Chinese Antarctic investigation and research in physical oceanography and meteorology during the Chinese Polar Programs 2011–2015

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Abstract Within the context of developing a research presence in the Antarctic region, the first phase of the Chinese Polar Programs covered the period 2012–2015, which almost coincided with the 12th Five-Year Plan (2011–2015). For the promotion of full understanding of the progress of Chinese expeditions and research in Antarctica, the observations and achievements of cruises during 2011–2015 are summarized in this paper. Four Antarctic cruises (28th–31st) were performed in the Prydz Bay and Antarctic Peninsula regions during the first phase of the Polar Programs. These cruises performed systemic collections of physical oceanographic and meteorological data to support further research on the ice–ocean–atmosphere interactions in Antarctica. Overall, 248 CTD/LADCP stations, 66 microstructure profiles, 507 XBT/XCTDs, 181 air sounding balloons, 58,000 total gaseous mercury (TGM) concentrations, 452 aerosol samples, 294 atmospheric samples, 11 moorings, and 28 surface drifters were acquired or deployed during the four cruises. Using these extensive observations and other data, Chinese scientists have achieved new recognition in the fields of Antarctic physical oceanography and meteorology, as well as in other interdisciplinary subjects. These studies, which have been associated with scientific techniques, instrumentation, ocean circulation, water mass formation, energy transformation, and carbon uptake, have elucidated the dynamic mechanisms and potential effects of climate change in Antarctica. Finally, some observations based on experience gained during previous Chinese Antarctic Research and Expedition campaigns are summarized with advice for the improvement of future investigations in the Antarctic region.

Keywords: physical oceanography, meteorology, Five-Year Plan, CHINARE, Chinese Polar Programs

1 Introduction

As the coldest part of Earth's environmental system, the Antarctic region has significant influence on global climate change[1]. The Antarctic environmental system encompasses atmosphere, ocean, land, ice, snow, and ecosystem interactions. It is closely connected to low-latitude regions via the meridional heat transport associated with atmospheric and oceanic circulations. Given the significant influence of the Antarctic and its surrounding oceans to Earth's environmental system, any change in these regions could have global consequences[2]. In the context of global warming, both the polar and the global environments are faced with greater uncertainties. Direct observations have revealed considerable temperature trends around Antarctica. There has been strong and significant warming of the Antarctic Peninsula over the last 50 years[3-5], accompanied by rapid melting of ice from the Fleming and other glaciers in the region[6-8]. Latest evidence indicates glacier retreat in the western Antarctic Peninsula is dominated by ocean forcing[9]. The marked reduction in the biomass of Antarctic krill and the increase in the abundance of salps could be of potential importance reflecting the regional changes in sea ice conditions[10]. As an international initiative of both the Scientific Committee on Antarctic Research and the Scientific Committee on Oceanic Research, the Southern Ocean Observing System has been developed to address six subjects of high scientific and societal relevance in 2012: (1) the role of the Southern Ocean (SO) in the planet's heat and freshwater balance; (2) the stability of the SO overturning circulation; (3) the role of the ocean in the stability of the Antarctic ice sheets and their contributions to sea level rise; (4) the future and consequences of SO carbon uptake; (5) the future of Antarctic sea ice; and (6) the impacts of global change on SO ecosystems[11]. Currently, increasing numbers of countries are turning their attention to polar investigation and research to detect and interpret climate change and to enhance the ability of humankind to react to those changes.

The first Chinese Antarctic Research and Expedition (CHINARE) campaign was undertaken in 1984, and the first Chinese Antarctic scientific expedition station (the Great Wall station) was constructed on the Antarctic Peninsula during that cruise. The second Chinese Antarctic station (Zhongshan station) was constructed in 1989 in Prydz Bay and thence, two investigative modes, i.e., “one ship–one station” and “one ship–two stations” were applied in subsequent CHINAREs. Most investigative activities of the CHINAREs have centered on the Antarctic Peninsula and Prydz Bay regions near the two base stations, and they have focused on observations in the fields of physical oceanography, meteorology, geology, biology, glaciology, and space physics. During 2007–2008, China brought forward the Prydz Bay–Amery Ice Shelf and Dome A observational plan, which was one of the primary plans in the International Polar Year program.

China’s interest in Antarctic Ocean science began since the first station built and it has since developed steadily. Chinese investigations and research into physical oceanography and meteorology in Antarctica have made considerable progress and have achieved fundamental results in several respects[12-19]. For example, multiple observational datasets of temperature, salinity, and current in the SO have been obtained. Accumulated CTD section datasets, obtained over 20 years in Prydz Bay, are considered among the most complete datasets in this region. The basal structures of the water masses and circulations in Prydz Bay, around the Antarctic Peninsula, and in their adjacent sea areas have been recognized. The structure and variability of oceanic fronts along cross sections in the Antarctic Circumpolar Current region have been studied based on observational and remote sensing data, and model projections have been developed for Prydz Bay and the entire SO. However, Chinese Antarctic investigation and research remains weak in comparison with countries with well-developed polar science programs, such as the US, Russia, Japan, and Australia.

Certain problems have restricted China's development in polar research in the past, e.g., the lack of specific objectives in initial designs, poor ability in macro-control, scattered and random observations, few high-level productions, small research teams, and a lack of shipboard time. However, this situation was ameliorated when the Chinese Polar Environment Comprehensive Investigation and Assessment Programs (Chinese Polar Programs for short) began.

