Chinese Journal of Polar Science, Vol. 18, No. 1, 18-26, June 2007

Thermohaline structure inhomogeneity associated with polynia at the northern margin of Emery Ice-shelf

Pu Shuzhen(蒲书箴)[1,2], Ge Renfeng(葛人峰)[1,2], Dong Zhaoqian(董兆乾)[3], Yu Weidong(于卫东)[1,2], Shi Jiuxin(史久新)[4] and Xiang Baoqing(项宝强)[1,2]

1. *First Institute of Oceanography State Oceanic Administration, Qingdao 266061, China;*
2. *Key laboratory of Marine Science and Numerical Modeling, State Administration, Qingdao 266061, China;*
3. *Polar Research Institute of China, Shanghai 200136, China;*
4. *College of physical and Environmental Oceanography, Ocean University of China, Qingdao 266001, China*

Received June 6, 2007

Abstract Based on the hydrographic data in austral summer during the 22nd Antarctic Expedition of China (2005/2006), some features can be found about the northern margin of Emery ice shelf as follows. The heat content in the surface layer (0-50 m) at the eastern end and the western end of the ice-shelf margin is much higher than that at the middle. The upper mixing-layer depth and the seasonal thermocline depth at the middle of the ice-shelf northern margin are much shallower than those at the both ends. However there is much less difference between the middle and the ends in the bottom layer. The remote sensing photos show that the inhomogeneity in the surface-layer water is closely related to the spatial distribution of the floes and polynia in the area.

Key words Emery Ice-Shelf, thermohaline structure, floe, Inhomogeneity, polynia

1 Introduction

The eastern Antarctica is the most northward land in the Antarctica, extending across the Antarctic circle toward the Southern Indian Ocean. Prydz Bay is a small water area stretching into the eastern Antarctica and it is thus affected to a great degree by the continent. In addition to the continental effects on the bay, the Lambert glacier slowly moves toward the bay and becomes connected with Emery ice-shelf at the inland limit of the bay. Therefore the bay is also affected by ice. Furthermore the atmosphere can heat the water in austral summer and cool it in austral winter. All those causative factors make Prydz Bay with its adjacent sea area a complex system effected by the interactions among the ocean, the continent, the ice, and the atmosphere.

On 14-18 January 2006, R/V *Xuelong* dashed into the seasonal floe area along the northern margin of Emery ice-shelf and completed a hydrographic section (see Fig. 1) in order to study the thermohaline structure and its spatial variability in the marginal area. It is found by means of the full depth CTD data obtained during the cruise that the thermohaline structure has spatial inhomogeneity in the northern margin area of Emery ice-shelf. In this paper the hydrographic data are used for both the surface layer water-mass analysis and the lower layer water-mass analysis in the first section and the second section, respectively. Then the heat content in the upper layer was calculated showing its spatial inhomogeneity and the abnormality of its geographic distribution. Finally it comes how the inhomogeneity and the abnormality can be caused and explained. Conclusions are drawn at the end of the paper.

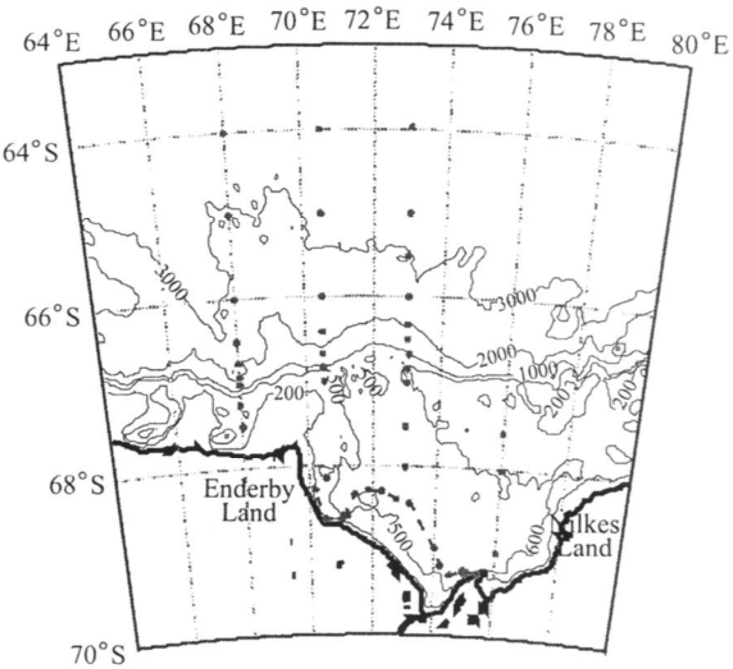

Fig. 1 Station locations of the 22nd Antarctic Expedition, the dash line shows the northern margin of Emery ice-shelf

