

Hydrological character and sea-current structure in the front of Amery Ice Shelf

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Received March 22, 2005

Abstract Hydrological character and Sea-current profiles structure are studied and analyzed in sea-area of the front of Amery Ice Shelf, Prydz Bay with LADCP, CTD data. These LADCP, CTD data were acquired during the 19th Chinese Antarctic Scientific Expedition. Results of this study agree with that, there exist four different kinds of water masses in the area of the front of Amery Ice Shelf in the summer of Antarctica. Current distribution presents a semi-circumfluence which flows in at the east and flows out in the west. Moreover, clockwise and anti-clockwise vortices were found in upper layer and mid-layer in the Prydz Bay. Western areas of these anti-clockwise vortices are positions of inflows from Prydz Bay to Amery Ice Shelf. The source of these inflows is the coastal westward current originated in the east of Prydz Bay. All these characteristics come down to the pattern of circumfluence, ice melt rate under Ice Shelf, scale of Ice Shelf water production and form of water exchanges between area of Ice Shelf and area of Prydz Bay.

Key words Prydz Bay, Amery Ice Shelf, Ice-Shelf water.

1 Introduction

Prydz Bay locates at the south of the Indian Ocean in the area of the Southern Ocean. Its north side faces to the open southern Indian Ocean, the other three sides are surrounded by the Antarctic continent and ice shelf. Prydz Bay embeds further most into the Antarctic continent and it is the third bay in area except for the Weddel Sea and the Ross Sea. The famous Lambert Glacier(Christie *et al.* 1990) stretches out from the Antarctic continent to Prydz Bay, and Amery Ice Shelf is formed as the west-southern boundary of Prydz Bay. The Sea area in Prydz Bay we studied in this paper locates at the front of Amery Ice Shelf, and it spans 5 longitudes from west to east. The whole bay is frozen-over with 2-meter thickness sea ice in winter. While in summer, sea ice broken up with some of them melted, there are still much floating ice, and ice coverage area is changeful(Dong *et al.* 1984). The time when the Prydz Bay was surveyed in the 19th Chinese Antarctic Scientific Expedition is between the end of Jan. and the beginning of Feb. of 2003. Most of floating ices in front of

Ice Shelf were melted then, and the rate of floating ices coverage was small. It was a good chance for the survey to be done in the very near front of Amery Ice Shelf, and four survey points located at the south of the southmost point ($69^{\circ}00'S, 75^{\circ}00'E$) which was defined by Albert(Alberts 1995). This time very precious Hydrological data were acquired.

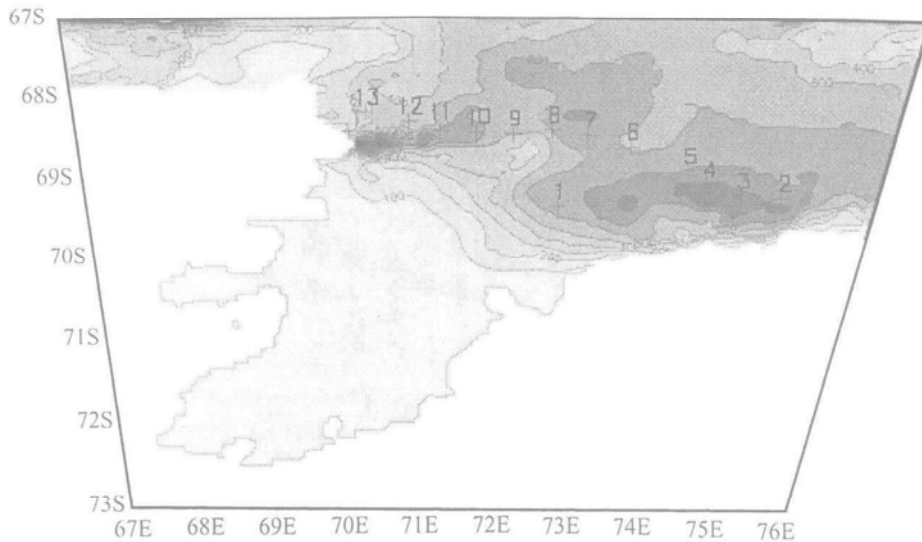


Fig. 1 Geographical and Topographical features and survey stations in the region of Prydz Bay and Amery Ice Shelf. (Crosses numbered from 1 to 13 stand for station points of CTD and LADCP)

The purpose of this paper is to make it clear that the hydrological character of sea water and water mass distribution with such characters, and make it clear that sea-current profiles structure and time-changes in the front of Amery Ice Shelf after integrative analysis of actual data of observation.

