Chinese Journal of Polar Science, Vol. 12, No. 2, 89－98, December 2001

Upper layer waters and their northward extension from Prydz Bay in summer

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Received September 6, 2001

Abstract In this paper, CTD observational data obtained during the 15th Chinese National Antarctic Research Expedition (CHINARE-15) in the Southern Ocean are used to analyse and study water mass distribution in the Prydz Bay and its adjacent seas. The area, depth, and the thermohaline characteristics are identified for the Prydz Bay summer coastal surface water, the Prydz Bay winter water, the Prydz Bay shelf water, and the circumpolar deep water. Based on the above discussion, the northward extention of the Prydz Bay shelf water are found. Then the thermodynamic and the dynamic characteristics are further discussed, dealing with the inversion layer depth of the water temperature. the locations of the minima of the vertical temperature distribution and the temperature vertical gradient in the water column, the baraclinicity, and the effect of Coriolis deflection force.

Key words Prydz Bay, water mass, northward extention.

1 Introduction

Prydz Bay has its open water in the north adjacent to the Indian Ocean sector of the Southern Ocean. It borders upon the ice shelf to its south, and the Antarctic continent to its east and west. It is the largest water stretching southward into the inland except the Weddell Sea and the Ross Sea. The bay is narrow in the southwest and wide in the northeast, with the furthest eastern end at 70°S, 76°E near Four Ladies Bank, and the furthest western end at 68°S, 69°E near Fram Bank. The water on the continental shelf of the bay is shallow, with the depths from 400 m to 600 m (Alberts 1995). The Lambert Glacier extends from the inland to the bay (Christie *et al*. 1990), and connects with Amery Ice Shelf which is the southern boundary of Prydz Bay. The most area of the bay is covered by ice about 2 m thick in winter. The ice becomes broken and partly molten, but the ice amount is still great and the floe distributed area is changeable in summer (Dong *et al*. 1984). The water becomes sharply deeper in the north of the bay, and keeps the flat bottom to the further north on the continental shelf which extends to the slope break at about 67°S. The water as deep as 3000 m or deeper, is distributed to the north of the continental slope in the

Southern Ocean (Fig. 1). As Prydz Bay is narrow in width and its water stretches into the icy land of the Antarctic continent, the special geographic conditions and topographic features make the shelf water of the bay keep "a long time memory" of the extremely cold events which occur in the continent in winter. "The memory" can be evidenced by the bottom water with low temperature and high salinity on the shelf of the bay, and it can be explained as follows. In late autumn or winter, the cold air cools the surface water and the strong wind above the sea surface causes the deep convection in the shelf water so that the cooled and denser water near the sea surface subsides downward to the bottom and at the same time takes part into the coastal circulation which includes the wind drive current by polar easterly. After the sea surface has become frozen, the ice-covered water can still be further cooled by surface ice rather than the wind mixing. Furthermore, the salt-release process starts to effect and make the salinity and the density of the ice-covered water increase when surface water becomes frozen. Therefore the extremely cold, salty, and dense water will go down to the bottom of the bay to form the shelf water which bears the memory of the extremely events in winter.

When it is summer the density of the upper layer water decreases by effect of the seasonal warming and the fresh water flux coming from the molten ice in the seasonal ice zone around Prydz Bay. The seasonal thermoclines are formed, and the vertical stability of water column is increased. However these surface changes can not penetrate through the thermoclines and reach to the lower layer because the wind force seasonally decreases and wind mixing becomes weaker. Therefore the winter water or the bottom water still bear the memory of the coldest events in the previous winter. The purpose of this paper is to study and determine the physical features of the water in Prydz Bay and the oceanic area adjacent to the bay, and the spacial distribution of the water masses which are characterized by these physical features,

