Chinese Journal of Polar Science, Vol. 18, No. 2, 100-109, December 2007

Features and spatial distribution of circumpolar deep water in the southern Indian Ocean and the effects of Antarctic circumpolar current

Pu Shuzhen(蒲书箴)[1], Dong Zhaoqian(董兆乾)[2], Yu Weidong(于卫东)[1], Lu Yan(卢 燕)[1] and Xiang Baoqiang(项宝强)[1]

1 First Institute of Oceanography, Qingdao 266061, China

2 Polar Research Institute of China, Shanghai 200136, China

Received July 12, 2007

Abstract The data from the Southern Ocean observations of World Ocean Circulation Experiment (WOCE) are used for analysis and illustration of the features and spatial distributions of Circumpolar Deep Water (CDW) in the southern Indian Ocean. It is learnt from the comparison among the vertical distributions of temperature/salinity/oxygen along the 30°E, 90°E and 145°E sections respectively that some different features of CDW and the fronts can be found at those longitudes, and those differences can be attributed to the zonal transoceanic flow and the merizonal movement in the Circumpolar Deep Water. In fact, the zonal transoceanic flow is the main dynamic factor for the water exchange between the Pacific Ocean and the Indian Ocean or between the Atlantic Ocean and the Indian Ocean, and for the effects on the spatial distributions of the physical properties in CDW.

Key words Southern Indian Ocean, Circumpolar Deep Water, Water mass properties, spatial distributions

1 Introduction

As early as in 1937, Deacon used the data obtained in the Southern Ocean by Royal Research Ship "Discovery" to evidence the existence of the Antarctic Deep Warm Water (ADWW) underlying the cold surface layer water[1]. Later on, physical-oceanographers found that the water-mass with the same feature as ADWW are extensively distributed in the deep layer of the Southern Ocean (SO) around Antarctica and the Antarctic circumpolar current (ACC) mainly comprises the water-mass. Therefore it is renamed Circumpolar Deep Water (CDW). CDW is the most extensive and voluminous water-mass in SO. Carmark (1975)[2] estimated and showed that CDW has a volume as large as 55% of the total water in SO[3]. Gorden (1975)[4] used the hydrographic data of the 170°E section and divided CDW into two cores according to the depth where the maximum water temperature appeared and the depth where the maximum salinity appeared in CDW. One is the upper core with water temperature (T) about 0.9~2.5 °C and salinity (S) about 34.60~34.75 at the depths between 250 m and 600 m. The other is the lower core with T about 1.0~1.8 °C and S about 34.70~34.75 at the depths between 500 m and 3 000 m[3]. Smith *et al.* (1984) used the CTD and XBT data obtained along the 8 sections in the sea area (60°~90°E, 60°S and the further south) adjacent to Prydz Bay in austral summer, and analyzed for the first time in more details both the water-mass and the circulation in the southern Indian Ocean south of 60°S. They pointed it out that the upwelling of CDW could reach the surface water at 67°S, and the water transformed from CDW could be found in the shelf of Prydz Bay[4,5]. Su and Dong (1984) used a limited quantity of the historical data to analyze the features of water-mass and fronts in the Southern Indian Ocean in austral summer[6]. Pu *et al.* (2002)[7] showed by means of the hydrographic data obtained along the 3 sections (70°~75°E) in Prydz Bay and its adjacent water that the physical features of CDW are similar to Gorden's results from the Pacific sector of SO[8]. They take the 1.2 °C isotherm as the margin of the high salinity core to derive the results listed in Table 1. It is learnt from Table 1 that both the high temperature core and the high salinity core of CDW extends further southward along the 75°E section than along either the 70°E section or the 73°E section, and that not only the vertical thickness values but also the maxima of either the high temperature core or the high salinity core are greater along 75°E. As for the 70°E section, the southward extension of either the high temperature core or the high salinity core are much limited, the vertical thickness ranges for the cores are much smaller, and their maxima lower. Those results by Pu *et al.*[7] show that the thermohaline features of CDW and its spatial distribution obviously have the zonal variability. Yuan *et al.* (2004)[9] utilized the XBT/XCTD data obtained by RV *Xuelong* during the five summer cruises and discussed the thermohaline structure and its temporal variation of the upper water including the CDW cores in the southeastern Indian Ocean. He *et al.* (2006)[10] used the data from WOCE, satellite-remote sensing, and the Chinese Expedition of the southern Indian Ocean and analyzed the interactions among the upper water-mass and the annual frontal-variation related with the sea surface wind in the southeastern Indian Ocean[8].