The remainder of the paper is organized as follows. Section 2 describes the Chinese Polar Programs and details certain information relating to each cruise. Section 3 presents the main achievements in observations of physical oceanography and meteorology, together with improvements and primary results. Section 4 acknowledges the significance of the Chinese Antarctic expedition and of its achievements within the context of international Antarctic and SO scientific research. Section 5 offers some advice for subsequent CHINAREs, and Section 6 presents a summary of the major content.

2 Chinese Polar Programs

The initial phase of the Chinese Polar Programs was implemented in 2012, and it covered the period 2012–2015, which almost coincided with China's 12^{th} Five-Year Plan (2011–2015). The Chinese Polar Programs were intended to obtain information on both the environmental changes occurring in the Antarctic Ocean and the interactions of the ice–ocean–atmosphere system. The objectives were to elucidate the mechanisms of both the formation and transport of Antarctic bottom water and the overturning circulations, and to provide services for research on global climate change, resource exploitation and utilization, and environmental estimation. The Chinese Polar Programs constitute the first comprehensive large-scale polar investigation for China, in which all the scientific subjects, team sizes, observational areas, and instruments are highly improved compared with Chinese earlier polar science research. Four Antarctic cruises (28^{th}–31^{st}) were undertaken by the *R/V Xuelong* during 2011–2015, with particular emphasis on the sea areas around Prydz Bay and the Antarctic Peninsula. This commitment demonstrated that Chinese polar investigation was becoming a serious systemic operation.

Observations were acquired during the 28^{th} and 30^{th} expeditions in the northwestern Weddell Sea and to the east of the Antarctic Peninsula during 2011–2012 and 2013–2014 respectively. The former campaign was considered a pilot cruise for the Chinese Polar Programs. New SBE 911plus CTD instruments equipped with double sensors were deployed for the first time onboard the *R/V Xuelong* during the 28th CHINARE cruise, and they demonstrated improved data accuracy and quality. Furthermore, direct microstructure measurements were performed for the first time during the 30th cruise. The CHINARE investigation conducted around the Antarctic Peninsula was on a scale larger than ever undertaken before[20]. Based on data collected during these two cruises, the export of Antarctic bottom water from the Weddell Sea can now be estimated precisely, and the energy dissipation and exchange processes can be illustrated.

Prydz Bay is characterized by a broad shelf and the existence of the Amery Ice Shelf. The direct observations acquired during the 29th and 31st cruises of 2012–2013 and 2014–2015, respectively, were conducted to establish the potential for bottom water formation in Prydz Bay, cross-shelf water exchange, and ocean–ice shelf interaction. These two cruises represented the largest scale investigations ever conducted in Prydz Bay, and the former constituted the first official cruise of the Chinese Polar Programs. Several primary studies based on the observational data obtained in Prydz Bay have been conducted and notable results concerning dense shelf water export and its contribution to bottom water formation, decadal changes of shelf water properties, and the 3-D structure of the circulation in Prydz Bay have been achieved. The Chinese government has attached much greater importance to polar science in recent years. The first four cruises (28th–31st) of the Chinese Polar Programs have laid the foundations for China's future Antarctic science development, and they represent China's increasingly significant contribution to international cooperation in Antarctic research.

3 Achievements in physical oceanography and meteorology

3.1 Observational data

Various observations were acquired during the four Chinese Polar Programs cruises to detect the variations and long-term trends of the ocean, atmosphere, and sea ice in the Antarctic. Section observations in crucial regions, cross-section observations in the SO, and long-term observations were the three basal modes used in the Antarctic investigation. The main oceanic instruments used in the section observations included SBE 911plus CTD instruments (to measure temperature, salinity, and oxygen profiles), LADCPs (to measure current profiles), and VMP-200s (to measure turbulent dissipation rate). Air sounding balloons (to measure air temperature, wind speed and direction, and moisture), XBT/XCTD (to measure underway temperature and salinity profiles), SBE21s (to measure underway surface temperature and salinity), and shipborne ADCPs (to measure underway current profiles) were used in the cross-sectional observations in the SO. Furthermore, long-term observations acquired by moorings, sea surface drifters, ice drifting buoys, and instrumented elephant seals have also been used in recent years.

Tables 1–5 show the statistics of the CTD/LADCP, VMP, XBT/XCTD, air sounding balloons, and atmospheric samples obtained during the 12th Five-Year Plan, respectively[21]. There are 169 and 79 CTD/LADCP stations in Prydz Bay (Fig. 1) and off the Antarctic Peninsula (Fig. 2), respectively, which were deployed during

2011–2015, and provide basal information of the water masses and circulation structures. Observations of turbulent mixing using the VMP-200s began during the 29^{th} cruise to help quantify the kinetic energy dissipation rate and the controlling factors in the ocean interior. Overall, 66 stations (50 in Prydz Bay and 16 in the Antarctic Peninsula region) for observing turbulent mixing were operated during the 29^{th}–31^{st} cruises. There were 507 XBT/XCTD observations acquired (322 XBTs and 185 XCTDs) and 181 sounding balloons launched, most deployed when crossing the SO[22], which have been used to identify fronts in the SO and the oceanic responses to changes in the westerly wind. Atmospheric samples obtained during the four cruises comprised 58,000 TGM concentrations, 452 aerosol samples, and 294 atmospheric samples. Moreover, data have been acquired from 11 moorings and 28 surface drifters, together with a mass of observations of sea surface temperature, salinity, and current, and some ice–ocean–atmosphere turbulent flux observations since the 28^{th} cruise. The extension of the collection of various observations provides the opportunity to reveal additional details of the underlying physical processes, which will be useful for in-depth research in the near future.

