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Evidence of dense water overflow on the Ross Sea shelf-break

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Abstract: This paper presents the results of the analysis of hydrological data of a 5-day mesoscale experiment (53 CTD casts) conducted during the XIIIth Italian Expedition to Antarctica (1997–98 cruise) in the framework of the CLIMA (Climatic Longterm Interaction for the Mass balance in Antarctica) Project of the Italian National Programme for Antarctic Research (PNRA). The experiment site was chosen for studying the dense water overflow in relation to the shelf-break in the central Ross Sea, after a large-scale synoptic survey, aimed to detect the general hydrological characteristics of the basin. A classical θ/S analysis was carried out for better understanding of the shelf-slope connection and the interactions between the water masses of this zone: the Circumpolar Deep Water (CDW) coming from the oceanic domain and the Ice Shelf Water (ISW) spreading from the Ross Ice Shelf (RIS) edge. Our results show the evidence of an overflow of dense water, originated on the continental shelf, on the shelf-break. This supercold water signal is found on the continental slope down to 1200 m depth. The shape of this tongue of modified ISW, whose thickness reaches up to 100 m, is very narrow, suggesting that the overflow occurs in very localized areas.

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Key words: Ice Shelf Water, Ross Sea, shelf-slope interactions, water masses, θ/S analysis

Introduction

The deep circulation in the world ocean is driven by dense water formation at high latitudes (Gordon 1986). The primary source of deep waters is located in the Southern Ocean, in the Weddell and Ross seas. The Weddell Sea is thought to be the most important source (Jacobs *et al.* 1970, Foster *et al.* 1987), but the Ross Sea seems to have a crucial importance in the circulation of the Pacific Ocean (Jacobs *et al.* 1970, Locarnini 1994). In particular, the Ross Sea is the formation site of two shelf waters (SWs), which constitute an important part of the Antarctic Bottom Waters (AABWs): the High Salinity Shelf Water (HSSW), characterized by salinity values ranging from 34.75 to 34.85 psu (Jacobs *et al.* 1985), and the Ice Shelf Water (ISW), defined by temperatures below the surface freezing point.

The Circumpolar Deep Water (CDW), the most voluminous water mass carried by the Antarctic Circumpolar Current, flows in the Ross Gyre, reaches the continental slope and, at the shelf-break, mixes with the SWs forming the AABWs (Locarnini 1994).

The AABWs overflow influences the mass exchange budget at basin scale, and it affects to some extent the global ocean circulation and the climate of the planet.

The dense waters, accumulated on the shallow continental shelves, migrate to the shelf-break, spill over the shelf edge and descend the continental slope as a shelf-break gravity current (Whitehead 1987), subject to friction and possibly enhanced by topographic channelling. For mesoscale processes like this density-driven downslope motion or cascading friction is important, because it breaks the constraint of potential vorticity conservation and counteracts the geostrophic tendency for alongslope flow (Huthnance 1995, Shapiro & Hill 1997). The downslope motion entrains ambient water, namely the CDW, reaches a depth where density is the same and spreads off-slope (Huthnance 1995). The role of entrainment is fundamental because without entrainment the cascading event is inhibited by friction (Shapiro & Hill 1997).

The downslope mechanisms are important for ocean–continental shelf exchange (Huthnance 1995), in particular for the export of organic carbon, suspended material and dissolved gases such as oxygen, responsible for the ventilation of the deep ocean. Dense overflows were observed in different marginal seas (Huthnance 1995) and around Antarctica in the Weddell Sea (Gill 1973, Foster & Carmack 1976, Foster *et al.* 1987) and in the Ross Sea (Baines & Condie 1998).

This paper presents the first analysis of field observations focussed on describing a possible cascading-like overflow of ISW on the continental slope in the central Ross Sea, where a five day mesoscale experiment was carried out. A description of the water masses present in the investigation area and of the sampling design is given. A classical θ/S analysis was performed in order to investigate the water masses interactions on the shelf-slope edge. Our observations show evidence of the presence of ISW down to 1200 m depth on the slope, suggesting an overflow occurring in very localized areas.