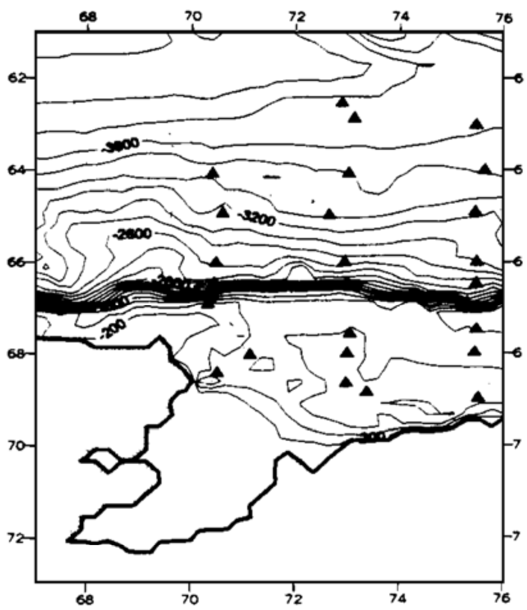

Fig. 1. Geographical and topographical features, and the CTD stations in the region of Prydz Bay.

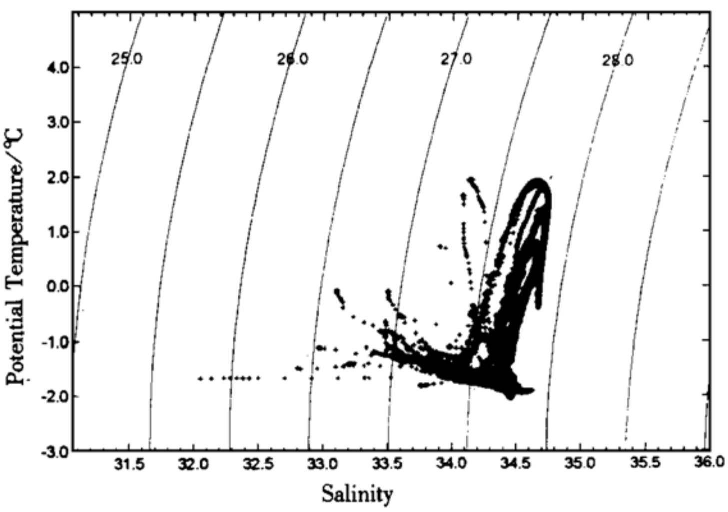

Fig. 2. Scatter plots of temperature and salinity for all the stations (thin lines mark contours of constant density).

to evidence the northward extension of the shelf water from Prydz Bay, the temperature inversion related to the waters, and the baroclinity, and to discuss the spacial variability of these physical features.

2 Data and accuracy

The data used in this paper were obtained on board of R/V *"Xuelong"* at the 26 CTD stations during the cruise (from November 1998 to February 1999) in the Antarctic Ocean by the 15th Chinese National Antarctic Research Expedition (see Fig. 1 for the station locations, and refer to the Data Rport by First Institute of Oceanography, State Oceanic Administration 1999). The 26 CTD stations for the full depth measurements are distributed along the 70°E, the 73°E, and the 75°E longitudinal sections. According to the cruise plan, the stations should be located along the longitudinal circle, but the actual positions of them were different from the planned as shown in Fig. 1 because the distribution of icebergs or big floes, and the ship drift exerted a heavy influence on the ship navigating route. The accuracy of the conductivity is 0.02 $ms \cdot m^{-1}$, and the temperature ±0.002℃. The values of conductivity can be converted into the values of salinity (see UNESCO Technical Report 1988).