2 Data

Full depth profiles of LADCP and CTD data acquired during the investigation of the Chinese 19th Antarctic Expedition at 13 stations (Fig. 1) are used in this study, these data were collected from 3th to 5th February, 2003 on board of icebreaker "Xuelong". Because of the influence of iceberg, huge float ice and excursion of icebreaker, these survey stations which should be evenly distributed on investigation line are located as shown in Fig. 1. There are 12 stations in front of the Amery Ice Shelf and the other one is less than 1 nautical mile away from Amery Ice Shelf.

CTD deployed in the investigation is MARKIII C, its resolution of conductivity is ± 0.0002 milli-mho/cm and resolution of temperature is ± 0.002 °C. Salinity data are derived from in-situ conductivity data according to method mentioned in UNESCO (1988). Workhorse Sentinel LADCP Self-Contained 300 kHz with bottom track was used for current measurement. Parameters of LADCP were set as: Pings/Ens = 1, Time/Ping = 1s, 1st Bin Range (m) = 14.11, Bin Size (m) = 10.00. Data of magnetism deviation are acquired from NOAA's National Geophysical Data Center (Version 2004). Under these parameters,

resolution of velocity is less than $\pm 3.5\text{cm/s}$ while resolution of direction deviation is $\pm 5^\circ$.

3 Distribution and hydrological characters of water mass

From data acquired in the 19th Chinese Antarctic Scientific Expedition, we can see that, mostly in the front of the Amery Ice Shelf salinity is about 32.6 – 34.6 PSU, temperature is about -2.0°C – -2.0°C and potential density is between 26.5 kg/m^3 – 28.2 kg/m^3 , exclude those areas around icebergs and floating ice which are influenced by ice melting in summer. As shown in the figure 2, influenced by variable sea ice distribution, ice melting, precipitation and the change of day and night, the distribution of temperature and salinity in the sea surface water are sporadic. This is consistent with the results of Pu Shuzheng (Pu *et al.* 2001).

In addition, the vertical distribution of the temperature, salinity and density are also differs in the 13 stations because of the different location and influence of iceberg and floating ice around.

From the figure 3.1, we can see that there are three typical temperature profiles. The same characteristic is that there is a strong thermal layer and sub-mixed layer 100 m depth hereinafter, whilst different characteristics of temperature distribution exist in the upper layer. As the first type, there is an evident ob-thermal layer hereinbefore 50 m depth while the upper mixing layers doesn't exist or isn't obvious. The second type is the most complex type: an evident upper mixing layer and an ob-thermal layer exist simultaneously, and the upper mixing layer above the ob-thermal layer is thin and the scope of ob-thermal layer is small. There is no ob-thermal layer for the third type with the upper mixing layer and the thermal layer connected. Ob-thermal layer is a familiar phenomenon in the high latitude area, and there are 6 stations temperature profiles, in which exist ob-thermal layer out of 13 investigation stations. Only the station 1 and station 2 present the first type while the station 1 is the nearest station from the Ice Shelf and the station 2 is the easternmost station. Because of the influence of cool interface, ice melted water and inconspicuous wind – wave mixing, ob-thermal layer is formed without upper mixing layer exist at these two stations. Although ob-thermal layer exist at station 4, 9, 11 and 12, there is a thin homo-upper layer above, temperature profiles at these station present the second type. At the others, temperature profiles present the third type because of the strong wind-wave mixing.