2 Surface layer water at the northern margin of Emery ice-shelf in austral summer

R/V *Xuelong* navigated in Prydz Bay and its adjacent sea area to complete the 56 hydrographic stations and totally 94 CTD full depth casts (Fig. 1 for the station locations) in the period from 14th to 18th January 2006, when it was right in austral midsummer. The 13 CDT stations among the 56 are located in the dense floe area at the margin of the ice-shelf. The navigating route went from the east to the west. Multi-disciplinary observations continued for 25 hours at both the 1st station (i. e. at the east end of the section) and the 13th station (i. e. at the west end). The others of the 56 stations were arranged for the 4 sections in the sea area adjacent to Prydz Bay, which will be discussed in another paper in the future. It can be seen from Fig. 1 that the section or the ice-shelf margin appears a geometric curve being northward convex and further offshore at the middle part about 68°20′S, 72°E (the location of Station IS10). To compare with the middle part of the section, the east part of the section is rather southward and reaches 69°15′S at Station IS01, while the west reaches 68°39′S at Station IS12. Obviously Emery ice-shelf became melted to a larger extent at the east and the west than at the middle. The temperature, salinity, and density of the section are shown in Fig. 2. The hydrographic features can be described as follows. The surface layer water with its temperature higher than −1.0℃ are thicker at either the east or the west of the section comparing with the middle. It became as thick as 60 m at the east and 40 m at the west but it was only 15 m thick at the middle where Emery ice-shelf with its ice-tongue is the most northward convex. The surface layer water with its salinity less than 34.2 had the vertical distribution similar to the temperature section and became as deep as 40 m at either the east or the west, almost twice thick as that at the middle. The vertical distribution of density also shows similar features, i. e. the surface water with lighter density is thicker at either the east or the west. The hydrographic features described above can be summarized as follows. The surface water lying at the northern margin of Emery ice-shelf has higher temperature, less salinity, and a greater thickness at either the east or the west comparing with the surface water at the middle. Although the latitude of the middle part of the section is lower than the latitudes for either the east or the west, the water at the middle part of the section is colder and fresher than that at either the east or the west, and not only the thermocline but also the halocline is shallower there. Therefore the temperature and salinity distribution has the spatial inhomogenneity in the section and the geographic irregularity in the surface water, i. e. water is colder at the lower latitudes and warmer at the higher latitudes along the section.

