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Progress of Chinese research in physical oceanography of the Southern Ocean

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Abstract Oceanographic surveying has been one of the key missions of the Chinese National Antarctic Research Expedition since 1984. Using the field data obtained in these surveys and the results from remote sensing and numerical models, Chinese physical oceanographers have investigated the water masses, fronts and circulation patterns in the Southern Ocean. The results of nearly 30 years of research are summarized in this paper. Most oceanographic observations by Chinese researchers have been conducted in Prydz Bay and the adjacent seas. CTD (Conductivity Temperature and Depth) data, collected during the past 20 years, have been applied to study several features of the water masses in this region: The spatial variation of warm summer surface water, the northward extension of shelf water, the flow of ice shelf water from the cavity beneath the Amery Ice Shelf, the upwelling of the Circumpolar Deep Water, and the formation of the Antarctic Bottom Water. The circulation and its dynamic factors have been analyzed with dynamic heights calculated from CTD data as well as by numerical models. The structure and strength of the fronts in the southeast Indian Ocean and the Drake Passage were investigated with underway XBT/XCTD (Expendable Bathythermograph/Expendable CTD) and ADCP (Acoustic Doppler Current Profiler) data. Their interannual variations have been determined and the factors of influence, especially the atmospheric forcing and mesoscale oceanic processes, were studied using remote sensing data. The dynamic mechanism of the Antarctic Circumpolar Current (ACC) was analyzed by theoretical models. The transport and pattern of the ACC have been well reproduced by coupled sea ice-ocean models. Additional details of ACC variability were identified based on satellite altimeter data. The response of the ACC to climate change was studied using reanalysis data. Prospects for future research are presented at the end of this paper.

Keywords **water mass, circulation, front, Southern Ocean, Chinese research**

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1 Introduction

Chinese research in the Southern Ocean began with the investigation of water masses and circulation in cooperation with Australian scientists in the early 1980s[1]. Since the first Chinese National Antarctic Research Expedition (CHINARE) in 1984, multidisciplinary surveys have been conducted in the Southern Ocean as one of the key missions of CHINAREs, accumulating significant amounts of *in situ* observational data for Chinese oceanographers. In particular, CTD (Conductivity Temperature and Depth) has been deployed in fixed sections and stations in Prydz Bay and the adjacent seas, following the establishment of the Chinese Zhongshan Station in 1989. Field data, spanning over 20 years, have promoted significantly Chinese studies of physical oceanography in the Southern Ocean. Additionally, Chinese researchers have studied the Antarctic Circumpolar Current (ACC) and fronts in the Southern Ocean both by using field data, remote sensing data and reanalysis data provided by other nations, as well as by using theoretical and numerical models. The main progress of Chinese re-

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search in physical oceanography of the Southern Ocean, during the past nearly three decades, is summarized in this paper, providing a source of reference for future fieldwork and studies in related disciplines.

2 Observations in the Southern Ocean

Observations and investigations of physical oceanography in the Southern Ocean conducted by Chinese researchers commenced with international cooperation in the early 1980s. Dong Zhaoqian, a physical oceanographer of the State Oceanic Administration of China, measured the sea surface temperature and observed sea ice during an Australian cruise to Casey Station in Antarctica in 1980. This was the first time that a Chinese scientist conducted field observations in the Southern Ocean. The 1st CHINARE set out in 1984 and provided the earliest opportunity for Chinese researchers to observe the Southern Ocean aboard a Chinese research vessel. A multidisciplinary survey was completed aboard R/V *Xiangyanghong* 10 in the regions of the South Shetland Islands and the northeastern Bellingshausen Sea in January and February 1985. The hydrography group deployed CTD at 34 stations, launched XBT (Expendable Bathythermograph) probes at 62 locations, and measured currents and sea waves with instruments made in China. R/V *Jidi* started her maiden voyage to the Antarctica during the 3rd CHINARE and served a scientific survey in the region of the South Shetland Islands throughout January and February 1987.

The CHINAREs have focused on oceanographic surveys in Prydz Bay (Figure 1) and the adjacent seas in the Indian sector of the Southern Ocean since 1989 when the second Chinese Antarctic research station, Zhongshan Station (69°22′24″S, 76°22′40″E) was established. Other than underway measurements and a few observations (e.g., Yang et al.[2]) in the ocean near the Great Wall Station (62°12′59″S, 58°57′52″W), most oceanographic observations have been conducted in this region. All CHINAREs since the 6th CHINARE in 1990 that have engaged research vessels (R/V *XUE LONG* icebreaker came into service in 1994) have carried out multidisciplinary surveys in several meridional sections near Prydz Bay. CTD data spanning more than 20 years have been collected, which makes China the nation with the greatest quantity of field observations and data from this region. An oceanographic section along the front of the Amery Ice Shelf (AIS) has been established since the 19th CHINARE in 2003, which has offered the opportunity to study ice shelf-ocean interactions.

Supported by a Sino-US joint research project, high-resolution XBT/XCTD (Expendable CTD) sections were conducted between Australia and Antarctica during the ten years around the turn of the century. These data were used for investigation of the fronts in the southeast Indian Ocean and their interannual variability. Recently, observations have been conducted by other newer platforms, such as XCTDs launched from helicopter[3], continuous measurements by programmed profilers mounted on the sea ice[4], and deployed buoys and moorings, which have enriched significantly Chinese research work in the Southern Ocean. In January 2012, a scientific survey was conducted by CHINARE in the region of the South Shetland Islands, where Chinese oceanographers had first taken observations 25 years earlier.

