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Marine hydrographic spatial-variability and its cause at the northern margin of the Amery Ice Shelf

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Abstract Conductivity, temperature and depth(CTD) data collected along a zonal hydrographic section from the northern margin of the Amery Ice Shelf on 25–27 February 2008 by the 24th Chinese National Antarctic Research Expedition (CHINARE) cruise in the 2007/2008 austral summer are analyzed to study thermohaline structures. Analysis reveals warm subsurface water in a limited area around the east end of the northern margin, where the temperature, salinity and density have east-west gradients in the surface layer of the hydrographic section. The localization of the warm subsurface water and the causes of the CTD gradients in the surface layer are discussed. In addition, the results from these CTD data analyses are compared with those from the 22nd CHINARE cruise in the 2005/2006 austral summer. This comparison revealed that the thermoclines and haloclines had deepened and their strengths weakened in the 2007/2008 austral summer. The difference between the two data sets and the cause for it can be reasonably explained and attributed to the change in ocean-ice-atmosphere interactions at the northern margin of the Amery Ice Shelf.

Keywords **Amery Ice Shelf, marine hydrography, spatial variability causes**

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0 Introduction

In recent years, climate change phenomena, such as glacier retrogression, snowline ascent and polar ice melting, have been widely reported and have drawn great attention. Facing this global warming situation, some oceanographers have focused on polar sea ice distribution and its effects on marine hydrography to understand ocean-ice interactions [1–4]. In this paper, the spatial variability of hydrographic features at the northern margin of the Amery Ice Shelf is described using conductivity, temperature and depth (CTD) data collected during the 24th Chinese National Antarctic Research Expedition (CHINARE) cruise on 25–27 February 2008. In those 3 days, Research Vessel (R/V) *Xue Long* (also known as Snow Dragon) navigated along the northern margin of the Amery Ice Shelf to carry out full-depth CTD measurements at 11 marine hydrographic stations. These kinds of measurements were also conducted in the 2005/2006 austral summer, and the two data sets will be compared and discussed later in this paper.

The Amery Ice Shelf is located at the inland end of Prydz Bay in eastern Antarctica, and connects with Lambert Glacier at its far inland end. Even in austral mid-summer when the air temperature reaches its annual high, numerous ice floes can be found in Prydz Bay. Sometimes, under the combined forcing of certain winds and currents, the ice floe concentration becomes too dense for ships to navigate there. In the following sections, upper layer hydrographic features are described in detail based on data collected in the 2007/2008 summer, and the causes for mixing layer variations and the warm subsurface water are analyzed and discussed. Data collected on the 22nd CHINARE cruise are then compared with data from the 24th cruise to understand

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changes in the hydrography at the ice shelf margin.

1 Inhomogeneity of marine hydrographic features at the northern margin of the Amery Ice Shelf, 2007/2008

R/V *Xue Long* steamed from east to west along the northern margin of the ice shelf to conduct CTD casts and collect data at 11 marine stations. The station locations, CTD cast times and water depths are listed in Table 1. As a result of the heavy concentration of ice floes on the sea surface, the CTD casts could not be continued along the section and measurements were interrupted after operations at Station IS12 had been completed. The station distribution is shown in Figure 1(a); station numbers are marked on the figure. On the basis of data collected at the stations, thermohaline and density sections are plotted (see Figure 2). As can be seen in Figure 2(a), warm water with lower salinity and density is distributed in the top layer. Water warmer than −1.8℃ is located at depths of 50–150 m from 72°E to 74°E.