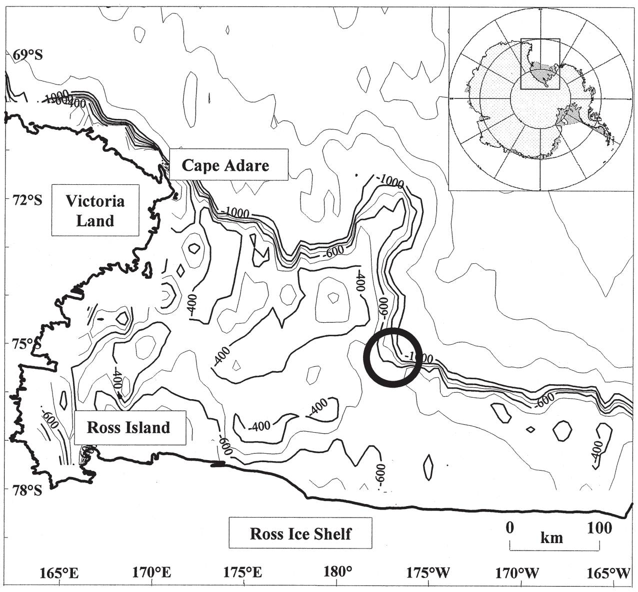

Fig. 1. The Ross Sea with the indication of the area under study (circled zone).

The water masses

The Ross Sea is located in the Pacific sector of the Southern Ocean. Its southern boundary is limited by the Ross Ice Shelf (RIS), a wide floating ice sheet, separated from the sea bottom by a cavity, where water masses can circulate. The presence of this ice cavity strongly influences and

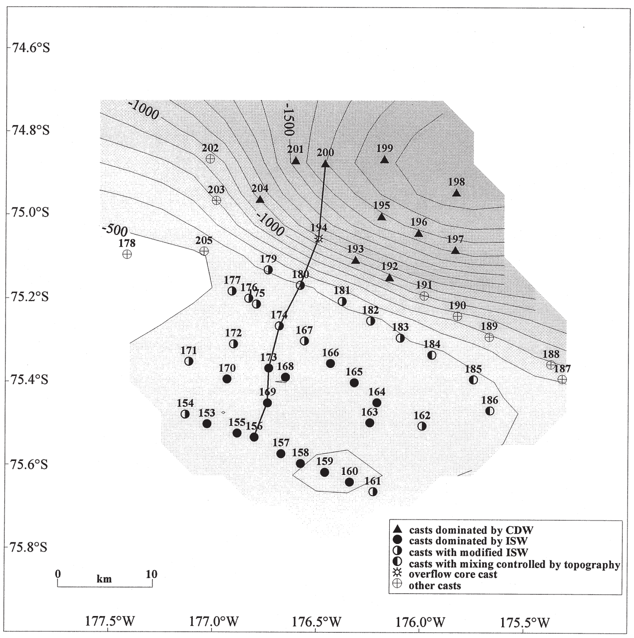

Fig. 2. Detail of the area studied, with bottom topography. The characterization of the hydrological casts is summarized in the legend. The position of the section reported in Fig. 4 is indicated.

modifies the characteristics of the waters penetrating southward in this area. Direct oceanographic observations under the ice shelves are limited to investigations using hot-water drills (Jacobs *et al.* 1979, Nicholls *et al.* 1991), so several model approaches has been proposed to improve the picture of the processes of ice shelf-ocean interaction (Gade 1979, MacAyeal 1985, Jenkins 1991, Nøst & Foldvik 1994, Hellmer & Jacobs 1995, Grosfeld *et al.* 1997). These interactions take place through a circulation driven mainly by thermohaline differences (Jacobs *et al.* 1992, Hellmer & Jacobs 1995, Grosfeld *et al.* 1997).