3 Distribution of water masses and their characteristics in the upper layer of Prydz Bay and its adjacent ocean

Based on the measurements conducted in the summer cruise, the salinity has got a value between 32.7 and 34.7 except that it is effected by the icebergs and big floes which were melting. The water temperature is between −2.0℃ and 2.0℃. The potential density is between 25.5 $kg \cdot m^{-3}$ and 27.9 $kg \cdot m^{-3}$. The values of the surface layer temperature are dispersed to some extent because they might be effected by ice distribution, fresh water from melting ice, rainfall, and solar radiation (see Fig. 2 and Fig. 3). Their values of the lower layer temperature and salinity between the 250 m depth and the 300 m depth are concentrated in a range between −2.0℃ and 1.9℃, and between 34.3 and 34.7 respectively (see the plotted dots in Fig. 2). The spacial variability of temperature and salinity in Prydz Bay and its adjacent sea area can be briefly learnt from the above description. However the details of the spacial variability of temperature and salinity show some unique features, which are different from the features of the oceans in the middle or low latitudes where the temperature and salinity vary basically with the latitudes. The typical features in the Southern Ocean is that the water masses corresponding to their special values of temperature and salinity are separated from each other by zonal fronts. It can be obviously seen from Fig. 3 that a temperature front lying east and west is located between 64°S and 67°S on the 250 db isobaric surface. The Prydz Bay shelf water is situated south of the front, with a temperature about −2.0℃ and a salinity about 34.5. Another water mass is located north of the front with a temperature about 1.94℃ and a salinity about 34.67. The frontal distribution can be seen more clearly in a vertical section (see Fig. 4). The front is located between the 50 db depth and the 100 db depth at 63°S. It becomes almost vertically distributed between 65°S and 66°S, and reaches to the lower layer deeper than 300 db. The frontal strength is about

2. 5℃/degree of latitude. It is called Antarctic Continental Water Boundary (CWB), a zonal front that separates the two water masses with their respective features mentioned above. It is around this front that the interactions between the shelf water and the circumpolar deep water (CDW) take place, and the mixed circumpolar deep water (MCDW) is formed (Witworth *et al*. 1998). MCDW is one of the water masses for forming the Antarctic Bottom Water (Foster and Middleton 1980). It is learnt by comparison between the results in the paper of Witworth *et al*. (1998) and the results from the data obtained at the 70° E section during CHINARE-15 that the central location of CWB (about 65°30′S) is situated northward, much more north than the continental slope front which is determined from the data obtained at the 71°E section by Witworth.

In addition, it can be found by analyzing the water temperature distribution at the 10 db depth that a surface layer front is located south of 68° S (see Fig. 3(a)). The maximum temperature is above 1.9℃ to the south of the front. The front slopes downwards and becomes deeper than 50 db when it reaches to the higher latitudes (see Fig. 4). Water masses can be distinguished from each other, their physical properties shown in Fig. 2, Fig. 3, and Fig. 4 are summarized. (1) The summer coastal surface water of Prydz Bay with the salinity about 34.00 and the maximum temperature about 1.9℃ is located in the surface layer shallower than 50 db to the south of 68°S. It is the warmest water in the studied area. It seems unusual that this surface water with the temperature higher than the water temperature to the north appears in such high latitudes. However it can be explained and consistent with the observations by Kupetskii (1959) and Mellor (1960), and other satellite remote sensing data. Small pieces of ice-free area can appear in the outer area of Amery Ice Shelf in early spring when the inner area is still covered with ice. Therefore more solar radiation can be absorbed by the surface layer of the ice free area and the summer coastal surface water can be formed with temperature higher than that in other sea area (Smith *et al*. 1984). (2) Prydz Bay winter water can be found in the layer about 50 db in the area north of 64°S. Its water salinity is about 34.0 and its