Figures 3 and 4 show the *T*–*S* curves based on CTD profiles from Prydz Bay and around the Antarctic Peninsula during 2011–2015, respectively. It is evident that the water masses observed in Prydz Bay mainly comprise relatively warm and fresh Antarctic Summer Surface Water (AASSW) and Antarctic Winter Water (WW) in the upper layer. The deep layer is mainly relatively warmer Circumpolar Deep Water (CDW). Salty and dense Antarctic Bottom Water (AABW) is found in the bottom layer. Regional Shelf Water (SW) covers the continental shelf, with relatively salty High Salinity Shelf Water (HSSW) and relatively cold Ice Shelf Water (ISW) formed near the Amery Ice Shelf (AIS) (Fig. 3). Some of the water masses mentioned above (i.e., the AASSW, WW, and CDW) are also observed around the Antarctic Peninsula region; however, some of the regional water masses differ from those of Prydz Bay. Relatively warm water observed in the Powell Basin is named the Weddell Deep Water (WDW) or Warm Deep Water (WDW). The Weddell Sea is one of the most important regions for the formation of AABW. Weddell Bottom Water (WBW) and Bransfield Strait Bottom Water (BSBW) are the two principal AABWs in this region (Fig. 4). Because of the enlargement of the observational areas, as well as the improvements in the observational techniques and instruments, the water masses within these two regions can be depicted more clearly than ever before.

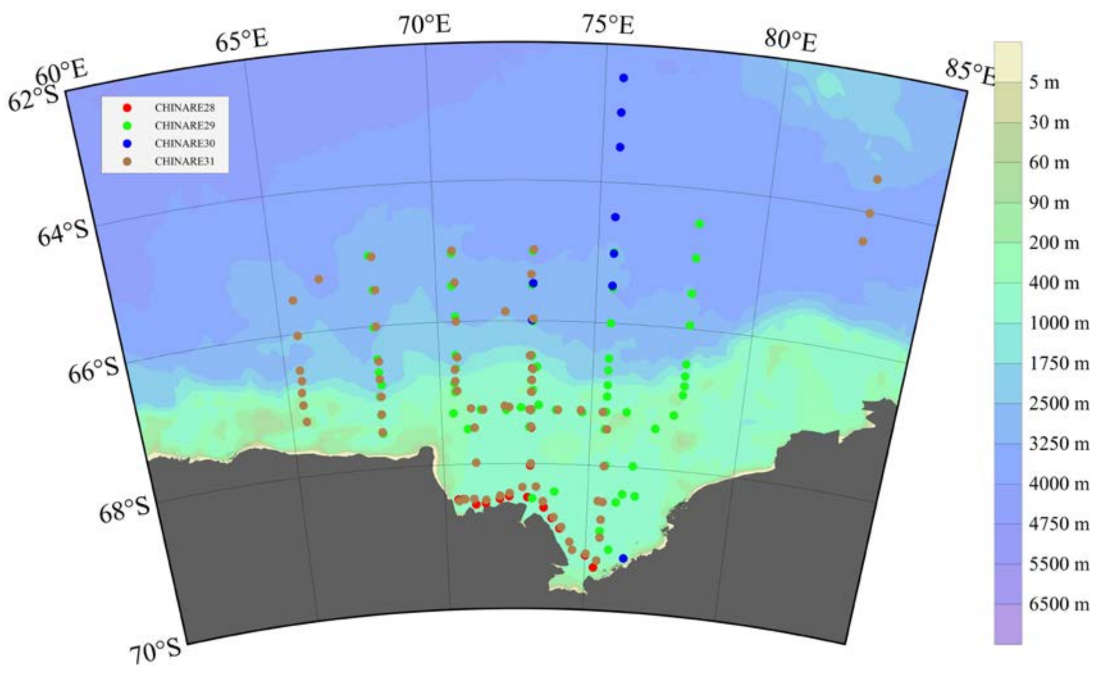

Figure 1 Hydrologic stations in Prydz Bay 2011–2015.