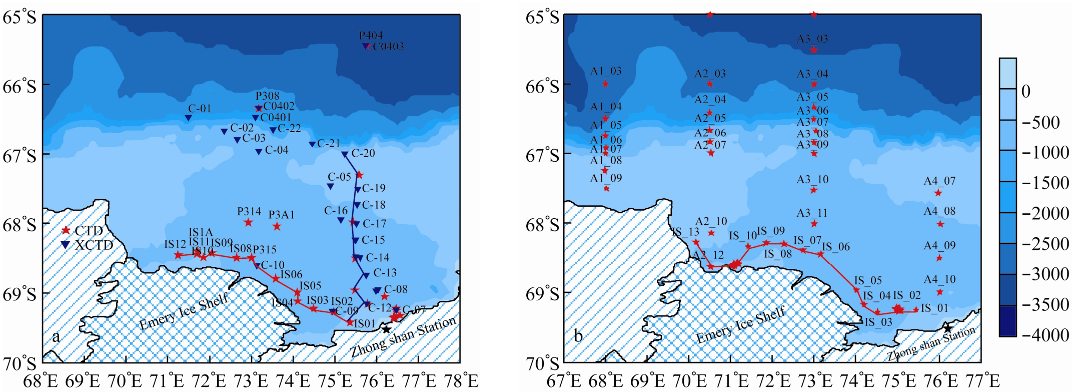

Figure 1 (a) Locations of the CTD and XCTD stations during the 24th CHINARE cruise (2007/2008 summer); (b) The locations of the CTD stations during the 22nd CHINARE cruise (2005/2006 summer). The red line is for the section along the northern margin, and the blue line is for the longitudinal section.

Table 1 Data from the observation stations along the northern margin of the Amery Ice Shelf

Ordinal number	Station	Latitude / °S	Longitude / °E	Date(DD/MM/YYYY)	Time (GMT)	Water depth / m
1	IS21	75.366 0	69.420 5	25/02/2008	16:10	540
2	IS02	74.973 2	69.267 6	26/02/2008	12:30	870
3	IS03	74.493 7	69.226 2	26/02/2008	15:41	800
4	IS05	74.100 3	68.991 7	26/02/2008	20:02	710
5	IS06	73.583 2	68.794 3	26/02/2008	23:43	780
6	C-10	73.136 7	68.611 7	27/02/2008	04:05	760
7	IS08	72.644 9	68.493 6	27/02/2008	06:54	750
8	IS09	72.058 6	68.430 6	27/02/2008	11:25	510
9	IS10	71.850 4	68.491 1	27/02/2008	13:04	530
10	IS11	71.708 8	68.402 8	27/02/2008	16:45	600
11	IS12	71.246 3	68.456 8	27/02/2008	19:47	780

The isotherm pattern shows that warmer water piles up into a thick layer at the east end of the ice-shelf margin, and upwelling colder water appeared at the west end. In addition to the temperature contrast between the ends of the ice-shelf margin, subsurface warm water at about －0.4℃ is situated at 100 m depth within a narrow latitudinal range west of 74.5°E. Farther west of this subsurface warm water, a warm water tongue extends and rise toward the 50 m isobath. From Figure 2(b) it can be seen that the isohalines tend to rise from east to west, and to reach the 50 m isobath, the salinity at the west end of the section becomes 0.2‰ higher. This means that the subsurface salinity has an east-west gradient, with lower salinity in the east and higher salinity in the west. As shown in Figure 2(c), the isopycnals gradually rise from east to west, with denser water in the west and lighter water in the east. The density difference between the two ends is about 0.4 g/cm^3.