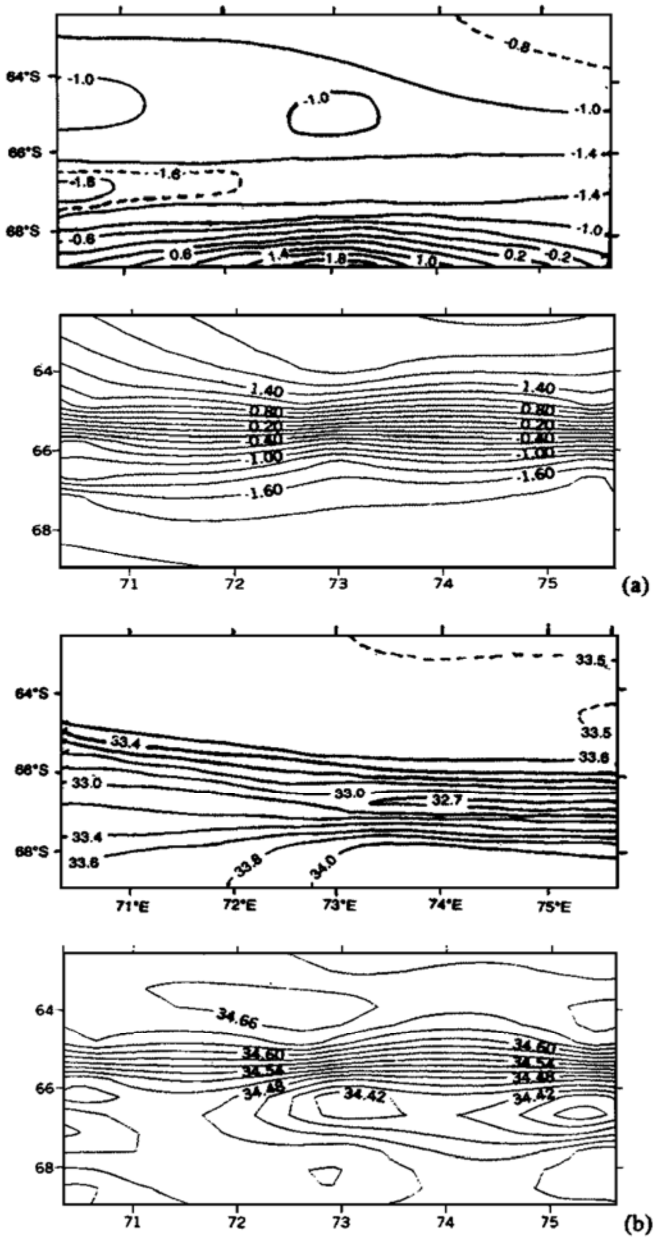

Fig. 3. (a) Temperature distribution at 10 db (upper) and 250 db (lower) in the studied area; (b) Salinity distribution at 10 db (upper) and 250 db (lower) in the studied area.

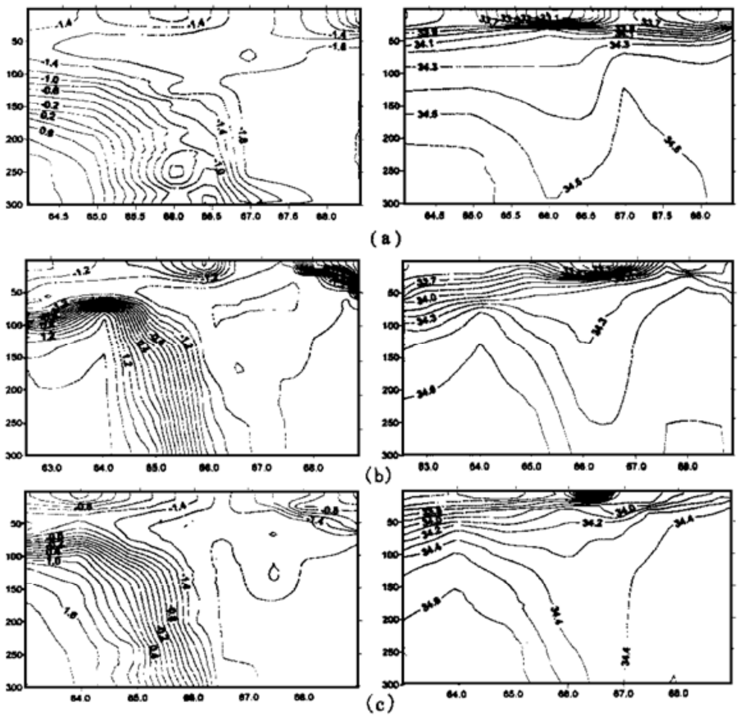

Fig. 4. Meridional profiles of temperature (left) and salinity (right) at (a) 70°E, (b) 73°E and (c) 75°E.

