Antarctic Research, Vol. 5, No. 1, 62～74, June 1994

# A condition for the formation of Antarctic Bottom Water in Prydz Bay, Antarctica

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Received January 26, 1993

**Abstract** Through pseudoinverse inference of the circulation in Prydz Bay and its adjacent open ocean during January to March 1981, and comparing the results with that of 1991, we find that when the polar easterly hence the east wind drift is strong and extends its influence north of the slope, it is difficult for the Circumpolar Deep Water (CDW) to upwell onto the shelf, and consequently the Antarctic Bottom Water (AABW) cannot form in the bay by way of mixing scheme of Foster and Carmack (1976). However, when the East Wind Drift weakens and confines itself over the shelf, the westerly current will press on the slope and revolve anticyclonically so long as it is fairly strong. Such an anticyclonical pattern manifests itself mainly in the lower layer, and as a result, it will make the CDW upwell onto the shelf, providing an essential prerequisite for the formation of the AABW. We have analyzed this phenomenon from a dynamical view, and pointed out that the law of heat conduction accounts for its formation, in which the planetary and topographical beta effects play major roles.

**Key words** AABW, pseudoinverse inference, beta effect, upwelling, heat conduction

## 1 Introduction

Antarctic Bottom Water (AABW) is the water that sinks around Antarctic continent shelf and enters the bottom layer of the open areas. It occupies a large proportion of the deeper part of the world ocean, not only affecting the adjustment of circulation processes, the ventilation of the world ocean masses and the global climate variations, but also exerting great influences upon the sea floor — in the form of well-developed small- or large-scale current ripples and erosional/depsitional features, manganese-nodule formations, and unconformities and reworking of sediments observed in cores (Kolla *et al.*, 1976).

It is well known that the AABW originates mainly in two sources: One in Weddell Sea, another in Ross Sea. The other Antarctic regions, such as Adelie Coast, have some contributions too (Gordon and Tchernia, 1972). These years, the Enderby Land-Prydz

Bay Coast in the Southern Indian Ocean (Fig. 1) has been identified as another minor source of dense bottom water (Jacobs and Georgi, 1977). Minor as it might be, it is still worth notice, and for many years Australia and China have carried out a lot of hydrographic observations in this region, and the Chinese Antarctic Zhongshan Station, is located rightly at the inner coast of Prydz Bay (69° 22′24″S, 76°22′40″E). Thus far, however, no convincing evidences of AABW have been found. For this reason, this paper aims at discussion of the prerequisite for the formation of AABW on basis of these observations, and consequently provides theory basis for the arrangement of hydrographic observations of CHINARE cruises in the future.

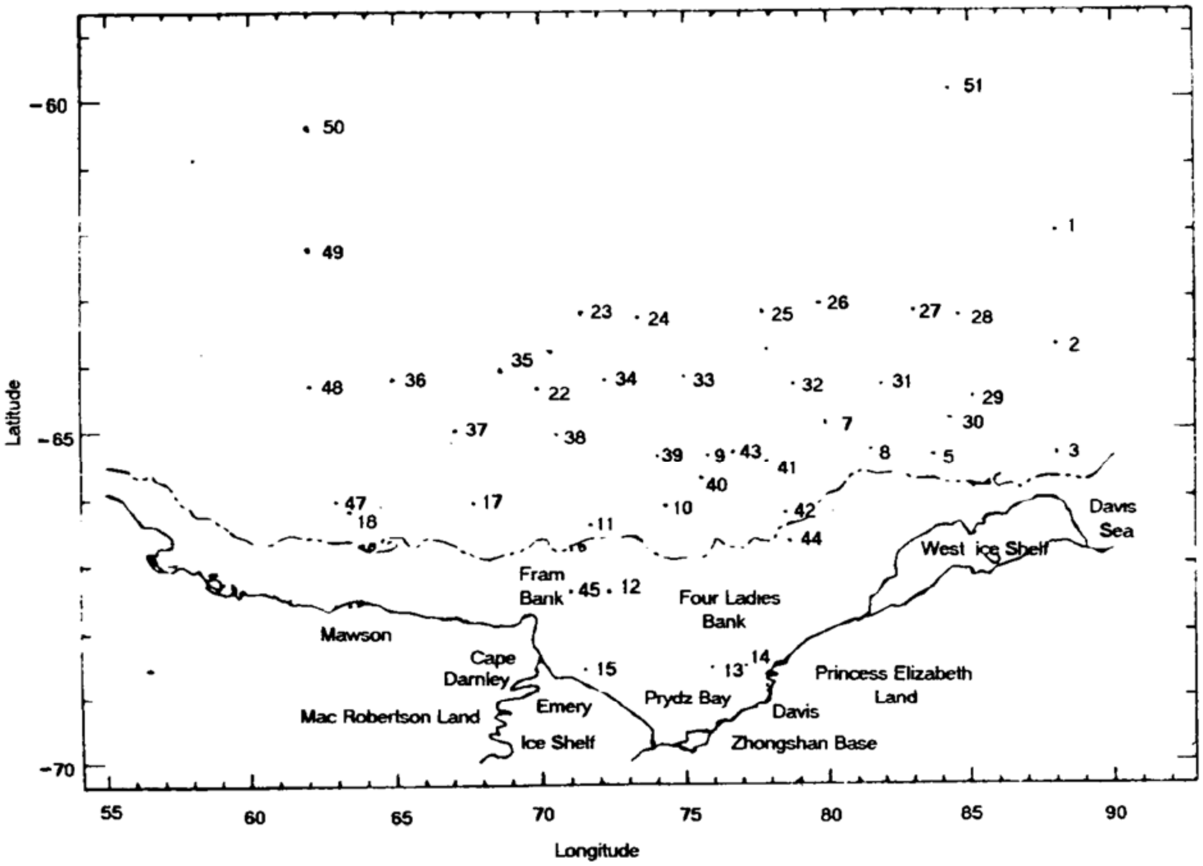


Fig. 1. Location of CTD stations. The dotted line marks the 1000m contour (from Dong *et al.*, 1982).

