Antarctic Science 16 (2): 199–204 (2004) © Antarctic Science Ltd Printed in the UK DOI: 10.1017/S0954102004001981

Downslope flow observations near Cape Adare shelf-break

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Abstract: The analysis of two high resolution hydrological datasets acquired during the 1997 and 2001 summers across the Antarctic continental shelf-break near Cape Adare (Ross Sea) is presented. The main focus of these cruises was the investigation of the overflow of the High Salinity Shelf Water (HSSW). This dense and salty water mass forms along Victoria Land and flows northward, descending the slope near Cape Adare. Water types characterizing the study area are detected through vertical salinity profiles and by the horizontal distributions of the temperature and salinity. Temperature and salinity hydrological sections obtained by means of objective analysis method well describe the water masses interactions at the shelf/slope edge. The 1997 dataset shows evidence of a strong HSSW signature on the slope, but it is difficult to quantify the spatial scales involved in the spreading mechanism, because the overflow takes place at the edge of the investigation area. The 2001 data, collected at the same position with improved spatial and temporal resolution, clearly indicates the absence of a "true" HSSW downslope process. Even though no estimation of the amount of downslope flow can be given at present due to the resolution of the available dataset, it is possible to get a better phenomenological picture of the process by comparing the two years.

Received 27 January 2003, accepted 16 February 2004

Key words: Antarctica, downslope processes, High Salinity Shelf Water, Ross Sea, shelf/slope interactions, water masses characterization

Introduction

The formation of dense water at high southern latitudes is a key process for the global deep ocean circulation. Most of dense deep water production at these latitudes takes place on the Antarctic shelves (Baines & Condie 1998). Dense shelf waters migrate to the continental shelf-break, then flow off the shelf and onto the continental slope, mixing with ambient water in the upper parts of its path (Whitehead 1987, Huthnance 1995, Shapiro & Hill 1997, Bergamasco *et al.* 2002). The downslope flow occurs essentially in three stages (Baines & Condie 1998). The first stage is characterized by dense water formation through convection driven by surface cooling and brine rejection as sea ice freezes.

The second stage is the geostrophic adjustment of the newly formed water mass as it spills over the shelf, creating a boundary front at the shelf-break. The downslope flow may be increased by baroclinic instability along this front and eddy formation.

A possible third stage is the downflow enhancement by topographical channelling due, for example, to the presence of submarine canyons. Alternatively, gravity and friction can drag dense water down the slope as a sheet with eddy formation and Ekman drainage. Friction, in particular, breaks the constraint of potential vorticity conservation, counteracting the geostrophic tendency for along slope flow (Huthnance 1995, Shapiro & Hill 1997).

The formation of deep water in the first stage involves two Antarctic continental shelf mechanisms (Grumbine 1991): the Ice Shelf Water (ISW) formation and the High Salinity Shelf Water (HSSW) formation. The HSSW is a dense and salty water mass with salinities higher than 34.75 psu and temperatures close to the sea surface freezing point, ranging from -1.95°C to -1.75°C (Jacobs *et al.* 1970, 1985, Kurtz & Bromwich 1985, Budillon & Spezie 2000, Budillon *et al.* 2002). Its formation is assisted by the Modified Circumpolar Deep Water intrusions along the Victoria Land coast and by the presence of polynya areas, maintained open by the strong katabatic winds pushing the newly formed ice offshore (Kurtz & Bromwich 1985). Coastal polynyas, especially the Terra Nova Bay (TNB) polynya along Victoria Land, recur annually and are characterized by salt fluxes large enough to increase the water column salinity (Zwally *et al.* 1985). HSSW, originated in the TNB polynya region, accumulates in the Drygalski Basin, flows northward (Budillon *et al.* 1999) and at the shelf-break near Cape Adare descends the slope interacting with the Circumpolar Deep Water (CDW).

This paper presents the first analysis of hydrological data acquired during two high resolution surveys carried out in 1997 and 2001 in the western Ross Sea by the Italian National Programme for Antarctic Research (PNRA) within the framework of the CLIMA Project. The main focus of these two localized investigations was the study of the shelf-slope processes near Cape Adare where a HSSW overflow signature had already been detected during the 1995 cruise of the PNRA.