Salinity profile forms are more complex, but we also classify them by salinity trend into three typical forms for convenience to compare (Fig. 3.2). Corresponding to the first type of temperature profile, the first type of salinity profile presents that there is a strong gradient saline layer without upper mixing layer. This type turns up at station 1 and 2. Only at station 6 present the second type, and the outstanding character of this type is that there is a thin ob-saline layer between two saline layers. This kind of profile reflects complicate origin of water mass. As for the third type of salinity profile corresponding to the third type of temperature profile, there is a homo-upper layer hereinbefore 50 m depth with a saline layer below. This type turns up only at the station 10. At other stations salinity profiles present transition and interweavement of the first and the third type, with upper mixing layer and saline layer exist at long intervals. Three type salinity profiles are consistent hereinafter the main saline layer with a mixing layer below.

The distribution of the density mainly lie on salinity distribution since the scope of temperature is no more than 4.0°C . Corresponding to three typical types of temperature and salinity, density profiles can be marked off as three typical types as shown in Figure 3.3. The first type is familiar: there is the upper mixing layer, the pycnocline and the lower mixing layer from sea surface to sea bot tom in turn. There are 6 density profiles presenting the first type. As for the second type, there are two, even three pycnoclines exist between 50 m – 100 m; While the third type has no apparent upper mixing layer, the density profile is made up of a pycnocline and a lower mixing layer.

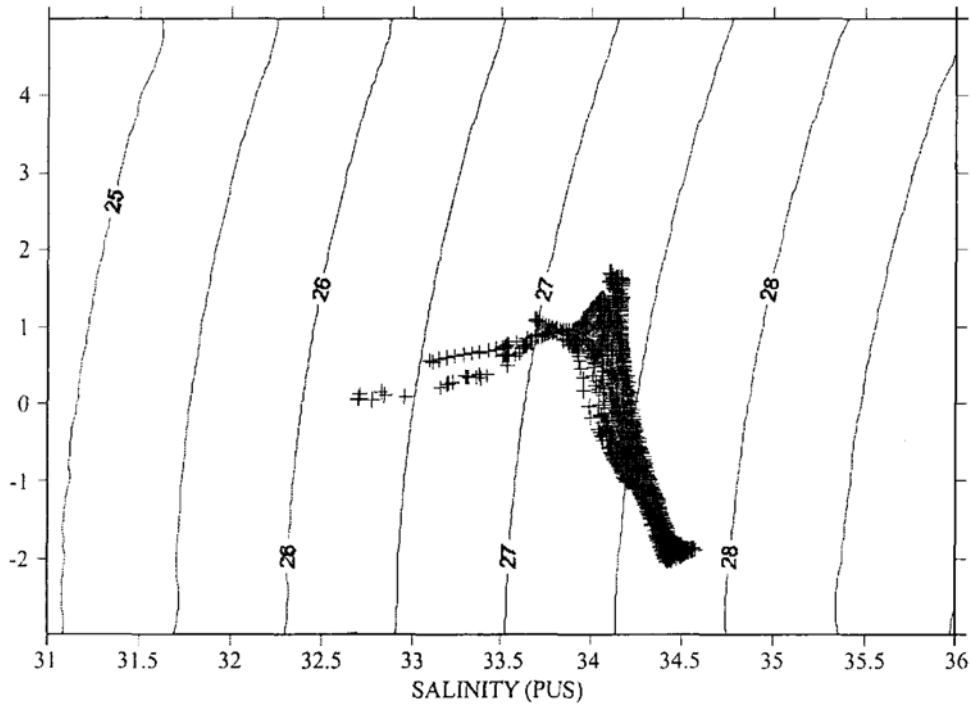


Fig. 2 Scatter plots of temperature and salinity determinations for standard depths of all stations (thin lines mark contours of constant density).