The formation of AABW is closely connected with the circulation (Gill, 1973). In Prydz Bay and its adjacent area, the flow pattern is not clear because of the scarce observations. Grigor'yev (1967) calculated the geostrophic flow relative to a level of no motion, and found that the circulation in the bay is characterized by a cyclonic gyre. The chart of surface dynamic height relative to 300 dbar of Smith *et al.* (1984) confirmed this pattern, and showed that there exist two other cyclonic gyres centering at the Antarctic Divergence. However, the geostrophic flow relative to some presumed no-motion level cannot tell much because of the strong barotropicity (Gordon, 1983). To overcome this, Liang *et al.* (1993) used the inverse model of Tziperman and Hecht (1988) to infer the circulation in the study area from the hydrographic data acquired by the cruise of the Seventh Chinese Antarctic Research Expedition (CHINARE-7), January to March 1991, and obtained the corresponding barotropic flow and vertical components by means of pseudoinverse searching. Bypassing the details, they got an eastward flow with a slightly anticyclonic meandering pattern. Such an anticyclonic pattern makes the Circumpolar Deep Water (CDW) press on the slope and tend to upwell onto the shelf (See Figs. 4, 5, 6 and 14 ).

The inverse model Liang *et al.* (1993) adopted has its solid mathematical foundation, but the data points they exploited are few and scattered, and in addition, they used only the data of that year, short of interannual comparison. For this reason, here we'll employ the data (Dong *et al.*, 1982) obtained during First International BIOMASS Experiment (FIBEX) Voyage MV *Nella Dan* of Australia, January—March 1981, to re-infer the circulation in this study area, and compare the results with those of Liang *et al.* (1993) to try to find some relationships between the flow pattern and the AABW production. The paper is arranged as follows: The second section is about the model description and pseudoinverse selection, and the third the result analysis. The necessary environment and condition for the AABW's formation are discussed in detail in Section 4. In the last, a brief summary is presented.

## 2 Model description and pseudoinverse selection

The model employed in this paper is an inverse problem involving temperature and salinity, which was presented by Tziperman and Hecht (1988). For its application in Prydz Bay region, Liang *et al.* (1993) have given a detail description, so here only a brief introduction is given. Neglecting the horizontal diffusion term, the steady advection-diffusion equations of temperature and salinity are:

$$uT_x + vT_y + wT_z = (k_v(z)T_z)_z \tag{1}$$

$$uS_x + vS_y + wS_z = (k_v(z)S_z)_z \tag{2}$$

where the symbol denotations are well-known. Decomposing the velocity (u, v, w) into a baroclinic component and a component at the reference level, we get from Eq. (1) and (2) an algebra equation set for the reference velocities:

$$\mathbf{A}\,\mathbf{X} = \mathbf{B} \tag{3}$$

If 6 levels are selected at every station, Eq. (3) has 410 equations, with 124 unknowns. Eq. s (3), together with six inequalities:

$$\mathbf{K}_v(z) > 0 \tag{4}$$

constitute a linear inverse problem. It should be noted that this problem is rank-deficient and is always undetermined though in (3) the number of equations exceeds greatly that of unknowns. By the techniques presented in Liang *et al.* (1993), we choose the pseudorank 103, and consequently obtain the pseudoinverse vector. As a matter of fact, in this case, the null space isn't small, and we can select the inverse vector in the solution space by minimizing the euclidean norm of the residual vector, with little compromise to the solution norm minimization.

Following the procedure of Liang *et al.* (1993), we find that here the vertical velocity can also be partly resolved (more about it later), and the mixing coefficient is:

$$K_v(z) = \sum_{n=1}^{10} C_{v,n} T_{n-1}(z/1800) \tag{5}$$

where $T_n$(n=1,2,3,...) are Chebyshev polynomials, and

$$\mathbf{C}_v = (1.35E-6,\ -4.90E-8,\ 6.39E-7,\ 1.93E-8,\ -3.63E-7,\ -1.36E-8,\ 1.29E-7,\ 1.04E-8,\ -6.64E-8,\ -8.38E-9)^T$$

which is the same order of that presented by Liang *et al.* (1993).

## 3 Result analysis

### *3.1 Horizontal circulation.*

#### *3.1.1 Horizontal distribution.*

Figures 2, 3 and 4 present the horizontal velocity distributions at surface, 50m and 300m levels, respectively. Compared with that during the voyage of CHINARE-7 (Liang *et al.*, 1993), the flow outside the bay is stronger, and the maximum velocity reaches to 10 cm/s ( Only 6cm/s in the summer of 1991). On the whole, however, it is still very weak. During this cruise the stations were arranged and occupied in a relatively close form, this results maybe show more details (such as the eddy features) than that of Liang et al. (1993). So we still think our results agreeable with them in magnitude.

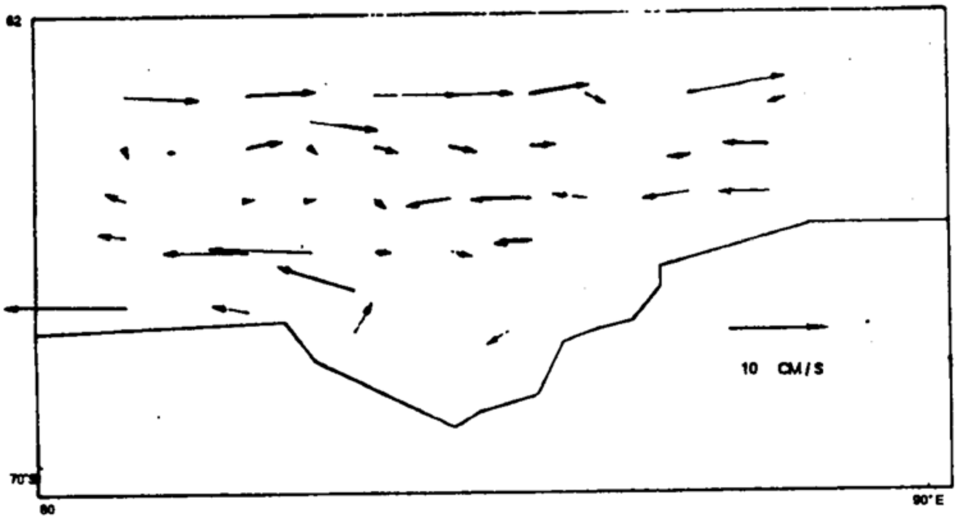


Fig. 2. Absolute velocity distribution at the surface level.