Thermohaline convection in which shelf dense water evolves into ISW is believed to be responsible for sub-ice processes like melting and freezing beneath the Filchner–Ronne and Ross ice shelves (Jacobs *et al*. 1992). The ISW formed is characterized by an *in situ* temperature below the sea surface freezing point. At the RIS edge it presents two different cores (Jacobs *et al.* 1985): the Shallow ISW (SISW) and the Deep ISW (DISW). The DISW seems to derive from the interaction between the ice shelf base and the HSSW (MacAyeal 1984, Jacobs *et al.* 1992). In fact, the HSSW, having temperatures near the sea surface freezing point, provides the heat necessary for melting the interior cavity due to the reduction of the seawater freezing point with increasing pressure (Hellmer & Jacobs 1995).

The DISW once formed beneath the RIS flows out northward in a plume-like shape and migrates to the shelf-break, maintaining this well defined structure. On the continental slope this dense water mixes with the CDW, coming into the Ross Sea from the southern margin of the Ross Gyre (Locarnini 1994). The CDW is characterized by a temperature maximum ($T > 1.0°C$) and by relatively high salinity values (up to 34.70 psu). The mixing among the CDW, the Antarctic Surface Water (AASW) and the SWs originates a modified portion of the CDW, defined by temperatures up to –1.0°C at the shelf-break (Jacobs *et al.* 1979, Jacobs *et al.* 1985).

The interactions and mixing processes with the water masses present on the continental slope influence the downslope flow of the DISW, which maintains fairly constant hydrological characteristics up to the shelf edge. The aim of our work was to concentrate our attention on the fate of the DISW at the continental shelf break.

The experimental design

The interaction between the ISW and the CDW at the shelf-break, in relation to the Antarctic slope front (Whitworth *et al.* 1998) was chosen as the focus of a mesoscale experiment carried out in the 1997–98 late summer in the framework of the activities of the CLIMA Project (PNRA 1998). The experiment was conducted after a large-scale synoptic survey, aimed at monitoring the general hydrological characteristics of the Ross Sea.

Table I. Technical characteristics of the CTD sensors.

Parameter	Sensor	Measurement range	Accuracy
Pressure	Paroscientific - Digiquartz	0–10000 psia	± 1.5 psia
Temperature	SBE3	-5 to +35°C	± 0.002°C
Conductivity	SBE4	0.0 to 7 S m^{-1}	± 0.0003 S m^{-1}
Oxygen	SBE 13Y	0 to 15 ml l^{-1}	± 0.1 ml l^{-1}
Light transmission	Sea Tech 25 cm	0 to 100%	± 0.5%
Fluorescence	Chelsea - Acquatracka III	0.01 to 100 µg l^{-1}	± 0.01 µg l^{-1}
pH	SBE18	0 to 14	± 0.1
Distance from bottom	Datasonic PSA-900	0 to 300 m	± 0.75 cm

Figure 1 shows the Ross Sea general bathymetry, the circled area indicating the mesoscale experiment site. This area was identified, (once the presence of the ISW coming out from below the RIS edge was assessed as a spreading tongue), for the investigation of the water masses interaction on the shelf-slope break. The map of 53 hydrological stations carried out during the five days of the experiment is shown in Fig. 2 together with the legend indicating the characterization of the casts. This sampling scheme was obtained by adjusting the ship's track transect by transect, to encompass the area of the water masses detected along the way and comply with the weather and the sea ice coverage.

CTD measurements were performed using a Sea-Bird Electronics (SBE) 9/11 Plus equipped with different sensors and with a sampling frequency of 24 Hz. Table I reports the type, the measurement range and the accuracy of the CTD sensors. Temperature and conductivity sensors were calibrated before and after the cruise at the Saclant Undersea Research Centre of La Spezia (Italy). Moreover, *in situ* calibration with reversing thermometers (SIS RTM 4002) and with water samples analysed with Autosal Guideline model 8400B salinometer was performed, in order to check the quality of the temperature and salinity data and to find out possible trends due to sensors failure.