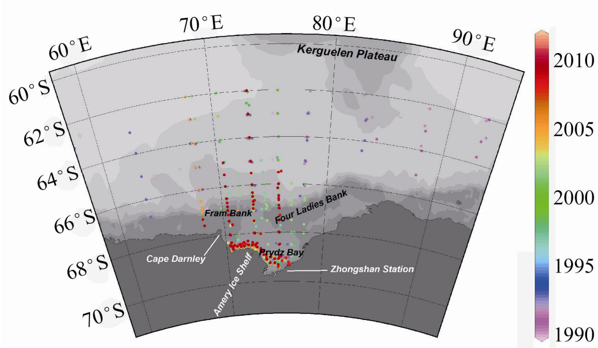


Figure 1 Locations of CTD observations conducted by CHINAREs in the region of Prydz Bay during 1990–2010. Color of the dots marks the year of observation.

3 Water masses and circulation in the region of Prydz Bay

3.1 Water masses

Knowledge of water masses in the Southern Ocean is based mostly on observations in the austral summer (Figure 2). In Prydz Bay, relatively warm and fresh summer water was observed in the surface layer and cold, salty Shelf Water (SW) observed in the lower layers. Ice Shelf Water (ISW) with a temperature lower than freezing point was also detected in the area near the front of the AIS. In basins north of the bay, a thin layer of cold water, the Winter Water (WW), was discovered between the Antarctic Summer Surface Water(AASSW) and the relative warmer Circumpolar Deep Water (CDW). Antarctic Bottom Water (AABW) with a temperature below 0℃ was found in the bottom layer of the basin. The study of water masses in this region conducted by Chinese oceanographers has focused on the following five aspects.

3.1.1 Spatial pattern of summer surface water in Prydz Bay

The abnormal meridional variation of the surface water features in Prydz Bay has been noticed by Chinese researchers. The thickness of the surface water increased with latitude[1], and reached a maximum in the southern end of the bay[5]. The temperature of the surface water also increased with latitude and its maximum was detected in the southwest of the bay, close to the AIS[6]. Temperatures above 5℃ were recorded in the sea surface east of the AIS in the summer of 1992[7]. Sun[7] attributed the warmer surface water forming in this area to the special distribution pattern of sea ice, weak vertical mixing owing to sea ice melting, and weak mass exchange between the bay and open seas. Pu et al.[8] also explained the inhomogeneous thermal structure in the surface layer along the section to the north of the AIS front, observed in January 2006, by the spatial distribution of sea ice and polynya. However, analysis with high-resolution remote sensing data of sea ice is still needed to clarify fully the influence of sea ice on the summer surface water.

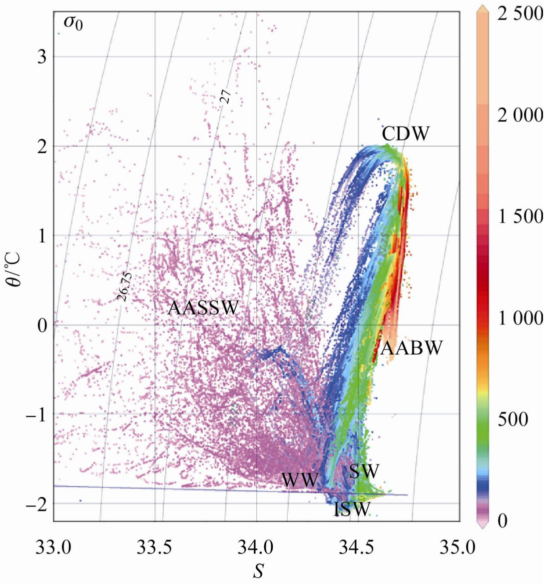


Figure 2 θ(potential temperature)-S(salinity) diagram based on 1dbar-pressure-interval CTD data obtained by CHINARE in the region of Prydz Bay during 1990–2010. Data with irregularities and spiking are not used for plotting. Also shown are the water mass classifications referred to in the text. Gray lines mark contours of constant potential density (σ_0, kg·m^{-3}); blue line indicates the freezing points. Color of dots indicates depth (m).

3.1.2 Shelf Water vs. Winter Water

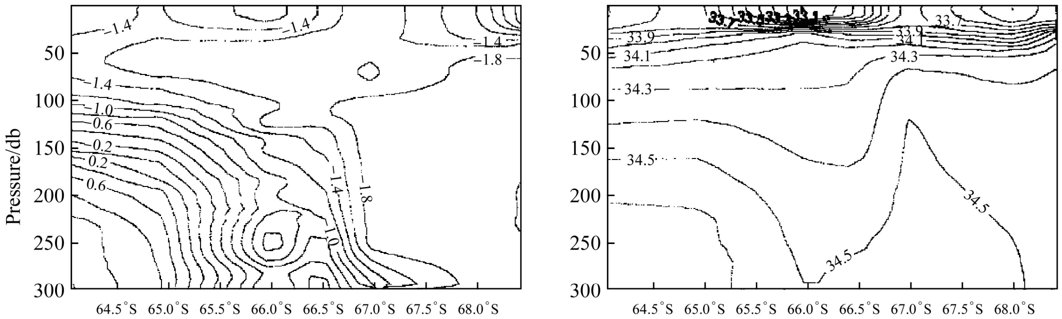
Two cold-water masses, SW and WW, occur under the summer surface water in the shelf region and the basin region, respectively. Based on CTD data obtained by the 9th CHINARE during December 1992 to February 1993, Zhou and Sun[9] found two cold cores in the subsurface at depths of less than 100 m in Section 63°E (west of the bay): the WW at 64°S and the SW at 66°30′S. They were separated from each other at this section. However, at Section 73°E (just across the bay), there was a cold tongue with a temperature lower than –1.5℃, extending to 65°S. This pattern also occurred in the sections observed by the 15th CHINARE during November 1998 to February 1999[10]. At Sections 70°E, 73°E and 75°E, there was a cold-water wedge with a minimum temperature of –1.8℃ and with salinity between 34.3 and 34.4 interposed between the AASSW and CDW. This extended northwards from 67°S to form an isothermal layer in the center of the wedge up to 50-m thick. Pu et al.[10] termed this pattern the northward extension of SW and regarded it as a crucial process in the shelf region without AABW forming and flowing out (Figure 3), compensating for the southward transport of AASSW in the region south of the Antarctic Divergence (AD). Furthermore, they determined that the strength of the water extension became greatest at Section 70°E, which implies that the Coriolis force has an effect. However, it should be noted that no pattern corresponding to the northward extension could be found in the salinity sections. The temperature minimum in the basins was normally identified as the WW, differing from the SW by its relatively lower salinity. Under the WW, a temperature inversion existed above the CDW[10-11], whereas the SW always existed in the middle and bottom layers on the continental shelf. Therefore, there are disputes about the subsurface cold water in the basins north of Prydz Bay.