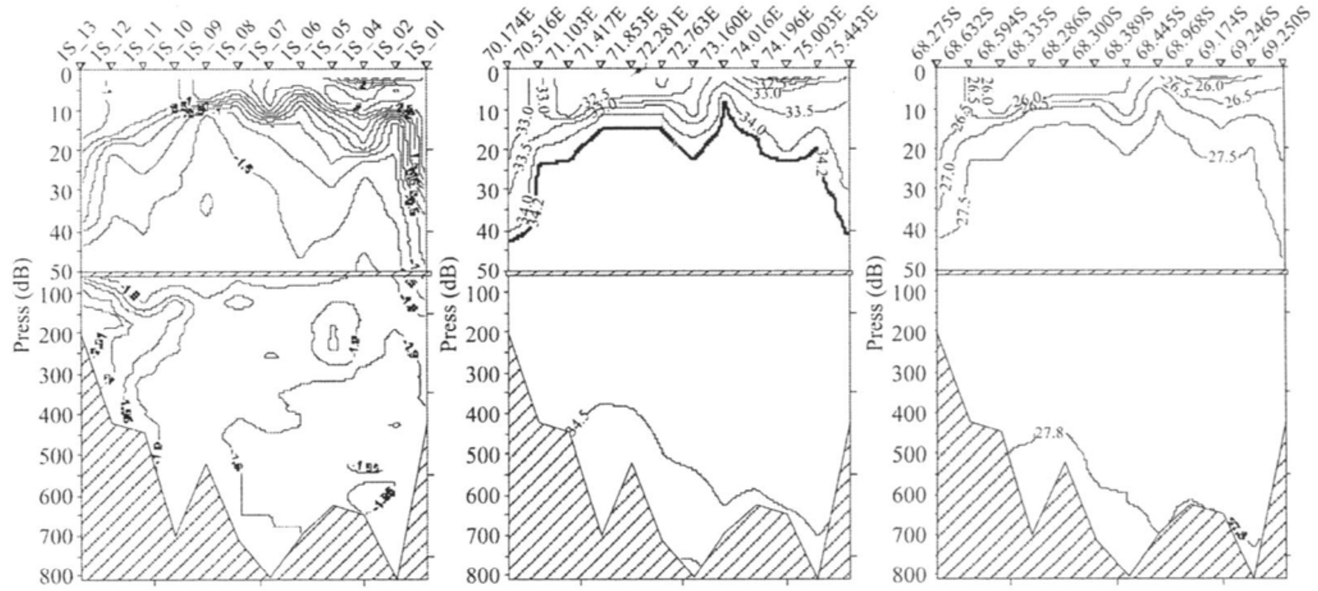

Fig. 2 Sections for temperature (left), salinity (middle), and density (right) at the northern margin of Emery ice-shelf, respectively.

Pu *et al.* (2000, 2004) [1][2] used the CTD data obtained during the Chinese 15th Antarctic Expedition to analyze the physical features of the surface water in Prydz Bay and its adjacent sea, showing that the surface water with a highest temperature about 1.9℃ and the salinity about 34.0 are distributed mainly in the top layer shallower than 50 m. They also found that the temperature and salinity are variable in the top layer because it is affected by various causative factors such as floe distribution, ice-melting degree, rainfall, and solar radiation, etc. Therefore the values of temperature and salinity are dispersed in a large extent. Chen *et al.* (2005) [3] draw the same conclusion based on the data obtained during the 19th Antarctic Expedition. Therefore the spatial inhomogeneity and the geographic irregularity of the temperature and salinity distribution along the northern margin of Emery ice-shelf can be expected as the reasonable conditions in summer. The causes for those inhomogeneity and irregularity will be discussed in Section 4 of this paper.

3 Prydz Bay shelf water in the lower layer at the northern margin of Emery ice-shelf

Prydz Bay continental shelf water are distributed below the surface water in the bay, from the 100 m depth down to the sea bottom. It can be seen from Fig. 2 that the salinity of Prydz Bay shelf water is about 34.5, higher than the surface water; its temperature is lower than −1.8℃, colder than that of the surface water; and its density is 7.8 kg/m^3, denser than that of the surface water. The Prydz Bay shelf water, unlike the surface water, is rather homogeneous and stable. It is formed in the long time polar night in austral winter, when atmospheric cooling is strong, wind is bitter, Emery ice-shelf is northward extended, salt-rejection from the new ice which is recently frozen becomes strong, density is heavy, and descending motion happens. Therefore Prydz Bay shelf water with such a heavy density is a kind of ‘memory’ kept by sea for the atmospheric extreme cold event in austral winter. When weather turns to (be) warm in summer of the following year, fresh water flux becomes increased due to the melted sea-ice in the surface water layer. Furthermore wind gets weaken and sun heating increases in midsummer, a warmer, less salty, and lighter surface water is formed and overlies the denser bottom water. Because of the maintenance of the stable structure (lighter at the top and denser at the bottom), the surface layer with greater buoyancy plays a role like a barrier layer to obstruct the downward transmission of the heat flux and momentum flux and to isolate the Prydz Bay continental shelf water underlying the summer surface water with the bottom layer being kept undisturbed. If one bears in mind that the northern margin of Emery ice-shelf is a floe-densest area in Prydz Bay and the multi-year ice coverage is distributed to the further south of the ice-shelf margin, it can be understood that both the summer heating to the surface layer and fresh water flux due to the floe melting are much stronger in the northern margin area comparing with the sea area south of the margin, where the sea surface is covered by the multi-year ice of the ice-shelf. Therefore in this sense, the floe area at the northern margin of Emery ice-shelf is most affected by the interaction among the atmosphere, ocean and sea-ice.