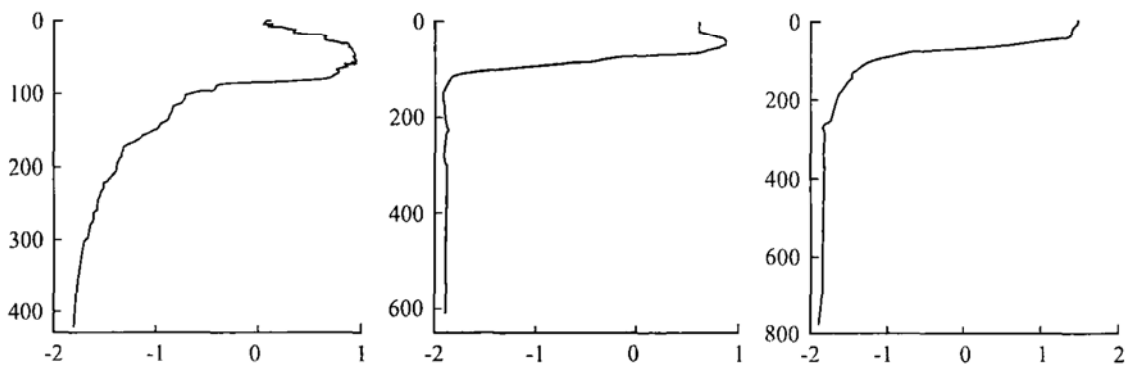


Fig. 3.1 Three typical profiles of temperature distribution (X-coordinate is temperature in unit $^{\circ}\text{C}$ while Y-coordinate is pressure in unit meter.)

As a whole, temperature and salinity distribution affected by wind-wave mixing, ice melted water and the form of circumfluence present multiformity in the upper layer. Less in-

fluenced by wind-wave mixing and ice melted water, distribution of temperature and salinity below pycnocline reflect the form of circumfluence in the under layer. For convenience to analyze and compare with spatial info of the stations preserved, these stations (from station 2 to station 13) are regarded as a section. As starting from the station 13, this section is formed with distance added-up between adjacent stations as abscissa. For example, X-coordinate of the station 11 is the sum of distance between station 13 and 12 and distance between the station 12 and 11. Sectional distributions of hydrological factors are showed in Fig. 4 except for the station 1. While hydrological factor profiles of the station 1 include each first plot of Fig 3. 1, 3. 2 and 3. 3.

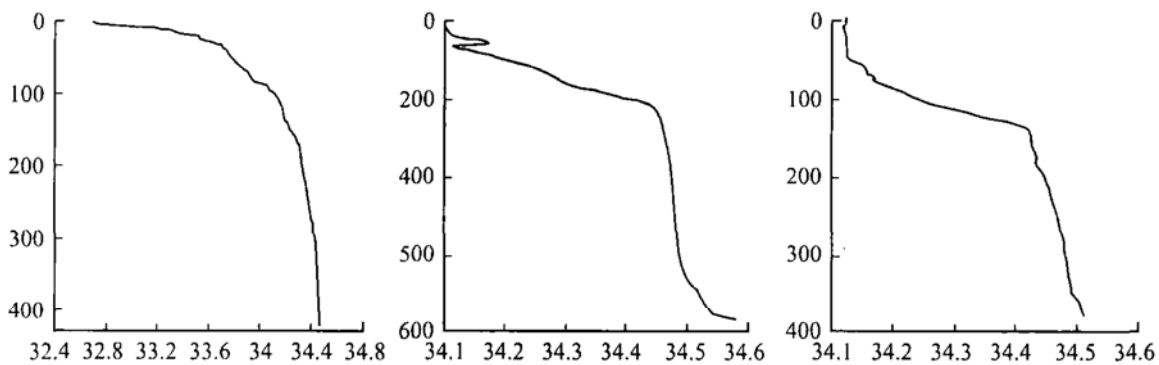


Fig. 3.2 Three typical profiles of salinity distribution (X-coordinate is salinity in unit psu while Y-coordinate is pressure in unit meter.)