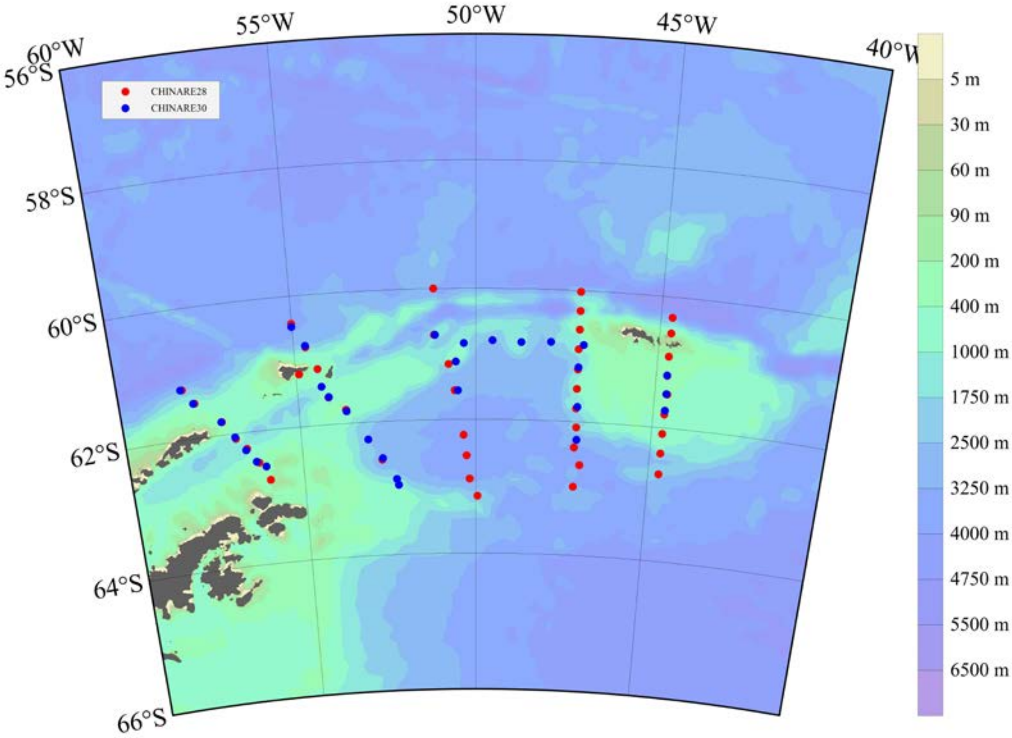

Figure 2 Hydrologic stations around the Antarctic Peninsula 2011–2015.

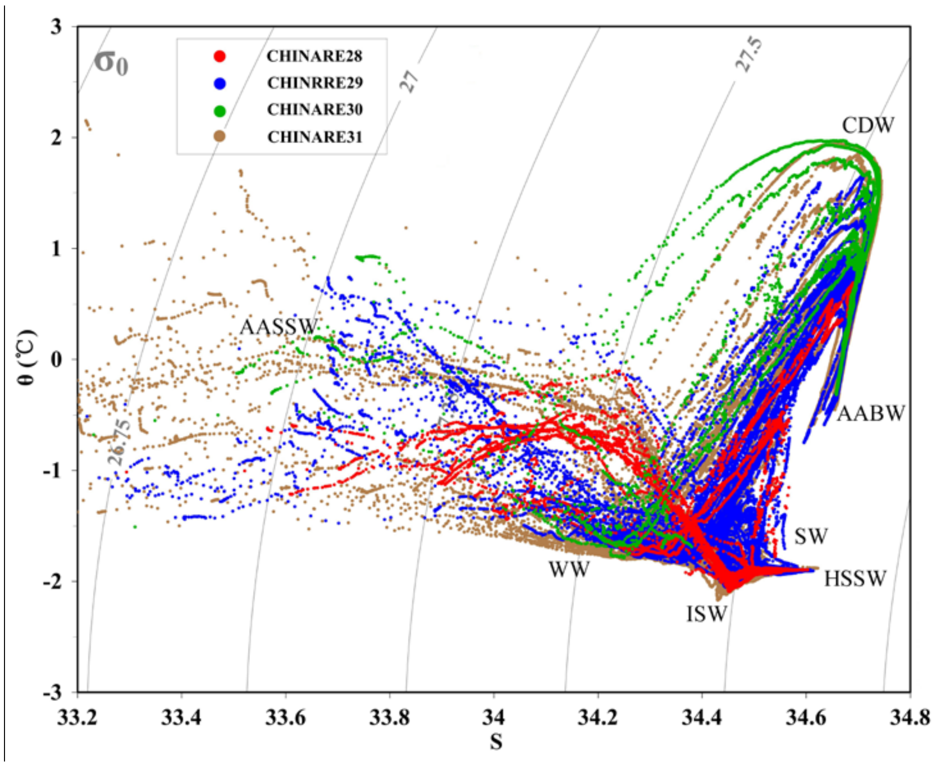

Figure 3 Diagram of θ (potential temperature) vs. *S* (salinity) based on CTD profiles in Prydz Bay obtained during the 28th–31st CHINARE cruises.