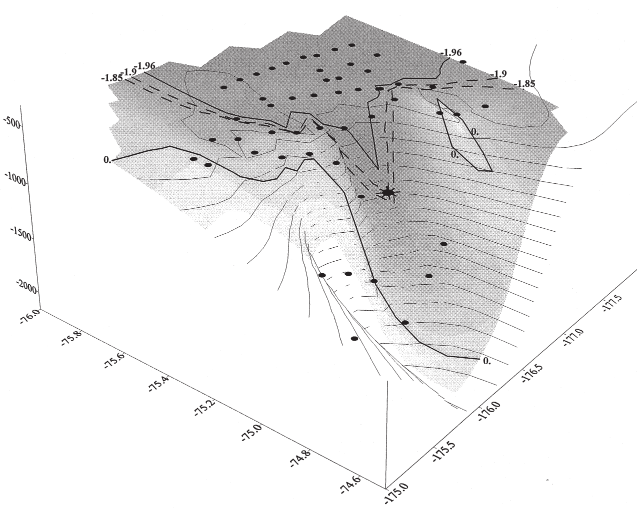

Fig. 3. Distribution of temperature minimum versus its depth. The interval between isobaths (thin black lines) is 100 m. The solid black lines represent the isotherms. Station number 194 is highlighted between the two dashed lines corresponding to the -1.9°C and to the -1.85°C isotherm. The black circles represent the other hydrological stations. Negative longitude indicates west, while negative latitude indicates south.

Figure 3 shows the distribution of the temperature minimum, chosen to highlight the ISW, according to its depth. The black circles indicate the hydrological stations. The casts characterized by T < -1.96°C are on the shelf, where the ISW is present. The three-dimensional picture represents very clearly the descent of the ISW core tongue, marked by the -1.96°C (continuous line), the -1.9°C and the -1.85°C isotherms (dashed lines). The highlighted station (cast number 194) between the two dashed lines presents a relative temperature minimum (T ≅ -1.9°C) and indicates the presence of ISW on the slope. The water column surrounding the tongue on the slope is dominated by the southern limit, marked by the 0°C isotherm, of the CDW penetration in this area.

To investigate the ISW presence on the slope, the temperature distribution along the S–N section indicated in Fig. 2 is shown in Fig. 4 after objective analysis (Bretherton *et al*. 1976, Roemmich 1983). This particular section indicates clearly the water masses interacting in the investigation area. The stations on the shelf are characterized by the ISW signature with temperatures lower than -1.9°C. The warm core of the CDW is evident at the northern end (cast number 200) of the section with temperature values of about 1.0°C, and penetrates the shelf at the shelf-slope edge, mixed with intermediate shelf water, characterized by T ≅ -1.0°C.

The evidence of an ISW overflow event on the continental slope at about 1200 m depth is shown in relation to cast 194, completing the view of the water column structure given by Fig. 3.

Hydrological data analysis

In this section a classical θ/S analysis is performed in order to investigate the interactions between the water masses present in the study area and illustrated in Fig. 4.

First, the cumulative potential temperature profile is drawn for all stations (Fig. 5a). The black solid circles

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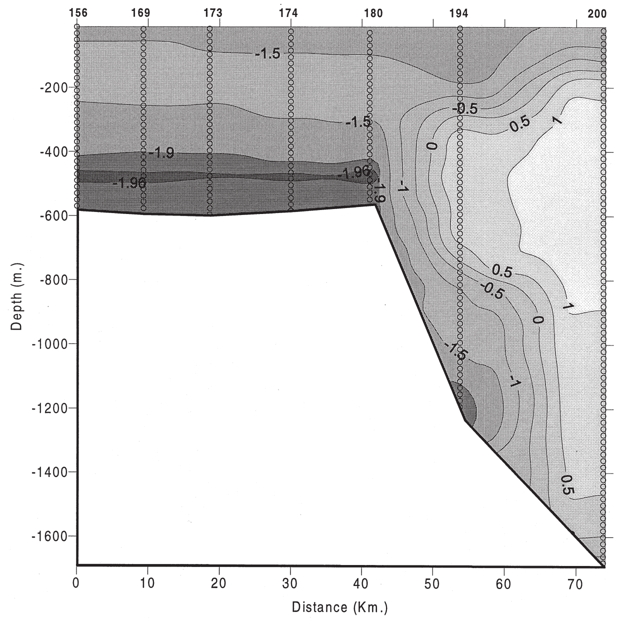