3.1.3 Outflow from cavity beneath AIS

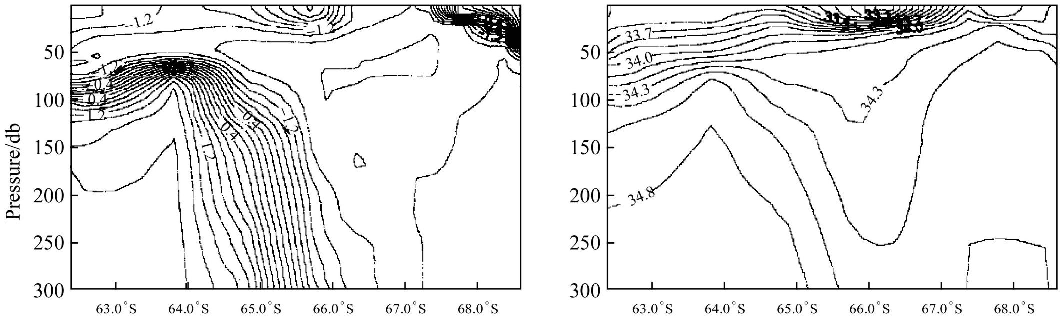
The southern part of Prydz Bay is covered by the AIS, the largest ice shelf in East Antarctica. The ocean cavity beneath the AIS nearly reaches 73°S. Earlier researchers (e.g., Smith and Dong et al.[1]; Dong and Liang[12]) have reported ISW colder than –1.9℃ in Prydz Bay and attributed its extremely cold characteristics to the extra cooling in the cavity beneath the AIS. A section in the ocean along the front of the AIS was established in 2003 by CHINARE and since then, a time series of data for ISW studies has been constructed[13-14]. With this data series and additional data collected in 2001 and 2002 by Australian cruises, Zheng et al.[15] studied the spatial distribution of ISW. The relatively cold and fresh ISW existed as several discrete water blocks with cold cores, beneath the seasonal thermocline in front of the AIS. The coldest ISW occurred mostly at the west end of the AIS front section, where the ISW might have experienced the longest cooling period under the ice shelf. Data at Section 70.5°E from 2003 showed that ISW could spread northwards to the continental break of Prydz Bay. Therefore, it is possible for ISW to mix with upwelling CDW and contribute to the formation of AABW. Supercooled water with a temperature below freezing point was found at depths of 63–271 m in the region north of the AIS front[16], with the maximum supercooling of 0.16℃ below the *in situ* freezing point (Figure 4). The analysis by Shi et al.[16] indicated that this supercooled water also originated from the cavity beneath the AIS. The supercooled water had less variability in the vertical profile compared with the peripheral shelf water, which implies that supercooling resulted from the upwelling of a buoyant outflow emanating from the AIS front.

3.1.4 Upwelling of CDW

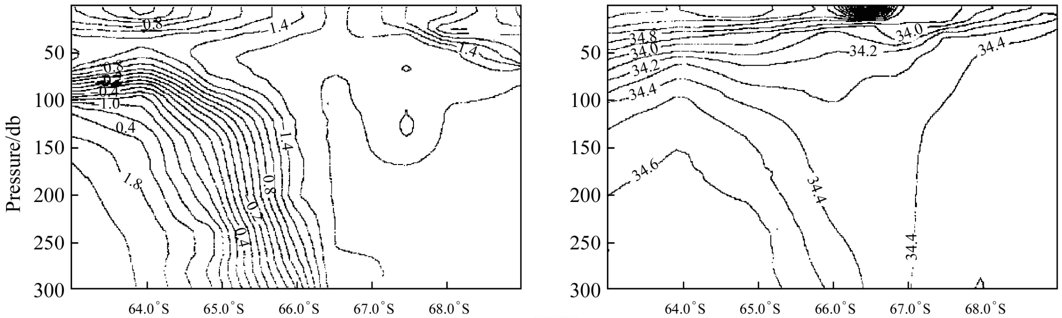
Dense water produced by the mixing of the salty CDW and the cold SW in the Antarctic shelves is a crucial precondition for AABW formation. Therefore, the upwelling of CDW has received considerable attention from Chinese researchers (e.g., Su[17], Shi and Ning[18], Pu et al.[19]). Intensive CDW upwelling has been identified in different locations in different years[20]. In January 1991, only CDW just north of Prydz Bay upwelled to the layer with a depth of less than 100 m at Section 64°S[21]. In January and February



a 70°E



b 73°E



c 75°E

Figure 3 Meridional sections of temperature (℃, left) and salinity (right)[10].