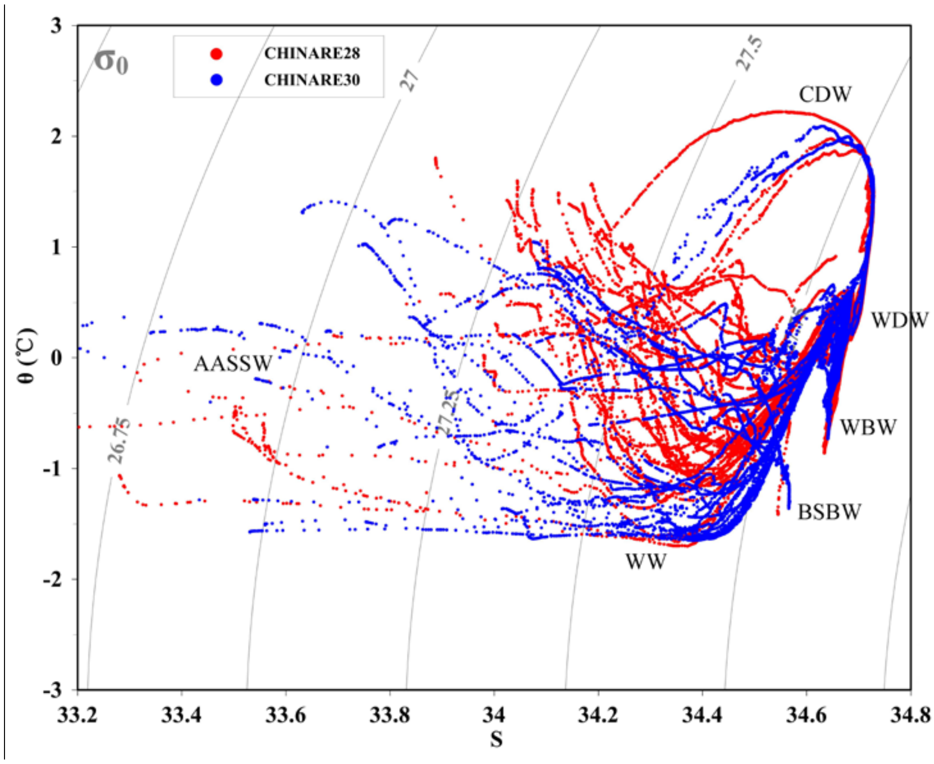

Figure 4 Diagram of θ (potential temperature) vs. S (salinity) based on CTD profiles around the Antarctic Peninsula obtained during the 28th and 30th CHINARE cruises.

Table 1 Statistic of CTD/LADCP stations

Cruise	28th	29th	30th	31st	Total
Time	2011-2012	2012-2013	2013-2014	2014-2015	2011-2015
Prydz Bay	21	66	14	68	169
Antarctic Peninsula	46	--	33	--	79
Total	67	66	47	68	248

Table 2 Statistics of VMP stations

Cruise	29th	30th	31st	Total
Time	2012-2013	2013-2014	2014-2015	2011-2015
Prydz Bay	21	--	29	50
Antarctic Peninsula	--	16	--	16
Total	21	16	29	66

Table 3 Statistics of XBT/XCTD stations

Cruise	29th	30th	31st	Total
Time	2012-2013	2013-2014	2014-2015	2011-2015
XBT	98	124	100	322
XCTD	61	68	56	185
Total	159	192	156	507

Table 4 Statistics of air sounding balloons

Cruise	28th	29th	30th	31st	Total
Time	2011-2012	2012-2013	2013-2014	2014-2015	2011-2015
Profiles	28	78	35	40	181

Table 5 Statistics of atmospheric samples

Cruise	28th	29th	30th	31st	Total
Time	2011-2012	2012-2013	2013-2014	2014-2015	2011-2015
TGM	10000	10000	18000	20000	58000
Aerosol	100	100	110	142	452
Atmosphere	96	70	80	48	294

3.2 Highlighted improvements and primary results

Many aspects of CHINARE have been highly improved during the 12th Five-Year Plan. Using the extensive observations of the Chinese Polar Programs as well as other data, Chinese scientists have achieved some notable accomplishments and scientific results in the fields of Antarctic physical oceanography and meteorology, some representative examples of which are presented below.

(1) The observational areas and scientific objectives, techniques, and instrumentation adopted in the Antarctic during the 12th Five-Year Plan have been much improved on earlier campaigns. This has provided a good foundation for further Chinese Antarctic investigation and research. Historically, The Prydz Bay and the Antarctic Peninsula, as well as their adjacent areas, have been the main regions of interest for Chinese investigations in Antarctica; however, the earlier research was rather inadequate in terms of its scientific approach and pertinence, with poorer quality observational techniques and a lack of modern instrumentation. The

implementation of the new Chinese Polar Programs has obviously improved most of these aspects.

(2) The standardization and stabilization of mooring observational systems has provided new insights regarding ocean circulation and the variability of the water masses around the Antarctic continental shelf and slope. China has deployed 11 moorings around Prydz Bay already, and the data acquired have proven very useful in clarifying the long-term controversy of whether Prydz Bay is an AABW formation region or a region that contributes to AABW production in the SO[23]. The most recent studies have provided novel evidence suggesting that the export of the dense shelf water (DSW) from Prydz Bay makes an important secondary contribution to the Cape Darnley Bottom Water, but that freshening from ocean/ice shelf interactions limits the overall formation of the DSW in Prydz Bay (Fig. 5). This highlights the susceptibility of AABW to increased freshwater input from enhanced melting of ice shelves, and ultimately, the potential collapse of AABW formation in a warming climate[24].

