

## **The fieldwork during the "Polarstern" cruise ANT XVI/2 as a contribution to the study of bottom water formation and sea ice transport in the Weddell Sea**

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### **Introduction**

The field work during "Polarstern" cruise ANT XVI/2 aimed to measure circulation and water mass properties in the Atlantic sector of the Southern Ocean, to investigate the contribution of the Weddell Sea to the ocean's role in climate. In this respect water mass modification plays an important role, because it leads to the formation of Antarctic Bottom Water which is an essential part of the global thermohaline circulation (Fahrbach and El Naggar, in press).

Comparatively warm and salty, lower Circumpolar Deep Water, which has its origin in the North Atlantic, flows from the Antarctic Circumpolar Current into the Weddell Sea. Here, this water mass, designated as Warm Deep Water, is carried to the south, where it upwells and transfers heat to the much colder Antarctic atmosphere. The cooling leads to a density increase of the water, resulting in a sinking motion that is convection. Fresh water gain due to precipitation and melting of sea ice, ice shelves and icebergs counteracts the density increase and this freshening has to be compensated by salt gain from sea ice formation, for convection to occur. Consequently the net sea ice formation rate determines the upper limit of deep and bottom water formation at a given salinity of the surface water. In the central Weddell Sea, convection supplies enough heat to limit the sea ice formation. Therefore formation of high salinity and consequently bottom water occurs only on the shelves. The high salinity water can cascade into the deep ocean either directly or after circulation under the shelf ice. The mixing of Weddell Sea Bottom Water or shelf waters descending the continental slope with adjacent water masses which consist mainly of modified Warm Deep Water results in Weddell Sea Deep Water. This exits the Weddell Sea into the Antarctic Circumpolar Current and moves from there into the different ocean basins (Fig. 1).

At the northern threshold of the Filchner Depression, the so-called Ice Shelf Water drains into the deep sea. This water mass forms because water of high salinity flows in beneath the ice shelf. At a depth of 1000 m, the freezing point of seawater is lowered to -2.5°C. As a result the inflowing water, even if it was at the freezing temperature at the sea surface, can be further cooled at the base of the ice shelf through melting which also reduces the density of the sea water. In this manner, the coldest water found anywhere in the ocean is formed. As the freshened sea water rises, part of this supercooled water freezes onto the underside of the ice shelf on its way back out, so forming marine ice. Another part exits from the front of the ice

shelf as supercooled water. In the Filchner Depression this water flows to the north, where, with a temperature of  $-2.1^{\circ}\text{C}$ , it crosses a low saddle at the edge of the continental shelf, and as a result of its high density, caused by its low temperature, drains into the deep sea. This outflow contributes to the formation of Weddell Sea Bottom Water, which feeds into the circumpolar ocean to the north, from where it flows further into the three ocean basins as Antarctic Bottom Water.

It is the objective of our work to quantify the transport of Ice Shelf Water into the deep sea, using direct measurements of the currents made with moored instruments. The mixing of the Ice Shelf Water with the lighter surrounding water determines the depth to which the outflow can sink. To measure in this region, four moorings were placed in the outflow last year by HMS Endurance. In order to record the distribution of water masses, CTD (Conductivity, Temperature, Depth) sections were carried out, one extending from the iceberg A-38B, onto the continental slope, a second section in the region of the descending flow of Ice Shelf Water and a third along the northern threshold of the Filchner Depression. These investigations are a cooperation between the AWI, the British Antarctic Survey, the Geophysical Institute of the University Bergen, Norway and Earth and Space Research, Seattle, USA.

### **The outflow from the Filchner Depression**

In the southern Weddell Sea, a CTD section was taken, extending from iceberg A-38B onto the continental slope (Fig. 2 and 3) and a detailed survey was carried out between the Ronne Ice Shelf up to Lassiter Coast and the iceberg A-38B (Fig. 4). An 100km wide outflow of Ice shelf Water was observed at the eastern side of the Ronne depression, which resulted in a strip along the ice shelf front of temperatures in the water column below the surface freezing point. The coldest temperatures of  $-2.12^{\circ}\text{C}$  were observed at station 30 and even at the sea surface temperatures around  $-2^{\circ}\text{C}$  were encountered indicating the upwelling of supercooled water. The outflow of Ice Shelf Water was surveyed on a three-dimensional grid. The temperature minimum at the eastern slope of the depression decreases clearly to the north. It is curious that the northward directed outflow of Ice Shelf Water follows the eastern slope whereas due to the effect of Coriolis force it is expected at the western slope.

The distribution of the water masses sinking along the continental slope and at the northern threshold of the Filchner Depression was also measured (Figs. 3 and 5). The descending plume of former Ice shelf Water now transformed to Weddell Sea Bottom Water was surveyed on three transects. The core of cold water with low salinity is located at the northern threshold of the Filchner Depression in 400 m to 500 m depth (Fig. 5). After crossing the sill the plume turns to the left under the influence of Coriolis force and sinks between the eastern section (not shown) and the western section (Fig. 3) from 1500 m to 2500 m depth. As the plume sinks, its temperature increases significantly due to mixing with ambient water masses. However, the core can still be clearly identified. On a section along the 2800 m depth contour, higher temperatures are found as in shallower parts of the slope, suggesting that the cold core did not exit seaward between the eastern and western sections.