What differs greatly from Liang *et al.* (1993) lies on that during this cruise, the East Wind Drift is significant. This might be related to the climate conditions. During the voyage of CHINARE-7, for most of time the wind directed eastward. This westward current, which flows mostly along the slope, together with the West Wind Drift north of it, gives rise to a complex horizontal velocity structure, which is characterized by two cyclonic gyres centering at the Antarctic Divergence. As for the formation of the two

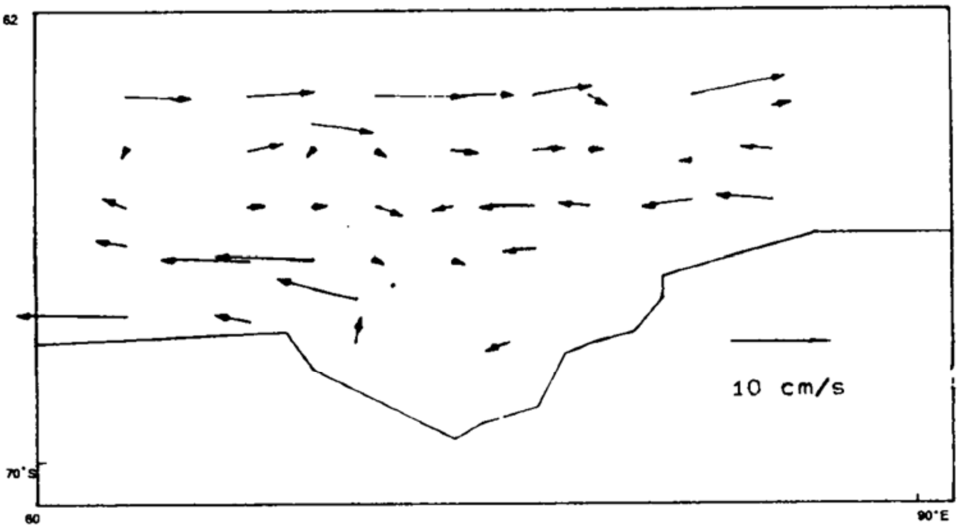


Fig. 3. Absolute velocity distribution at 50m level.

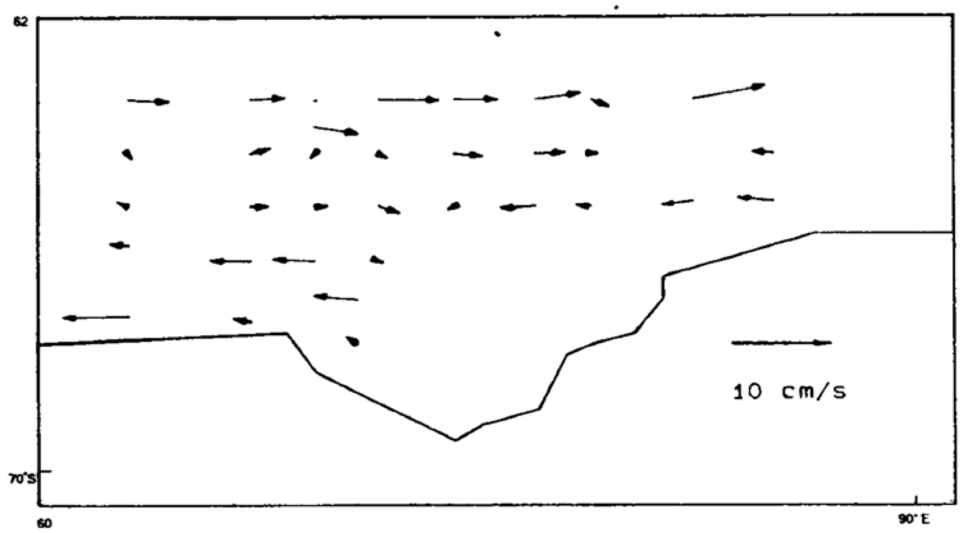


Fig. 4. Absolute velocity distribution at 300m level.

gyres, the reader is suggested to refer to Liang and Su(1994). Besides, no indication of the anticyclonical 'pressing' appears in Figs. 2～4.

In their dynamic height chart, Smith *et al.* (1984) also showed there're two cyclonic gyres centering at the Antarctic Divergence, but they gave no vertical structures. In fact, because of the strong barotropicity in Antarctic Ocean ( Figs. 6 and 7), the vertical structures given by dynamic calculation will be misleading. From Figs. 2, 3 and 4, one can see that the two gyres have a close vertical correlation, confirming another time the predecessor's view (Gordon, 1983). It is interesting to find, after comparing Fig. 2 with Fig. 3, that the gyres are more significant in the lower layer. Such an important phenomenon makes the two cyclonic gyres unable to induce upwelling (Fig. 8). We'll present more discussions in the following sections.

Over the continental shelf, the circulation in Prydz Bay is also characterized by a cyclonic gyre, agreeing with the former's results (Grigoy'ev, 1967; Smith *et al.*, 1984). Comparing Fig. 2 with Fig. 3 enable one to find that it is surface intensified.

Along the Mawson Coast, there seems to exist a relatively strong coastal current flowing westward (as strong as 10 cm/s). The origin of this current is still unclear because of the scarce observations. Fig. 2 shows that it seems to come from the Prydz Bay Coast. It is a pity that there are no stations occupied in the inner bay and we cannot verify this view, but Grigor'yev (1967) and Liang *et al.* (1993) found there did exist a relatively strong cold current along the Amery Ice Shelf during their respective voyages.