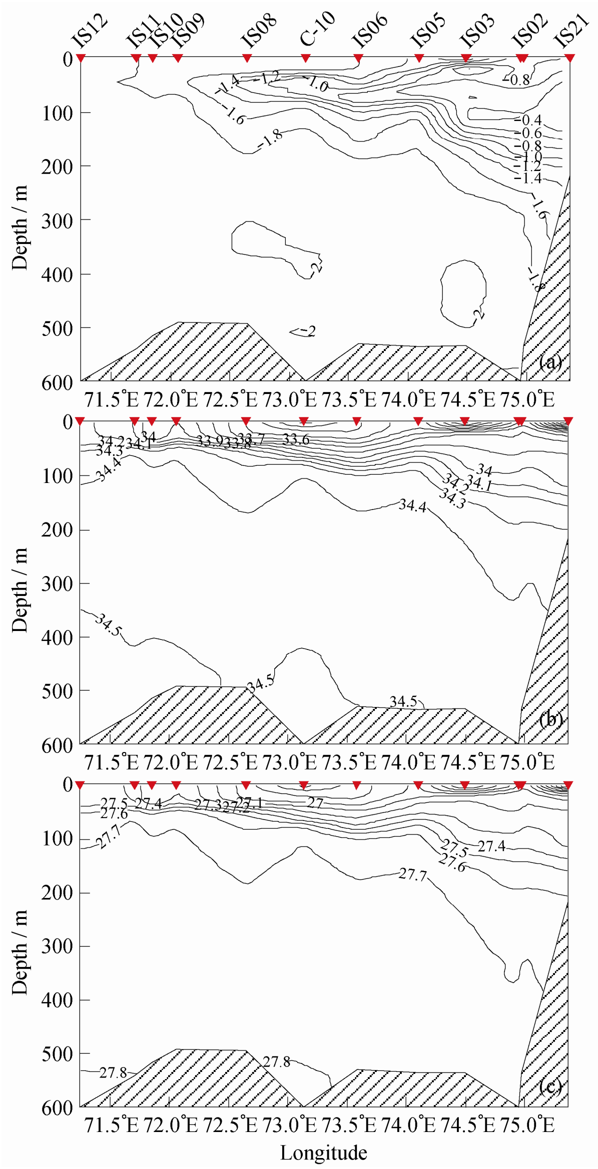

Figure 2 (a) Temperature, (b) salinity and (c) density sections along the northern margin of the Amery Ice Shelf.

On the basis of the analysis described above, it can be summarized as follows: there are inhomogeneous spatial distributions of water temperature, salinity and density in the upper layer along the northern margin of the Amery Ice Shelf, with the temperature higher at the east end and the salinity lower. The density is obviously affected by both temperature and salinity. Therefore, remarkable temperature-salinity-density gradients can be found in the upper layer.

2 Hydrographic gradient formation and warmer subsurface water at the northern margin of the Amery Ice Shelf

As it has been pointed out above, ice floes can be very dense at the northern margin. This was the case on the 24th CHINARE cruise, when the floe concentration became denser at the west end although it was much less in the east. Therefore, a feedback happens between the lower floe concentration and the warmer temperatures at the eastern end; i.e., the lower the concentration of floes, the warmer the surface layer of water. Contrarily, at the west end, the denser the floes become, the colder the surface layer of water, resulting in a contrariwise feedback. At the east end, where the floes decrease, i.e., where fresh water from the melting ice increases, conditions are favorable for the surface water to receive more transmitted solar radiation and more fresh water flux. This helps the surface layer to warm up and become less salty and less dense. Mid-summer is the optimal season for water to gain heat from solar radiation. The feedback difference between the east end and the west end of the ice shelf margin is a reasonable explanation for the temperature, salinity and density gradients in the sea surface layer.

The distribution of warm subsurface water already has been shown in Figure 2(a). To further discuss its location and formation, a meridional hydrographic section derived from data collected on the 24th CHINARE cruise is used to describe the water in more detail (See Figure 3). The information for this meridional section is listed in Table 2. It can be seen in Figure 3(a) that water as warm as − 0.4℃ is limited to the top layer above the 200 m isobath, at the southernmost end of the section. In contrast, water colder than - 1.6℃ is found above the 200 m isobath at the northern end of the meridional section. The temperature difference is as much as 1.2℃. What is interesting is that the warmer water is located in the higher latitudes (for example, IS21 is at 69.420 5°S), where the water should have been colder according to the normal geographic temperature distribution, and colder water is found in the lower latitudes (for example, XCTD20 is at 67.004 6°S), where the water should have been warmer. This abnormal longitudinal distribution in water temperatures indicates that the warm water does not originate from lower latitudes and must be locally formed. This conclusion can be further supported by temperature profiles collected at the stations surrounding station IS02, where the − 0.4℃ water layer is as thick as 100 m (from 50 m to 150 m below the sea surface). Furthermore, the temperature, salinity, and density profiles measured at stations IS04, IS03, IS02, C-09, IS21, C-12, P4A1 and P413 are shown in Figure 4. The station information is listed in Table 3.

Figure 4 shows that there are the subsurface warm water at all the eight stations listed in Table 3, but the water temperature becomes as high as − 0.4℃ only at IS02, IS03, IS04, C-09 and IS21, and it is far below − 0.4℃ at the other stations. Therefore, water as warm as − 0.4℃ is clearly limited to a small area around the IS02 station.