The hydrological characterization of the study region is

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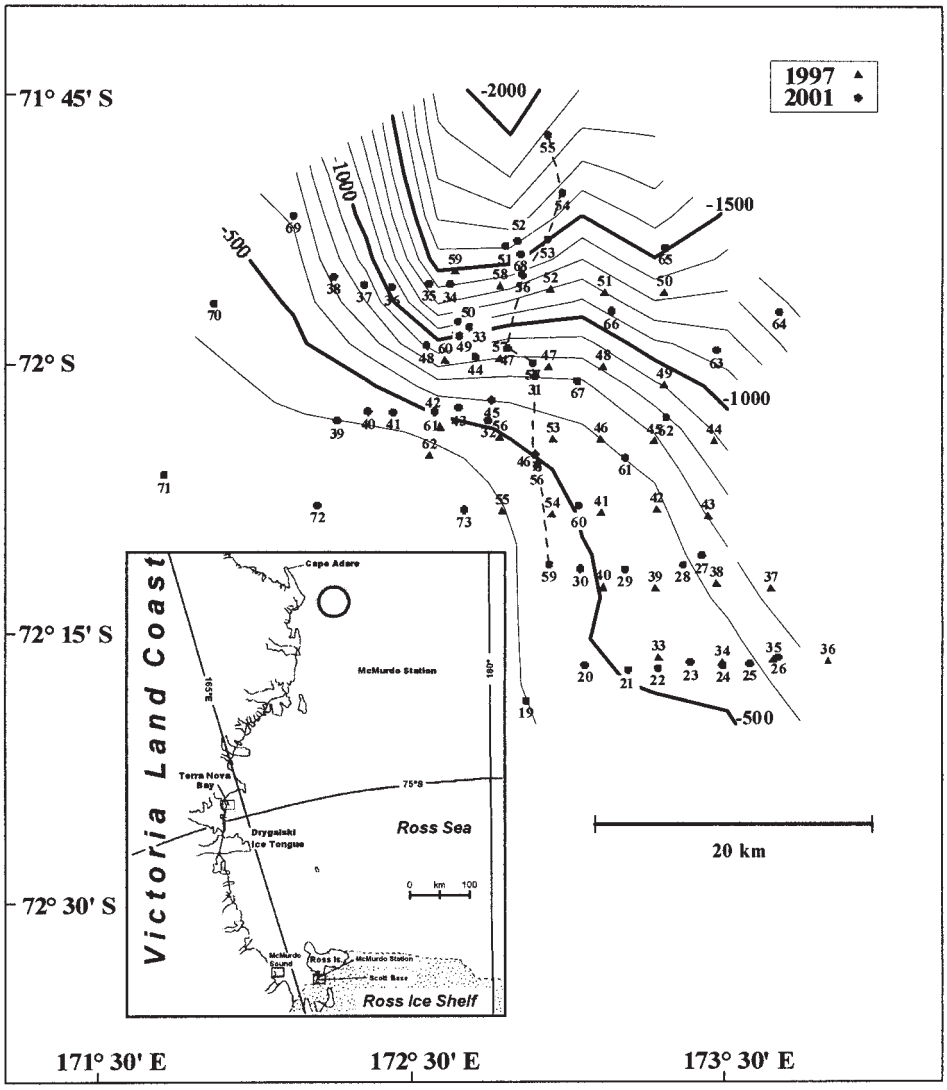


Fig. 1. Bottom topography of the investigation area and position of the hydrological stations carried out during 1997 and 2001. Circled zone on the small map indicates the survey location inside the Ross Sea. The dashed line represents the hydrological section analysed in the text.

performed through vertical salinity profiles, temperature and salinity horizontal maps and temperature and salinity sections obtained by means of objective analysis (Bretherton *et al.* 1976, Roemmich 1983). The comparison of the two datasets put in evidence some differences between the two years of acquisitions. In 1997 the HSSW signature on the shelf is very strong and the salty water tongue descends from the shelf onto the slope, where its signal is clear. During 2001 the experimental evidence of a "true" HSSW overflow process is not present being the descending shelf waters characterized by salinities in the range values of the CDW (S ≅ 34.7 psu), even though associated with a temperature minimum typical of denser water masses.