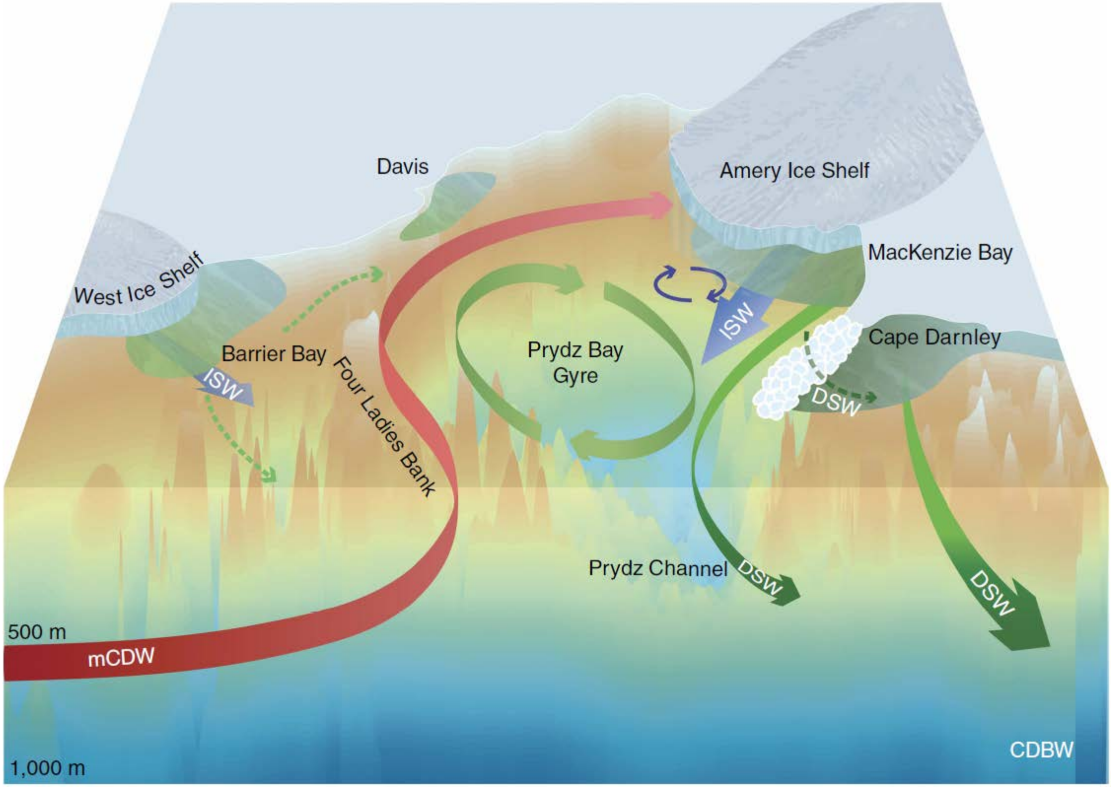

Figure 5 Evolution of Prydz Bay's dense shelf water (DSW) contribution to Cape Darnley bottom water[24].

(3) Meteorological observations obtained as part of the Chinese Polar Programs have played an important role in international rescues, e.g., when the Russian vessel *Akademik Shokalskiy* and the *R/V Xuelong* were trapped in Commonwealth Bay in January 2014[25]. Following comprehensive analysis of the sea ice, oceanic, and atmospheric conditions, Chinese scientists discovered the primary reason for the vessels becoming trapped. Continuous strong easterly winds appeared largely responsible for an accumulation of sea ice in that area, and it was only when the wind turned westerly that the vessels were able to escape. Nevertheless, meteorological and oceanic predictions in the polar region have proven a challenge regarding logistical supply capability. The importance of independent real-time data resources and weather forecasting capacity has been recognized,

and real-time monitoring of sea ice conditions and the provision of precise weather forecasts are considered crucial for guaranteeing the safe operation of the *R/V Xuelong*.

(4) Using observational data collected south of Tasmania during 14 austral summer cruises during 1993–2011, the response of sea surface fugacity of carbon dioxide (fCO_2) to the shift of the Southern Annular Mode (SAM), which occurred around 2000, has been examined[26]. In the southern part of the SO or the Polar Zone (PZ), and the Polar Frontal Zone (PFZ), fCO_2 increased at a faster rate at the sea surface than in the atmosphere before the SAM shift, but not afterwards. In the northern part of the SO or the Subantarctic Zone (SAZ), however, surface fCO_2 increased at a faster rate than atmospheric fCO_2 both before and after the shift. The SAM shift had an important effect on the trend of surface fCO_2 in the PZ and PFZ but not in the SAZ, which has been attributed to differences in regional oceanographic processes. The SAM shift might have reversed the negative trend of SO CO_2 uptake (Fig. 6).

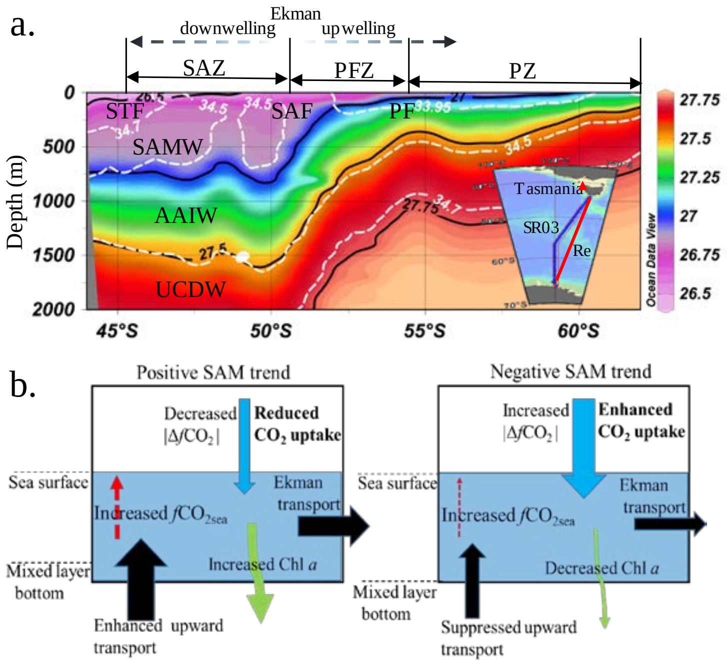

Figure 6 (a) Potential density (kg m-3) (shaded and solid contours) and salinity (white contours) profiles along Transect SR03, (b) impact of SAM trend on CO_2 uptake in the SO[26].