In addition to the physical features and the spatial distribution of CDW, its zonal and meridional movements attract much attention of scientists. As shown in Table 1, both the high temperature core and the high salinity core are situated to the north of 65.5°S and their vertical thickness ranges are limited within the depth between 100 m and 2000 m in any of the 3 sections. This spatial distribution of CDW is consistent with the space where ACC flows. Clarke (1982)[11] utilized a nonlinear model to discuss the ACC response to the wind stress with a wide-band of frequency-spectrum, and pointed it out that ACC have a barotropic rather than baroclinic response to the wind stress with its period less than years. Therefore ACC is characterized with its features similar to a depth-independent flow[10]. Base on the TOPEX/POSEIDON altimetry data (from October 1992 to March 1993, totally 18 months), Park *et al.* (1995)[12] calculated the surface layer flow of SO and compared it with the results derived from the gravity potential distribution and the simulation results by means of Fine Resolution Antarctic Model (FRAM). The similarity among the three is further confirmed in the papers[11,12]. Sloyan (2006)[13] utilized the data of the hydrographic measurements and the current-meter mooring array deployed in Perth Basin of the southeastern Indian Ocean to analyze the meridional movements of the Antarctic Bottom Water and the lower Circumpolar Deep Water (LCDW, i.e. the water featured with the high salinity core). He pointed it out that the northward transport of LCDW is 2.4~3.3 Sv[13].

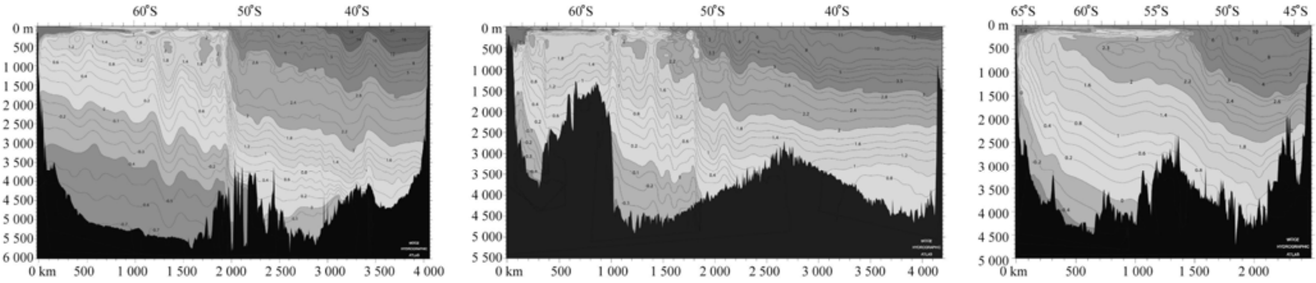
Table 1 The statistics of the spatial distribution of CDW

	high temperature core (bounded by the 1.2°c isotherm)			high salinity core (bounded by the 34.70°c isohaline)		
	70°E	73°E	75°E	70°E	73°E	75°E
Horizontal extension	62.4°s	65.1°s	65.2°s	64.6°s	65.3°s	65.4°s
Vertical thickness/m	280-650	100-1320	100-1320	340-1380	350-1980	320-2000
Maximum	1.38 ℃	1.92 ℃	1.96 ℃	34.738	34.746	34.746

CDW is not only closely related to the eastward (zonal) flow of ACC but also to its meridional movement tendency. Deacon (1937)[2] showed the subsurface meridional circulation in a scheme, which comprises the northward flow in the intermediate layer and the southward flow in the deep water[2]. Later, Döös *et al.* (1994)[14] used FRAM[15] to simulate the meridional circulation in the south hemisphere, and showed the Deacon circulation cell, the sub-polar cell, and the bottom cell in their schematic plot. The upwelling between the subsurface and the 2000 m depth in 55°~65°S can be clearly observed in their plot, and also both the northward movement, as a component of the Deacon cell and the sub-polar cell, and the southward movement in CDW is obvious in their plot. In addition, Pu *et al.* (2002)[7] described the features of the CDW movement by use of the related CTD data[7]. It is obvious in the above description that CDW possesses the features not only for its southward movement but also for its upwelling in the higher latitudes. In order to study the physical features of CDW in the integral area of the Southern Indian Ocean rather than in a limited area, the WOCE data are used as follows to discuss the CDW spatial distribution and the movement characteristics in the whole ocean.