Now, where does this cold current come from? At present there exist three different points of view: One from the shelf between the Shackleton and West Ice Shelves, another from Ross Sea through some tunnels under the ice, and thirdly from the surface water off the shelf. It is difficult to verify the first saying, let along the second. The third is inferred by Smith *et al.* (1984) on basis of their dynamical height chart. Our Figs. 2～4 show that the East Wind Drift is blocked near 73°E, so there are only two ways for it to go: either to converge or to be pushed aside. Here in the lower layer (Fig. 3) also takes place convergence phenomenon, and the lower-layer convergence will give rise to the upper-layer divergence. Thus whether the deeper water downwells or upwells depends upon the relative intensity of convergence in the upper and lower layers. The ensuing sector (Fig. 8) shows that here a weak upwelling takes place. Hence the surface cold water is very easy to be pushed into the bay, and what Smith *et al.* (1984) said has its dynamical basis.

#### 3. 1. 2 *Section distribution of zonal velocity.*

*3. 1. 2. 1 Section at 67°30′E.* On this section, as shown in Fig. 5, latitude 65°40′S marks the interface between the East and West Wind Drifts. North of it is the westerly, which strengthens and concentrates in the upper layer toward the north. South of the interface, near 66°30′S exists a current core, where the East Wind Drift attains its maximum value, as large as 7. 8cm/s. Comparing with Fig. 1, one will find here the slope lies rightly beneath it. This suggests that the easterly current has been mostly trapped at the shelf break.

*3. 1. 2. 2 Section at 72°20′E.* Fig. 6 is the velocity distribution at the section immediately east of Fram Bank. It indicates that south of 66°30′S the flow directs westward, the strongest part of which appears at the surface near 67°15′S, with a value of as large as 5. 7 cm/s. From Fig. 1 one knows here is the shallow area, thus the surface water outside the bay can really be brought over the shelf. Between 66°30′S and 64°30′S, the flow is very weak, and north of it 64°30′S it becomes stronger and stronger with the decreasing of latitude. In the study region, the maximum surface velocity reaches to 7. 3 cm/s.

*3. 1. 2. 3 Section at 83°35′E.* A significant feature of the zonal velocity distribution on Section 83°35′E (Fig. 7) is its strong barotropicity. The isolines seem to go straight downward from the surface to the deepest data-available level, without any indication of closing. On this phenomenon, Liang *et al.* (1993) have emphasized several times in their paper. Here another evidence is presented for them. On this section, the interface between the East and West Wind Drifts appears at about 64°30′S.

### 3. 2 *Vertical circulation.*

Usually, the inverse model of Tziperman and Hecht (1988) has a bad resolution of

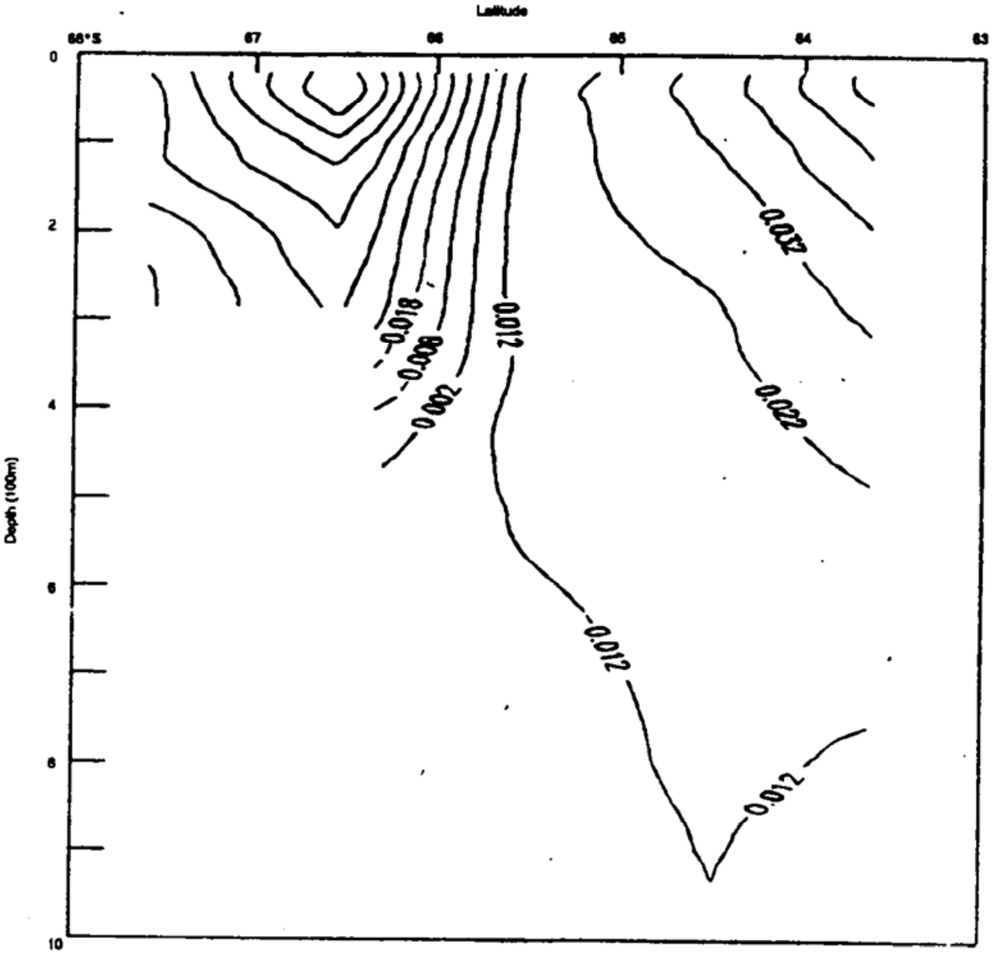


Fig. 5. Meridional profile of zonal velocity (m/s) at 67°30′E.

the vertical velocity. However, Liang *et al.* (1993) find, after verifying in many ways, it can be at least partly resolved in their study region. Here we have repeated their work, and come to the same conclusion.