Experimental design

During the 1997 summer, a two day (26–28 December 1997) mesoscale experiment (30 CTD stations) was carried out near Cape Adare. Stations were positioned on a grid

Table I. Type, measurement range, and accuracy of the CTD sensors.

Parameter	Sensor	Measurement range	Accuracy
pressure	Paroscientific - Digiquartz	0 to 10000 pa	± 1.5 pa
temperature	SBE3	-5 to +35°C	± 0.002°C
conductivity	SBE4	0.0–7 S m^{-1}	± 0.0003 S m^{-1}
oxygen	SBE 13Y	0–15 ml l^{-1}	± 0.1 ml l^{-1}
light transmission	Sea Tech 25 cm	0–100%	± 0.5%
fluorescence	Chelsea - Acquatracka III	0.01–100 µg l^{-1}	± 0.01 µg l^{-1}
pH	SBE18	0–14	± 0.1
distance from bottom	Datasonic PSA-900	0–300 m	± 0.75 cm

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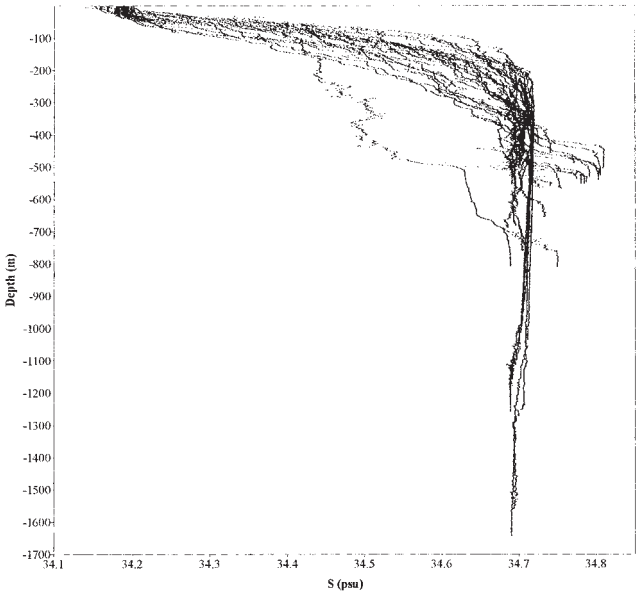


Fig. 2. The 1997 cumulative S/h profile.

ranging from 4 to 6 km in order to follow the HSSW downslope flow already detected in this area in 1995.

This investigation was repeated with a higher resolution (59 CTD stations) from 22–28 January 2001 during the 2000–01 cruise of the PNRA. The main aim was to improve our understanding of the HSSW overflow behaviour through a comparison with the 1997 results.

Figure 1 presents the bathymetry of the investigation area (see the small map for its location inside the Ross Sea) and the CTD casting positions during 1997 and 2001.

The hydrological stations were performed with a sampling frequency of 24 Hz using a Sea Bird Electronics SBE 9/11 PLUS probe, equipped with sensors for temperature, conductivity, pressure, oxygen, fluorescence, light transmission and pH. The technical characteristics of the CTD sensors are summarized in Table I. The temperature and conductivity sensors were calibrated at the SACLANT CENTRE of La Spezia (Italy) before and after the cruise. Moreover, during the cruise, temperature was controlled by means of two digital reversing platinum thermometers (SIS RTM4200) and salinity was checked on water samples analysed with an Autosal Guildline Salinometer.

The CTD, whose descent velocity was never more than 70 cm s^{-1}, was coupled to a Carousel water sampler SBE 32 equipped with 24 twelve-litre bottles.

