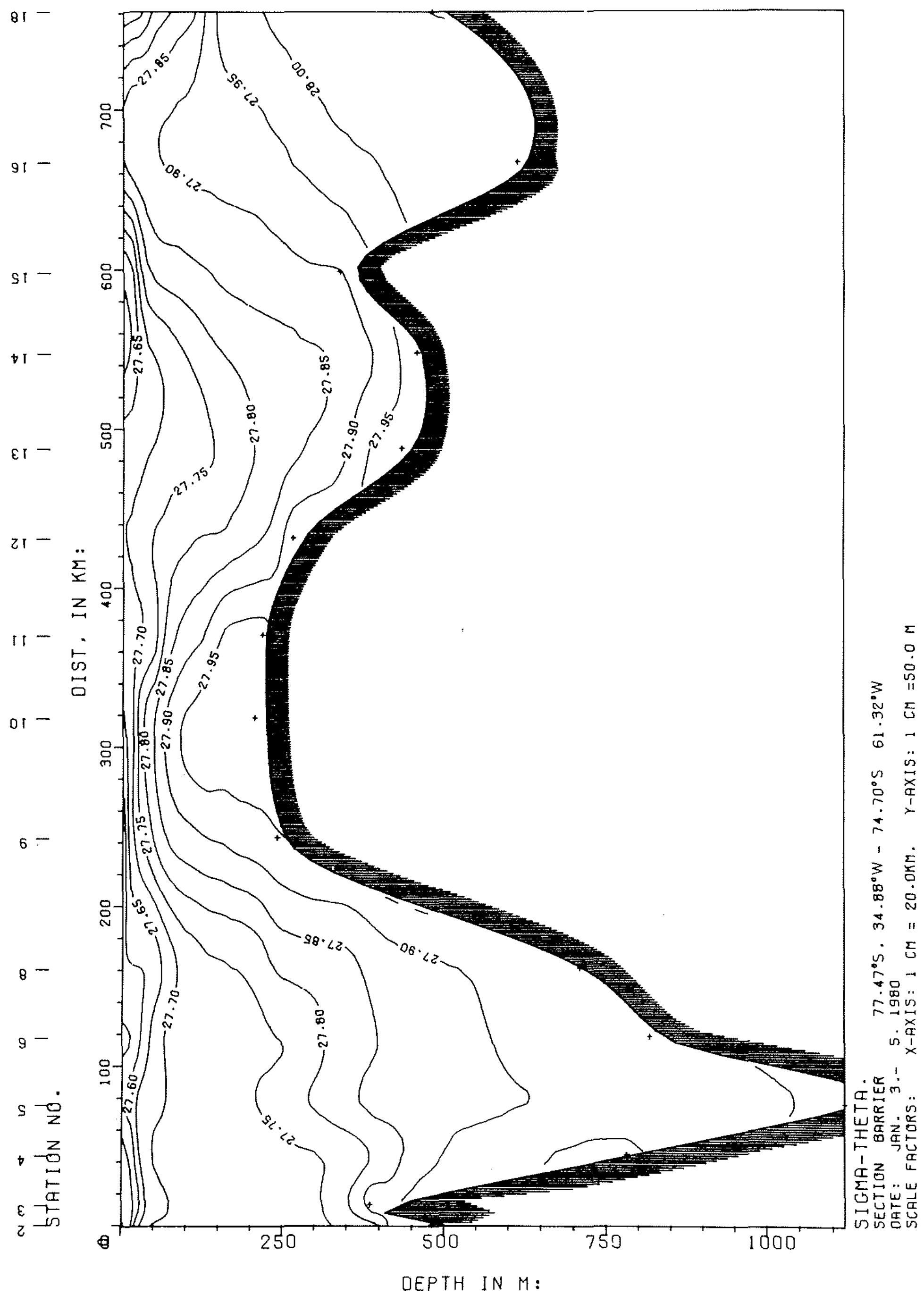

Fig. 2c: A vertical section along the barrier showing the distribution of density.