Pu *et al.* (2000)[1], Pu *et al.* (2004)[2] pointed it out that Prydz Bay continental-shelf water is situated at the depths deeper than 100 m in the sea area north of 67°s with its salinity between 34.4 and 34.5 and its temperature below −1.8℃, according to the 15th Antarctic Expedition data. However the data obtained during the 22nd Antarctic Expedition show that the extremely high salinity was about 34.6 at the depth of 750 m at Station IS07 and the extremely low temperature was about −2.01℃ at the depth of 150 m at Station IS12 and Station IS13. This is because this section went along the northern margin of Emery ice-shelf and it is geographically situated south of the sections of the 15th Antarctic Expedition. The comparison result between the two means that the salt-rejection by ice freezing and the seasonal cooling in winter time is stronger in the seasonal floe area at the northern margin of Emery ice-shelf than that in the sea area north of the northern margin of Emery ice-shelf, where the 15th Antarctic Expedition was carried out.

To sum up the above-description, it is learnt that Prydz Bay continental-shelf water is distributed in the lower layer at the northern margin of Emery ice-shelf, and the water being relatively homogeneous has higher salinity, lower temperature, and denser density. This water is formed in polar night, keeping “a memory” of atmospheric cold events in the previous winter. Although the spatial inhomogeneity of the water is not as obvious as the surface layer water, the salinity and density of the lower layer water is still a little higher at the middle part of the northern margin than either of the both ends of the margin section, while the temperature is lower at the western end. Comparing with the northern area of Prydz Bay, the salinity of the continental-shelf water at the northern margin of Emery ice-shelf is still higher, the temperature lower, and the density denser.

4 Heat content in the upper layer at the northern margin of Emery ice-shelf

In order to expound the seasonal heating effect on the heat content in the oceanic upper layer at the northern margin of Emery ice-shelf in the 2005/2006 summer, the following equation can be used to estimate the heat content in a water column on an unit base between the water depth Z_1 and Z_2.

$$H = \int_{Z_1}^{Z_2} c_p \rho T dz$$

where C_p is the specific heat of seawater, z the depth, $\rho = \rho(x, y, z)$ the density at the location x, y, z, $T = T(x, y, z)$ the location temperature, and $H = H(x, y)$ the heat content in the water column between Z_1 and Z_2. As it is usually done, C_p can be roughly taken as a constant and the density variation $\Delta\rho$ is negligible if seawater is taken as incompressible liquid, i.e. C_p and ρ give much less effects on the heat content comparing with temperature. Finally H can be expressed by $\int_{Z_1}^{Z_2} T dz$, which will be used to estimate the heat content in a water column on an unit base in any depth interval. Fig. 3 shows the heat content variation along the section of the northern margin between the sea surface and the depth of 50 m, because in general the summer heating effect is limited in the top layer shallower than the 50 m depth, which can be identified as the temperature section shows in Fig. 2.

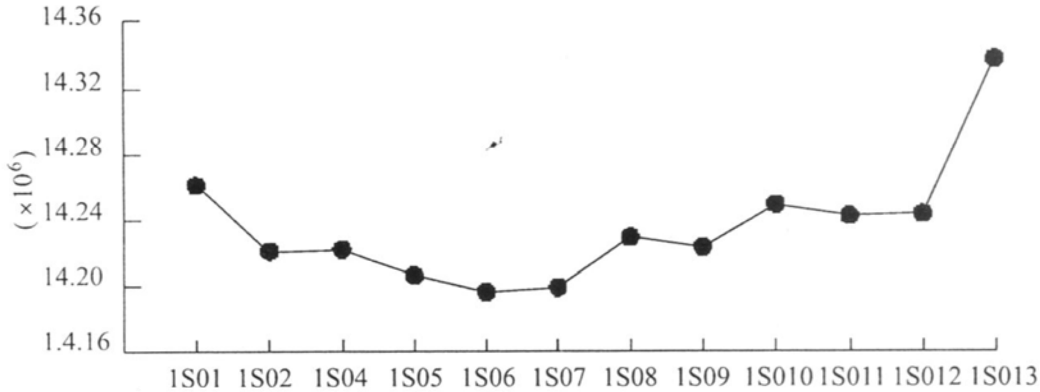

Fig. 3 Heat content variation in the upper layer (0-50 m in depth) at the northern margin of Emery ice-shelf