1993, the most intensive upwelling occurred in a region (around 63°E, 65°S) west of Prydz Bay at a depth of 50–200 m[22-23]. From November 1998 to February 1999, the CDW at Section 75°E was the thickest and extended the furthest south[24]. In fact, the CDW observed in the region to the north of Prydz Bay originated from the Atlantic sector and was carried by the ACC into the Indian sector; thus, the temperature and salinity of the CDW core showed a generally decreasing pattern from east to west[25]. This basic pattern should be kept in mind for understanding the zonal variations of CDW features.

Furthermore, remarkable interannual variations of CDW have also been identified in the same meridional section. Such studies focused on Section 73°E. From 1992 to 2002, the CDW at this section showed a warming trend with a rate of 0.008℃·a^{-1} at a depth of 2 500 m at 65°S[26], which is similar to results in other regions of the Southern Ocean. The southward extension of the CDW was strongest in 2002, but relatively weak in 1999 and 1992[26]. It is most likely that CDW upwells on the continental shelf along this section. Zhou and Sun[9] thought that the salinity distribution showed no evidence for the existence of CDW on the continental shelf in 1993, despite a relatively warm water tongue with temperature lower than –0.5℃ upwelling on the continental shelf. Based on the thermal pattern of a warm core with a temperature of –0.8℃– –0.6℃ at Section 68°30′S, Dong et al.[6] proposed that modified CDW (MCDW) could enter the continental shelf through the trough between Fram Bank and the Four Ladies Bank.

3.1.5 Formation of AABW

Whether or not Prydz Bay is a source of AABW is a crucial problem of physical oceanography in the region. Data obtained by previous CHINAREs have facilitated the identification of the preconditions necessary for AABW formation, i.e., the upwelling of CDW(or MCDW) and the existence of high salinity SW on the continental shelf[21], as well as the identification of the area in which mixing between the CDW and SW was most likely to occur[27], even though this did not happen every year[20]. Measurements down to the sea bottom in later cruises provided opportunities for observing AABW in the basins south to Prydz Bay. For example, CTD data obtained in 1993 showed that AABW existed at depths greater than 2 200 m at 66°S[22-23]. Pu et al.[24] found that, in 1999, water with

>27.875 kg·m^{-3} occurred not only at the lower slope, but also at the shelf break and they thought that these two waters had the same source. Although Gao et al.[26] thought that the AABW observed in the summers of 1999 and 2000 in the basins might be formed locally (Figure 5), the formation of AABW in Prydz Bay will be an unsolved secret until the dense water plume overflowing from Prydz Bay and sinking to the bottom of the basins is recorded directly.

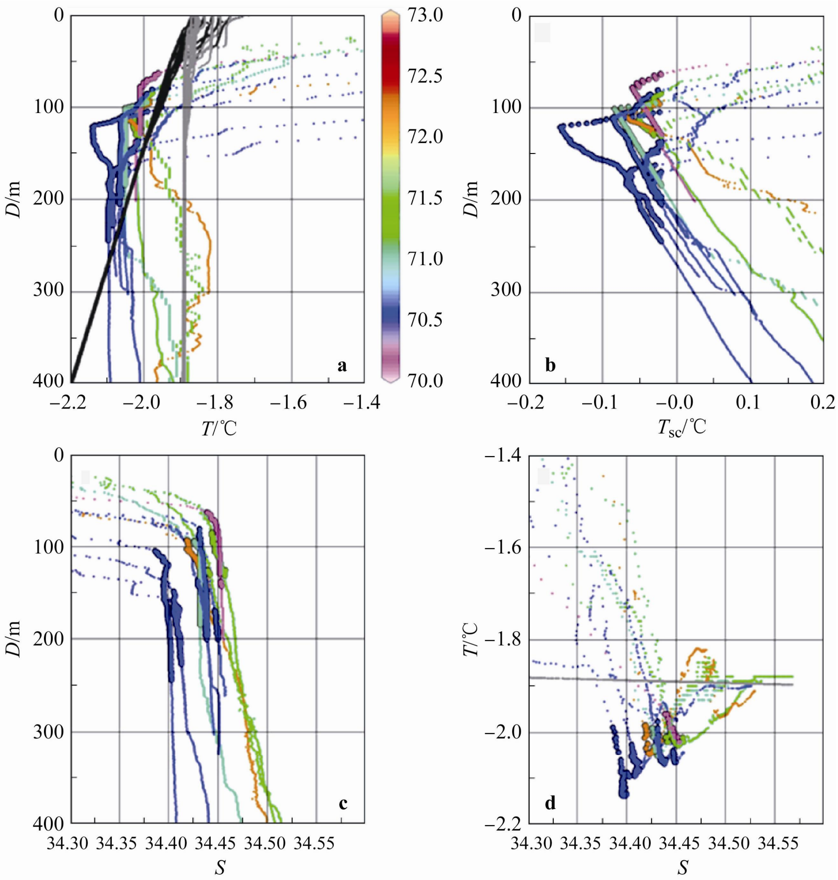


Figure 4 Vertical profiles of T (**a**, temperature), T_{SC} (**b**, $T_{SC}=T-T_f$, T_f is the *in situ* freezing point) and S (**c**), as well as the T-S diagram (**d**) of CTD data with supercooled water collected by CHINARE. Supercooled waters are shown by larger dots and the other parts by smaller dots; both colored by the longitude of the observation location. The black dots in **a** denote the *in situ* freezing points and the gray dots in **a** and **c** denote the surface freezing points[16].