Abb. 2c: Ein Vertikalschnitt entlang der Eisfront mit Dichte-Verteilung.

the most westerly position. Several water masses can be recognized in this section and will be denoted in agreement with accepted classification. In spite of the limited extension of our observations in north-south direction some information about the circulation can be deduced, especially when compared with earlier investigations.

3.1.1. *Eastern Shelf Water*
In the eastern part on Fig. 2 between 100—400 m a rather homogeneous water mass is present with temperature near -1.8 °C and salinity around 34.40 ‰. This is mainly Eastern Shelf Water which normally occupies a significant volume on the shelf to the east of the Filchner depression.

3.1.2. *Ice Shelf Water*
At both sides of the depression, in depth around 500 m, water with temperature below -2.0 °C and salinity close to 34.60 ‰ can be seen. This is the Ice Shelf Water. The conditions in the depression near the Filchner Ice Shelf have been extensively observed and described by CARMACK & FOSTER (1975). They suggested a cyclonic circulation of the Ice Shelf Water. This is supported by the density structure, Fig. 2, and also from temperature distribution this appears likely as the coldest core of this water (minimum -2.24 °C) is observed at the western slope, indicating a recent contact with the ice shelf. As mentioned earlier more recent investigations also indicate a flow out of the depression of this water (FOLDVIK & GADE, 1978). FOLDVIK & KVINGE (1977) observed in this region in situ supercooled water at 400 m depth.

3.1.3. *Western Shelf Water*
To the west of the depression on the relative shallow shelf we find the dense Western Shelf Water with bottom salinity S> 34.70 ‰ and temperatures near the freezing point at one atmosphere pressure.

The circulation on the shelf is poorly known. It is believed (CARMACK & FOSTER, 1975) that a part of the dense water sinks into the Filchner depression. The station graphs for st. 157 at the slope (Fig. 3) clearly show that more saline water exists close to the bottom. Other CTD stations on the slope indicate the same and it seems evident that Western Shelf Water penetrates into deeper parts of the depression, as this water is heavier than Ice Shelf Water (Fig. 2).

On the basis of T-S characteristics, high oxygen content and saucer-shaped isolines CARMACK & FOSTER (1975) suggested that Western Shelf Water sinking into the depression have a cyclonic circulation in the deeper part of the depression. Our observations support this hypothesis.

3.1.4. *An undefined watermass.*
To the west of the Western Shelf Water, at stations 12—14 on Fig. 2, a water mass is present at 200—300 m which is less saline and warmer than the surroundings. We have found no place where this water has been referred to and the origin and extension is not known. It seems to be present as far east as to the leg 107—111 (Fig. 1), exemplified by station graphs for st. 108, Fig. 4.

The most likely explanation is that this watermass acquires its properties from outside the shelf region, especially the temperature indicates this. It might be that the well known westward flow (the coastal current) above the continental slope split up and a branch flows towards southwest along the isobaths of the western edge of the shallowest part of the continental shelf. This is indicated by an arrow on the map (Fig. 1). Another speculative suggestion is that this water is a remnant of the observed onshore moving Modified Warm Deep Water (CARMACK & FOSTER, 1975) at the continental edge at 40°W.

3.1.5. *The most dense watermass*
When we approached the Antarctic Peninsula we observed the most dense water in the southern Weddell Sea (Fig. 2), with salinity around 34.80 ‰ near bottom and temperature close to the freezing point at one atmosphere. (In the literature this watermass is sometimes included in the Western Shelf Water).