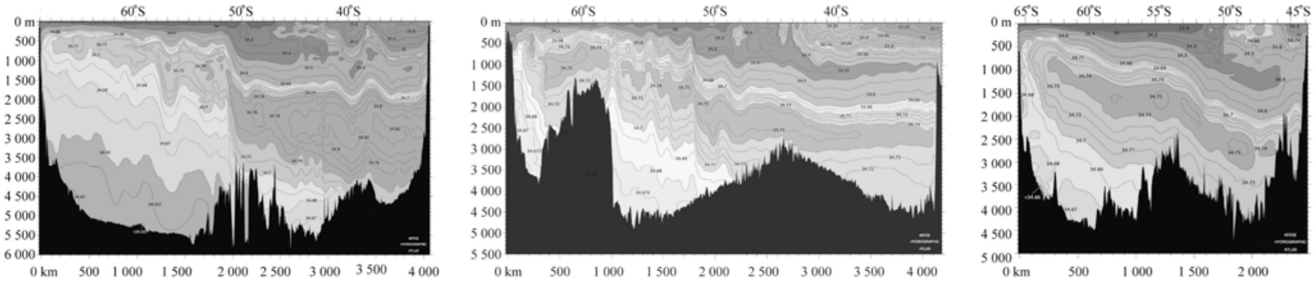
2 Temperature distribution pattern and features in the southern Indian Ocean

In order to expound the spatial distribution and variability of CDW in the Southern Indian Ocean, three meridian sections in a sequence from the west to the east of the ocean are selected to show the difference, which are all associated with three physical factors, i. e. potential temperature (Fig. 1), salinity (Fig. 2) and dissolved oxygen in sea water (Fig. 3). The 3 sections are respectively located between the Cape of Good Hope and Antarctica along the 30°E longitude, between Australia and Antarctica along 90°E right at the middle of the ocean, and between Tasmania and Antarctica along 145°E. It is learnt from Fig. 1 (a) that Polar Front (PF) is located at 59°S and subantarctic Front (SAF) at 51°S in the temperature section along 30°E. They are clearly observed in the water from the sea surface down to the thousands meters, especially SAF. The isotherms identified as the fronts tend to extend almost vertically downward and the temperature gradient becomes the greatest at the fronts. In the upper layer shallower than 300 m, PF is located at 58°S and it forms the boundary between the Antarctic surface water with its temperature lower than 0 ℃ and the subantarctic water with its temperature higher than 0 ℃. SAF is located at 51°S and it is the boundary between the subantarctic water and the temperate water with its temperature higher than 2 ℃. Obviously the subantarctic water, the water colder than 2 ℃ can not be found to the north of SAF. In addition, i. e. the continental water boundary (CWB), a front closest to Antarctica, seems to be further south of 68°S (See the 0 ℃ isotherm) in the water shallower than 1000 m. Besides the upwelling tendency of the temperate water warmer than 2 ℃ is identical around SAF.



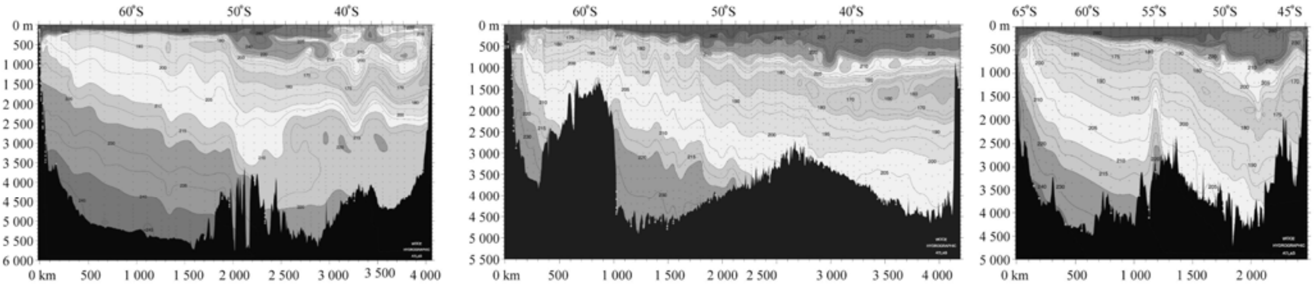
a b c

Fig. 1 Potential temperature along (a) 30°E section, (b) 90°E section, and (c) 145°E section in the southern Indian Ocean



a b c

Fig. 2 Salinity along (a) 30°E section, (b) 90°E section, and (c) 145°E section in the southern Indian Ocean



a b c

Fig. 3 Oxygen along (a) 30°E section, (b) 90°E section, and 145°E section in the southern Indian Ocean

As it is shown in Fig. 1 (b), the 2 fronts, i. e. PF and SAF can be both clearly identified, but PF appears stronger in the 90°E section than in 30°E section because of the frontogenesis effected by the bottom rising relief at about 60°S, while SAF becomes weaker to be compared with the front at the 30°E section. Upon the whole, the upwelling of the water warmer than 2℃ tends to be much weaker in the 90°E section than in the 30°E section. In addition, further difference between the two sections is that CWB, which is situated at 65°S can be taken as the boundary between the water warmer than 0℃ and the water colder than 0℃ becomes more obvious in the 90°E section, especially in the layer lower than the 1500 m depth. As for the upwelling feature at the 30° section E, it seems that CWB is limited within the upper layer shallower than, 1, 000 m and located to the south of 68°S.