Fig. 8 is the computed upwelling area distribution. On the whole it is consistent with that of Liang *et al.* (1993). In order to verify its correctness, we'll review the preceding horizontal circulation pattern in addition to analyzing it.

As described above, during this voyage, the circulation in Prydz Bay and its adjacent open ocean is characterized by three cyclonic gyres, of which the one over the shelf manifests itself mainly in the upper layer, suggesting some kind of upwelling in this area. The other two centers at the Antarctic Divergence, lie on the western and eastern sides, respectively. Usually it seems that upwelling will take place at the two gyral centers, but Fig. 8 exhibits no such indications. Maybe the vertical components cannot be resolved in these areas? No. Definitely not. As mentioned above, the two gyres are both more significant in the lower layers, thus at these cyclonic centers downwelling phenomena will take place according to Margules' law. As for this, Liang and Su (1994) have presented a very good example in East China Sea. Therefore, like the 'heton' of Hogg and Stommel (1985), cyclonic gyres doesn't always induce upwelling, and the pattern shown in Fig. 8 has its dynamical foundations.

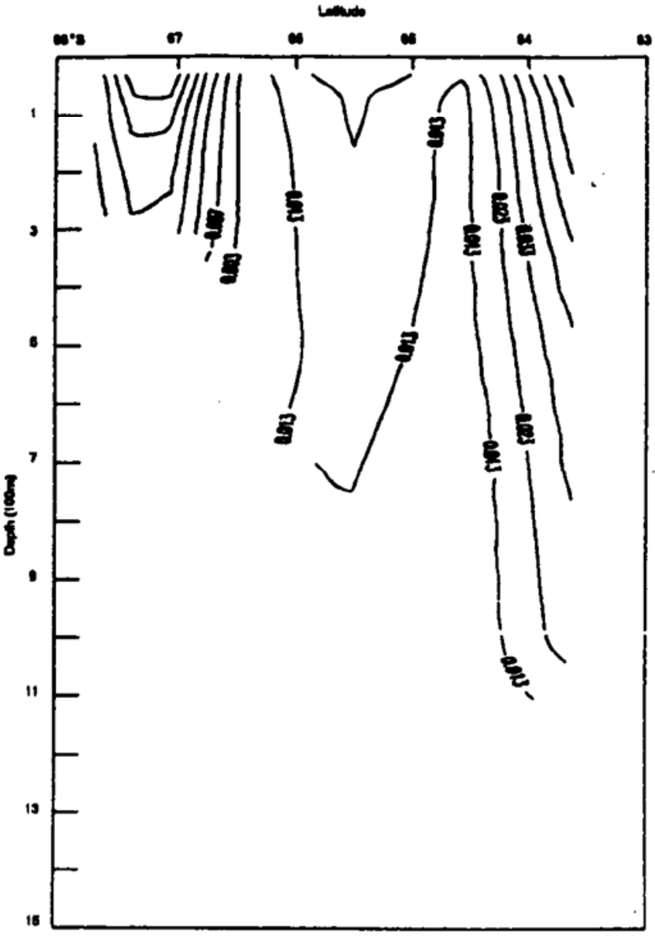


Fig. 6. Meridional profile of zonal velocity (m/s) at 72°20′E.

The upwelling area at the Divergence near 75°E is consistent with the fact that here the lower-layer convergence exceeds the upper-layer convergence. From the figure one can also find the indication of the surface water off the shelf intrudes into the bay.

In a word, the upwelling area shown in Fig. 8 is similar to that of Liang *et al.* (1993), and it agrees with not only the ice conditions at that time, but the mass distribution of krill (Marr, 1962). From a global view, the Antarctic Divergence is a zonal band where upwelling takes place, but in local regions, as our results, things are not always the same.

## 4 Discussion

Foster and Carmack (1976) proposed that the formation of AABW in the Atlantic sector takes place in three stages. In the first stage, CDW, characterized in the Weddell Sea by relatively high values of temperature, silica, and salinity and by low oxygen, is modified by the overlying cold, low-silica, low-salinity, and high-oxygen Winter Water (WW) in the southeastern Weddell Sea. In the second stage, the modified CDW is carried westward where it mixes with Western Shelf Water (WSW, near freezing temperature, high salinity, high oxygen, and low silica) to form Weddell Sea Bottom

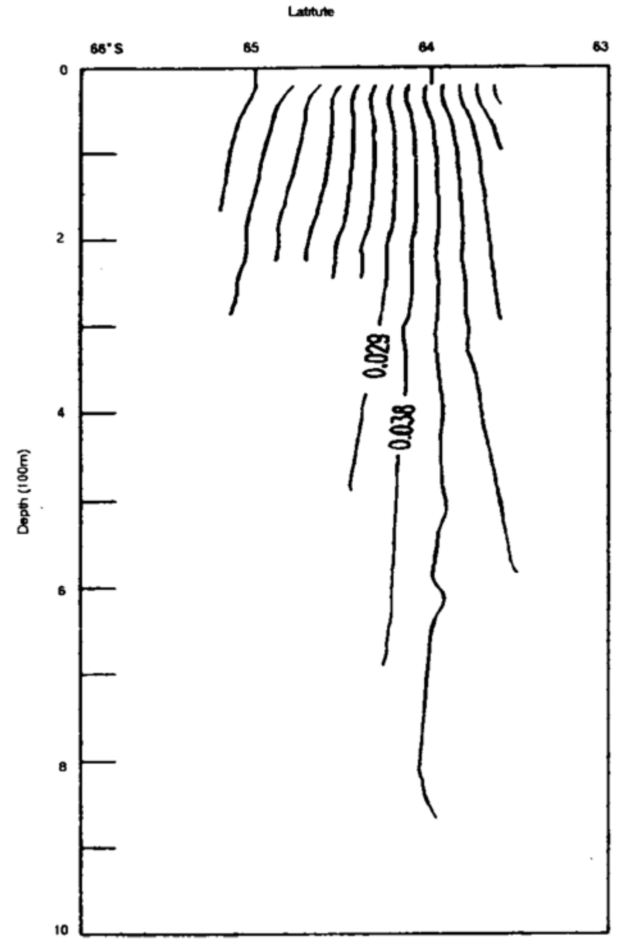


Fig. 7. Meridional profile of zonal velocity (m/s) at 83°35′E.