Fig. 4. Temperature distribution along the S–N section indicated in Fig. 2.

indicate station number 194. The vertical profile shows great variability, since the region studied is the limit between two areas with different hydrological and dynamic characteristics. It is possible to group stations in relatively coherent clusters (see Fig. 2), corresponding to rather well defined water masses. The two limits are determined by:

a) the CDW from the offshore area, characterized by a temperature maximum (T > 1.0°C) between 300 and 600 m depth,

b) the ISW on the shelf, which presents an absolute temperature minimum (T < -1.9°C) around 500 m, i.e. as discussed below, around 50–100 m above the sea bottom.

In between, stations present intermediate characteristics and a more detailed analysis has to take into account also salinity.

In the context of the connection between shelf and slope in terms of water masses, a particular interest lies in the stations right on the slope, i.e. station number 194 and the neighbouring ones. As it can be seen by the vertical temperature profile of station number 194 (black solid circles), the hydrological properties relative to the upper 800 m still reproduce the CDW signature, even if the temperature is lower than 1.0°C and the typical bell shape is eroded. Below 800 m depth, the temperature decreases strongly and the thermal stratification shows three layers about 100–200 m thick. The bottom layer, located between 1150 and 1250 m, reaches a temperature of -1.92°C, a value in the range of the supercold water. This is the observational evidence of the presence at this station of dense water coming from the shallower area on the shelf, as indicated in Figs 3 & 4. Among the neighbouring stations only number 193 shows an analogous behaviour for a layer of only 10 m, suggesting that the overflow process is strongly localized across the supercold water tongue.