A set of four moorings which were deployed in 1998 were recovered on the continental slope northwest of the Filchner Depression (Fig. 6). The moorings were well located in the plume of descending bottom water. The annual mean current speeds in the layer 50 m above the bottom ranged between 44.7 cm/s on the upper continental slope and 6.6 cm/s at the deepest mooring (Fig. 8). The combination of the velocity data and the temperature field (Fig. 7) shows that in southern summer the uppermost mooring, where the highest velocities occur, is not in the plume. However, the temperature time series indicate that cold water was present on the upper

slope for significant periods of time. This shows that the high variability of the plume implies a high uncertainty estimating its transport. A preliminary estimate of the annual mean transport in the plume amounts to  $1.8 \pm 0.9$  Sv. Entrainment of ambient water masses have to be considered, if ventilation rates are to be derived.

### **The flow of bottom water in the northwestern Weddell Sea**

The outflow of newly formed bottom water in the western Weddell Sea has been monitored by CTD transects and moored instruments over a period of more than 8 years between 1989 and 1998. Weddell Sea Bottom Water is defined by a potential temperature of less than  $-0.7^\circ\text{C}$ . The outflow of bottom water from the formation area in the southwestern Weddell Sea towards the northern limb of the Weddell gyre (Fig. 1) was observed at the northern tip of the Antarctic Peninsula on a transect towards the central Weddell Sea. The flow in the bottom water plume is determined by use of five CTD surveys and moored instruments in a 400-m thick bottom layer along the sea floor (Fig. 9).

The average flow in the bottom water plume in the northwestern Weddell Sea deduced from the combined CTD and moored observations is  $1.3 \pm 0.4$  Sv (Fahrbach et al., in press). Intensive transport fluctuations of a wide range of time scales including annual and interannual variations are present (Fig. 10). The variations are partly induced by fluctuations in the formation rates and partly by current velocity fluctuations related to the large scale circulation. Taking into account entrainment of modified Warm Deep Water and Weddell Sea Deep Water during the descent of the plume along the slope, between 0.5 Sv and 1.3 Sv of surface ventilated water are supplied to the deep sea. This is significantly less than the widely accepted ventilation rates of the deep sea which are in the order of 10 Sv. If there are no other significant sources of newly ventilated water in the Weddell Sea, either the dominant role of Weddell Sea Bottom Water in the Southern Ocean or the global ventilation rates have to be reconsidered.

### **Sea ice transports in the Weddell Sea**

Time series of sea ice draft have been measured in the Weddell Sea with moored upward looking sonars (ULS) since 1990 on two transects, one from the Antarctic Peninsula to the Antarctic Continent (Fig. 1), the other one along the Greenwich Meridian (Harms et al., in press). The ice draft measurements are transformed into ice thickness distributions. Time series of ice drift can be estimated assuming an empirical relationship from the surface air pressure fields compiled by the European Centre of Medium Range Weather Forecast (ECMWF). The combination of ice drift and thickness allows us to calculate the sea ice transport in and out the southern Weddell Sea, the area where the major transformation of water masses occur. During the two year period 1991/1992 the mean sea ice volume export from the southern Weddell Sea was  $(50 \pm 19) \times 10^3 \text{ m}^3\text{s}^{-1}$  (Fig. 11). This export of sea ice with a salinity of 4 implies a potential of bottom water formation between 1.3 and 3.3 Sv, assuming that the salinity of the surface waters in the open Weddell Sea ranges between 33.5 and 34.2 and has to increase to 34.65, the salinity of the bottom water.

### **Observations of iceberg drift**

The motion of icebergs was studied by tagging 11 icebergs with satellite transmitters, allowing them to be followed once per day for approximately two years (Fig. 12). The icebergs originate at the Antarctic coast or ice shelf edge, when the ice masses from the inland reach the ocean and break off. With a typical velocity of 15 km per day, they might drift for several years in the Weddell Sea until they finally break into small pieces and supply continental fresh water to the

ocean. If they encounter shallow water during their drift they may stay at a fixed location for years until either they break into smaller bergs or melt sufficiently to drift free. The Weddell Sea receives about 410 Gt of fresh water per year from melting icebergs. If this is evenly distributed over the Weddell Sea, it is a small contribution to the fresh water budget, however if concentrated locally, it has the potential to become significant.