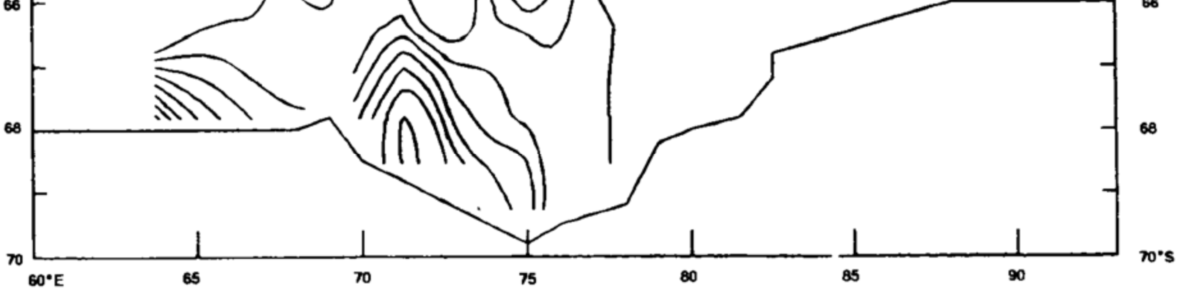


Fig. 8. The computed upwelling area.

Water (WSBW). WSBW then mixes with CDW as it follows eastward from the northwest corner of the Weddell Sea to form AABW. Thus AABW is roughly made up of 5/8 CDW + 1/4 WSW + 1/8 WW. This suggests that whether the CDW can upwell onto the shelf or not has a crucial effect on the AABW's formation.

In Fig. 8, the upwelling in Prydz Bay is caused by the shelf circulation system, involving little about the interaction between the shelf water and the open ocean water. The center at Antarctic Divergence near 75°E is brought about by the convergence of the lower-layer water, so here some CDW might be brought upward. The Fig. 4 of Smith *et al.* (1984) also showed here the layer of the Antarctic Summer Surface Water (AASSW) is relatively thin. However, such kind of upwelling is confined only outside the bay, and it has little chance to facilitate the interchange between the deep ocean water and shelf waters. For this reason, during this FIBEX voyage, no indication of AABW's formation in Prydz Bay was found (Smith *et al.*, 1984).

However, a quite different pattern exhibits if the CHINARE-7 data are exploited (Liang *et al.*, 1993). During this voyage, even in the Polar Easterly Zone, the wind directed eastward for most of time, hence the flow in the study region, especially outside the bay, generally directed eastward, and the East Wind Drift was very weak and confined in the shelf region. After bypassing Fram Bank, the westerly current flows along the slope in an anticyclonical pattern, exhibiting a V-shape form, and tends to press onto the shelf at that position. Liang *et al.* (1993) noticed that the CDW upwelled at this anticyclonic center. They also pointed out that planetary and topographical beta effects will make the anti-cyclonic pattern intensify towards west and intrude onto the shallow regions, hence it was very possible for the CDW to upwell onto the shelf immediately east of Fram Bank. As a matter of fact, if we judge the AABW by the T-S indices presented by Gordon (1971), $T<0℃$, $S=34.60$ to $34.72$, the figures 9a and b of their paper have shown some indications of AABW, whose $T$-$S$ properties are $T=-1.78℃$ to $-0.98℃$, $S=34.60$ to $34.68$.

Comparing the above two results, it seems reasonable to think that if the East Wind Drift is strong and extends its influence north of the slope, then it is difficult for the CDW to upwell onto the shelf, and hence the AABW cannot form. On the contrary, if the easterly current is confined south of the shelf break, the CDW may find its way on the western shelf so long as the current is fairly strong. This provides an important prerequisite for the AABW's formation.

Now the question arises: Why will such phenomenon take place? What's its dynamical basis?

For the anticyclonical pattern during the voyage of CHINARE-7, the theory of Liang and Su (1994) can give a satisfactory explanation. Its dynamical mechanisms lie on many aspects, of which the diffusive effect of bottom friction seems dominant. Since the benthic friction exceeds greatly the interfacial friction, such a pattern manifests itself mainly in the lower layer. It should be noted that for a 'heton' of Hogg and Stommel (1985) the lower-layer anti-cyclonical center will induce upwelling. This is why such a pattern can lead the CDW to upwell onto shallow areas. But how the open ocean current can intrude onto the shelf still needs explaining. Since Liang and Su (1994) pointed out this is a high-order process, and the lower-layer pattern resembles very much to its barotropic counterpart, we'll set out our analyses by reduce the problem to a steady linear barotropic vorticity equation.

The governing equations are:

$$f\,\hat{k}\times V = -g\,\nabla\zeta - \frac{\tau_B}{\rho} \tag{6}$$

$$\nabla\cdot(HV) = 0 \tag{7}$$

where $\nabla$ is horizontal gradient operator, $\zeta$ is the free surface elevation, and the benthic friction is thought to be proportion to velocity:

$$\tau_B = \rho C_B V \tag{8}$$

From (7), a stream function $\psi$ can be defined such that:

$$V = \hat{k}\times\frac{\nabla\psi}{H} \tag{9}$$

If the bathymetry is a function of latitude only, i. e., $H = H(y)$, then substituting (9) into (6) and taking curl on both side to eliminate the pressure gradient, gives:

$$-\left(\beta - \frac{f}{H}\frac{\partial H}{\partial y}\right)\frac{\partial\psi}{\partial x} = \frac{C_B}{H}\nabla^2\psi \tag{10}$$

Because of the uncertainty of turbulent descriptions, one term, $-\frac{2C_B}{H}\frac{\partial H}{\partial y}\frac{\partial\psi}{\partial y}$ has been ignored on the left hand side of Eq. (10).