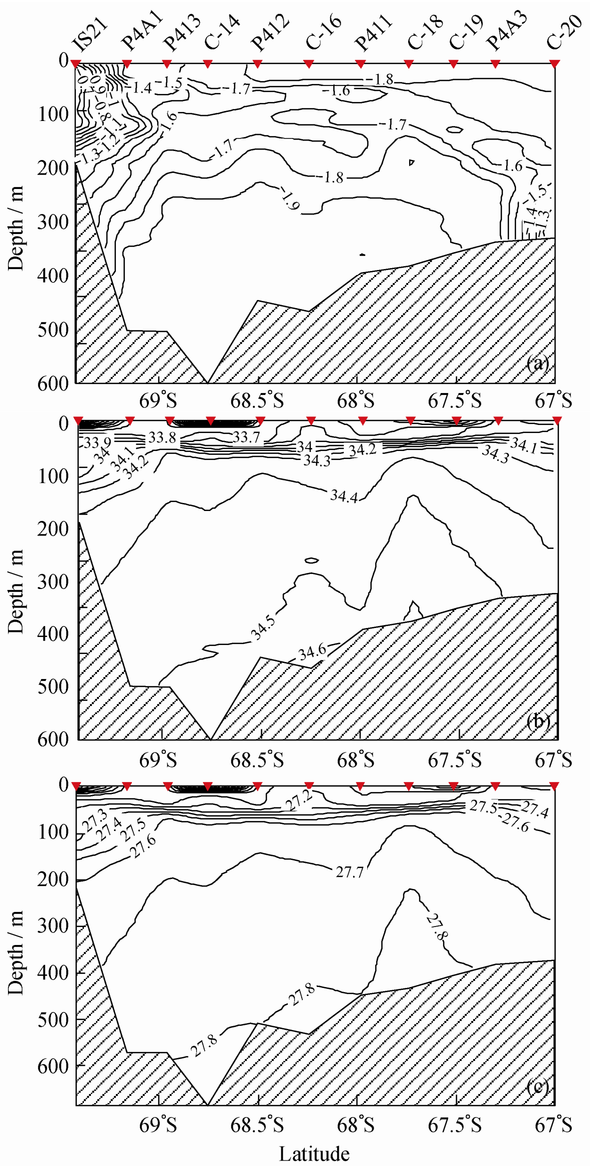

Figure 3 (a) Temperatur, (b) salinity and (c) density patterns in the meridional sections derived from data collected on the 24th CHINARE cruise.

Prydz Bay and the Amery Ice Shelf are located in the polar easterlies. Ice floes often drift westward due to forcing by the easterlies and pile up on the western shore of Prydz Bay. This westward drifting and dense floe concentration at the west end of the ice shelf margin led to CTD measurement interruption on board R/V *Xue Long*, as reported in the cruise log. As a result of gentle easterly forcing and dense floe covering, a deep cold layer is remained below the sea surface at the west end of the ice shelf margin in the 24th CHINARE cruise. Furthermore, the sea surface air temperature can often reach as low as −8 ℃ or lower in late summer (see Figure 5). Therefore, the surface water temperature can drop faster because of cooling by cold air, and a thin colder layer is formed at the sea surface. This cold layer overlies the warm subsurface water that formed in mid-summer in the floe-free top layer at the east end of the ice-shelf margin, as shown in Figure 4. It should be emphasized that sea surface warming by solar heating and the area of floe-free sea surface under easterly forcing play important roles in mid-summer, and sea surface cooling due to cold air in late summer results in a thin, colder surface layer over the subsurface warm water. Therefore, the cause of the localized subsurface warm water formation can be reasonably explained. It can be expected that the subsurface warm water will dissipate when autumn comes and strong cold winds blow, increasing the wind mixing effect, so that the residual thermohaline structures formed in summer are destroyed.

To summarize, horizontal gradients of temperature, salinity and density in the top water layer are closely associated with ice floe concentration and fresh water flux from ice melt at the ice-shelf margin. Subsurface water as warm as about − 0.4℃ is distributed in the area between 76.5°E and 74.3°E and 69.2°S and 69.5°S, at depths from 50 m to 150 m. The warm water forms at the surface in mid-summer and becomes covered by water cooled by cold air in late summer.

Table 2 Information for the CTD and XCTD stations along a meridional section northward from the east end of the ice shelf margin

Ordinal number	Station	Longitude / °E	Latitude / °S	Date(DD/MM/YYYY)	Time (GMT)	Water depth / m
1	C-20	72.240 2	67.004 6	11/03/2008	06:03	371
2	P4A3	75.588 5	67.302 3	10/03/2008	20:22	410
3	C-19	75.545 5	67.513 2	10/03/2008	13:51	403
4	C-18	75.532 9	67.741 6	10/03/2008	11:34	432
5	P411	75.438 8	67.983 7	06/03/2008	11:30	500
6	C-17	75.512 8	68.013 8	10/03/2008	10:06	485
7	C-16	75.499 6	68.244 6	10/03/2008	09:13	530
8	P412	75.489 7	68.502 9	06/03/2008	18:19	650
9	C-14	75.753 1	68.754 6	10/03/2008	07:09	690
10	P413	75.482 2	68.959 3	07/03/2008	01:54	720
11	P4A1	75.786 7	69.162 7	07/03/2008	07:21	600
12	IS21	75.366 0	69.420 5	25/02/2008	16:10	540