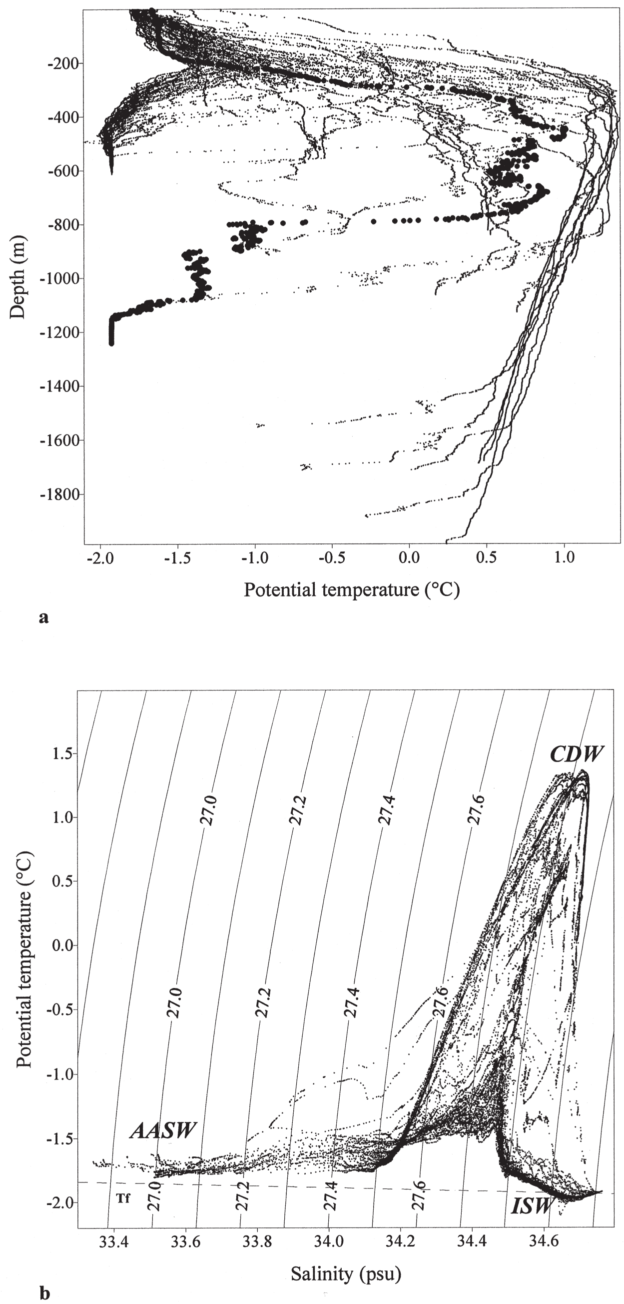

Fig. 5. Cumulative **a.** θ/h profile, and **b.** θ/S diagram of the 53 hydrological casts. Station number 194 is indicated by black circles. The three characteristic water types of this area are indicated in the θ/S diagram together with the temperature freezing line (Tf) as a dashed line.

In Fig.5b the cumulative θ/S diagram, the dashed line indicates the surface freezing point (Tf). The thermohaline

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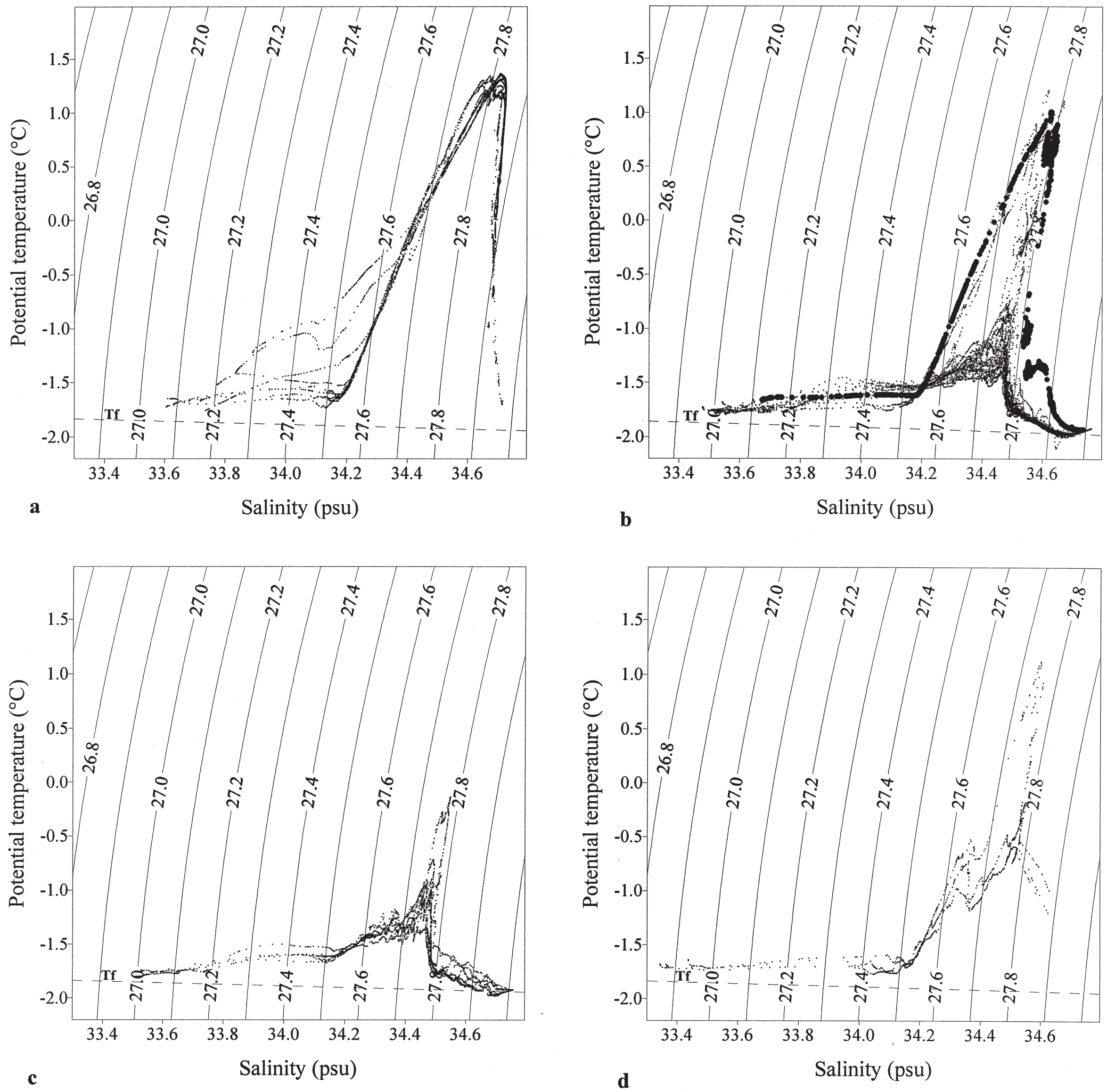