temperature ranges from − 1.5℃ to − 1.8℃. It is much colder, and obviously different from the summer coastal surface water. The winter water remains in the subsurface layer as the oceanic "memory" for the cold convection in winter of the previous year, although the surface layer becomes warmer in summer. In the depths below the winter water, there is CDW. It is much warmer than the winter water. (3) There is Prydz Bay shelf water in the layer deeper than 100 db on the continental shelf south of 67°S. Its salinity is about 34.5 and its temperature is lower than − 1.8℃. Therefore the shelf water is colder than either the summer coastal surface water or the Prydz Bay winter water and it has higher salinity than either of the two because the shelf water is formed in the coldest season when it becomes cooled and salt is released from sea ice. (4) There is CDW in the layer deeper than 200 db in the sea area north of 64°S. Its salinity is higher than 34.6 and its temperature is above 1.8℃. CDW is extensively distributed in a large area around Antarctic continent, and it is one of the main water masses of which Antarctic circumpolar current consists. Gorden (1975) discussed some aspects of CDW using data of the 170°E section. He divided the CDW into two cores: the upper core and the lower core. The temperature range of the upper core is 0.9 ~ 2.5℃, the salinity range is 34.60 ~ 34.72, and it is located in the depths between 250 db and 600 db. The temperature range of the lower core is 1.0 ~ 1.8℃, the salinity range is 34.70 ~ 34.75, and it is located in the depths between 500 db and 3000 db. The physical properties shown in Fig. 4 are similar to those of the upper core (see also paper by Liang and Su (1995)). Deacon (1937) called this water masses as "warm deep current". As Carmack (1977) estimated, CDW makes up about 55% of the whole water volume of the Southern Ocean. It is thus clear that CDW has a large volume. The properties of the 4 water mass described above can be summarized in Table 1.

Table 1. Water masses and their T&S properties in the region of Prydz Bay

Water masses	Latitude	Depth	Salinity / ‰	Temperature/ ℃
Prydz Bay summer coastal surface water	South of 68°S	Shallower than 50 db	About 34.0	About 1.9
Prydz Bay winter water	About 66.5°S	0 - 50 db	~34.0	- 1.5 - - 1.8
Prydz Bay shelf water	South of 67°S	Deeper than 100 db	34.4 - 34.5	Lower than - 1.8
Antarctic Circumpolar Deep water	North of 64°S	Deeper than 200 db	Higher than 34.6	About 1.8

4 Northward extension of Prydz Bay shelf water and its thermodynamic features

As shown in Fig. 4, there is a cold water wedge with the temperature of about - 1.8℃ and the salinity between 34.3 and 34.4, intercalating between the summer surface water and CDW and extending northward from 67°S to form a isothermal layer in the center of the wedge as thick as 50 m. The obvious features of the wedge are that the water temperature and the vertical temperature gradient reach to their minimum in the layer. Those features become less obvious in the further north possibly because confusion and mixing between the upper layer and the lower layer take place when the cold water of the wedge extends northward.