It is learnt from Fig. 3 that the heat content reaches the highest at Station IS01 of the east end of the section, where the latitude is the highest. The next comes the heat content at Station IS13 of the west end. The heat content at either of the both ends becomes higher than at the middle part of the northern margin of the ice-shelf, where the latitude is the lowest in the section. In addition, it can be also learnt from Fig. 3 that the lowest heat content of the upper layer is situated at Station IS07, where Emery ice-shelf becomes the most prominent northward in its ice tongue. Therefore the heat content distribution along the section shows that the heat content within the upper layer shallower than 50 m depth also has its spatial inhomogeneity and geographic abnormality, i. e. lower at the middle of the section (at the lower latitudes) and higher at the both ends (at the higher latitudes).

As it is described in the above paragraph, in general temperature or heat content should have become higher as the latitudes decreased. However as it is expounded in Section 2 the temperature becomes lower rather than higher at the stations of the middle area along the northern marginal section, where the latitudes of the stations are decreased than either of the both ends, where they are located at the higher latitudes in the section. In order to understand the cause for the spatial inhomogeneity and the geographic abnormality, the explanation will be expounded in the next section by means of the seasonal variation of polynia and floe area at the northern margin of Emery ice-shelf.

5 Effects of polynia development and floe coverage on the seasonal oceanic heating

Papers discussed polynia and its effects on thermohaline structure (Gorden and Comiso 1988[4]; Dong and Liang 1993[5]; Pu *et al.* 2000[1]; Pu *et al.* 2006[6]; Smith *et al.* 1984[7]), and expounded oceanic upper layer heating affected by polinia. Concerning the causes of polynia formation in the southern Ocean and the Antarctic coastal waters, usually polynia can be divided into 2 kinds. One kind is formed in the ocean away from coast, resulting from upwelling of Circumpolar Deep Water (CDW), featured with its warm temperature and high salinity, and heating the cold sea surface which was originally covered by ice and became open after the ice had been gradually eroded and finally melted by CDW. This kind of polynia is surrounded by ice where no upwelling occurs, and (it is) called as oceanic polynia. Another kind is called as coastal polynia, and it is formed when the offshore strong wind of polar cyclones or the Antarctic down slope wind from the pole blows the newly formed ice away from the coast. Obviously both the geographic locations and the forming causes for the two kinds of polynia differ from each other. It is evidenced by satellite remote images that coastal polynia is often formed at the northern margin of Emery ice-shelf. Fig. 4 is the images for the polynia forming and developing there. When it was early austral spring on 24th September 2005, a narrow ice gap were already formed (see Fig. 4(a)). The gap became gradually widened and eastward extended. Especially the west part of the gap became obviously wider on 3rd October 2005 (see Fig. 4(b)). On 18th November 2005, the floe area north of the polynia became obviously shrunk after some of floes had been melted. At the same time, the polynia became also shrunk because the remaining floes moved toward the northern margin of Emery ice-shelf (see Fig. 4(c)). On 28th December 2005, the floe area was further melted and shrunk. Especially the floe coverage northeast of the polynia became obviously decreased (see Fig. 4(d)). On 14th January 2006, when R/V *Xuelong* started the summer cruise along the northern margin of Emery ice-shelf, some floes still remained to the northwest but no ice could be observed in the northeast (see Fig. 4(e)). Thereafter the polynia is going to be disappeared. However, in sharp contrast with the temporal variation in the floes area to the north of the polynia, the northern margin or the ice tongue of Emery ice-shelf kept its northward prominence and configuration invariable, (see Fig. 4). It is because the ice tongue is the thickest part of the ice-shelf and can not be melted by seasonal heating. Therefore it is learnt from the above description that (1) the seasonal melting of the floe area to the north of the polynia is the main cause for the