Fig. 6. θ/S diagram of **a.** the cluster dominated by CDW, **b.** the cluster dominated by ISW, **c.** the cluster with modified ISW, and **d.** the overflow transition cluster (topographically controlled). The temperature freezing line (Tf) is shown as a dashed line.

properties of the three major water types detected in the study area (see Fig. 4) are determined by the edge points of an ideal triangle and are reported on the diagram. All waters with σ_θ less than 27.55 kg m^{-3} can be generically encompassed under the definition of AASW (T > -1.9°C, S < 34.2 psu). Temperatures higher than 1.0°C are typical of the stations dominated by the CDW signature. The waters with temperatures below the sea surface freezing point (Tf) define the ISW. This is the definition of supercold water (Jacobs *et al.* 1985).

It is interesting to recall that in the case of the casts dominated by the ISW, the signal relative to this water type is centred 50–100 m above the bottom (see Fig. 5a) and it is characterized by salinity values higher than 34.6 psu.

According to the characterization of Fig. 2, we have grouped the stations with similar θ/S diagrams (Fig. 6) in order to give a more detailed analysis. Figure 6a represents the θ/S diagram of the cluster with the casts dominated by the CDW. The temperature values are always above Tf and the CDW signal is identified by the typical bell shape with temperatures higher than 1.0°C. Two different temperature maxima around the σ_θ = 27.8 kg m^{-3} can be seen, the former corresponding to σ_θ = 27.78 kg m^{-3} and the latter to σ_θ = 27.82 kg m^{-3}. The importance of these isopycnal values will be discussed below.

The complementary situation to that of Fig. 6a presents the stations on the shelf characterized by the higher presence of the ISW (Fig. 6b) and its modifications

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(Fig. 6c). In particular, in Fig. 6b two interesting slope stations, namely number 193 and 194 (black solid circles), are indicated, because they point out the presence of ISW on the slope.

In this figure the ISW signal is very clear and is represented by the lower temperature limit of the layer whose salinity is greater than 34.5 psu. The absolute temperature minimum (T < -2.0°C) is located at a 470 m depth on the shelf (Fig. 5a) and it has σ_θ = 27.92 kg m^{-3} and S > 34.6 psu. The bottom layer of these stations is characterized by salinity values higher than those relative to the absolute temperature minimum and temperatures near Tf, but still in the range of the supercold water.

As in Fig. 6a, two temperature maxima can be highlighted. The first (T ≅ 1.0°C) along σ_θ = 27.78 kg m^{-3} is aligned with the temperature maximum of the shelf stations, and the second (T < 1.0°C) along σ_θ = 27.8 kg m^{-3} is aligned with a relative temperature minimum (T = −1.75 °C) on the shelf. The bottom layer has temperature values slightly lower than Tf, S > 34.6 psu and σ_θ > 27.9 kg m^{-3}, thermohaline properties in the range of the ISW confirming its presence on the slope.