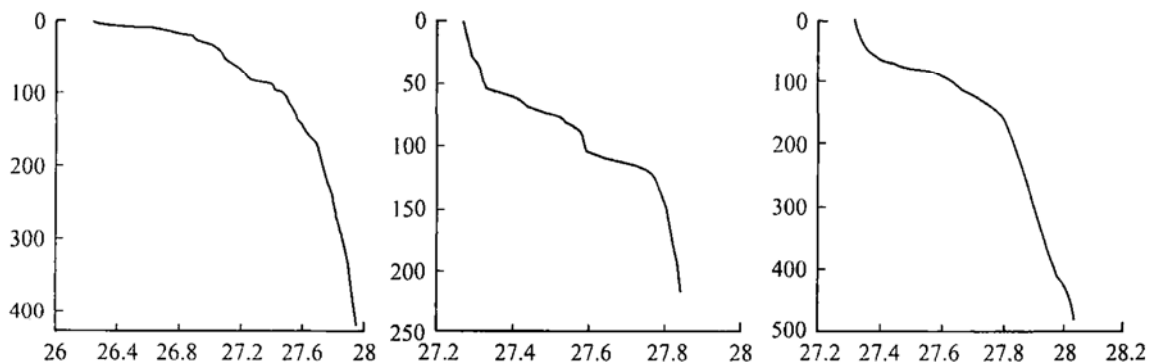


Fig. 3.3 Three typical profiles of density distribution (X-coordinate is density while Y-coordinate is pressure in unit meter.)

Based on the integrated study of Fig. 3 and Fig. 4, we found that there are four different water masses. Above 50 m depth of the station 1, there are the lowest temperature, salinity and density in all the stations. The lowest salinity is 32.8 PSU, whilst the lowest temperature is 0°C. This kind of water maybe produced by melted Ice Shelf water since the station 1 is the nearest station from Ice Shelf. And this kind of water mass should be looked upon as summer surface water in front of Ice Shelf. Above 50 m depth of the station 2 and station 11 there exists the most proximal temperature of the station 1. If we take 400 m isobaths as the end of the Amery Ice Shelf fringe, the station 2 and station 11 are the two stations which is the nearest to the 400m isobaths in the front of the Amery Ice Shelf. Different from temperature profiles above 50 m, salinity at the station 2 and 4 are almost proximal to

salinity at the station 1 which is about 0.3 PSU lower than the other stations. In this case we can say that summer surface water in front of Ice Shelf has much more effect in east than in west in front of Amery Ice Shelf. For surface layer water of all stations, the range of temperature is about $1^{\circ}\text{C} - 1.6^{\circ}\text{C}$ and the max. value exist at the station 5, 6 and 10. While the change of salinity is no more than 0.2 PSU and basically consistent (34.0 ± 0.1) except little variety exist at the station 6 and 4. This kind of water mass, which temperature is about $1^{\circ}\text{C} - 1.6^{\circ}\text{C}$ and salinity is about 34.0 exist in front of Amery Ice Shelf, is consistent with summer shore surface water in Prydz Bay mentioned by Pu Shuzhen(Pu *et al.* 2001).

Secondly, there exist the main thermal layer, salinity layer and pycnocline in 50 m – 200 m, and in this layer isolines of each hydrological factor are very dense, gradients of each factor are great. This kind of water mass can be looked upon as summer pycnocline water in front of Ice Shelf. In 50 m – 200 m, temperature and salinity at the station 1 is close to those at the station 2. From fig. 4, we can see that there are four max values and four min values of each hydrological factors and each max value alternate with a min value. Maximum horizontal grads come forth at the station 8, and this is begotten by run – up of shelf water of Prydz Bay at depth 120 m with temperature lower than -1.8°C , salinity higher than 34.5 PSU.

Thirdly, shelf water of Prydz Bay exist at all stations below 200 m, with salinity about 34.4 – 34.5 and temperature below -1.8°C . This kind of water mass characterized by high salinity and low temperature results from cooling and salting out of surface water in autumn and winter(Pu *et al.* 2001). The water mass with temperature lower than -1.9°C was also named as Ice Shelf Water, Shi Jiuxin(Shi and Le 1999) considered that this kind of water comes from cooling process under Ice Shelf and always exists in front of Ice Shelf.