Large icebergs can be followed on satellite images. However, a many icebergs are too small to be repeatedly identified on satellite images, although they might contribute significantly to the fresh water input. To better understand their drift, the tracks of relatively small bergs are measured to determine the appropriate parameters in a numerical model of iceberg drift which is run in AWI. This model includes atmospheric driving forces, ocean currents and sea ice. It takes into account that iceberg motion can be determined by the surrounding sea ice, if the ice cover is closed and rigid enough to transfer a significant portion of the wind momentum to the iceberg. The observed and the model trajectories will be compared to optimise the model parameters. In a final state, it will be possible to determine with the model the effect of variations in the iceberg drift due to climate changes on the fresh water input into the Weddell Sea and consequently on water mass formation.

The iceberg motion determines where the fresh water from the Antarctic continent is supplied to the ocean. Together with the other components of the fresh water cycle, such as precipitation minus evaporation and differential freezing and melting of sea ice, the melt water of the icebergs can locally affect the stability of the water column and consequently deep and bottom water formation.

## **Acknowledgments**

We are grateful to Andreas Wisotzki who participated in the field work, data processing and figure production.

## **Figures**

Fig. 1: Schematical representation of the circulation in the western Weddell Sea and the location of the transect displayed in Fig. 9.

Fig. 2: Locations of the CTD stations during ANTXVI/2 (a) and the enlargement of the area adjacent to the Filchner Depression (b) with the down slope flow of the bottom water plume (dark arrow) and iceberg D11 (light grey area).

Fig. 3: Vertical distribution of potential temperature (a) and salinity (b) on CTD sections which were measured during ANTXVI/2 from the edge of the Ronne Ice Shelf (St. 42) into the deep Weddell Sea (St. 85).

Fig. 4: Vertical distribution of potential temperature (a) and salinity (b) on a CTD section which was measured during ANTXVI/2 along the Ronne Ice Shelf south of the iceberg A-38B (left) to the Lassiter Coast at the Antarctic Peninsula (right).

Fig. 5: Vertical distribution of potential temperature (a) and salinity (b) on a CTD section which was measured during ANTXVI/2 along the northern sill of the Filchner Depression from west (left) to the east (right). The location of the stations is indicated in Fig. 2.

Fig. 6: Vertical section of the potential temperature across the continental slope west of the Filchner Depression (Fig. 2) showing the current meters moored from 1998 until 1999.

Fig. 7: The potential temperature contour plot of the 400-m thick bottom layer along the transect as shown in Fig. 6 and the location of the moored instruments. The  $-0.7^{\circ}\text{C}$  isotherm of the potential temperature indicates the upper boundary of the Weddell Sea Bottom Water.

Fig. 8: Map of the continental slope west off the Filchner/Ronne Ice Shelf showing the annual mean current vectors measured from austral summer 1998 to 1999. The current speeds are indicated in cm/s at the end of the vectors.

Fig. 9: Vertical section along the western part of the section across the Weddell Sea as displayed in Fig. 1 showing the moored current meters and thermistor strings of four observation periods from 1989 until 1998. At each location the availability of a record is indicated by the instruments' serial numbers marked right of the location.

Fig. 10: Smoothed time series of daily means from 1989 until 1998 (A) of the thickness of the Weddell Sea Bottom Water plume at mooring 207 as determined from the  $-0.7^{\circ}\text{C}$  potential temperature, (B) the cross-section area occupied by the plume, (C) the averaged cross-section current velocity for the plume, and (D) the resulting volume transport.

Fig. 11: Integrated sea ice volume transport in  $\text{m}^3\text{s}^{-1}$  normal to the transects as derived by Harms et al. (2000) from ice draft measurements with moored upward looking sonars and winds derived from the ECMWF data set.

Fig. 12: Drift of icebergs on which satellite transmitters were deployed during ANT XVI/2 in the northern Weddell Sea, the Antarctic Coastal Current and in front of the Ronne Ice Shelf.

## Literature

Fahrbach, E and S. El Naggar (Eds.): Cruise Report ANT XVI/2. In: The Expeditions ANTARKTIS XVI/1-2 of the Research Vessel "POLARSTERN" in 1998/1999. Ber. Polarforsch., in press.

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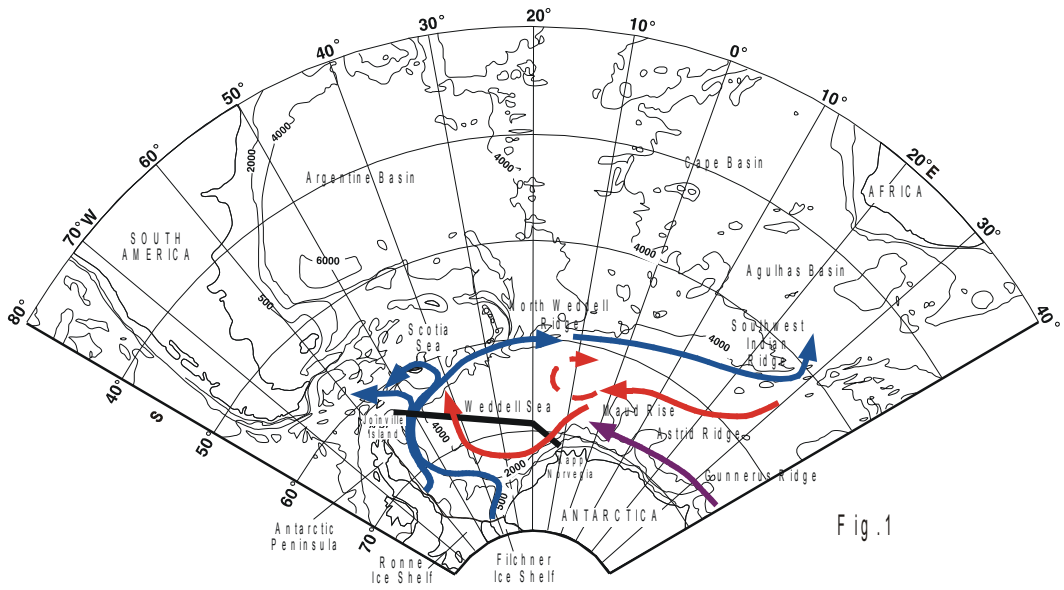