As shown in Fig. 1(c), the 0℃ isotherm identified as CWB in the depth interval between 200m and 2,500m at 65°S becomes almost perpendicular to the horizon. Comparing Fig. 1(c) with Figs. 1(a) and 1(b), it can be found that the 0℃ isotherm in Fig. 1(c) sharply slopes along the continental slope, and becomes less steep in the basin area, and reaches the seabed at 56°S. If the 0℃ isotherm is simply taken as the central location of CWB, its sharp inclination toward the north in the 145°E section means the frontogenesis around CWB takes place at 145°E. In contrast to the CWB frontogenesis, either PF or SAF becomes weaker at 145°E than at 30°E or at 90°E. Especially, the isotherms around PF become much less inclined at 58°S.

As the definition is given by Gorden[4], the CDW upper core within the depth interval between 250m and 600m has a temperature range between 0.9℃ and 2.5℃, and its lower core within the vertical interval between 500m and 3000m has a temperature range between 1.0°C and 1.8°C. By use of the definition, it is learnt that PF and SAF of the above-described fronts are situated not only to the north of either the CDW upper core but also the north of the lower core while CWB is to the south of them. From the comparison among Figs. 1(a), 1(b) and 1(c), it is easily found that PF and SAF tend to become weaker in sequence from the west to the east except that PF becomes stronger in the 90°E section (Fig. 1(b)) because the bottom rising relief at 60°S gives its effects on PF, which is located immediately to the north of the relief. Otherwise the weakening tendency could have been found more obvious.

3 Salinity distribution pattern and features in the Southern Indian Ocean

As shown in Fig. 2(a), the salinity front of CWB is the most obvious in the upper layer above the 1,000m depth at 68°~69°S in the 30°E section, PF is situated in the layer between 500m and 3000m at 58°S, and SAF is in the layer between 500m and 3500m at 51°S. It is clear in the isohaline distributional pattern that upwelling takes place obviously around those fronts. In addition, a high-salinity core is situated at the 2500m depth around 50°S with its salinity higher than 34.78, and even higher than 34.82 at the lower latitudes. Such a salinity value is higher than the salinity value of the CDW lower core, which is measured by Gorden[4].

Fig. 2(b) is the salinity distribution pattern in the 90°E section. Obviously the respective locations of CWB, PF, and SAF can be clearly identified in the figure. To compare it with the 30°E section (Fig. 2(a)), the salinity front of CWB is situated at 65°S in the 90°E section, being further close to the location of the temperature front of CWB in the 90°E section (Fig. 1(b)). Besides, there are two high salinity cores being located at the 1000m depth around 62°S and at the 2000m depth around 50°S, respectively. The highest salinity at the cores is about 34.75, lower than that in the 30°E section. However the salinity around CWB is higher than that in the 30°E section.

Fig. 2(c) is the salinity section at 145°E. To compare it with the above-described two sections, both PF and SAF become weaker as shown in Fig. 1(c). The isohalines around PF or SAF do not appear any more perpendicular to the horizon and the horizontal salinity gradient becomes obviously decreased at the fronts (Fig. 2(c)).

From the comparison among Fig 2(a, b, c), it is learnt that the salinity in the 30°E section is the highest (34.78) among the 3 sections and it decreased in sequence form the west to the east Furthermore, the area occupied by the high-salinity core with its salinity of 34.75 in the 145°E section is the smallest among all the 3 sections However one common feature of the three sections is that a high-salinity core can be obviously identified and it is located at the 2,000 m depth This means that the salinity core is a basin-wide structure

4 Dissolved oxygen distribution pattern and features in the Southern Indian Ocean

Fig 3(a) is the dissolved oxygen distribution pattern in the 30°E section As shown in the figure, CWB and SAF obviously appear at 68°S and at 51°S, respectively, while PF, being located at 58°S, is less obvious than either in the temperature section (Fig 1 (a)) or in the salinity section (Fig 2(a)). Besides, there is a low oxygen layer with its values lower than 180 μmol/kg in the depth between 400 m and 1200 m.