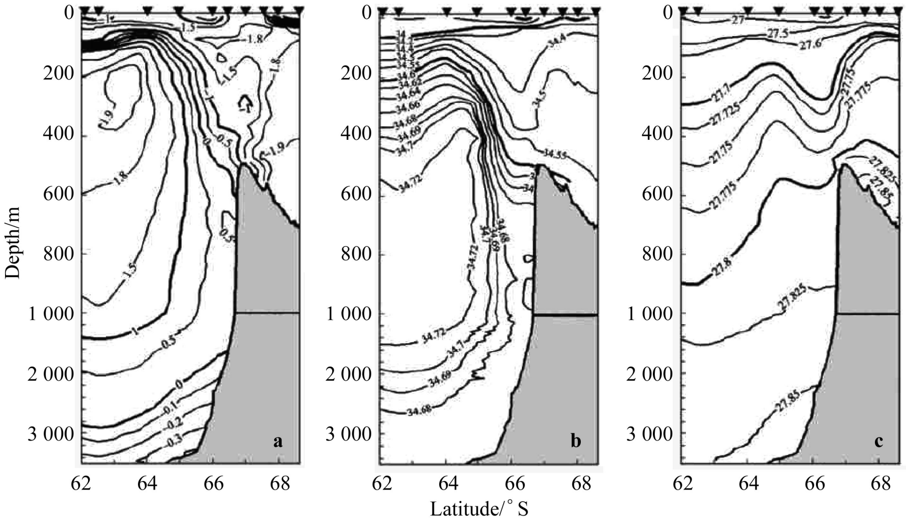


Figure 5 Potential temperature (℃,**a**), salinity (**b**) and potential density (kg·m^{-3}, **c**) distributions at Section 73°E in February 1999[26].

3.2 Circulation

In the region of Prydz Bay, the eastward ACC occupies the northern area while the westward coastal current occurs nearer shore. The former is much stronger than the latter. Between them lies the AD with eddies. A cyclonic gyre exists in Prydz Bay and this circulation pattern has been evidenced in many dynamic height results calculated from CTD data(e.g., Chen et al.[28], Gao et al.[29], Su[30], Yu et al.[22,31], Pu et al.[19,32]). Additionally, Le and Shi[27] thought the coastal current in this region was derived by the easterly and was basically baroclinic, while the ACC had the same magnitude of barotropic and baroclinic components. Pu et al.[33] found a convergence of meridional volume transport between 64°S and 66°S with a strong downwelling in the region of 66°–66.5°S, 73°–75°E, which they inferred was the possible site of AABW formation.

Numerical models of the circulation in the region of Prydz Bay have developed from the general circulation model[34-35] to the coupled sea ice-ocean model[36]. The simulated results of these models reproduced the basic circulation pattern discussed above. Numerical experiments indicated that bottom topography was a major determinant of the circulation in Prydz Bay and that winds had a very limited influence[34]. Sun et al. attributed the northward current near 83°E and southward current east of 98°E to a large-scale topographic standing Rossby wave[35]. The cyclonic gyre simulated by the coupled sea ice-ocean model showed a seasonal cycle that had not been detected by observations[37].

4 Fronts in the Southern Ocean

The earliest investigation of fronts in the Southern Ocean, conducted by Chinese researchers, is based on hydrographic data obtained by Australia[38]. Since the 1st CHINARE, Chinese researchers have collected temperature and salinity data by deploying XBT/XCTD probes on their way to and from Antarctica. These data comprise the basis on which Chinese researchers study the fronts in the Southern Ocean.

From north to south, there are several fronts in the Southern Ocean: the Subtropical Front (STF), the Subantarctic Front (SAF), the Polar Front (PF), and the Continental Water Boundary (CWB, also known as the Antarctic Slope Front, ASF). Additionally, the Southern ACC Front (SACCF) occurs in some regions. Most fronts largely parallel the lines of latitude. Chinese researchers have focused on the fronts in two regions: the southeast Indian Ocean and the Drake Passage, although fronts in other regions have also been studied (e.g., south Pacific Ocean, Miao et al.[39-40]).

4.1 Fronts in Southeast Indian Ocean

Most hydrographic data used for the study of fronts by Chinese researchers were collected during CHINARE's cruises between Fremantle Australia (about 110°E) and Prydz Bay (about 73°E). Some variations of fronts were detected by comparing data obtained in the early 1990s with previous data, such as the double-front structure of the STF and the southward shift of the SAF and PF[41-42]. In fact, the data collected during 1979–1992 indicated that all fronts show interannual variations in both their location and their strength[43]. Even the same front, e.g., the PF, occurs at different latitudes for different longitudes[44]. The intensive XCTD/XBT measurements conducted under international cooperation in the new century made it possible to investigate the detailed structure and evolution of the fronts[45-47].

Data other than temperature and salinity were also used for the analysis of the ocean fronts. From ADCP (Acoustic Doppler Current Profiler) data collected by CHINARE in February and March 1998, the locations and orientations of the SAF, the primary PF and the SACCF could be identified more precisely, because these fronts were usually accompanied by strong currents (jets). However, the STF and the second PF were not easy to identify through current data because they had no accompanying jets[48]. Analysis of sea level anomalies derived from satellite altimeter data revealed the significant influence of eddies on the fronts and jets. Eddies shift the SAF and even cause the accompanying jets of the SAF to split into two branches. Eddies could strengthen surface currents within the SAF to greater than 1 $m \cdot s^{-1}$[48]. The surface zonal geostrophic current of the 115°E section, calculated from altimeter data between October 1992 and February 2002, showed that the core of the ACC was composed of two parts, corresponding to the jet of the SAF and the jet in the Polar Front Zone (PFZ) (Figure 6). Both of these two parts exhibited significant periodicity, with annual, semi-annual and four-monthly cycles, but were out of phase with each other, which results in no notable semi-annual or four-monthly periods in the surface zonal geostrophic current in the core of the ACC. In terms of the annual cycle, the mean surface zonal geostrophic current in the core of the ACC showed its maximal velocity in June[49]. Studies of temperature data in the upper ocean and of remote sensing wind data during the period 1993–1998 indicate that the negative maximum of the wind stress curl might determine the intensity of the SACCF[48].