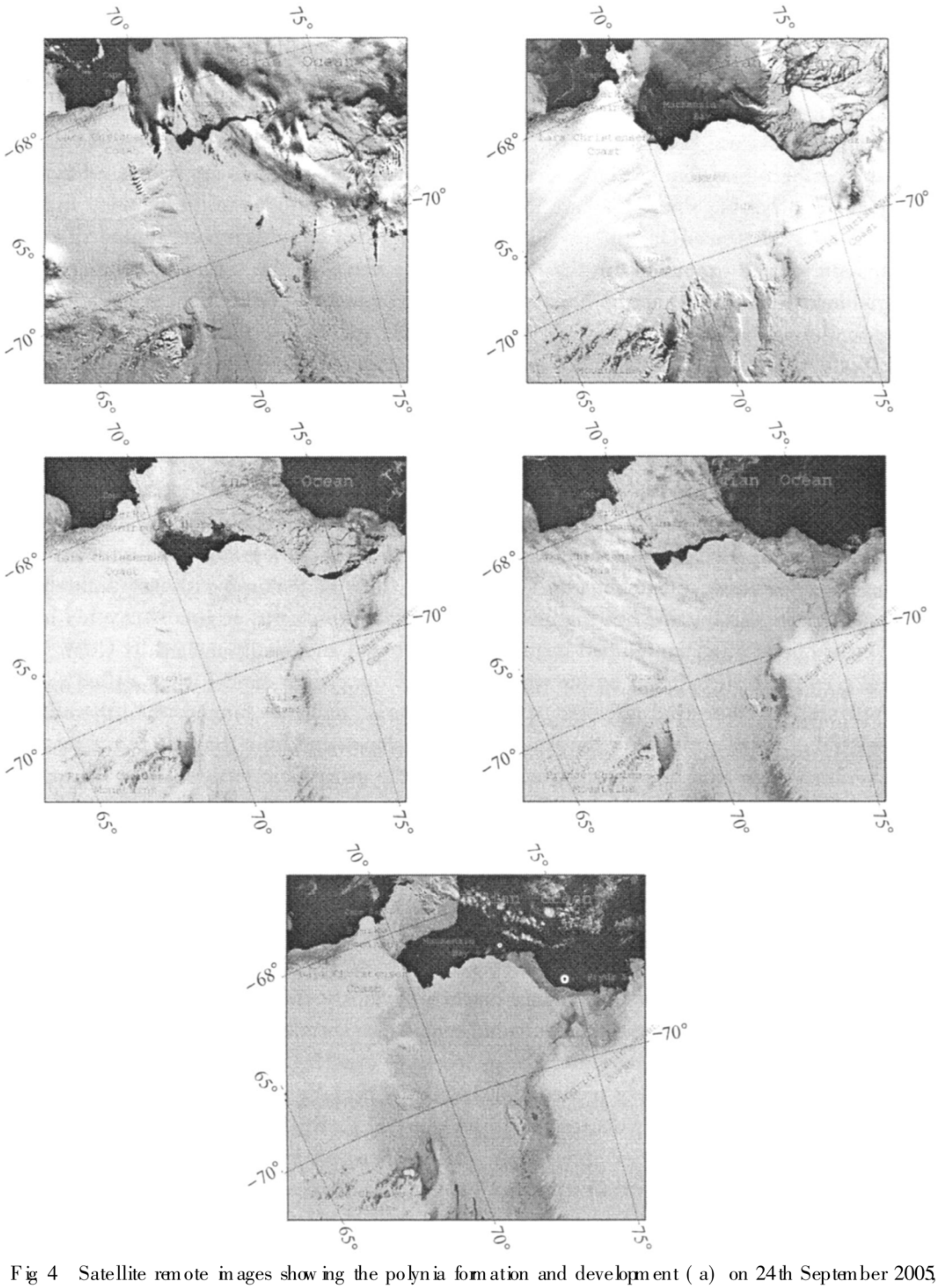

Fig 4 Satellite remote images showing the polynia formation and development (a) on 24th September 2005, (b) on 3rd October 2005, (c) on 18th November 2005, (d) on 28th December 2005, and (e) on 14th January 2006.