The cold water wedge makes it clear that Prydz Bay shelf water tends to flow out of the continental shelf. Firstly, as the results are presented by the authors in this paper and the others (Dong *et al*. 1984; Smith *et al*. 1984), the physical properties of the water flowing out of the continental shelf are similar to the properties of Antarctic winter water (defined as the water with minimum temperature in the vertical profiles in the deep ocean north of Antarctic Slope Front.), except that the salinity of the latter is slightly less than the former. In addition, the shelf water has a minimum temperature at the shelf bottom while the winter water has a minimum temperature in the upper layer of the deep ocean. It is learnt from the data of the observations that the two water masses are obviously apart from each other, and in between there is strong thermocline layer which is located near the continental rise and at the depth shallower than the continental shelf (Also see Fig. 9 (Witworth *et al*. 1998), Fig. 1 - 7 (Smith *et al*. 1984), and Fig. 4 (Wang *et al*. 1998)). Secondly the formations and the motions of the two water masses are totally different from each other. As it is described in the above, Antarctic winter water was formed in the upper layer of the deep ocean by the vertical convection which took place in the winter of the previous year and it remains in the subsurface as the oceanic "memory" for the vertically homogeneous winter mixing when its surface layer warms up in summer. The shelf water is formed by the interactions among the atmosphere, the sea, the ice shelf, and the glacial ice (Dong and Liang 1993). Furthermore, the dynamic causations for water transport related to the two water masses are different from each other. The northward transport of Antarctic winter water is Ekman transport forced by the prevailing west wind. However the southward transport is caused in the Antarctic coastal current area and makes surface water drift from the area south of Antarctic divergence toward Prydz Bay. At the same time the southward transport will give rise to a compensating current flowing northward in the subsurface for balancing the southward transport. There are two possibilities for generating the compensating current. (1) Because of the interaction among air, sea, and ice in the shelf area near Prydz Bay, it is possible for the water with greatest density to reserve up on the shelf bottom, to overflow from the shelf area, to flow downward on the continental slope into the deep ocean, finally to form Antarctic Bottom Water. (2) It is also possible for the water with greater density to extend northward from the shelf area in the depths between 50 m and 100 m if the bottom water with the greatest density does not overflow from the shelf area. Therefore the northward extension of the shelf water happens in the layer between the 50 m depth and the 100 m depth. The authors consider that the interaction among air, sea, ice, and land near Prydz Bay plays an important role for the northward extension of the shelf water in the middle layer and gives effects on climate and ocean to the north of the bay.

In addition, it can be found that the temperature inversion happens in the depths deeper than 50 db in the sea area north of 65°S, i. e. the temperature becomes slightly higher as water depth increases. The thickness of the inversion layer is about 150 ‒ 250 m (see Fig. 5(a) and Fig. 4(c)). Temperature inversion might tend to decrease the vertical stability of sea water and to cause convection of the lower layer water. Therefore it could not continue for a long time in other cases. However the salinity of the sea water greatly increases as the sea water depths increases in this sea area. The vertical stability in the water column does not decrease at all, which is evidenced by the σ_θ profile shown in Fig. 5(c). As shown in the figure, σ_θ greatly increases from the surface to the 200 db depth. It is the special density structure that keeps the temperature inversion in a stable status and remains there for a long time.

It should be pointed out that the stable structure as discussed above must not exist in some other places of the southern ocean as some evidences show. It is learnt from satellite images obtained since the 1970′s that there are large pieces of open sea surface surrounding by the ice covered sea area near Antarctic coast. It is called as palynya, which can be divided into two kinds. One is coastal palynya for it emerges in the coastal sea area, and the another is oceanic palynya for it emerges in the deep ocean area. It is considered by recent studies that the two kinds of palynya are formed by different actions. The coastal palynya is formed by cyclones or downslope wind from the Antarctic high land. During its formation the density of the sea surface water continue to increase because salt has been continually released from the

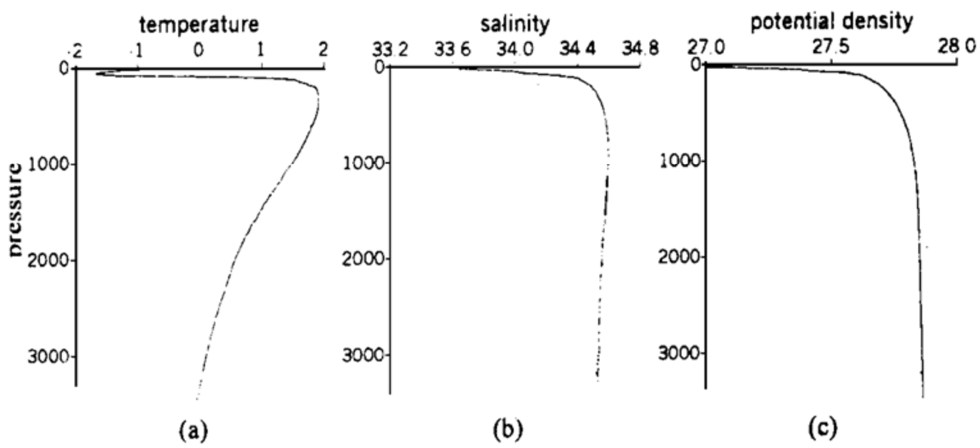

Fig. 5. Temperature (a), salinity (b) and density (c) profiles at CTD Station 6 (62°53.70′S, 73°6.53′E).