Results

Cape Adare 1997

The cumulative vertical salinity profile (Fig. 2) of the 1997 dataset shows clearly the two water types characterizing the investigation area: the shelf waters marked by a salinity

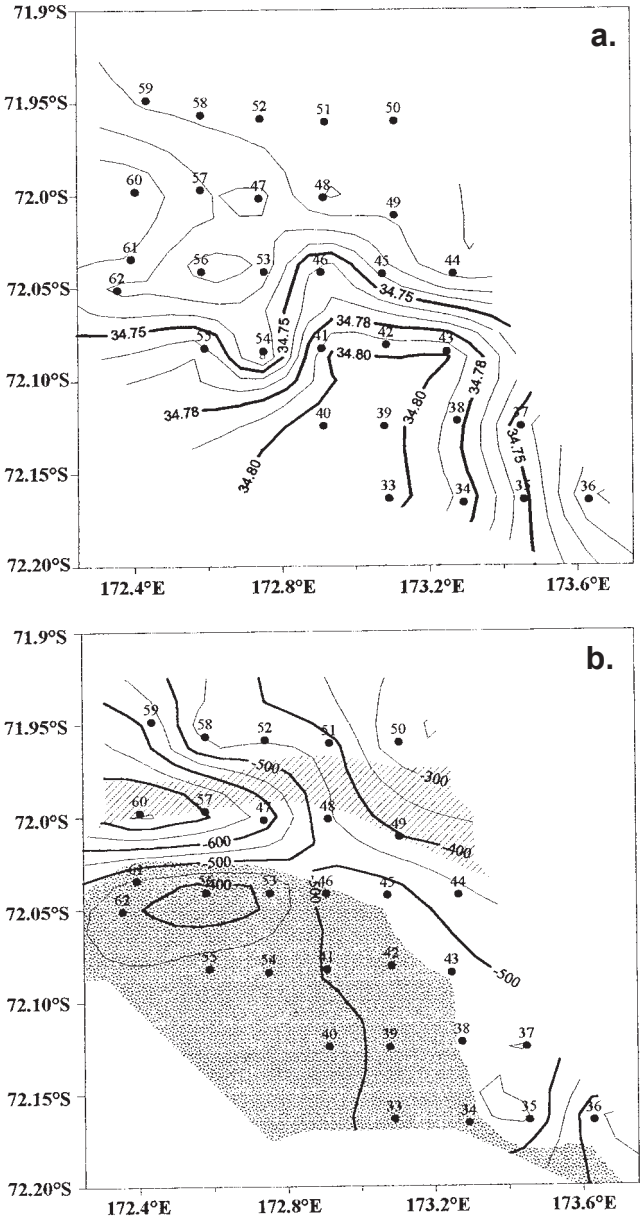


Fig. 3. The 1997 horizontal distribution of **a.** the salinity maximum, and **b.** the depth of the salinity maximum. The filled areas in Fig. 3b represent, respectively, the shelf zone (stipple pattern) and the highest gradient zone on the slope (shaded).

maximum (S > 34.8 psu) at about 400–500 m depth and the CDW exhibiting a salinity maximum (S ≅ 34.7 psu) on the slope at the deeper stations. It is particularly interesting to note the relative maximum of salinity (S ≅ 34.75 psu) at about 800 m depth, indicating the presence on the slope of waters in the salinity range of HSSW (S > 34.75 psu).

The horizontal distributions of the salinity maximum (Fig. 3a) and the salinity maximum depth (Fig. 3b) are used to map the HSSW path.

The shape of the salty water tongue (S > 34.8 psu) on the shelf (stations number 33, 39 and 40) shows that HSSW