As the front closest to the Antarctic continent, the CWB is identified by a maximum of temperature gradient in the subsurface layer. Observations in the summer of 1992/1993 showed that the CWB in the region of Prydz Bay was located at a depth of 60–400 m between 64°S and 66°S. It had a frontal strength of 0.014–0.025 $℃ \cdot km^{-1}$, whereas observations in the summer of 1998/1999 showed a relative weaker, deeper and thicker CDW with larger spatial variability on frontal width and strength[19].

4.2 Fronts in Drake Passage

XBT data at two sections across the Drake Passage were obtained by the 3rd CHINARE in 1986 and 1987 on the way of R/V *Jidi* to and from the Great Wall Station. An

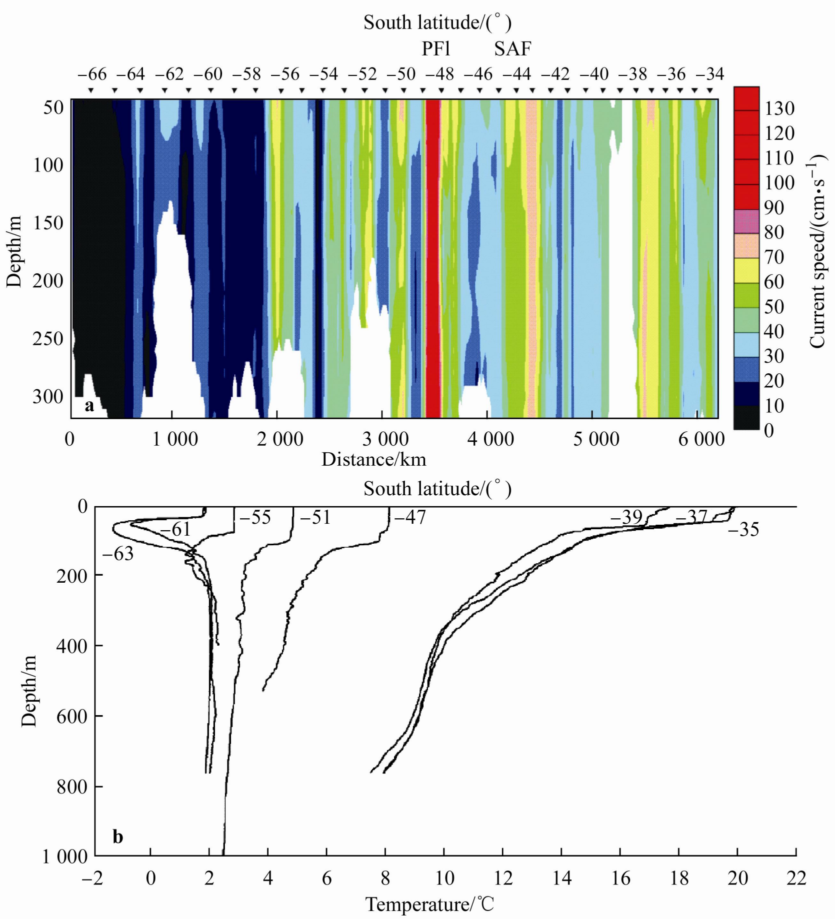


Figure 6 Speed at Section 06 (**a**) and profiles of potential temperature (**b**) measured by XCTD/XBT in the 14th CHINARE[48].

analysis of these data identified the SAF and the CWB in the subsurface layer and showed that the PF strengthened in early summer, with a temperature gradient maximum of 0.1 ℃·km^{-1} at the sea surface. The PF became weaker and retreated into the subsurface by the end of the summer[50]. With CTD data obtained in the region of the South Shetland Islands, additional hydrographic features of the CWB were studied[51]. The 9th CHINARE also collected temperature data in the Drake Passage. With these data and the mooring data provided by other countries, Pu et al.[52] found that the current in SAF was strongest in the upper ocean with relative stable direction and speed, while the current in the lower part was weaker and less stable. The temperature of the water in the southern part of the Drake Passage showed less variability than that in the north, while the deep water around the PF showed the most significant variability with time.

5 The Antarctic Circumpolar Current

5.1 Results from analytical and numerical models

Owing to the lack of current measurements, most research into the ACC has been conducted using analytical models or numerical models. Zhang et al.[53] established an ideal model of the ACC. In their model, the ACC was considered as a wind-induced barotropic zonal current controlled by the linearized potential vorticity equation. With a similar analytical diagnostic model, Qiao et al.[54] discussed the shift of the ACC after it leaves the Drake Passage. Zhang et al.[55] studied the influence of the Drake Passage on the ACC by finding the perturbation solution of a linearized vorticity equation with the meridional friction term. Based on geostrophic equilibrium, Dong and Yuan[56] analyzed the effects of an inhomogeneous density field and wind stress on topographic steering geostrophic flow. They simulated the circulation in the Southern Ocean using vertically integrated kinetic equations with the parameterized pulsating component and Levitus data. The simulated volume transport through the Drake Passage was 232 Sv. Their analysis indicated that the effect of inhomogeneous density on the ACC was stronger than the effect of wind stress. Chao and Li[57] investigated the ACC and its associated meridional overturning circulation (MOC) through a nonlinear inertia theory model, which comprised two layers: An upper Ekman layer driven mainly by sea surface wind stress, and a lower thermocline controlled by an ideal fluid nonlinear equation. Even when given the same Ekman layer condition, the thermocline has a solution of two equilibriums, one of which is more consistent with the observed data.