new ice when the strong wind continues to blow away from the coastal water. Therefore strong convection happens and the temperature inversion is destroyed. The oceanic palynya is formed by the upwelling of CDW with high temperature and high salinity. When the warm water reaches to the sea surface it will become ice-free (Gorden 1988; Gorden and Comiso 1988; Dong and Liang 1993). In addition to those actions for the palynya formation described above, some cases that warm CDW is found in the surface layer are reported (Foster 1985; Miao and Yu 1989). However how does it get through the temperature inversion and how does its upwelling happen in those cases? The reason keeps unknown. The authors consider that the inversion breaking is a transient phenomenon and limited to some particular area, although it can be observed in some cases. Up to now, no CTD profile has been found showing the inversion breaking evidence in the recent ten years when Chinese National Antarctic Research Expedition were conducted in summer and made the analyses of the physical oceanographic data of Prydz Bay and its adjacent ocean. It is a phenomenon awaiting to find further evidence when the winter expedition is conducted.

5 Dynamic features in Prydz Bay and its adjacent ocean

Some thermodynamic features have been described above. The dynamic features about northward extension of Prydz Bay shelf water will be discussed as follows. It can be seen from the comparison among Fig. 4 (a, b, c) that the vertically homongeneous layer with temperature less than − 1.6℃ becomes the thickest in the 70°E section, and the − 1.6℃ isotherm reaches to the north of 64.5°S. However the layer with temperature less than − 1.6℃ becomes the thinnest in the 75°E section, and the − 1.6℃ isothern is extended a shortest distance from 66°S and limited to the south of 65°S. It is clear that the northward extension of Prydz Bay shelf water reaches further to north of the bay and more shelf water volume overflows from the bay in the 70°E section. It means that a larger volume of the shelf water extended northward by way of the west side of the bay, which is consistent with Coriolis deflection. Actually Prydz Bay shelf water with lower temperature is mixed with a large amount of the water from Amery Ice Shelf. The latter with much lower temperature than the surface water in summer was first discovered in the 1980′s (Dong *et al*. 1984). It becomes mixed up in the northeast part of the bay. Besides Coriolis force, the compensating current for easterly drift could be another dynamic action for the shelf water to turn to extend toward the northwest of the bay. Therefore the northward extension of the shelf water becomes the strongest along the 70°E section.

In addition, the baroclinity of the northward extension of the shelf water can be analyzed and discussed by means of the isopycnal distribution. The isopycnal $\sigma_\theta = 27.5\ kg \cdot m^{-3}$ is chosen for representing the 50 db depth where the shelf water extends northward. The distribution of the isotherms, isobars and isohalines on the isopycnal are analyzed (see Fig. 6(a, b, c)). It is learnt from Fig. 6 that the isopycnal ($\sigma_\theta = 27.5\ kg \cdot m^{-3}$ tends to slope from the south to the north. Although the isobars lie approximately from east to west, the pressure gradient is not homogeneous on the isopycal. It reaches the maximum at the corner around 71°E, 64°S or further northwest. In other words the isobars and isotherms are intersected with each other, especially in the northwest corner, showing the most obvious baroclinity where the northward extension becomes the strongest.

It can be seen from Fig. 6 that there is a homogeneous water in the area between 64.5°S and 67.5°S on the isopycnal $\sigma_\theta = 27.5$ kg · m^{-3}. It is Antarctic winter water located north of the continental slope near Prydz Bay. Its salinity is 34.16 and temperature is −1.7℃ on the isopycnal surface.