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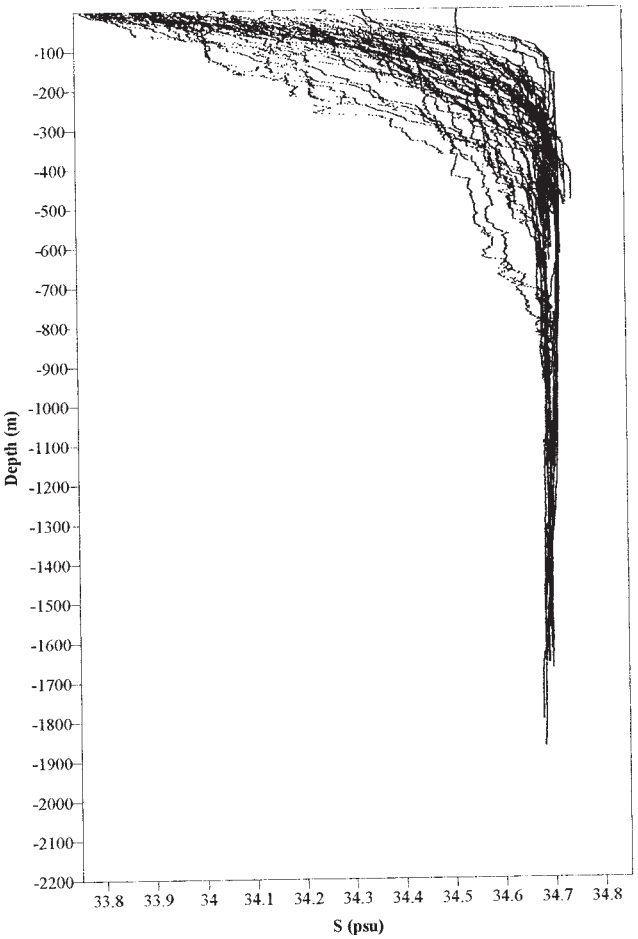


Fig. 4. The 2001 cumulative S/h profile.

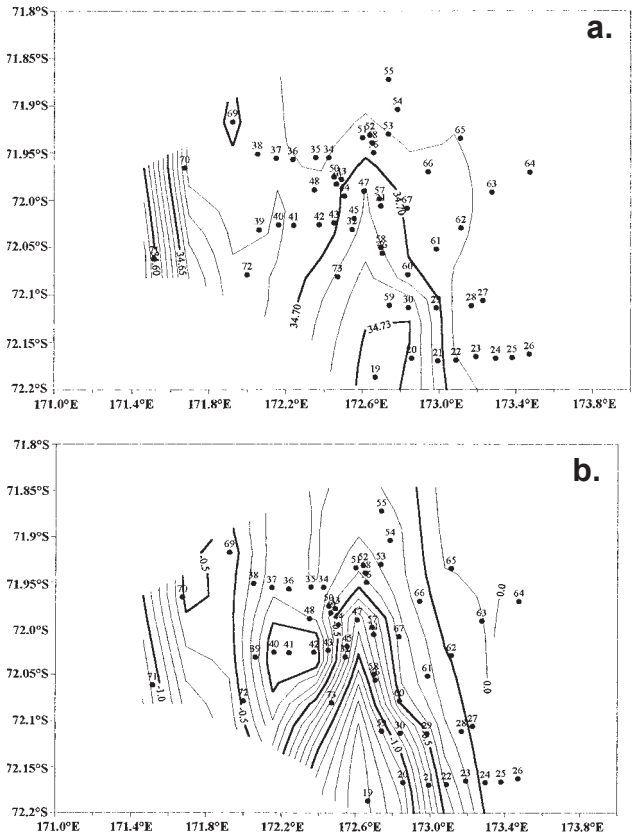


Fig. 5. The 2001 horizontal distribution of **a.** salinity, and **b.** temperature on the bottom layer.

reaches the shelf edge (Fig. 3a). This tongue, characterized by temperatures (not shown here) of about -1.9°C, is well defined and seems to spill over the shelf-slope edge in two directions corresponding to stations number 43 and 46. It is very difficult to draw inferences about the flow direction near station 43, because no other station is available in this area. The second tongue reaches station 46, but it seems to be stopped by a CDW intrusion indicated by the salinity values of the near stations. The descent of HSSW coming from the "main" salty shelf tongue onto the continental slope is demonstrated by the presence at station 60 (at about 781 m with a relative temperature minimum of -1.0°C) of a salinity maximum (S > 34.74 psu) higher than the CDW salinity signature at this depth.

To check the HSSW downslope hypothesis, the distribution of the depth of the salinity maximum (Fig. 3b) is plotted. The two shaded areas represent, respectively, the shelf zone (stipple) characterized by depths lower than 500 m and the highest gradient zone (shaded) between 800 m and 1000 m on the slope. The depth of the salinity maximum (S ≅ 34.80 psu) from Fig. 3a is at about 500 m on the shelf, while the minimum depth (Smax depth < 300 m) corresponds to station 50, where the salinity value is in the CDW range (S ≅ 34.70 psu). The sinking of the salinity maximum from station 47 (Smax depth = 643 m), to stations 57 (Smax depth = 722 m) and 60 (Smax depth = 781 m) confirms the HSSW downslope flow hypothesized from the salinity distribution (Fig. 3a).