Fig 3(b) is the dissolved oxygen section at 90°E As shown in Fig 3(b), CWB, PF, SAF are located at 65°S, 58°S, and 51°S, respectively Especially, they appear more obvious in the upper layer shallower than 1,500 m. In addition, a low oxygen layer with its values lower than 175 μmol/kg is located at the 300 m depth at 60°S, and the layer is shallower (Fig 3(b)) than the corresponding layer in the 30°E section (Fig 3(a)).

Fig 3(c) is the dissolved oxygen distribution pattern in the 145°E section As shown in Fig 3(c), CWB is located at about 65°S and it appears relatively obvious However PF and SAF, being located respectively at 58°S and 51°S, both become much weaker (Fig 3 (c)) compared with Fig 3(a) and 3(b). In addition the dissolved oxygen upwelling feature can be found at 50°S and a low oxygen layer (with its values lower than 175 μmol/kg) is located in the depth between 300 m and 500 m in the water south of 50°S

As shown in Fig 3 (a, b, c), the isopleths for dissolved oxygen do not appear any more perpendicular to the horizon in any of the 3 sections, and the low oxygen water are located at the depths about 300m or a little deeper Furthermore, the low dissolved-oxygen water has higher oxygen values in the west (30°E) of the Southern Indian Ocean than in the east (145°E) and it has a cross section area in the west (30°E) smaller than the area in the east (145°E) of the Southern Indian Ocean

5 Horizontal distribution pattern of dissolved oxygen at the CDW upper core in the Southern Indian Ocean

In order to describe the horizontal extent of the CDW upper core, the 27.84 kg/m^3 isopycnal surface is selected to discuss the space occupied by the water with low dissolved oxygen on the surface (Fig 4).

First of all, the features for the Southern Pacific Ocean, the Southern Atlantic Ocean, and the Southern Indian Ocean are compared with each other respectively As shown in Fig 4, the dissolved oxygen is higher on the 27.84 kg/m^3 isopycnal surface in the Southern Atlantic Ocean than either in the Southern Indian Ocean or in the Southern Pacific Ocean The oxygen content reaches its highest in the Weddell Sea of the Southern Atlantic Ocean, which can be evidenced by the 300 μmol/kg isopleth extending from the north to the south. Then the dissolved oxygen is higher in the Ross Sea of the Southern Pacific Ocean. Obviously the distributional feature with high oxygen is closely related to the fact that greater biomass lives in those seas and enriches the oxygen dissolved in the water. In contrast with the oxygen enrichment in the seas, the dissolved oxygen becomes much lower in the Indian Ocean sector of the Southern Ocean than in the Weddell Sea and Ross Sea. This regional feature of low oxygen may be closely related to the fact that less biomass lives in the narrow continental shelf of the eastern Antarctica and its adjacent water, and can not produce much oxygen in the water. As shown in Fig 4, the low dissolved oxygen water represented by the 180 μmol/kg isopleth is limited in the ocean north of 58°S. It is obvious that the water area of this low oxygen is much larger in the Indian Ocean sector than that in the Atlantic Ocean sector, but much smaller than that in the Pacific Ocean sector. Therefore the low oxygen water in the Indian Ocean sector has an intermediate area among the three sectors of the Southern Ocean.