To summarize the description in the above, the baroclinity can be found for the northward extention of Prydz Bay shelf water. Coriolis force, easterly drift, and the baroclinity play an important role for the water motion.

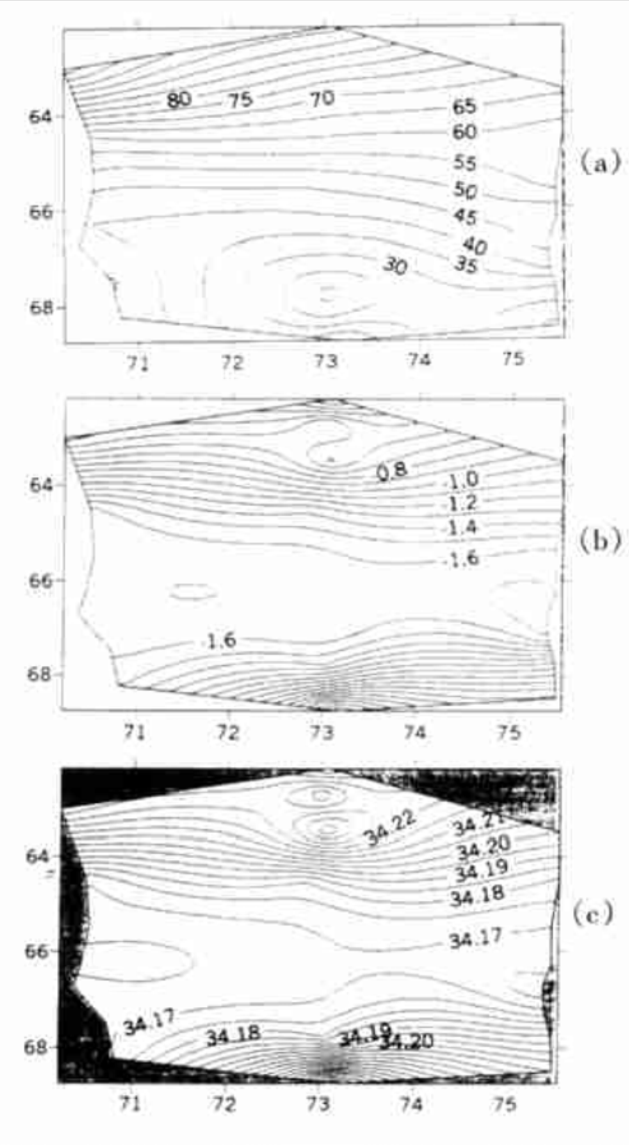

Fig. 6. Pressure (a), temperature (b) and salinity (c) at $\sigma_\theta = 27.5$ kg · m^{-3} surface (shadow parts mark where no CTD stations).

6 Conclusion

The following conclusion can be drawn by analysis of the data obtained during the 15th Chinese National Antarctic Research Expedition (CHINARE-15):

(1) Four water masses can be identified in the upper layer i.e. (a) Prydz Bay summer coastal surface water; (b) Prydz Bay winter water; (c) Prydz Bay shelf water; (d) Antarctic circumpolar deep water. Their locations, distributional area, and physical properties such as temperature and density are listed in Table 1.

(2) Prydz Bay shelf water extends northward in the depths about 50 db, and the strength of the water extention becomes the greatest in the 70°E section.

(3) The thermodynamic features for the northward extension of Prydz Bay shelf water are as follows: there is temperature inversion in the subsurface layer between 50 db and 200 db, and the maximum thickness of the inversion is about 250 m. there exist a temperature minimum and a temperature gradient minimum around the depth of 50 db, showing a homogeneous layer there.

(4) Coriolis force plays an important role for the northward extension of Prydz Bay shelf water, and the northward motion obviously has the baroclinity.

Acknowledgements This study is supported by National Science Foundation of China (No. 49836010). Authors take this chance to thank the 15th Chinese National Antarctic Research Expedition and the crew of R/V "*Xuelong*" for their great support to this study.

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