Cape Adare 2001

The 2001 cumulative vertical salinity profile (Fig. 4) exhibits a very different pattern from the 1997 one due to the absence, on the shelf, of the signature (S > 34.75 psu) of the HSSW. As can be seen, it is difficult to separate the cluster of shelf stations from the overlapping vertical profiles, because the salinity values on the shelf are comparable with those characterizing the CDW (S ≅ 34.7 psu).

A comparison with Fig. 2 shows that in 2001 the salinity values of surface and subsurface waters were lower than the 1997 ones by about 0.3–0.4 psu. A possible explanation of this difference is certainly the period of acquisition: December for the 1997 stations and January for the 2001 stations. Alternatively this discrepancy could be an indicator of varying winter conditions (for example higher temperatures and/or lower ice formation), because the

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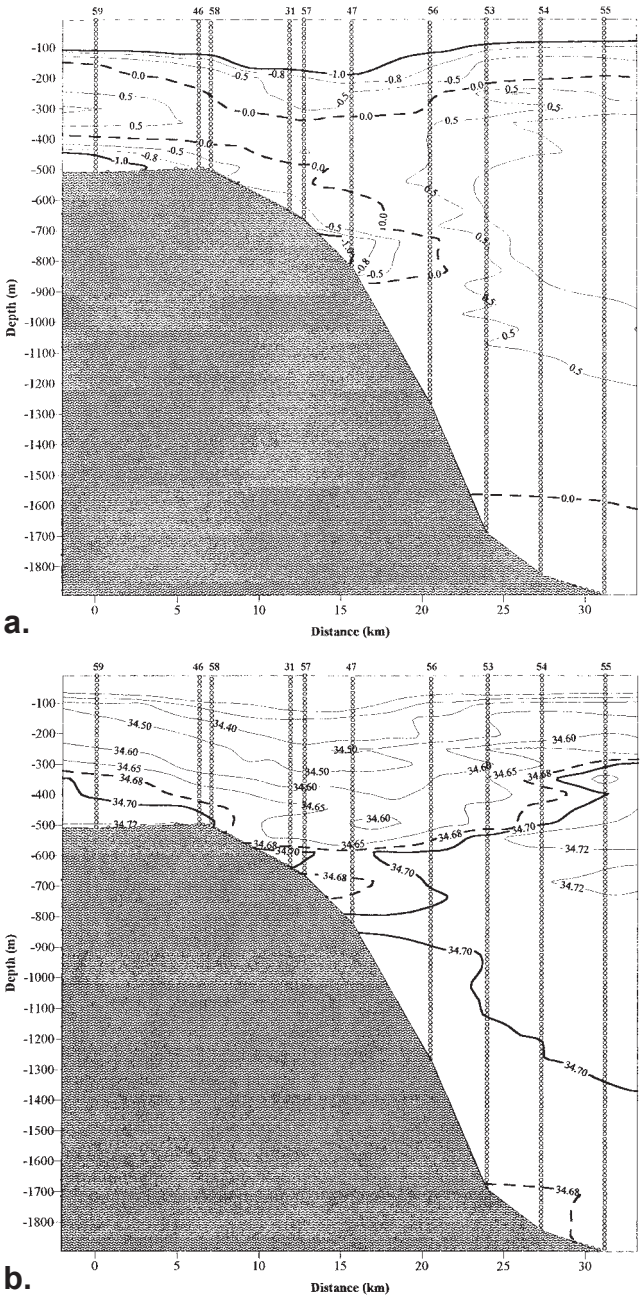


Fig. 6. Cross-slope section of **a.** temperature and **b.** salinity. The number of the stations of the 2001 dataset is reported on the top axis. For the section location see Fig. 1.

signal is not confined to the surface layer.