Table 1. Water masses and their T&S properties outside of Amery Ice Shelf

Water mass	Location	Depth (m)	Salinity(PSU)	Temperature($^{\circ}\text{C}$)
Summer surface water in front of Ice Shelf	Station1	<50	About 32.8	About 0
Summer shore surface water in Prydz Bay	Station3 ~ 13	<50	About 34.0	1 ~ 1.6
Summer pycnocline water in front of Ice Shelf	All stations	50 ~ 200	34.0 ~ 34.4	-1.9 ~ 0
Shelf water of Prydz Bay	All stations	>200	34.4 ~ 34.5	< -1.8 $^{\circ}\text{C}$

4 Sea-current status in the front of the Amery Ice Shelf

Data and info presented in table 2 and figure 5 are result of LADCP observation. In figure 5 directions of current vector are signed as upward for the North, rightward for the East. In the process of in – situ survey, LADCP were deployed down deep to the bottom of water at all these 13 survey stations. Data acquired when bottom track function works can be used for absolute velocity of reference layer calculation. With absolute velocity at reference layer, relative velocity grads can be used for full depth velocity calculation. More detail of velocity calculation from LADCP data can be found in reference paper(Xiong *et al.* 2003).

According to table 2, velocity in average is high in upper layer outside of Amery Ice Shelf, and velocities are over 50cm/s at the station 7, station2. Only at the station 4 and

station 13 velocities are less than 10cm/s. At all other stations velocities are greater than 20cm/s except for the station 5. West and west – northwest direction current dominate in upper layer ocean. Only at the station 1 the current flows southward, and at the station 10 and station 11 currents are west-southward, whilst at the station 4 and station 12 currents are east-north-north direction , at all other 8 stations current directions are west or west-northwest.

In the mid-layer, velocity is less than that in the upper layer obviously. Except for over 40cm/s velocity emerged at the station 2, at other stations the velocity is less than or about 20cm/s. At the station 4 and station 13, current direction vary relatively apparent, while at other stations scope of current direction variability is about $\pm 10^\circ - 30^\circ$.

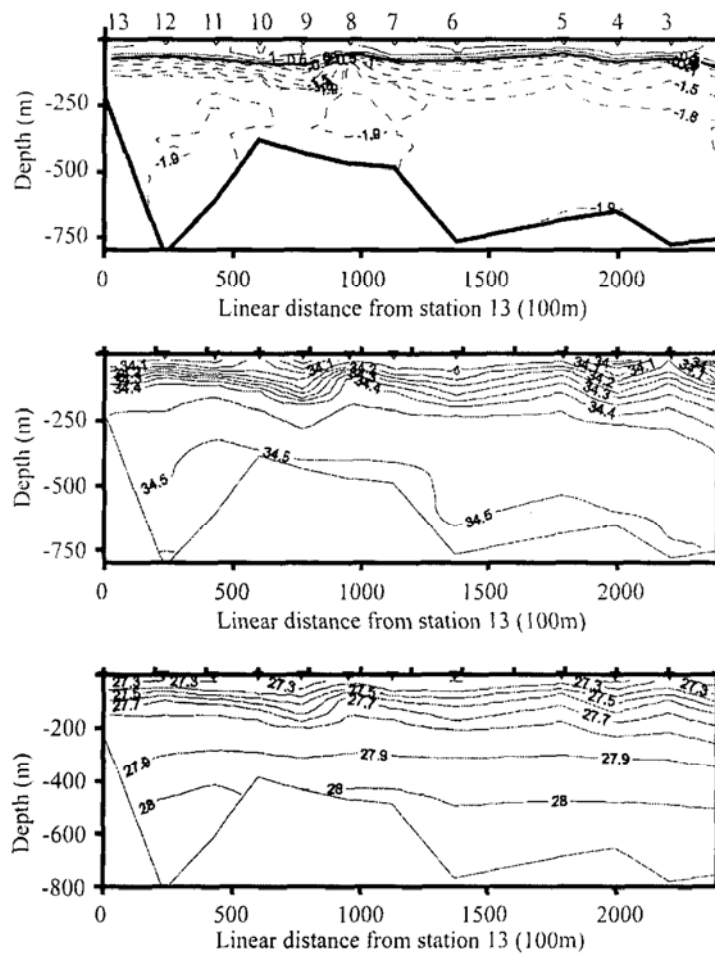


Fig. 4 Contours of temperature, salinity and density at section from station 13 to station 2.