Fig. 1

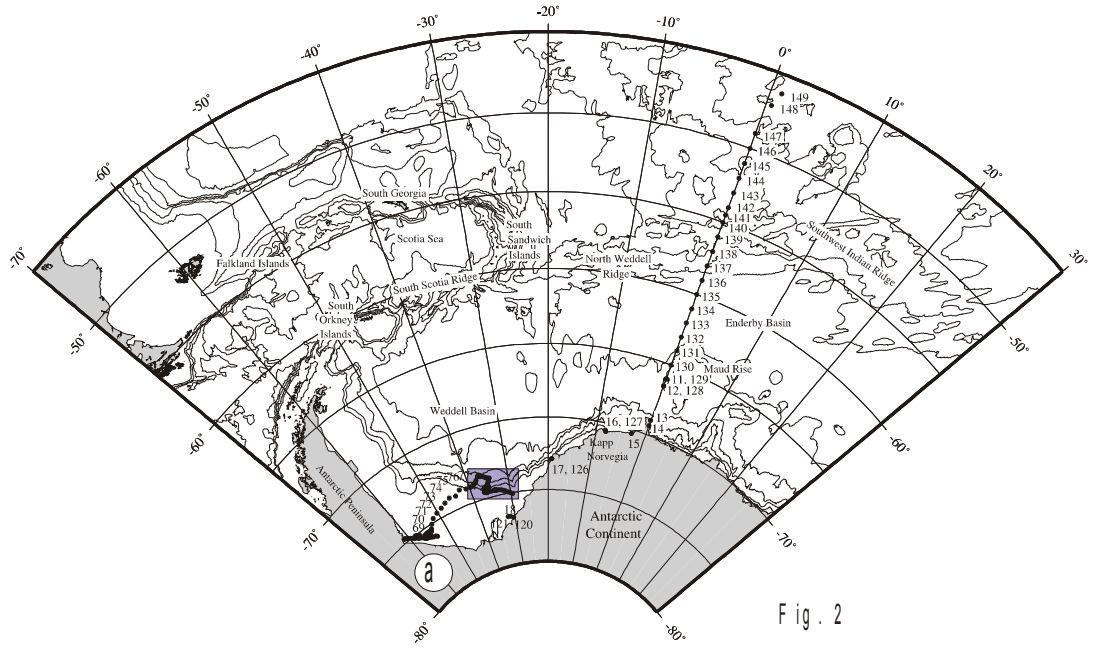
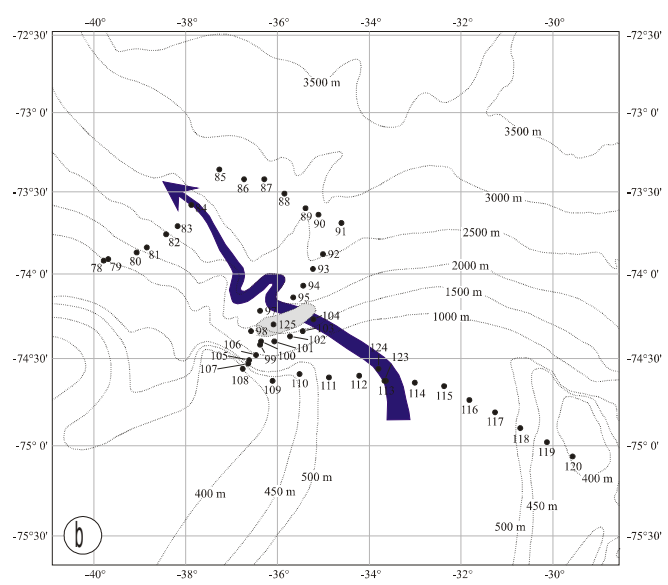