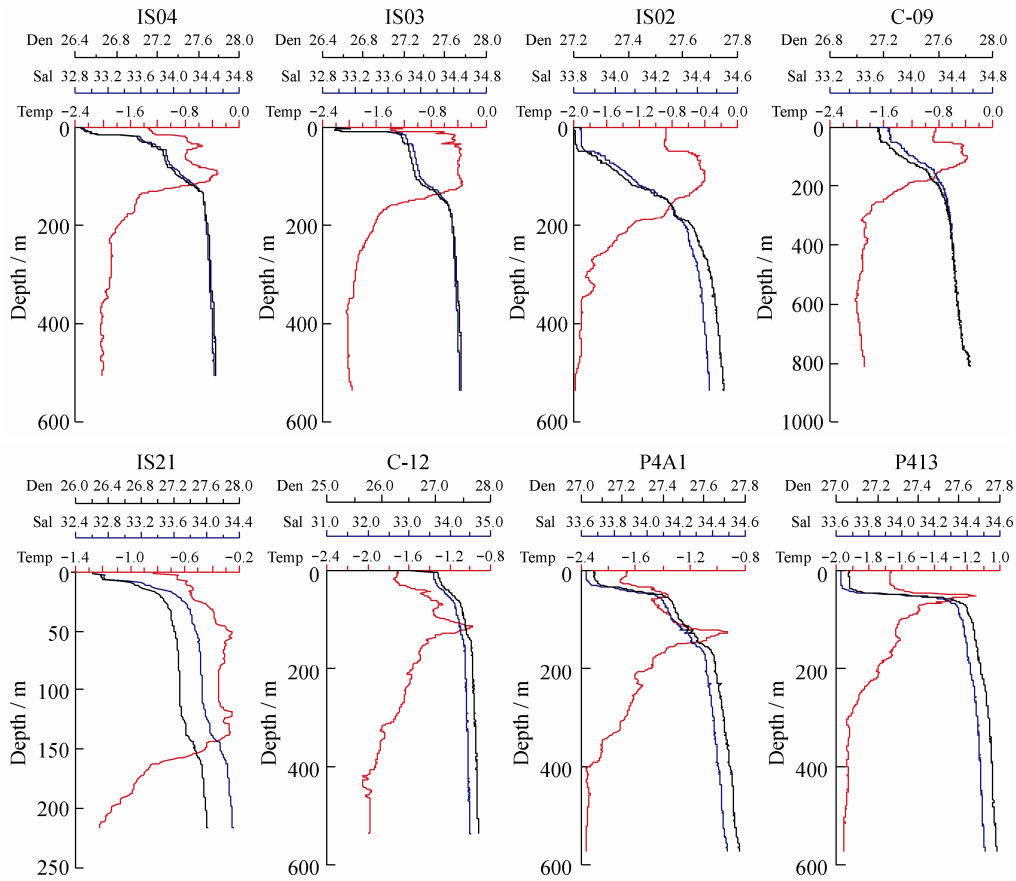

Figure 4 Temperature, salinity and density profiles at IS02 and its surrounding stations.

Table 3 Information for IS02 and surrounding stations

Ordinal number	Station	Longitude / °E	Latitude / °S	Date(DD/MM/YYYY)	Time (GMT)	Water depth / m
1	IS04	74.109 8	69.118 6	26/02/2008	17:42	690
2	IS03	74.493 7	69.226 2	26/02/2008	15:41	800
3	IS02	74.973 2	69.267 6	26/02/2008	12:30	870
4	C-09	74.948 6	69.266 4	26/02/2008	12:50	814
5	IS21	75.366 1	69.420 5	25/02/2008	19:24	530
6	C-12	75.765 4	69.160 2	07/03/2008	07:04	560
7	P4A1	75.786 7	69.162 7	07/03/2008	07:21	600
8	P413	75.482 2	68.959 3	07/03/2008	01:54	720