For an intuitional view, we can see that in the upper layer the whole trend of current in front of Amery Ice Shelf is westward, and velocity is greater at far afield than that at near-side of Ice Shelf front fringe in current – vector map Fig. 5(a). In the east side of Prydz Bay, velocity is relatively high. From the station 2 to station 5 velocity decreases rapidly with current direction changes from west-northwest to the west, then west-northnorth and then west again, with a weak clockwise vortex about at the station 4. This clockwise vortex is corresponding to the low-salinity and high – temperature core that emerged at upper layer of the same station in Fig. 4. Velocity reaches the maximum value 56.4 cm/s at the station

7 with current direction west-north. Current keeps to be west-northward from the station 6 to station 8. An anti-clockwise vortex emerges between the station 9 and station 11 with velocity over 30 cm/s. The center of this vortex is corresponding to the high-salinity core at upper layer of the station 10 in Fig. 4. A weak clockwise vortex presents between the station 11 and station 12, and at the station 12 the flow changes to be northward. Hereafter the flow becomes even weaker with direction changes to be west-northnorth. Except at the station 1, in other area the vector map is a result of interpolation. In the east-north side area of station the 2-9, the flow is west-northward; In the west of the station 1 and the south of station 7-11 current direction changes from west to west-south. In other area, velocity is relatively small.

Table 2. Velocity and current direction in upper layer(0 m-100 m) and mid-layer(100 m-300 m) outside of Amery Ice Shelf

Station No.	Velocity in upper layer (cm/s)	Current direction in upper layer(degree)	Velocity in mid-layer (cm/s)	Current direction in mid-layer(degree)
1	26.70	175.69	8.08	165.34
2	53.59	307.74	41.01	316.63
3	33.33	275.53	21.05	263.52
4	4.07	24.99	6.08	156.61
5	13.50	284.95	11.49	299.56
6	31.44	311.86	7.58	337.41
7	56.40	322.91	11.85	346.42
8	33.32	307.56	8.86	295.38
9	41.61	300.19	17.44	337.86
10	30.94	243.65	13.17	216.59
11	41.47	242.59	19.25	231.68
12	28.09	12.13	19.20	6.43
13	5.18	303.26	10.50	28.06

From the vector map of mid-layer [Fig. 5(b)], we can see that relatively high velocity only presents in the area at about the east of Prydz Bay, while in other area the velocity keeps to be weak. At station 3 there is an anti-clockwise vortex and this vortex is corresponding to the high-salinity core in hydrological profiles. The weak clockwise vortex that emerged in upper layer area of the station 4 changes to be a gradually change area of current direction with greater scale now. The flow changes to be west-northnorth about at the station 6. Similarly different from the upper layer, at the station 7 the velocity keeps sizable with other stations. Between the station 9 and station 10, the flow changes from west-northnorthward to west-southward rapidly and here can be taken as an anti-clockwise vortex. Similar to upper layer, the flow between the station 10 and station 11 is inflow to the Ice Shelf, its current direction is west-south and its velocity is about 15 cm/s. The weak clockwise vortex still exist in the mid-layer of the station 11 and station 12, which is the same to the upper layer by and large. At the station 13, velocity is greater than that in upper layer with current direction about east-northnorth. At the station 1 the velocity keeps to be small with current direction about east-south south.