Using a coupled ice-ocean isopycnal numerical model, Shi et al.[58] simulated the circulation and sea ice of the entire Southern Ocean and their seasonal variations. Their simulated annually averaged volume transport through the Drake Passage of 145 Sv is close to the observed value (134 Sv). The model had higher resolution grids in the region around the Kerguelen Plateau and reproduced the ACC with multiple jets and significant non-zonal features. The meridional streamfunction calculated from the simulated results showed several meridional cells that have reported in previous papers, such as the Subtropical Cell, the Deacon Cell and the Subpolar Cell (Figure 7). A new cell (named the Polar Cell) was found to cover a relatively large region between the Antarctic coast and 64°S in summer, but it becomes smaller in winter, which implies that the Polar Cell is related to the melting and freezing of sea ice.

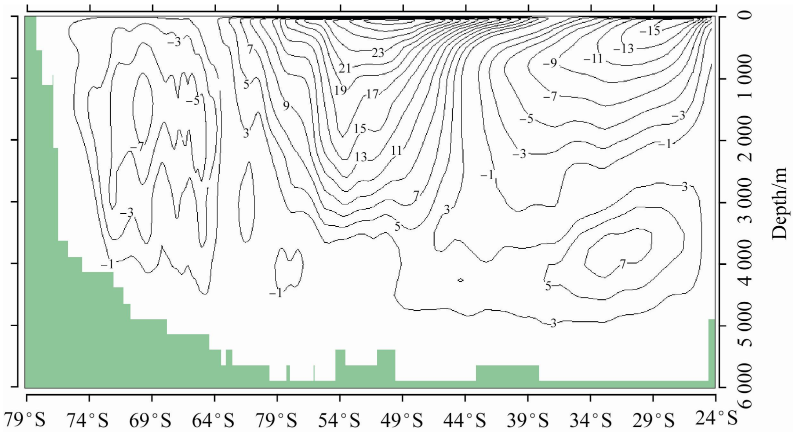


Figure 7 Meridional stream function (10^6 $m^3 \cdot s^{-1}$) in summer simulated by a coupled sea ice-ocean numerical model of the Southern Ocean[59].

5.2 Results from remote sensing data and reanalysis data

Satellite remote sensing is an effective means of long-term monitoring of the Southern Ocean. Most earlier research works conducted by Chinese researchers have analyzed sea ice variations and have seldom been related to oceanography[60]. At the beginning of this century, increasing numbers of Chinese oceanographers began using satellite altimeter data for the investigation of the ACC. Zhou et al.[61] analyzed the spatio-temporal variability of sea level in the ACC region by applying empirical orthogonal function (EOF) and empirical mode decomposition (EMD) to the merged Topex/Poseidon data (January 1993 to December 2000). Zhang et al.[62] discussed the feasibility of estimating the ACC from a mean dynamic ocean topography (MDT) dataset established by combining a geoid model and a mean sea surface height model, filtered with a wavelet denoising procedure. The comparison of sea surface dynamic topography, fronts and currents derived from satellite data with those derived from hydrographic data indicated that the ACC detected by satellite measurement had reached relatively high precision at the macro- and mesoscales. Zhang and Meng[63] detected significant interannual variations of eddy kinetic energy (EKE) by analyzing merged satellite altimeter data (Archiving, Validation and Interpretation of Satellites Oceanographic data, AVISO). They attributed this variability to the response of intensive interannual variations of wind stress with 3-year lag time relative to the baroclinic adjustment. Their research referred to the study of Yang et al.[64].

Through statistical analysis of the SODA (Simple Ocean Data Assimilation) dataset, Yang et al.[64] proposed that the ACC responds to the surface wind stress via two processes, i.e., the instant barotropic process and the delayed baroclinic process. Additionally, they studied the baroclinic instability mechanism in the ACC through calculating the isopycnal slope and baroclinic conversion rate. They determined that the strengthening of surface zonal wind stress causes enhanced tilting of the isopycnal surface, leading to more intense baroclinic instability, which results in the remarkable decrease of the ACC volume transport with a 2-year lag time via the transformation of mean potential energy to eddy energy by mesoscale eddies. They thought that this delayed negative correlation between the ACC transport and the zonal wind stress might account for the steadiness of the ACC transport during last two decades. In a previous study, using an oceanic reanalysis data set, Yang et al.[65] found a positive correlation between the ACC transport and the Southern Annular Mode (SAM) index on an interannual time scale. However, they did not find any significant trend in the total transport of the ACC.

Sun et al.[66] validated a new altimeter product, the Absolute Dynamic Topography (ADT) from AVISO with a two-year mooring observation, and then studied the ACC jet structure south of Australia in stream-coordinates. They found that the ACC jet structure varies strongly on both spatial and temporal (seasonal and interannual) scales. Even in a statistical sense, there is no stable relationship between jet velocities and sea surface height (SSH) values, i.e., the ACC jets do not correspond to particular streamfunction values. Zhang et al.[67] studied the interannual variability of ACC strength in stream-coordinates with 20-year (1992–2011) ADT data. They found that the interannual variability appeared mainly in the Indo-Pacific sector of the Southern Ocean and that the strongest signal was located south of Australia. They supposed that the intensification of the westerly wind in 1998 and 2008 caused the strengthening of the ACC via baroclinic processes. Zhang and Sun[68] developed an altimetric geostrophic empirical mode (η-GEM) by projecting hydrographic transects onto the ADT sea surface height coordinates. Comparisons with mooring measurements demonstrated that η-GEM technique could estimate accurately the profiles of temperature, salinity and velocity from the altimetric SSH. Thus, this provides a powerful means by which to reconstruct the subsurface structure of the ocean from the continuous measurements of the satellite altimeter.