Fig. 2



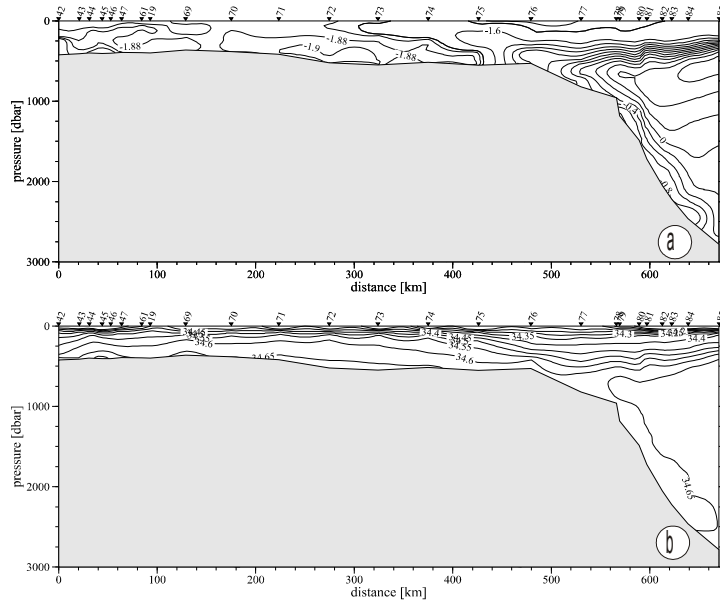


Fig. 3

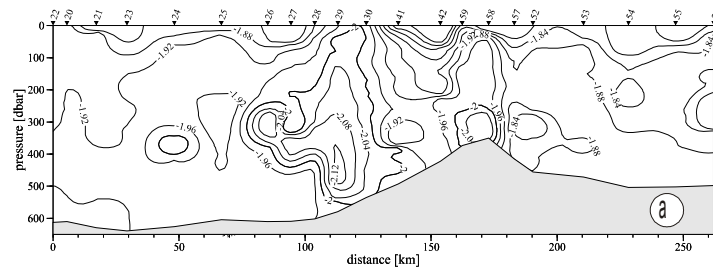


Fig. 4

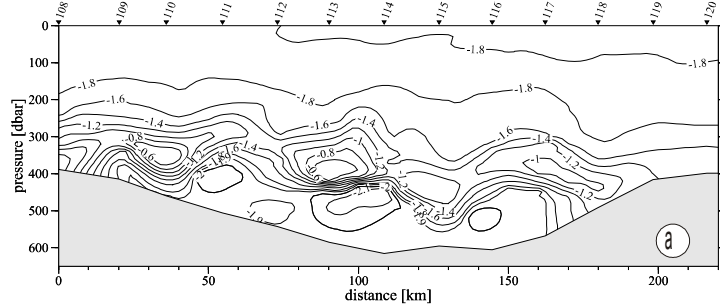
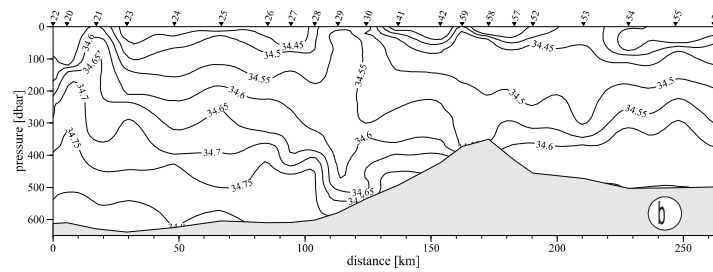
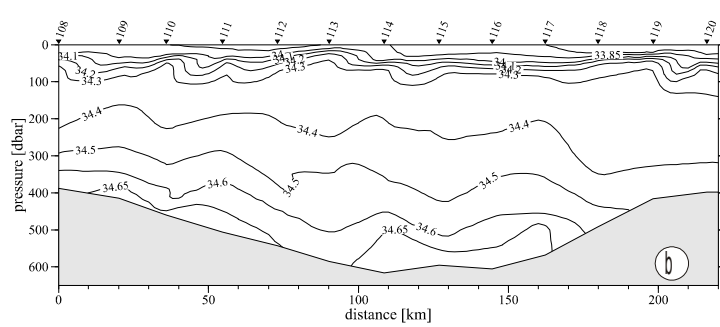