3 Comparison of Hydrographic Features in the 2007/2008 Summer with Those in the 2005/2006 Summer

The 22nd CHINARE expedition along the northern margin of the Amery Ice Shelf on January 14–18, 2006, at austral mid-summer, was similar to the 24th CHINARE expedition. Although the available CTD data from the two cruises are limited and it is too difficult to extrapolate interannual variation from these data, it is still significant to compare the data to expound the changeability of hydrographic features at the northern margin of the Amery Ice Shelf. It has been reported in references [3] and [4] that surface water as warm as 3℃ was observed at the ice-shelf margin in January 2006, but it was limited to a top layer as shallow as 10 m. It is pointed out by the authors of those papers that warm water formation is closely related to a polynya that formed at the ice-shelf margin in Prydz Bay. As a result of the polynya formation and its existence from late spring to mid-summer, ice-free sea water close to the surface could receive more heat from solar radiation and from the air-sea heat flux in the polynya at the ice-shelf margin. Therefore, polynya existence is one advantageous condition for polar ocean heating and increasing heat flux. No evidence was found for polynya existence in the 2007/2008 summer, however. Therefore, it can be easily understood why water as warm as 3℃ was not observed in the 2007/2008 summer. In addition, there is another important difference between the 24th CHINARE cruise and the 22nd one; the former was carried out in late summer (February 23–28, 2008) and the latter in mid-summer (January 14–18, 2006). The air temperature varied between 2℃ and − 6.3℃ for the 22nd CHINARE cruise while it varied between 0.7℃ and − 8.3℃ in the 24th CHINARE cruise(See Figures 5, 6). This difference in climatologic conditions between the two cruises results in significant differences in hydrography. The

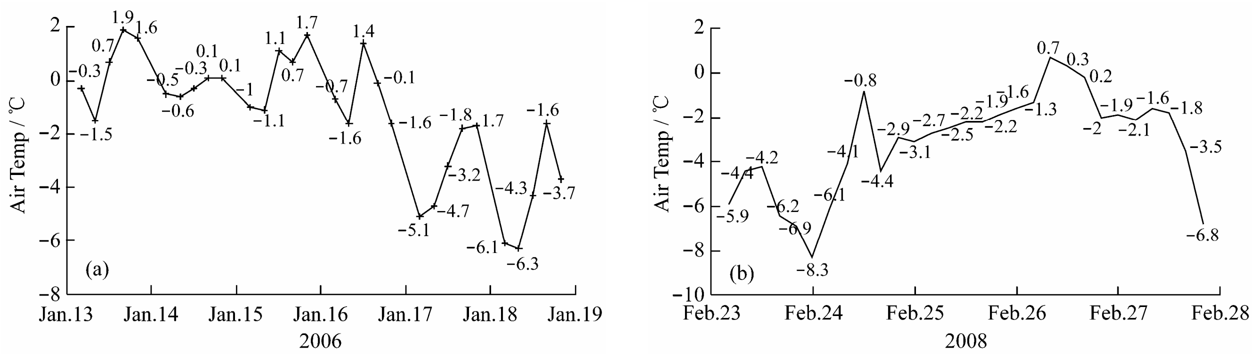

Figure 5 In situ air temperature variations observed during the 22nd CHINARE cruise and the 24th CHINARE cruise.