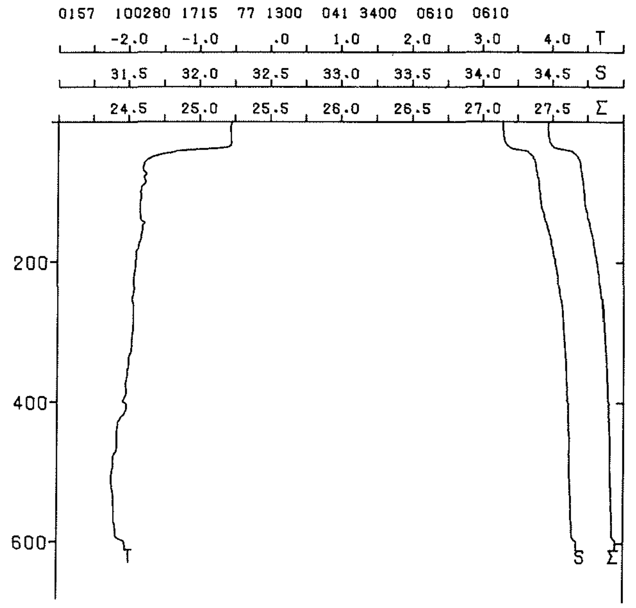

Fig. 3: Temperature, salinity and density versus depth (m) at Station 157 on the western slope of the Filchner depression.

Abb. 3: Temperatur, Salinität und Dichte in Abhängigkeit von der Tiefe an Station 157 auf dem westlichen Hang des Filchner-Grabens.

SEABROOKE, HUFFORD & ELDER (1971) explain the high salinity to the west of the Filchner depression as a result of alteration, due to freezing, of water flowing beneath the Filchner and Ronne Ice Shelf. GILL (1973) argued against this and pointed out that freezing on the surface (with accompanying brine release) together with the movement of ice (fresh water) out of the region, cause a net release of brine. This is still believed to be the major source for the high salinities observed.

KILLWORTH (1974) developed a model which explained the asymetric density distribution observed from the limited data collected from the Weddell Sea Shelf. He also concluded that the densest water moves north along the western boundary. The sloping density surfaces in the western part at depth below 100—150 m on Fig. 2 support the idea of a northward geostrophic flow.

3.2. *Time series*

When the ship was moored to the ice shelf near 50 °W we made time series of CTD-observations. Fig. 5

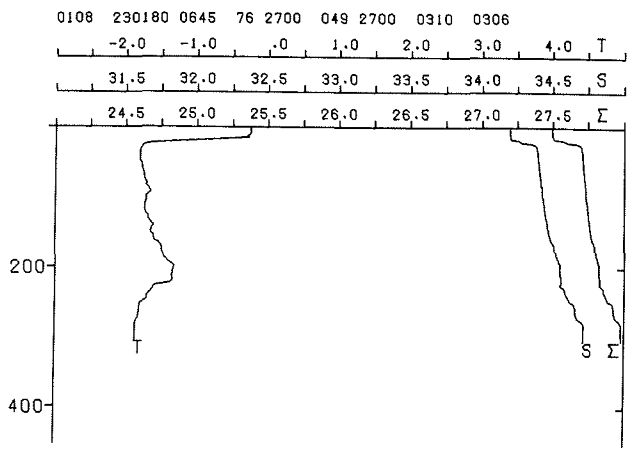

Fig. 4: Temperature, salinity and density versus depth (m) at Station 108 on the western shelf.

Abb. 4: Temperatur, Salinität und Dichte in Abhängigkeit von der Tiefe an Station 108 auf dem westlichen Schelf.

shows the development in salinity, temperature and density for a period of 1.5 days with measurements approximately every second hour. The most striking feature is the rise of the isolines in the middle of the series that leads to a nearly homogeneous water column. For example, properties observed at 160 m in the evening are found in the surface region in the early morning. An extensive upwelling seems to have taken place within a few hours. After the homogenisation the stratification develops again and the conditions are similar to the situation before the upwelling. About 12 hours after the upwelling there is a tendency of a new upwelling. It is reasonable to suppose that these processes close to the ice shelf are connected with the tidal currents, as will be discussed below.