Fig. 5



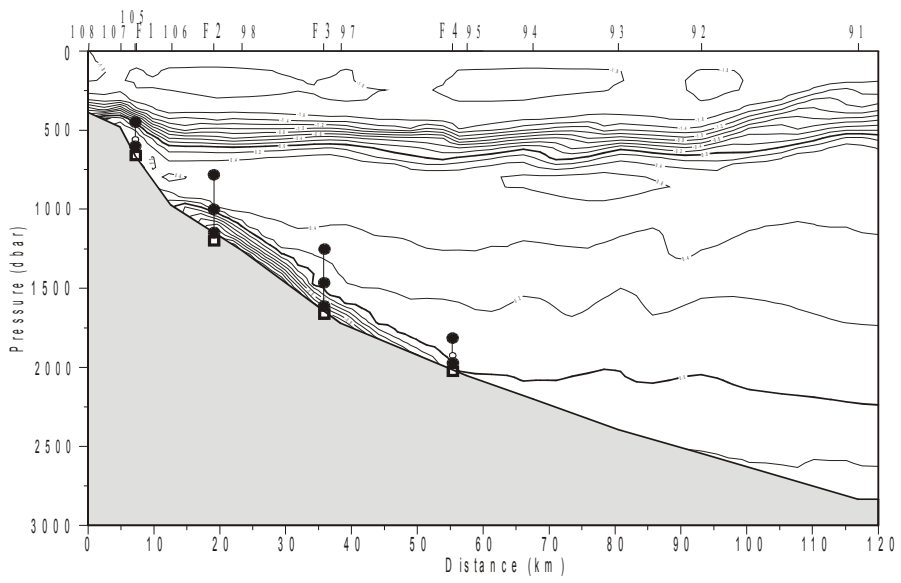


Fig . 6

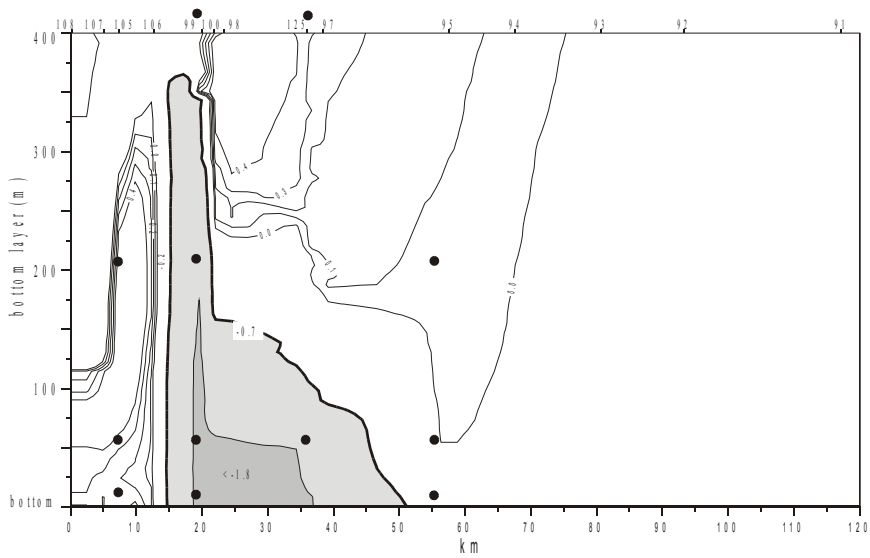


Fig . 7