With high-resolution hydrographic profiles from Argo floats, Wu et al.[69] investigated diapycnal mixing in the Southern Ocean (Figure 8). They found that the spatial distribution of turbulent diapycnal mixing at depths between 300 and 1 800 m is controlled by the topography by means of its interaction with the ACC. The seasonal variation of this mixing can largely be attributed to the seasonal cycle of surface wind stress and it is more pronounced in the upper ocean over flat topography.

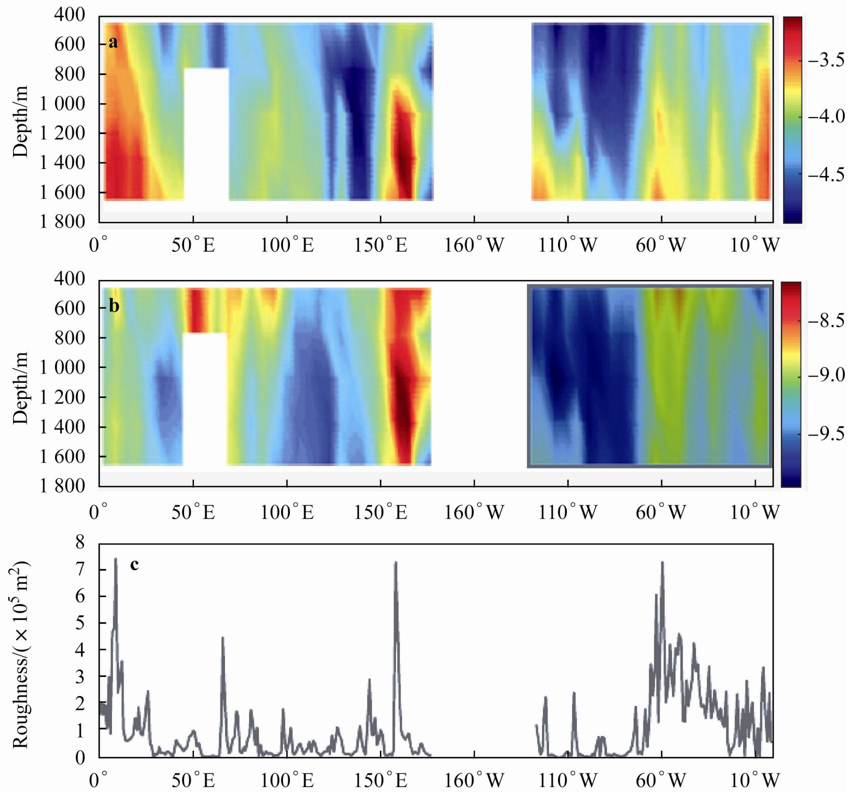


Figure 8 Depth-longitude distribution of diffusivity, dissipation rate and roughness averaged between 40°S and 75°S[69]. (**a**) time averaged diapycnal diffusivity K, with color scale representing Log10(K) in $m^2 \cdot s^{-1}$; (**b**) time averaged dissipation rate ε, with the color scale representing Log10(ε) in $m^2 \cdot s^{-3}$; (**c**) bottom roughness (m^2).

6 Prospects

After more than 20 years of observation and study, China has made considerable progress in the understanding of the physical oceanography of the Southern Ocean, with many fruitful research results. Nevertheless, owing to the relatively short history and limits on conditions and ability, Chinese research still generally lags behind the advanced level of the world and it needs to be strengthened in many aspects.

CTD data, i.e., temperature and salinity data have been the main source for most previous investigations while few current data have been used. Although underway ADCP was available on R/V *XUE LONG* icebreaker in 1995 and has been used for most cruises since the 12th CHINARE, ADCP data have not been fully utilized for various reasons[70-72]. Lowered ADCP (LADCP) has been deployed with CTD since the 19th CHINARE in 2003, in order to obtain current profiles from the surface down to the bottom. However, few results suitable for circulation analysis have been obtained owing to the complications of data processing and the difficulty in filtering inertial and tidal components. Floating buoys and moorings have been deployed in Prydz Bay in recent cruises, which will advance the understanding of the circulation and its seasonal variation in that area.

Sea ice is a crucially important factor for the processes in polar oceans, such as the formation of dense water and the MOC. About 44% of the Antarctic coastline has attached ice shelves. Processes in ice shelves and the cavities beneath should be considered in studies of the Southern Ocean. Studies of interactions between ocean and ice, especially the influences of sea ice, polynyas and ice shelves on ocean processes, will contribute to the association of dynamic and thermodynamic processes in the Southern Ocean.

Carried by the ACC, anomalies of heat and salt travel through the Pacific Ocean, the Atlantic Ocean and the Indian Ocean, (e.g., Wang et al.[73]), which establishes a tunnel for climatic signals to communicate in the ocean. The discovery of the Antarctic Circumpolar Wave (ACW) highlighted the importance of the Southern Ocean in the global propagation of climate anomalies, which is a hotspot of climate research in which Chinese researchers are engaged[74]. The interannual, decadal and even inter-decadal variations of the Southern Ocean and their roles in climate change will be the focus of future work for Chinese researchers.

International cooperation has been and will remain a crucial aspect in the observation and research of the Southern Ocean. Although Chinese physical oceanographers have made notable progress in data collection and scientific studies during the past 30 years, most of their contributions have not been recognized by the international community. To change this situation, Chinese scientists should engage in international research hotspots, adopt international standard instruments and methods for observations in order to improve data quality, and promote the integration of the Chinese national expeditions of the Southern Ocean into the international program, e.g., SOOS (Southern Ocean Observing System).

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