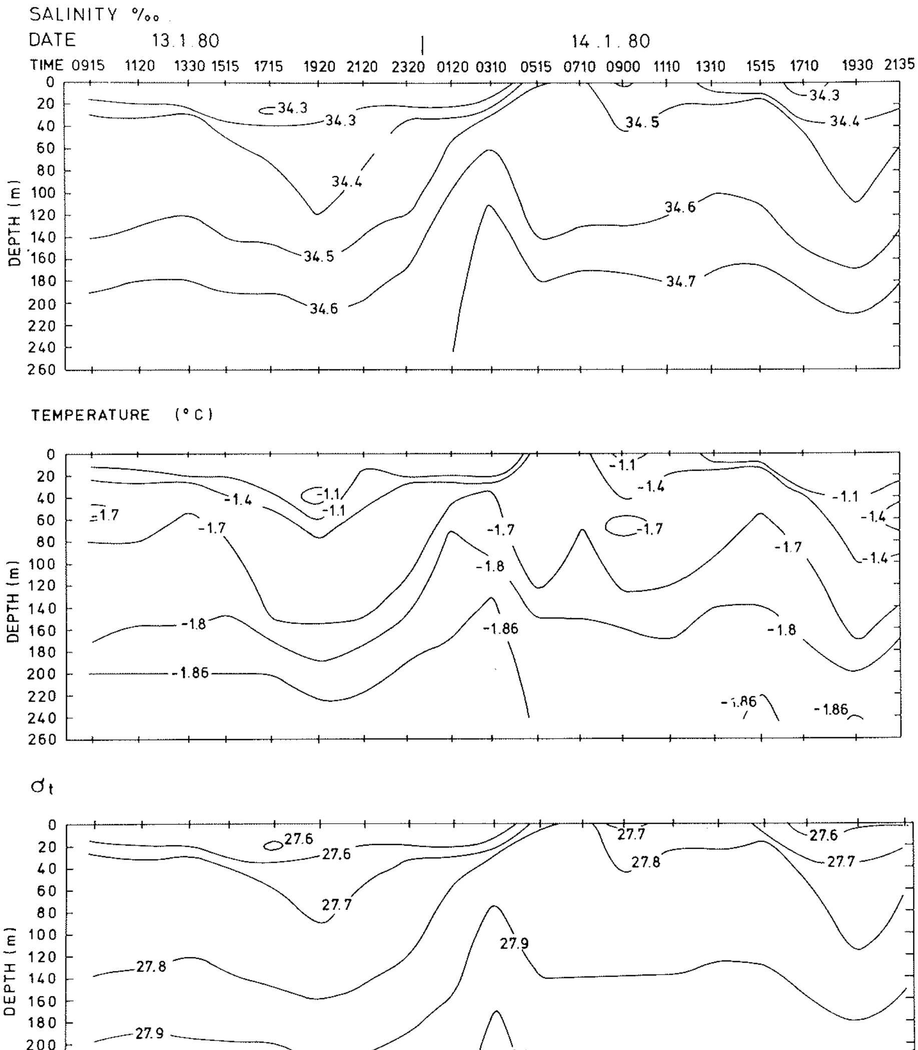

Fig. 5: Time series. Isolines of salinity, temperature and density based on observations about every second hour for 1.5 days in position S 77°00', W 50°07'.

Abb. 5: Zeitreihen. Isolinien der Salinität, Temperatur und Dichte basierend auf Stundenmessungen über 1.5 Tage an Position S 77°00', W 50°07'.