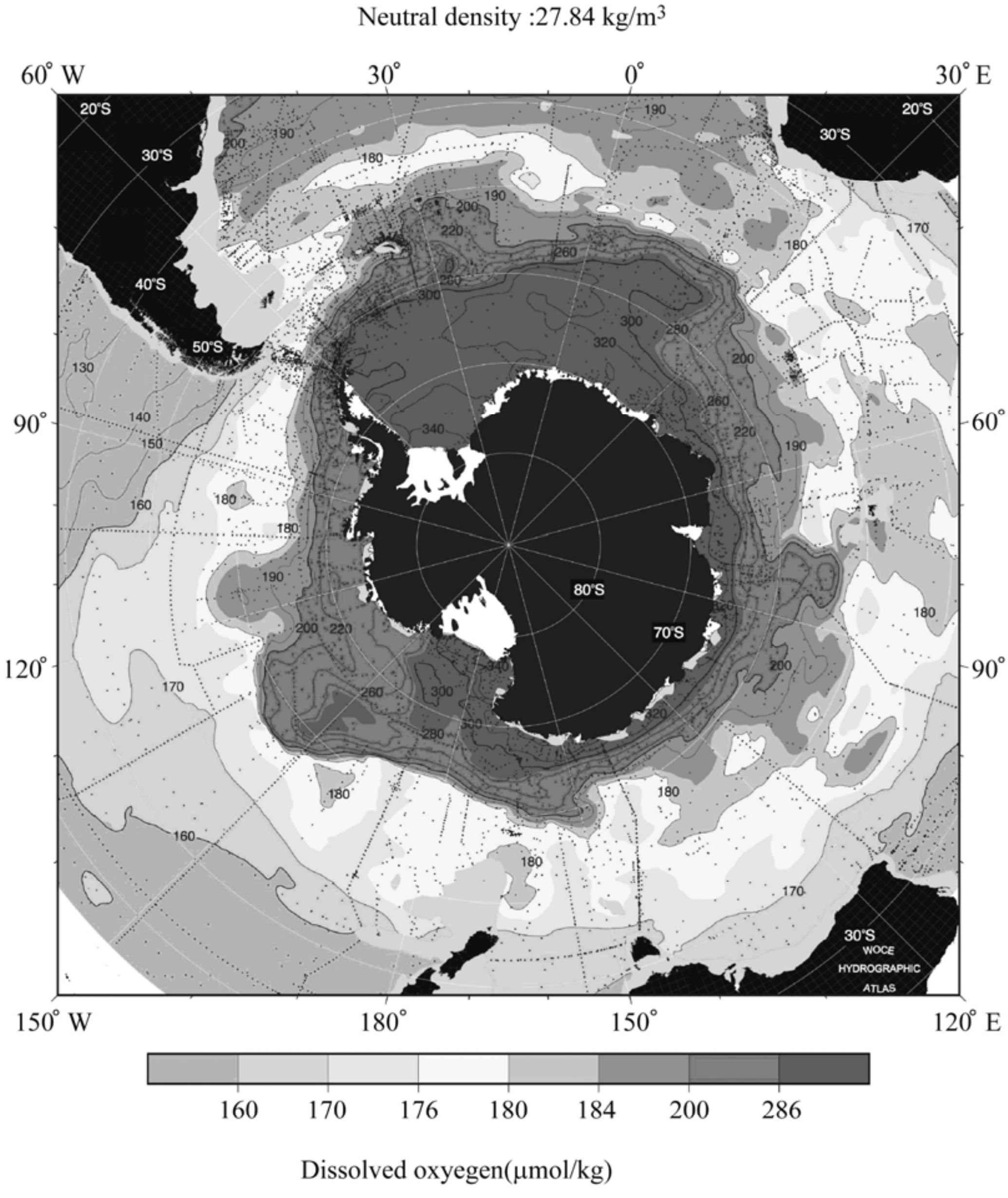


Fig 4 Low oxygen layer(μmol/kg) on 27.84 kg/m^3 density level

6 Horizontal distribution pattern of salinity at the CDW lower core in the southern Indian Ocean

In order to describe the horizontal extent of the CDW lower core, the 28.05 kg/m^3 isopycnal surface is selected to discuss the space occupied by the high salinity core on the surface. First of all, as shown in Fig. 5, the low salinity water (S< 34.70) is largely distributed in the coastal water area around Antarctica, while the high salinity water (S> 34.75) appears only in the southern Atlantic Ocean and the southern Indian Ocean, and it can not be found in the southern Pacific Ocean. As for the even higher salinity water (S> 34.80), it is mainly limited in the area of the Atlantic Ocean from South America to Cape of Good Hope, South Africa, and it is hardly found in the Southern Indian Ocean if the small piece of water area near African continent is excepted. Therefore as far as the CDW lower core is concerned, the Atlantic Ocean sector is an oceanic area with the highest salinity in the Southern Ocean. The next comes the Indian Ocean sector. And the Pacific Ocean.