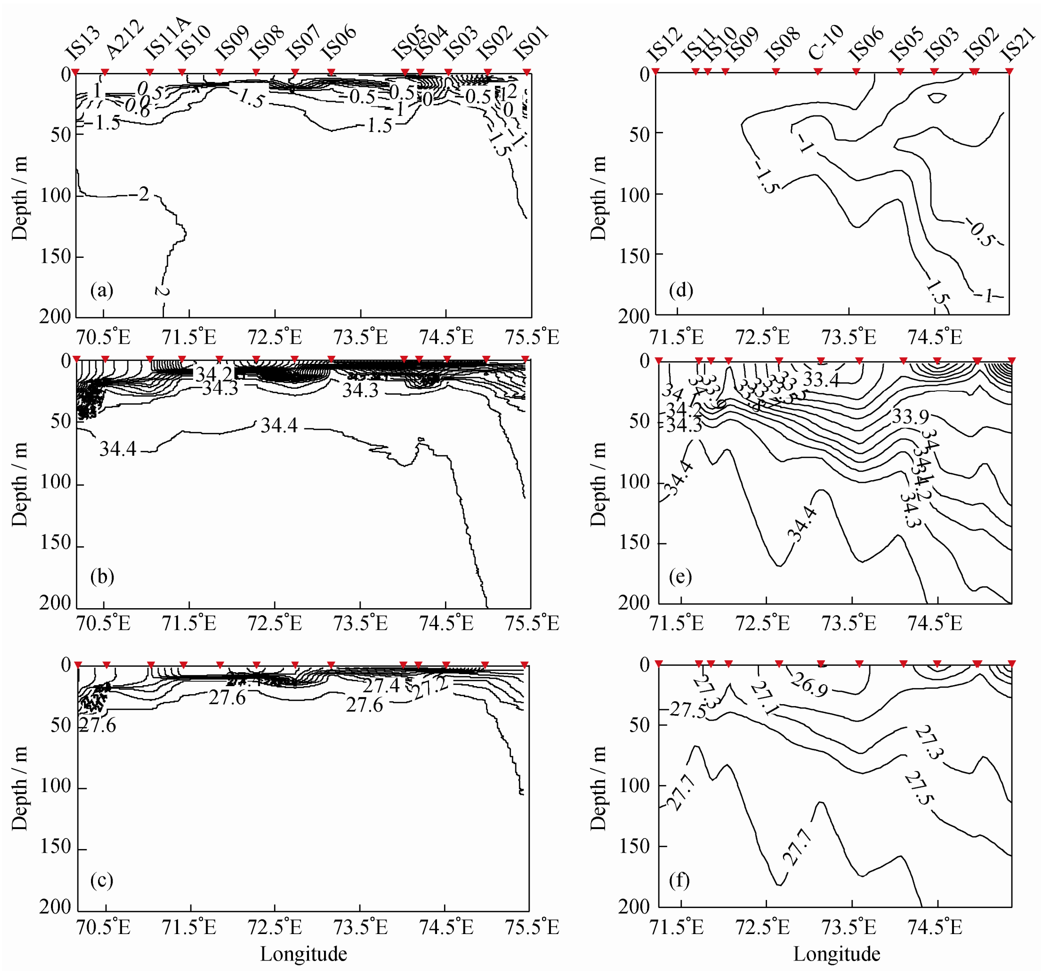

Figure 6 Comparison between the 22nd CHINARE cruise and the 24th CHINARE cruise: (a) temperature in the 2005/2006 summer; (b) salinity in the 2005/ 2006 summer; (c) density in the 2005/2006 summer; (d) temperature in the 2007/2008 summer; (e) salinity in the 2007/2008 summer; and (f) density in the 2007/2008 summer.

formation of the subsurface water as warm as − 0.4℃ instead of the surface water as warm as 3℃ can be reasonably explained by the climatologic conditions of the 24th CHINARE cruise in late summer 2008. This comparison demonstrates that hydrography is variable and complicated at the northern margin of the Amery Ice Shelf, and its spatial and temporal variability is inhomogeneous. Nevertheless, the observed air-ice-sea interactions provide clear clues for better understanding the complicated and changeable hydrography at the ice-shelf margin.

4 Conclusions

The following conclusions can be drawn from the above descriptions and analyses:

(1) Gradients of the hydrographic features were found in the top layer at the northern margin of the Amery Ice Shelf in February 2008. The water temperature was higher, the salinity lower, and the density less at the east end of the ice-shelf margin. The water temperature was lower, the salinity higher, and the density greater at the west end.

(2) Warm subsurface water with its maximum temperature as high as − 0.4℃ was found at the northern margin of the Amery Ice Shelf in February, 2008. It was distributed in the subsurface layer between 50 m and 150 m in the longitudinal range between 69.2°S and 69.5°S, up to the eastern shore of Prydz Bay. This warm water is confined to a small sea area. Its formation is closely related to floe distribution, mid-summer warming, easterly forcing, surface cooling by cold air in late summer, and air-ice-sea interaction. In contrast, water as warm as 3℃ was observed in the surface layer, as shallow as 10 m below the surface, in January 2006. The 3℃ water formation was closely related to solar radiation on the ice-free sea surface of the polynya.

(3) The floe concentration gradually increased from east to west along the ice-shelf margin in February, 2008, and became too dense at 71°E to continue navigation or the CTD operation.

(4) Hydrographic features are complicated and changeable in space and time at the ice-shelf margin. It is worth paying more attention to them, especially in these days when more and more phenomena related to climate change have been found.

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