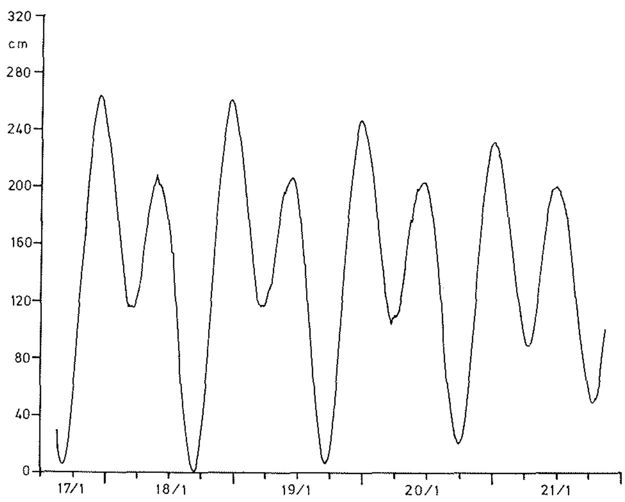

Fig. 6: Tidal measurements in the Weddell Sea 1980. Position S 77°07', W 49°03'.

Abb. 6: Gezeitenmessungen in der Weddell-See 1980. Position 77°07' S, 49°03' W.

Current measurements simultaneously with the CTD-observations reveal a relative strong (up to 20 cm/sec) outgoing current just below the underside (110 m) of the ice shelf between 2300 and 0300. This is the same period as that in which the rise of the isolines, Fig. 5, takes place and the only period with current direction away from the ice shelf (no current observations at the end of the time series.).

Figs. 6 and 7 show tidal and current observations which started 2.5 days after the CTD time series was carried out and covered a period of about 4 days. A typical mixed tide is present with a maximum range of 265 cm in this period. The tidal wave has the characteristics of a progressive wave as the maximum velocities occur at high and low water and the change of main direction take place at mean water level. The

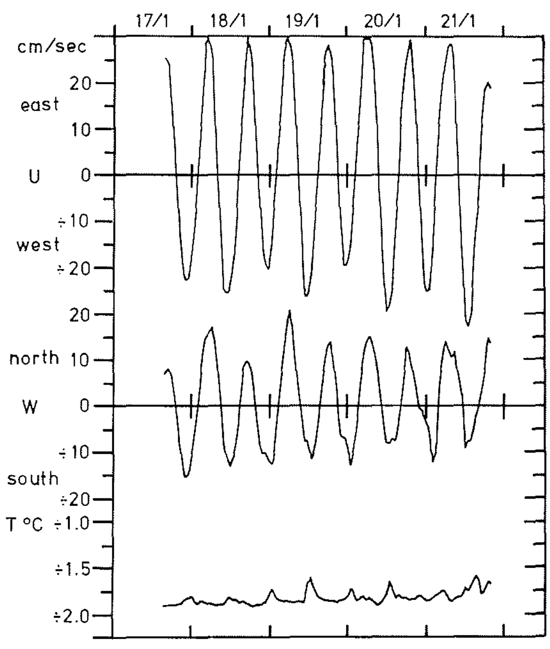

Fig. 7: Current measurements. Components of hourly mean values at 100 m depth in the tidal measurement position.

Abb. 7: Strömungsmessungen. Komponenten von Stundenmittelwerten in 100 m Tiefe (Position der Gezeitenmessung).

highest hourly mean velocities are 30—40 cm/sec. Extrapolation backwards of the above observations tells us that the upwelling observed takes place when the tidal current is flowing east-northeast, that is, away from the ice shelf. The temperature observations included in Fig. 7 show temperature increases serveral times when the tidal current flows in below the ice shelf, which is consistent with the results from the time series. The same phenomenon is present at 75 m depth in the 10 days series of current measurements.

If the above mentioned upwelling is linked to the tidal movements we should expect to observe similar situations in the other CTD time series. For the shortest time series this is also the case, but the manifestation is less clear due to a different stratification.

The 2.5 days series was done with the ship tied to the fjord ice and with a distance of 6 km to the ice shelf. As expected, no extensive upwelling is traced in this situation.

4. FINAL REMARKS

The upwelling shown in Fig. 5 may stimulate biological production near the ice shelf (see HARTLINE, 1980), and may also release the potential instability discussed by FOLDVIK & KVINGE (1974) and thereby cause convection of the entire water column.

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