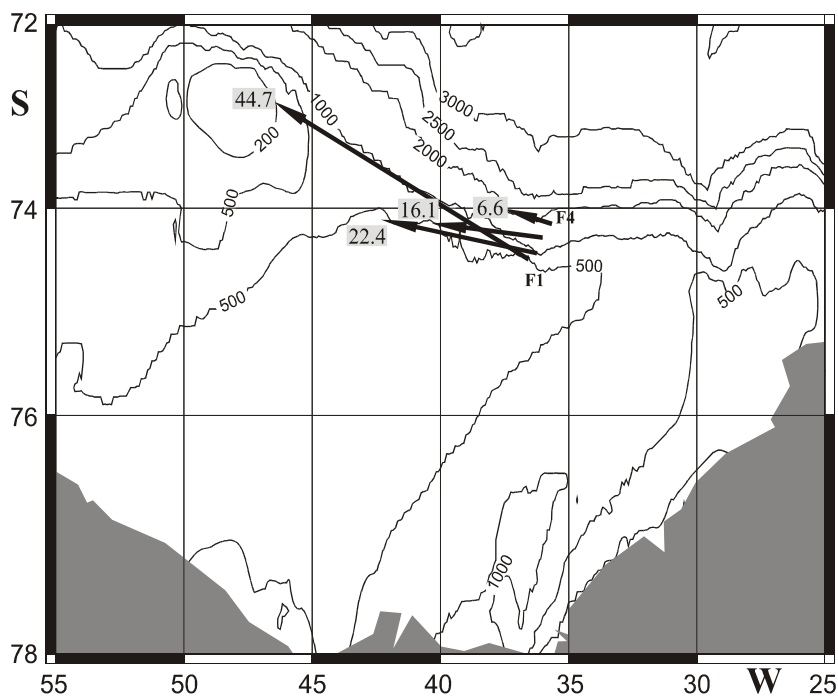


Fig . 8



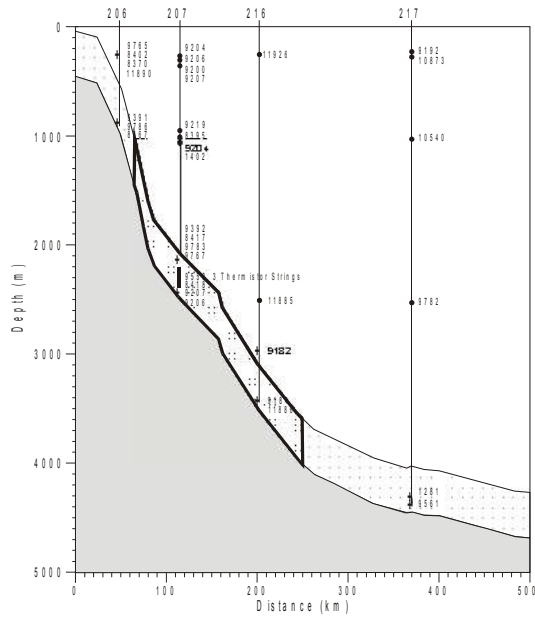


Fig . 9

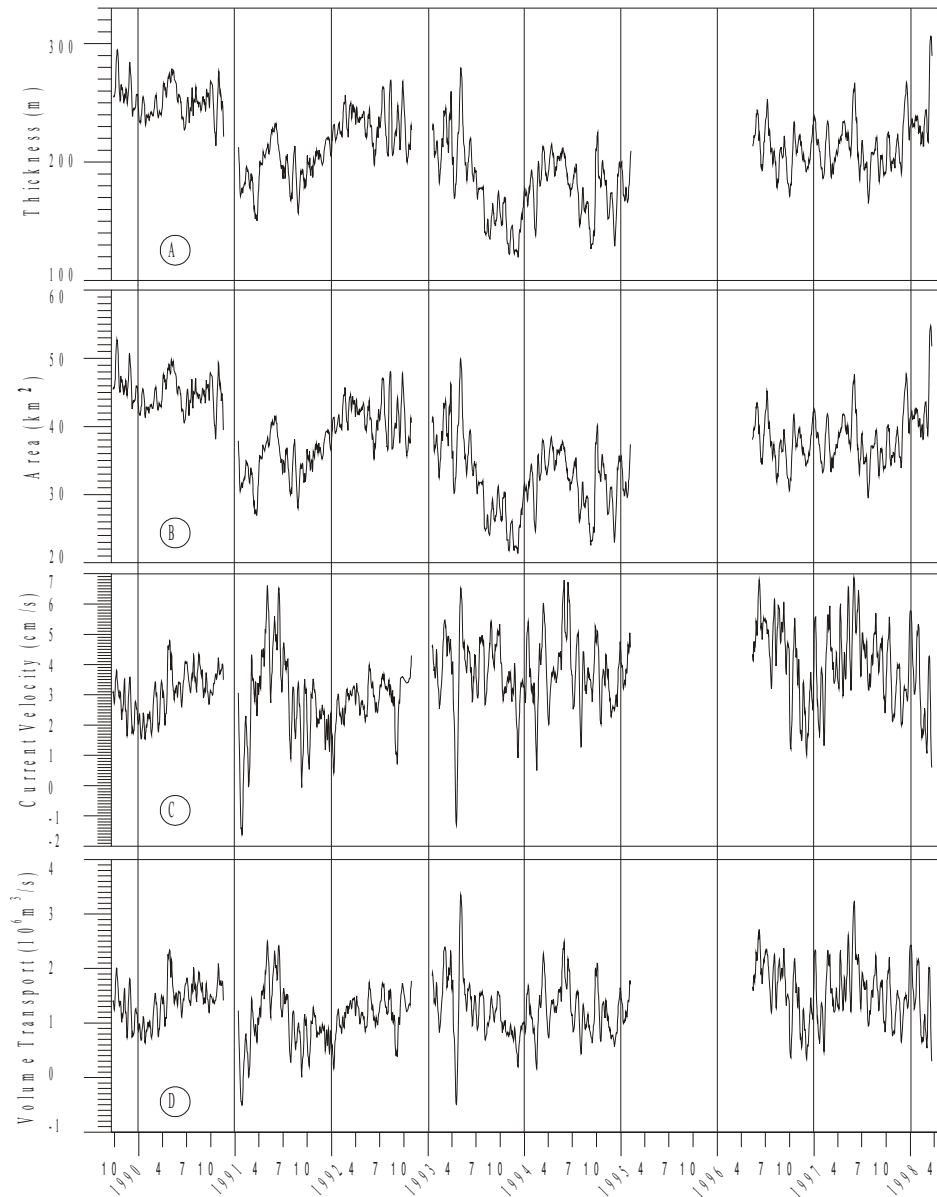