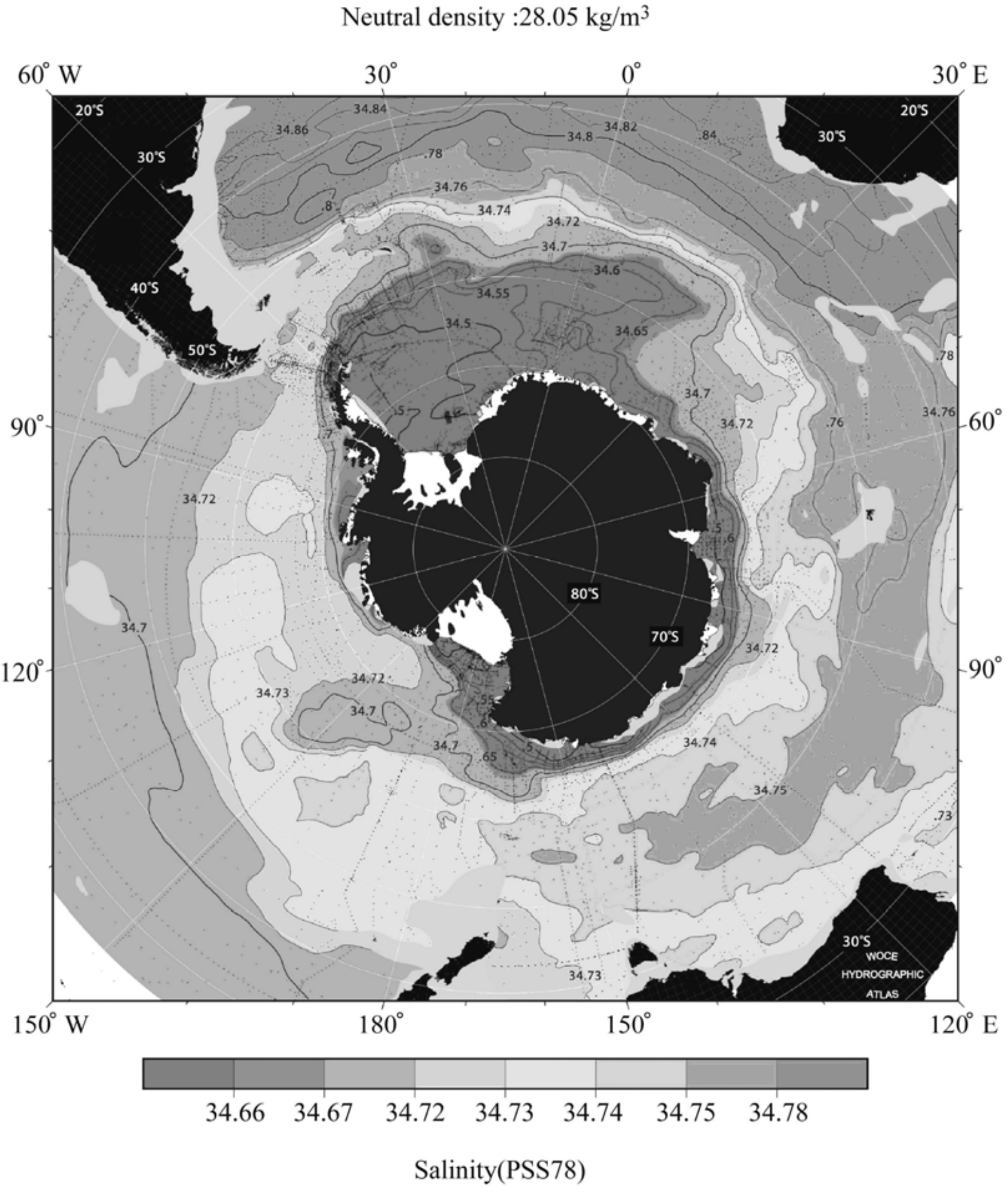


Fig. 5 Salinity on 28.05 kg/m^3 density level

sector is an oceanic area with the lowest salinity in the Southern Ocean. In general, the salinity of the CDW lower core becomes decreased in sequence from the west to the east in the southern Indian Ocean.

7 Thermohaline feature of CDW and their close relationship with circulation in the Southern Indian Ocean

If the 30°E, 90°E, and 145° section are utilized to represent for the west, the middle, and the east of the Southern Indian Ocean, respectively. The spatial distribution features of temperature, salinity, and dissolved oxygen in the Southern Indian Ocean can be expressed as follows.

(1) The strengths of the temperature front, the salinity front, and the dissolved oxygen front for PF and SAF, respectively tend to become weaker and weaker in sequence from the west to the east in the Southern Indian Ocean, i.e. the horizontal gradient of temperature, salinity, and dissolved oxygen around the fronts is obviously greater in the west of the Southern Indian Ocean than those in the east. This is an obvious feature of the spatial distribution of the hydrographic variables.

(2) Upwelling can be found in the water area around the fronts. It shows that those isopleths for temperature, salinity, and dissolved oxygen appear almost perpendicular to the horizon in the frontal area. However the upwelling tends to be weaker and weaker in sequence from the west to the east of the ocean.

(3) The space occupied by low dissolved-oxygen water of the CDW upper core becomes larger and larger in sequence from the west to the east of the ocean.

(4) The salinity becomes decreased in the CDW lower core in sequence from the west to the east of the Southern Indian Ocean.