This is a typical singular elliptical equation. By the results presented as follows, the coefficient of $\frac{\partial\psi}{\partial x}$ on the left hand side of Eq. (10) is negative, so the boundary layer lies on the west. Far from west, the $x$ direction scale is by far greater than the $y$ direction scale, thus (10) can be approximated as:

$$-\left(\beta - \frac{f}{H}\frac{\partial\psi}{\partial y}\right)\frac{\partial\psi}{\partial x} = \frac{C_B}{H}\frac{\partial^2\psi}{\partial y^2} \tag{11}$$

In the southern Hemisphere, the Coriolis parameter is negative ($f<0$), and for our study region, $\partial H/\partial y > 0$, so the topographic beta effect

$$\beta_T = -\frac{f}{H}\frac{\partial H}{\partial y} > 0 \tag{12}$$

and hence during the high-order dynamic processes, the continental slope off the bay plays the same role as planetary beta effect.

Rather more insight into the mechanisms is gained by noting that Eq. (11) has the form of the heat conduction equation in one dimension, with negative $x$ playing the role of time, and the stream function the temperature. The anology of thermometric conductivity is $\kappa = C_B/H\,[H\,(\beta+\beta_T)]$. The law of heat conduction is well known. If the flow directs eastward, then at the 'beginning time', or at the eastern boundary, the 'temperature' (stream function) is low to the north and high to the south, and at the western tip of the West Ice Shelf, the first-order derivative of $\psi$ is discontinuous (weak discontinuity). As time goes on (move westward along $x$-axis), the heat is diffused from the high-temperature area (shelf region) to the low-temperature area (open ocean), and hence the temperature distribution at the weak discontinuity become gradually uniform, and some water is brought upon the shelf. But when approaching Fram Bank, the boundary conditions there force the information from the east to reset, and the problem becomes singular, so there must be a boundary layer to match it. This boundary layer makes the flow pattern intensify towards the bank, providing dynamic possibilities for the anticyclonic flow to intrude onto the shelf. As mentioned above, what this barotropic flow reflects is the lower-layer pattern, so it will induce the CDW to upwell.

For the East Wind Drift, things are similar, but now the values of stream function are large to the north and small to the south at the eastern open boundary, and as a result, the easterly current will intrude onto the shelf and intensify towards Fram Bank, showing a cyclonic pattern. As analyzed above, it manifests itself mainly in the lower layer, and hence will lead to a downwelling phenomenon. Therefore, in this case, it is difficult for the CDW to upwell and hence no AABW will form. Now, with the horizontal circulation shown in Figs. 2, 3 and 4, one might have known why there's not any indication of AABW's formation during the FIBEX voyage, as reported by Smith *et al.* (1984).

## 5 Summary and conclusion

The pseudoinverse model of Tziperman and Hecht (1988) is applied to infer the circulation of Prydz Bay and its adjacent open ocean during the FIBEX voyage of Australia. The flow is still very weak, and barotropic component dominates, similar to that of CHINARE-7 cruise. What differs from Liang *et al.* (1993) is its relatively strong East Wind Drift, which extends to the north of the slope. At the Antarctic Divergence, there exist two cyclonic gyres.

The upwelling centers computed in this paper agree well with Liang *et al.* (1993), but except the one in the bay, the others seem to be brought about by quite different mechanisms.

Neither of the two cyclonic centers outside the bay during this voyage would bring about upwelling, while the anticyclonic pattern Liang *et al.* (1993) obtained can induce the upward movement of the CDW. With the observations of the two cruises, one knows that AABW didn't appear in 1981 while exhibited some indications in 1991. We think these phenomena have something to do with the upwelling mechanisms outside the bay, which seem closely related to the circulation pattern. During January to March, 1991, the East Wind Drift is very weak and the westerly current dominates outside the bay. In this situation, the stream function is large to the south and small to the north at the eastern open boundary, and the mechanism of heat conduction will lead the flow to diffuse onto the shelf in an anticyclonical form, while the planetary and topographical beta effects will make it intensify towards Fram Bank. Such an anticyclonic form is significant in the lower layer, hence it is in some way possible for the CDW to be induced onto the shelf, providing a crucial condition for the AABW's formation. In 1981, things are quite different, and the East Wind Drift dominated over the slope and the neighbour deep regions. At this time the pattern diffused upon the shelf in the lower layer is a cyclonic westward current, which cannot induce upwelling of the CDW, thus no wonder Smith *et al.* (1984) didn't find any indications of AABW formation during that voyage.

On the basis of the preceeding cruise comparison and mechanism analysis, it seems reasonable to come to a conclusion as follows: If the Polar Easterly hence the East Wind Drift is strong and its influences reach north of the slope, then the CDW cannot upwells onto the shelf, and the AABW cannot form; On the contrary, if the influences of the East Wind Drift is confined only to some of the shelf regions, then the CDW can be expected to upwell onto the shallow waters in the west of the bay so long as the eastward current is fairly strong. This is a prerequisite for the AABW to form and spread into the world ocean.

## References

Dong, Z., Kerry, K. R., Shearer, J. D. and Wright, S. W. (1982): First International BIOMASS Experiment (FIBEX) Voyage M. V. Nella Dan, January-March 1981. Data Report-Oceanography, Australian Antarctic Division publication, 154.

Foster, T. D. and Carmack, E. C. (1976): Frontal zone mixing and Antarctic bottom water formation in the southern Weddell Sea. *Deep-Sea Res.*, 23, 301—317.

Gill, A. E. (1973): Circulation and bottom water production in the Weddell Sea. *Deep-Sea Res.*, 20, 111—140.

Gordon, A. L. (1971): Oceanography of Antarctic water. In: Antarctic Oceanography I: Antarctic Research Series. Ed. by Reid, J. L., American Geophysical Union, 15, 169—203.

Gordon, A. L. (1983): Polar oceanography. *Rev. Geophys. Space Phys.*, 21 (5), 1124—1131.