Totally speaking, no matter in upper layer or in mid-layer, the current in sea area outside of the station 2 – 13 keeps to be westward or west-northward, while in the area about the station 7 and station 8, there are water mass accumulation of summer pycnocline water and Shelf water hereafter 50 m since the depth of water decrease along the flow, and in the west of Prydz Bay at about the station 12 and station 13 the flow turn northward. This is consistent with the view point that in the Prydz Bay the current in pours in the east and flow out in the west (Smith *et al.* 1984). Here the westward current at the station 2 and station 3 should be the westward coastal current, driven by the mean easterly winds from the Antarctic plateau (Williams and Bindoff 2003; Wong 1994). Whilst the velocity is greater than Wong's calculation result (8 cm/s). In upper layer and mid-layer of Prydz Bay, there are anti-clockwise and clockwise vortexes. The west wing of the anti-clockwise vortex in mid-layer at about the station 3 is the position of inflow to the Ice Shelf in the east of Prydz Bay, while the west wing of the anti-clockwise vortex at about the station 10 – 11 both in the upper layer and mid-layer is the main place of inflow to the Ice Shelf in the west of Prydz Bay. This tallies with the conclusion that the west wind driven coastal current is the main source of inflow in upper layer of Prydz Bay (Williams and Bindoff 2003). The clockwise vortex might be induced by the topographic factors. Taking velocity at the survey stations as the base, southward flow merely emerge in the upper layer and mid-layer of the station 1 and station 11, in the mid-layer at the station 4 and station 10 only, while the northward current distribute in a broad area of the other stations.

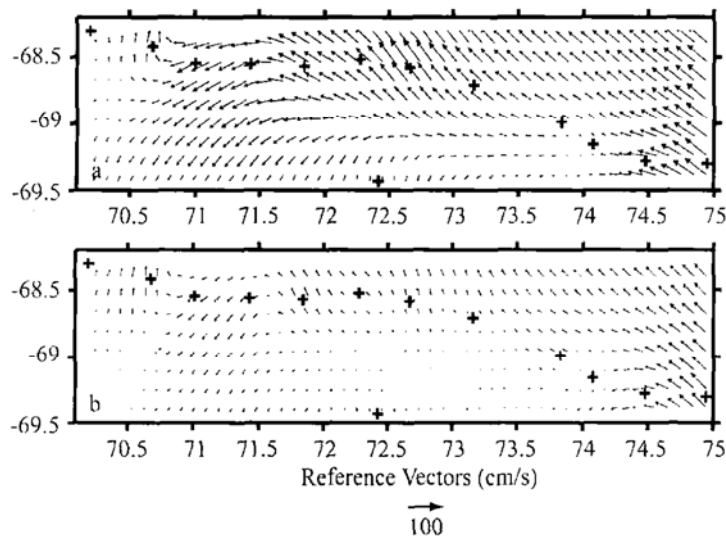


Fig. 5 Velocity vectorgraph outside of Amery Ice Shelf. Sign “+” stands for survey stations corresponding to Fig. 1, while velocity distribution is result of interpolation from real-surveyed velocity using Kriging method. a, b stand for upper layer and mid-layer respectively.

Since the depth of each survey station changes greatly, it is not suitable to define under-layer or bottom layer with a uniform range of water depth. Besides that, in the process of survey, the data collected near the bottom is relatively rare. Discussion of bottom layer current is not included in this paper.

It should be made out that the tidal current contribution is included in the current result measured using LADCP. Since there is no long-time survey for tidal current observa-

tion, it is difficult to delete the tidal current contribution. Firstly, results of G. D. Williams' study in Adelie Land(Wong 1994) shows that the tide correction is not to improve the velocity data. On the other hand, as the water depth for all survey points mentioned in this paper is more than 500 m, we consider that tidal current influence on the ocean current in the survey sea area can be ignored.

5 Results

On the base of analysis of the 19th Chinese Antarctic investigation data, it can be conclude as following:

1. There are four different water masses in the front of the Amery Ice Shelf and sea area around. (a) Summer surface water in front of Ice Shelf; (b) Summer shore surface water in Prydz Bay; (c) Summer pycnocline water in front of Ice Shelf; (d) Shelf water of Prydz Bay.

2. Isolines of hydrological factors fluctuate between 50 – 200 m in the sectional profiles from station 2 to station 13.

3. Velocity results derived from LADCP data shows the current status in the Front of Amery Ice Shelf as that the current flows in pours in the east and flows out in at west. There are anti-clockwise and clockwise vortexes in upper layer and mid-layer of sea area in the Prydz Bay, while west wings of anti-clockwise vortexes are the position of inflow from Prydz Bay to Ice Shelf, and the origin of the inflow is westward coastal current originated from the east of Prydz Bay.

Acknowledgements Acknowledgement This project was funded by the National Science Funded Key Project (Grant No. 40231013).

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