(5) Water characterized by high salinity and high dissolved oxygen is localized as the regional feature in the west of the ocean.

(6) Water characterized by low salinity and low dissolved oxygen is localized as the regional feature in the east of the ocean.

Obviously those spatial distribution features are closely related to the Antarctic Circumpolar Current (ACC), i.e. the high salinity and high oxygen water originated in the Southern Atlantic can be carried into the Southern Indian Ocean by ACC, and the across basin transport from the Southern Indian Ocean to the Southern Pacific Ocean by ACC will give effects on the salinity and oxygen decreasing tendency.

8 Conclusion

The above-analysis about the CDW distributional features can be summarized in the following conclusions.

(1) Salinity in the west (30°E) of the Southern Indian Ocean becomes obviously higher than in the east (145°E).

(2) The low dissolved-oxygen water in the west (30°E) of the Southern Indian Ocean has higher oxygen values than that in the east (145°E) and it has a cross section area in the

west (30°E) smaller than the area in the east (145°E) of the Southern Indian Ocean

(3) The low dissolved oxygen water on the 27.84 kg/m^3 isopycnal surface reflects the span of the CDW upper core in the ocean

(4) The high salinity water on the 28.05 kg/m^3 isopycnal surface reflects the span of the CDW lower core in the ocean

(5) The salinity and the dissolved oxygen of the Southern Indian Ocean are intermediate between the those of the Southern Atlantic Ocean and the Southern Pacific Ocean

(6) The spatial distribution features for the salinity and dissolved oxygen of CDW in the Southern Indian Ocean can be explained reasonably by the effect of the ACC transoceanic transport

Acknowledgements This study is jointly supported by the National Science Foundation of China under Contract Nos 40376009 and 40676011. The authors take this chance for their sincerely thanks

References

[1] Orsi A H, Whitworth ㊃T (2005): Hydrographic Atlas of WOCE, Volume 1: Southern Ocean Published by WOCE International Project Office, University of Southampton, Southampton, Y. K. 223

[2] Carmark EC (1977): Water characteristics of the Southern Ocean south of the Polar Front Deep-Sea Research, A Voyage of Discovery, George Deacon 70th Anniversary Volume, Supplement, 15–61.

[3] Deacon GER (1937): The hydrography of the Southern Ocean Discovery Rep [R] by Institute of Oceanographic Science, Wormly, England, 124

[4] Gorden A L (1975): An Antarctic oceanographic section along 170°E. Deep-Sea Research, 22 357–377.

[5] Dong ZQ, Kerry K (1981): Data Report—Oceanography, First International BIOMASS Experiment (FIBEX). Voyage M. V. Nella Dan, March 1981. Australian Antarctic publication, 154

[6] Smith N, Dong ZQ (1984): Kerry K and Right S Water Masses and Circulation in the Region of Prydz Bay, Antarctica Deep-Sea Research, 31(9): 1121–1147.

[7] Pu SZ, Hu XM, Dong ZQ *et al.* (2002): Circumpolar deep water and bottom water and its movement feature Acta Oceanologica Sinica, 24(3): 1–8(in Chinese).

[8] Su YF, Dong ZQ (1984): Fronts and Hydrographic Features in the Southern Indian Ocean in Summer Papers of the Antarctic Scientific Exploration, Ocean Press, 25–40 (in Chinese).

[9] Yuan X, Martingson DG, Dong ZQ (2004): Upper ocean thermohaline structure and its temporal variability in the southeast Indian Ocean Deep-Sea Research I, 51: 333–347.

[10] He ZG, Dong ZQ, Yuan XJ (2006): Fronts and strong currents of the upper Southeast Indian Ocean Acta Oceanologica Sinica, 25(2): 1–24

[11] Clarke A J (1982): The dynamics of large-scale wind-driven variations in the AACC. Journal of Physical Oceanography, 12 1092–1105.

[12] Park YH, Gamberoni G (1995): Large-scale circulation and its variability in the south Indian Ocean from TOPEX/POSEIDON altimetry. Journal of Geophysical Research, 100(C12): 24911–24929.

[13] Sloyan Bernadette M (2006): Antarctic bottom and lower circumpolar deep water circulation in the eastern Indian Ocean Journal of Geophysical Research, 111, C02006, doi: 10.1029/2005JC003011.

[14] D└└s K, WEBB DJ (1994): The deacon cell and other meridional cells of the Southern Ocean Journal of Physical Oceanography, 24 (2): 429–442

[15] The FRAM Group (1991): An eddy-resolving model of the Southern Ocean Eos Trans, AGU, 72(15): 169, 174–175.