This preliminary analysis highlights that during 2001, the shelf waters at the shelf-slope edge were characterized by salinity values comparable with the CDW ones. Due to the lack of the HSSW signature, the 2001 behaviour is better investigated by considering the distributions of salinity (Fig. 5a) and temperature (Fig. 5b) on the bottom layer. Figure 5a shows that the shelf waters exhibit a salinity maximum of about 34.73 psu (station 19), a value slightly below the HSSW "characteristic" salinity (S ≅ 34.75 psu). The absolute maximum of salinity (S = 34.78 psu) in the investigation area corresponds to station 74 (not shown here), located at about 8.7 km from station 19 at 518 m depth inside the shelf. It could be supposed that the HSSW spreading was confined on the shelf between stations 74 and 19, but the HSSW propagation on the shelf is not the main focus of this work.

The temperature distribution (Fig. 5b) shows a well defined water tongue, characterized by a temperature minimum of -1.5°C at station 19 on the shelf. This temperature value is representative of the shelf waters signature, even if it is higher than the HSSW temperature registered at station 74 (T ≅ -1.9°C).

It is very interesting to note how the flow direction of the shelf tongue interacts with the CDW, as can be seen by the presence of an isolated "warm eddy" (T > –0.1°C) at stations 40, 41 and 42. The scale of this peculiar structure (the 1997 temperature distribution here not shown is characterized by an analogue "warm eddy") could give an interesting indication about the phenomenological processes of mixing between shelf waters and CDW.

The following N–S temperature (Fig. 6a) and salinity (Fig. 6b) sections give a vertical picture of the shelf/slope area at Cape Adare. The vertical temperature structure (Fig. 6a) is characterized by the CDW penetration on the continental slope at the northern stations (number 55, 54 and 53), where the CDW signature is inferred by the temperature maximum (T > 0.5°C). Station number 47 shows, at the bottom (depth < 700 m), the same temperature signal (T < -1.0°C) of the relatively cold waters on the continental shelf. The structure of the shelf waters' tongue presented in Fig 5a & b is in agreement with the presence of modified shelf waters at this station.

The distribution of salinity (Fig. 6b) clearly emphasises that the shelf waters are not so dense as to cause a HSSW downslope flow. In fact, it is particularly interesting to note that the shelf waters and the CDW core on the slope have the same salinity value (S > 34.7 psu). The salinity maximum (S ≅ 34.7 psu) on the shelf-slope edge at stations 31 and 57 does not correspond to the temperature minimum shown by Fig. 6a at station 47. This station is the most important, in spite of its lower salinity value (T ≅ 34.68 psu), because its temperature signal at the bottom confirms the descent of modified shelf waters on the slope. In this case, salinity is not a good tracer showing similar values for shelf waters and CDW.

Conclusions

This work presents the first combined analysis of two high resolution surveys carried out in December 1997 and January 2001 on the western Ross Sea continental shelf-break near Cape Adare. This investigation area was chosen because the 1995 CLIMA cruise had clearly detected the signature of the HSSW flowing northward along Victoria

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Land from TNB. The HSSW, the saltiest and densest water mass of the Southern Ocean, near Cape Adare spills over the shelf edge, entrains ambient water and descends the continental slope. The dynamics of these downslope flows is interesting because it influences the ocean/continental shelf exchanges and the ventilation of the global deep oceanic waters.

Through the comparison of the 1997 and the 2001 datasets it is possible to give a sketch of the HSSW downslope process. The two years show clear differences probably due to the acquisition periods (December 1997 and January 2001), but the interaction, between the CDW intruding onto the continental slope and the dense shelf waters flowing off the shelf, is identified in both cases.

The 1997 dataset is characterized by the experimental evidence of the HSSW signature on the continental slope at about 800 m depth. The distribution of the salinity maximum, in fact, clearly shows the path of the salty water tongue from the continental shelf to the slope: the salinity maximum (Smax ≅ 34.75 psu) at about 781 m corresponds to a temperature value of -1.1°C, indicating that mixing processes have already occurred. The temperature distribution confirms the hypothesis of a HSSW overflow, indicating temperature values in the range of "newly formed" shelf waters.