Fig .10

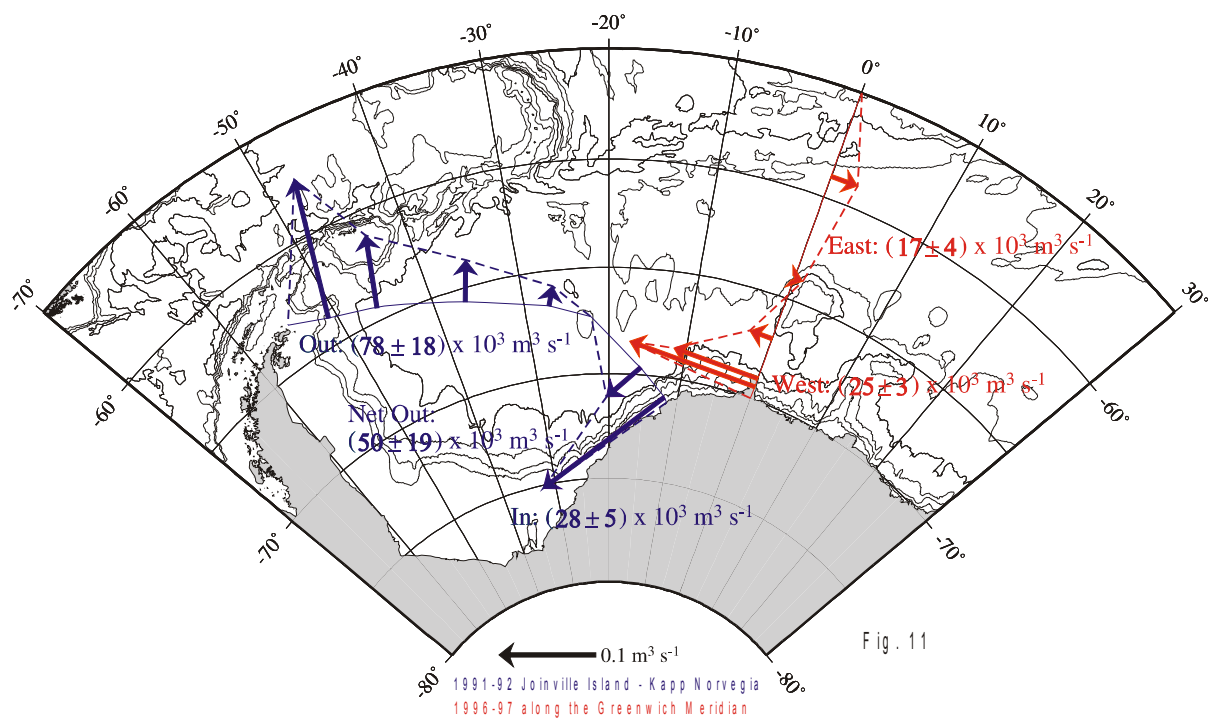


Fig. 11

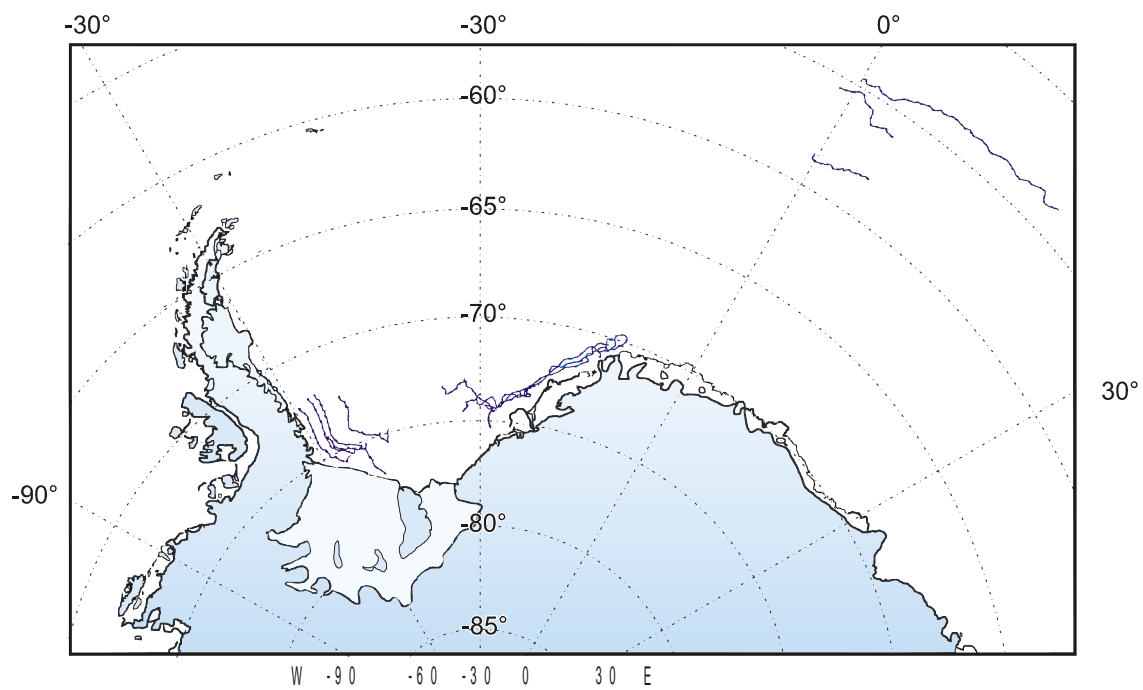


Fig. 12