(5) Historical surface drifter observations collected from the SO have been used to study the near-surface structure, variability, and energy characteristics of the Antarctic Circumpolar Current (ACC)[27]. A strong nearly zonal ACC, combined with complex fronts, dominates the circulation system in the SO. During austral winter, the current velocity increases because of the enhanced westerly wind. Aroused by the meridional motion of the ACC, the meridional velocity shows greater characteristics of instability than the zonal velocity over the core current. Additionally, the ACC exhibits an eastward trend of reduction in the core current velocity from southern Africa. The characteristics of the ACC have been considered from the perspective of energy. Energy distribution suggests that the mean kinetic energy (MKE), eddy kinetic energy (EKE), and $\sqrt{\text{EKE}}$ are strong

over the core currents of the ACC. However, in contrast, EKE/MKE suggests there is much less (more) eddy dissipation in regions with strong (weak) energy distribution. Both meridional and zonal energy variations have been studied to elucidate additional details of the ACC energy characteristics. Generally, all forms of energy, except EKE/MKE, present west–east trends of reduction, which coincide with the velocity statistics. It has been established that eddy dissipation has a much greater effect on MKE in the northern part of the SO (Fig. 7).

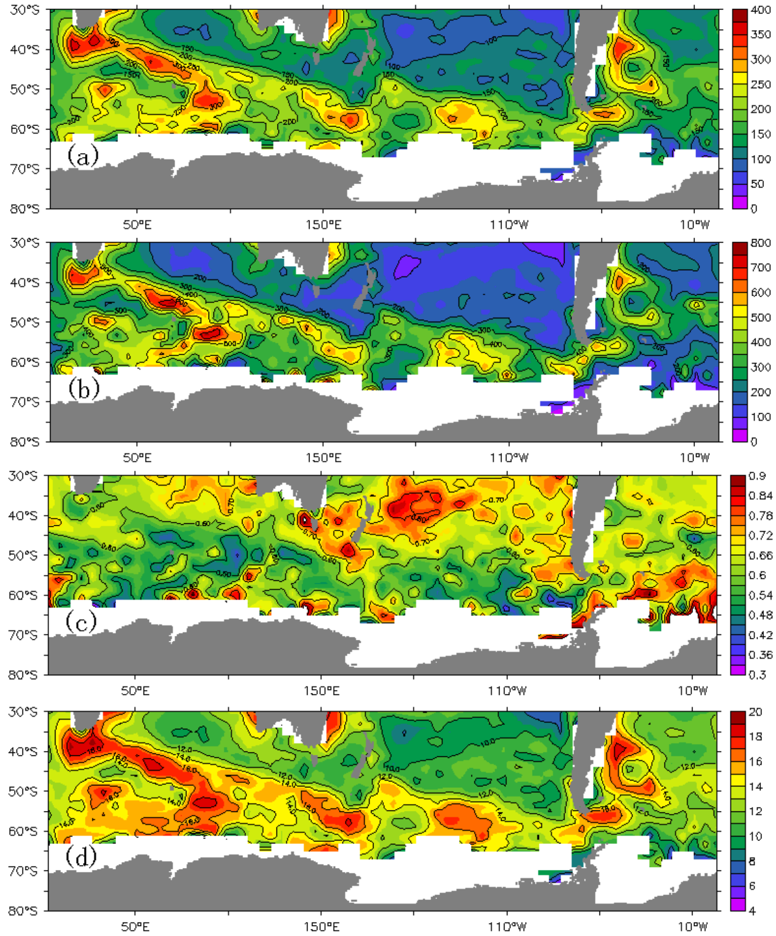

Figure 7 Energy distribution in the Southern Ocean (unit: $cm^2 \cdot s^{-2}$)[27]: (a) EKE; (b) MKE; (c) EKE/MKE; (d) $\sqrt{EKE}$ (unit: $cm \cdot s^{-1}$).

(6) The application of new methods in our long-term observation, such as elephant seals instrumented with CTDs, has enriched the acquisition of seasonal data in the

Antarctic[24, 28]. Equipping seals with CTDs is the best way to monitor the Antarctic oceans, especially in winter. With the data from the instrumented seals compensating the lack of winter observations from the *R/V Xuelong*, the seasonal evolutions of the thermocline and the halocline from winter to summer have been well recorded. During the 31st CHINARE, an instrumented seal was captured and a valuable raw data record was retrieved for further analysis. The CTD on the captured seal was calibrated and reattached to the seal's head before it was released.

(7) Drifting buoy, LADCP, CTD, and mooring measurements have provided deeper insight into the 3-D circulation in Prydz Bay[16-17, 29]. Previous studies on the Prydz Bay circulation have been insufficient and have focused mainly on the horizontal circulation based on data derived from dynamic meters. By contrast, the observations of drifting buoys, LADCPs, CTDs, and moorings obtained during the new Chinese Polar Programs have been used to illustrate the 3-D structure of the regional circulation. Prydz Bay contains a cyclonic gyre, with a westward flow around the Antarctic on the slope. Several drifting buoys have turned westward on leaving the cyclonic gyre in Prydz Bay, whereas others have left the bay in a northward direction across the shelf break and joined the ACC after bypassing the Kerguelen Plateau. The clockwise gyres that dominate the circulation in Prydz Bay and its adjacent area are related to the background circulation. Approximately 50% of these gyres evolve with a period of 2–4 days, with their diameters increasing during their life cycle. The intrusion of Modified Circumpolar Deep

Water can be inferred from dynamic meter contours, which show a strong southward inflow into Prydz Bay near 75°E. The most important cyclonic circulation in Prydz Bay is centered at 67.50°S, 72°E. Oceanic inflow intrudes into the bay from the northeast and turns westward along the front of the Amery Ice Shelf. Dynamic meters also show a contribution from a westward inflow from the east, which should be contributed by the West Ice Shelf.