Figure 6c shows the cluster with stations dominated by the modified ISW. The bottom layer, characterized by salinity higher than 34.6 psu, has temperatures near the surface freezing point. A relative temperature minimum (T = −1.78°C) with a salinity of 34.5 psu can be observed in correspondence of σ_θ = 27.8 kg m^{-3} as in Fig. 6b. The temperature maximum slightly lower than 0°C is probably due to the CDW influence. In fact, it is aligned along σ_θ = 27.78 kg m^{-3}, an isopycnal value corresponding to the CDW signal (see Fig. 6a).

Fig. 6d presents the θ/S diagram of stations east of the supercold water tongue, where the CDW presence is still very strong, as it can be seen by the temperature maximum (T > 1.0°C). In this case, as in Fig. 6a, the temperature values are always higher than the surface freezing point. The peculiarity of this diagram is represented by the bottom layer defined by σ_θ =27.78 kg m^{-3} as upper limit and characterized by S > 34.4 psu and T < −0.5°C. The progressive temperature decrease and the salinity increase suggest a mixing, probably induced by bottom topography, with the supercold bottom water. This hypothesis seems to be supported by the value of σ_θ, that is the recurrent value for isopycnal mixing between the CDW and the shelf waters (Locarnini 1994) and it is connected with the maximum temperature variability. In fact, the temperature maxima indicated in each diagram are aligned along this isopycnal line. The isoline σ_θ = 27.8 kg m^{-3} divides the θ/S plane in two sub domains: the former with σ_θ > 27.8 kg m^{-3}, in which the ISW signal dominates; the latter with σ_θ < 27.8 kg m^{-3}, in which the mixing with the CDW prevails. When the salinity of the shelf waters exceeds 34.5 psu (determined by σ_θ = 27.8 kg m^{-3}) the mixing of the CDW with the shelf waters occurs, as demonstrated in Fig. 6b, where the ISW overflow corresponding to station number 194 is confirmed by our observations.

Conclusions

This paper presents the analysis of the hydrological data from a mesoscale experiment, conducted in relation to the shelf-break in the central Ross Sea (cast 194: latitude 75°03'43"S, longitude 176°29'17"W). The study area is characterized by the presence of two water types in particular (see Figs 3 & 4): the CDW, carried on the continental slope by the southern limb of the Ross Gyre (Locarnini 1994), and the ISW, forming beneath the RIS cavity (Jacobs *et al.* 1985, Jacobs *et al.* 1992) and outflowing northward in a plume-like shape. The dense shelf waters, exported from the continental shelf, spill over the shelf-break and they are modified by the mixing with the CDW. The understanding of the driving mechanisms of the shelf-slope connection is a very important theme for understanding the ocean–continental shelves exchange. Moreover, the dense overflows are fundamental for the formation of the AABWs all around Antarctica and the Ross Sea seems to make a considerable contribution in this direction.

The investigation region considered in this work is the limit between two area with different hydrological and dynamic characteristics. In this context, the θ/S analysis performed is a useful and simple instrument for studying the water masses interactions and in particular the mixing processes.

The hydrological characteristics of shallow (Fig. 6b) and deep stations (Fig. 6a) confirm the dominating presence of the ISW and the CDW respectively. The intermediate casts (Fig. 6c) are in between these two sub-domains (separated by σ_θ = 27.8 kg m^{-3}) and are characterized by the isopycnal mixing (defined by σ_θ = 27.78 kg m^{-3}) between the CDW and the ISW.

The mixing of the CDW with the shelf waters along the specified isopycnal lines is clear on the slope in relation to station 194 (see Fig. 6b). The bottom layer at this station, located around 1200 m depth and about 100 m thick, is characterized by thermohaline properties indicating the presence of supercold water. The observational evidence of this overflow event on the continental slope is shown only by another cast (number 193), but for a water layer of about 10 m.

For this reason we can say that the overflow process is very localized across the ISW tongue. In fact, the analysis of the data of a transect across this tongue demonstrates that this overflow core is developed over scales of the order of 20 km (see Fig. 2). This information is of great importance from the point of view of the mass balance dynamics and has to be kept in mind, for the planning of future cruises aimed at quantifying such exchanges.

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