polynia vanishing (2) the polynia open water formed in early spring will be directly radiated by sun-light and heated by the atmospheric seasonal warming (3) the ice tongue i e the northward prominent part of Emery ice-shelf can not melt and vanish during the warming seasons but the floe area north of the polynia will be shrunk by solar radiation and atmospheric heat transfer, and (4) the configuration of the polynia open water determines the spatial inhomogeneity and geographic abnormality of the hydrographic features at the northern margin of Emery ice-shelf Therefore polynia formed in early spring is something like a ‘window’ through which solar radiation and atmospheric heat can transfer and warm the oceanic upper layer and melt the floe in the ocean

6 Conclusion

Conclusions can be drawn from the above analyses and descriptions

(1) Seasonal warming is observed in the oceanic upper layer (0~ 50 m in depth) along the northern margin of Emery ice-shelf in austral summer, temperature increases much more at the west end and the east end of the northern margin section than at the middle The sectional distribution of salinity is similar to that of temperature because of the increasing fresh water flux into the upper layer, which responds to sea-ice melting during the seasonal warming The water density response to the seasonal warming and freshening is that the density becomes lighter at either of the both ends of the section than at the middle However (a) the distribution of water temperature in the lower layer (deeper than 100m) is different to that in the upper layer Low temperature is observed in the lower layer at the section ends, and temperature is even lower at the west end Therefore the spatial inhomogeneity of the hydrographic features is obvious at the northern margin of Emery ice-shelf

(2) The heat content distribution also shows (the) inhomogeneity and irregularity in the upper layer (0-50 m) along the northern margin The heat content is higher at either of the two ends, especially at the east end, while it is lower at the middle of the section where the ice-tongue is northward prominent

(3) Formation and enlargement of the polynia at the northern margin of Emery ice-shelf are the main causes for (the) distributional inhomogeneity (of the hydrographic features). In early spring the open water of polynia is something like a ’window’ through which more solar radiation and heat flux are directly transferred to the oceanic upper layer Therefore polynia is an important causative factor for oceanic seasonal warming and freshening in spring and summer The polynia configuration gives effects on the thermohaline inhomogeneity at the northern margin of Emery ice-shelf

(4) Prydz Bay continental shelf water is situated in the lower layer at the northern margin of Emery ice-shelf It is rather homogeneous and of relatively low temperature, high salinity, and denser density This water keeps ‘its memory’ of the atmospheric cold event in the previous winter The lowest temperature is observed in the lower layer at the western part of the section, and how to explain it keeps unknown at the present

Acknowledgements This paper is supported jointly by the contracts No 40376009 and 40676011 of the National Science Foundation of China The authors take this chance to express their sincerely thanks to them.

References

[1] Pu SZ, Dong ZQ, Hu XM *et al*. (2000): Prydz Bay summer surface water and its northward extention (in Chinese). Chinese journal of Polar Research, 12(3): 157-168.
[2] Pu SZ, Dong ZQ, Hu XM *et al*. (2004): Physical oceanographpic features and oceanic frontal variations in Prydz Bay and its adjacent sea area. in: Studies of Polar Region Response and Feedback to Global Change(in Chinese), edited by Chen Liqi, Zhaoqian Dong, Dahe Qin, Shuzhen Pu, *et al*., Beijing Ocean Press, 36-58.
[3] Chen HX, Pan ZD, Jiao YT(2005): Features and currents in the water to the front of Emery ice-shelf (in Chinese). Chinese journal of Polar Research, 17(2): 139-147.
[4] Gorden AL, Comiso JC(1988): Polynyas in the Southern Ocean. Scientific American, 256(6): 90– 97.
[5] Dong ZQ, Liang XS(1993): Sea-ice, ice-cave and glacier, and their effects on water-mass formation and modification (in Chinese). Chinese journal of Polar Research, 5(3): 1-16.
[6] Pu SZ, Hu XM, Dong ZQ *et al*. (2006): Feaures of Physical Oceanography in the ocean near Prydz Bay during 1998/1999 austral summer. Acta Oceanologica Sinica, 25(6): 1– 14.
[7] Smith N, Dong ZQ, Knowles K, Siman RC(1984): Water masses and Circulation in the region of Prydz Bay of Antarctica. Deep– Sea Rearch, 31(9): 1121– 1147.