The 2001 dataset exhibits a different behaviour because of the absence of the HSSW signature on the continental slope. Moreover, the descending water tongue shows temperature and salinity values not properly in the HSSW range, comparable with those typical of the CDW. The north–south oriented section shows well the CDW intrusion onto the continental slope and the relatively cold shelf waters, characterized by salinities not high enough to produce a strong downslope of salty dense waters. Since the 2001 subsurface salinities were lower than in 1997, the 2001 behaviour could be due to the formation of shelf waters not dense enough to support the downslope flow as it is shown by the salinity distribution. An alternative hypothesis could be the inadequacy of the sampling scheme in capturing the downslope process which seems to be confirmed by the experimental evidence, found during the 2002–03 survey at Cape Adare, of the high variability of the downslope flows. This last consideration cannot be verified by this preliminary work, and further investigations are necessary.

Acknowledgements

This work was supported by the CLIMA Project of the Italian National Programme for Antarctic Research. The authors wish to thank the captain and the crew of the RV *Italica* for their assistance during the 1997 and the 2001 cruises. The authors are very grateful to Mrs Jane Frankenfield for her valuable help during the correction of the manuscript. We thank the referees for their critical comments.

References

Baines, P.G. & Condie, S. 1998. Observations and modelling of Antarctic downslope flows: a review. *Antarctic Research Series*, **75**, 29–49.

Bergamasco, A., Defendi, V., Zambianchi, E. & Spezie, G. 2002. Evidence of dense water overflow on the Ross Sea shelf-break. *Antarctic Science*, **14**, 271–277.

Budillon, G., Gremes Cordero, S. & Salusti, E. 2002. On the dense water spreading off the Ross Sea shelf (Southern Ocean). *Journal of Marine Systems*, **35**, 207–227.

Budillon, G. & Spezie, G. 2000. Thermohaline structure and variability in the Terra Nova Bay polynya (Ross Sea) between 1995–1998. *Antarctic Science*, **12**, 501–516.

Budillon, G., Tucci, S., Artegiani, A. & Spezie, G. 1999. Water masses and suspended matter characteristics of the western Ross Sea. *In* Faranda, F.M., Guglielmo, L. & Ianora, A., *eds. Ross Sea ecology*. Milan: Springer, 63–93.

Bretherton, F.P., Davis, R.E. & Fandry, C.B. 1976. A technique for objective analysis and design of oceanographic experiments applied to MODE-73. *Deep-Sea Research*, **23**, 559–582.

Grumbine, R.W. 1991. A model of the formation of High Salinity Shelf Water on polar continental shelves. *Journal of Geophysical Research*, **96**, 22049–22062.

Huthnance, J.M. 1995. Circulation, exchange and water masses at the ocean margin: the role of physical processes at the shelf edge. *Progress in Oceanography*, **35**, 353–431.

Jacobs, S.S., Amos, A.F. & Bruchhausen, P.M. 1970. Ross Sea oceanography and Antarctic bottom water formation. *Deep-Sea Research*, **17**, 935–962.

Jacobs, S.S., Fairbanks, R.G. &. Horibe, Y. 1985. Origin and evolution of water masses near the Antarctic continental margin: evidence from $H_2{}^{18}O_2/H_2{}^{16}O_2$ ratios in seawater. *Antarctic Research Series*, **43**, 59–85.

Kurtz, D.D. & Bromwich, D.H. 1985. A recurring, atmospherically forced polynya in Terra Nova Bay. *Antarctic Research Series*, **43**, 177–201.

Roemmich, D. 1983. Optimal estimation of hydrographic station data and derived fields. *Journal of Physical Oceanography*, **13**, 1544–1549.

Shapiro, G.I. & Hill, A.E. 1997. Dynamics of Dense Water Cascades at the Shelf Edge. *Journal of Physical Oceanography*, **27**, 2381–2394.

Whitehead, J.A. 1987. Dense water off continents. *Nature*, **327**, 656.

Zwally, H.J., Comiso, J.C. & Gordon, A.L. 1985. Antarctic offshore leads and polynyas and oceanographic effects. *Antarctic Research Series*, **43**, 203–226.

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