Gordon, A. L. and Tchernia, P. (1972): Waters of the continental margin off Adelie Coast, Antarctica. In: Antarctic Oceanology II, The Australian- New Zealand Sector, Antarctic Research Series, 19, Ed. by Hayes, D. E., American Geophysical Union, Washington, D. C., 59—69.

Grigor'yev, Y. A. (1967): Circulation of the surface waters in Prydz Bay. *Soviet Antarctic Expedition*, 7, 74—76.

Hogg, N. G. and Stommel, H. M. (1985): The heton. *Proc. R. Soc. Lond*, A397, 1—20.

Jacobs, S. S. and Georgi, D. T. (1977): Observations on the southwest Indian/ Antarctic Ocean. In: A voyage of discovery, Ed. by Angel, M., Pergamon Press, Oxford, 43—84.

Kolla, V., Sullivan, L., Streeter, S. S. and Langseth, M. G. (1976): Spreading of Antarctic Bottom Water and its effect on the floor of the Indian Ocean inferred from botom-water potential temperature, turbidity, and sea-floor photography. *Marine Geology*, 21, 171—189.

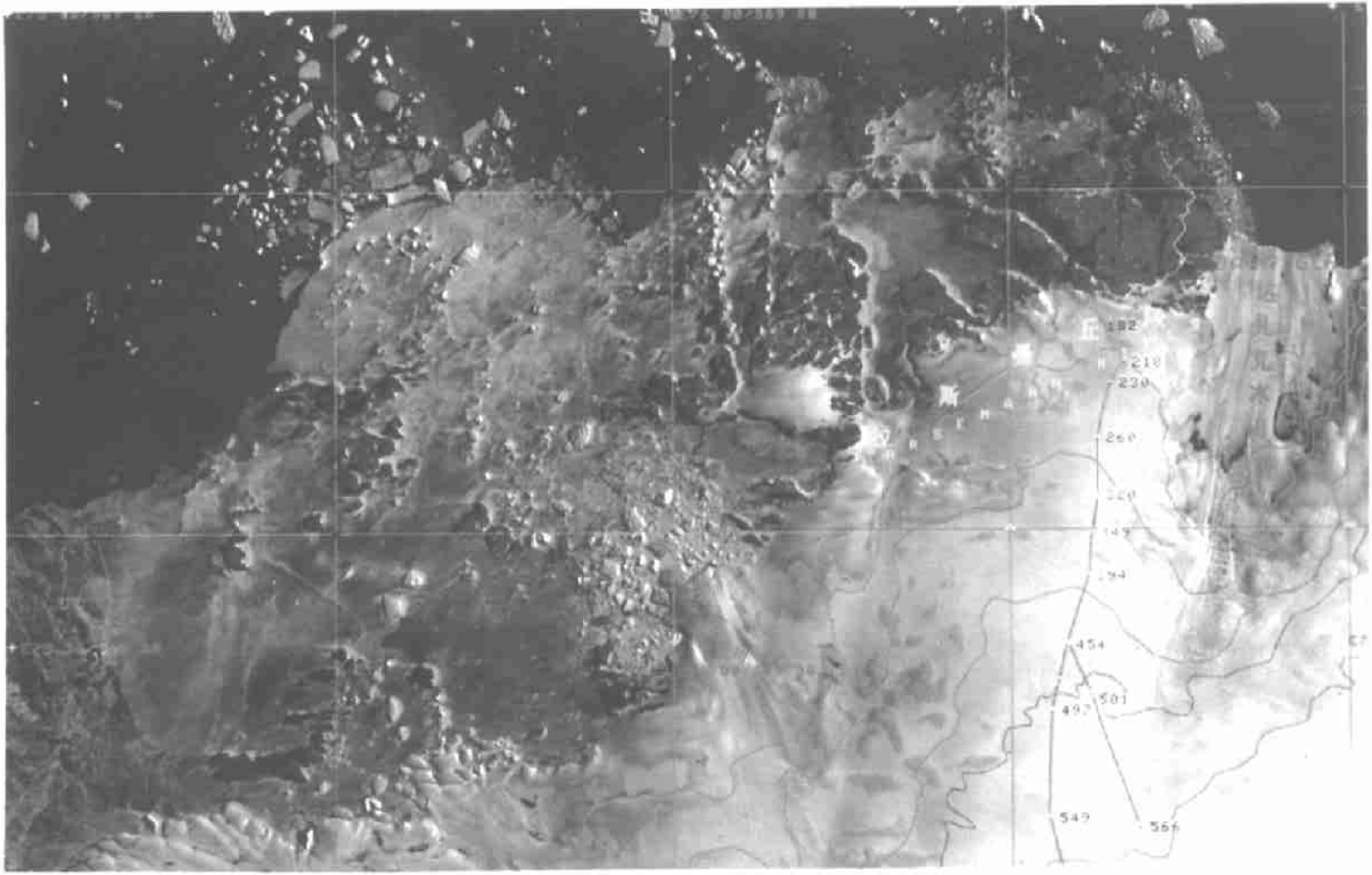
Liang Xiangsan and Su Jilan (1994): A two-layer model for the circulation in the East China Sea. *Acta Oceanol Sinica*, 13(3), 45—72.

Liang, Xiangsan, Su Jilan and Dong Zhaoqian (1993): Pseudoinverse determination of the circulation in Prydz Bay and its adjacent open ocean. *Antarctic Research*, 4(2), 42—61.

Marr, J. W. S. (1962): The natural history and geography of the Antarctic Krill (Euphausia Superba Dana). Discovery Rep., 32, 33—464.

Smith, N. R., Dong Zhaoqian, Kerry, K. R. and Wright, S. (1984): Water masses and circulation in the region of Prydz Bay, Antarctic. *Deep-Sea Res.*, 31(9), 1121—1147.

Tziperman, E., Hecht, A. (1988): Circulation in the Eastern Levantine Basin determined by inverse methods. *J. Phys. Oceanogr.*, 18, 506—518.



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