(8) The new Chinese Polar Programs have promoted the development of multidisciplinary research involving physical oceanography, meteorology, biology, chemistry, and geology. Physical oceanographic and meteorological observations obtained during the Chinese Polar Programs have been verified and used to support biological, chemical, and geological investigations, promoting the comprehensive development of Chinese Antarctic expedition and scientific research. For instance, the structure of the circulation in Prydz Bay derived from physical observations is coincident with the distribution of chemical isotopes and geological deposition rates. Moreover, the physical conclusions derived have provided evidence corroborating the explanations of the distributions of biological resources. Comprehensive investigations during the Chinese Polar Programs have provided better understanding of the regional oceanic situation, e.g., marine hydrology, meteorology, and sea ice, and enabled further study of both the changes in the oceanic environment and the interaction of the ice–ocean–atmosphere system.

(9) Turbulent mixing in Prydz Bay has been investigated in the SO. Turbulent mixing

observations commenced during the 29th CHINARE. Overall, 35 stations for microstructural observations have been deployed in Prydz Bay and 16 stations placed in the northwestern Weddell Sea near the Antarctic Peninsula. Based on these observational data, the mixing structure and associated energy resources within the study area have been elucidated[30]. The rate of turbulent dissipation in Prydz Bay is approximately 10^{-7}–10^{-9} W kg^{-1}, with higher values over areas of steeper topography. In front of the Amery Ice Shelf, the turbulent dissipation rate (ε) is around 10^{-7}–10^{-8} W kg^{-1}, from the surface to the bottom, with the strongest intensity on the western side. In the northwestern Weddell Sea, rough topography and the confluence of circumpolar water and Weddell Sea outflow cause very strong local mixing. The most intense mixing (>10^{-7} W kg^{-1}) occurs in the west of the Philip Passage, where it is two orders of magnitude larger than over the smooth South Orkney Plateau[30] (Fig. 8).

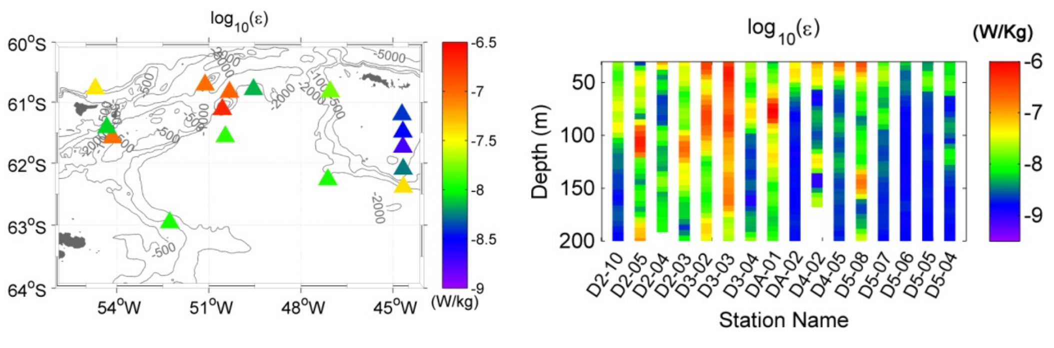

Figure 8 Depth-averaged (left) and vertical profiles (right) of ε for 30–200 m[30].

Note; a logarithmic scale is used for ε.

(10) Long-term observations of the ice–ocean–atmosphere system on the landfast ice sheet of the Zhongshan and Great Wall stations have revealed the thermohaline evolution in the upper ocean beneath the sea ice[31-32]. The observations of

temperature, salinity, and current profiles under the sea ice, together with air temperature, solar radiation, and sea ice thickness data, have extended our understanding of the dynamic evolution and heat flux in the upper ocean. Observational data have indicated that the water beneath the sea ice becomes warmer and fresher because of sea ice melting. The average current of the upper ocean is 5.7 cm s^{-1} (maximum: 20 cm s^{-1}), indicating the important effect of heat advection in this region.

(11) Underway high-quality ADCP data can benefit research on the fronts and ACC in the SO. Two new shipborne ADCPs were deployed on the *R/V Xuelong* in June 2014, and they were used to record underway current profiles for the first time during the 31st CHINARE. For the two sections from Tasmania and New Zealand to the Antarctic, the underway current profiles recorded by the 300-kHz ADCPs revealed vertical homogeneity, and the areas of high values coincided with the cores of the fronts in the SO, conforming well to the quasibarotropic and multicore properties of the ACC[21].

4 Contribution to international Antarctic research

Six subjects of overarching importance in relation to Antarctic and SO science have been identified by a Southern Ocean Observing System report[11, 33], which comprise freshwater and heat balances, overturning circulation stability, ice sheet melt and sea level rise, the future of sea ice, carbon and biogeochemical cycles, and the impact of climate change on ecosystems. These scientific challenges require an integrated international network of platforms and techniques, such as CTD/LADCP sections, Argo floats, underway measurements, animal-borne sensors, gliders, and ice tethered platforms. Furthermore, data collected during the 2011–2015 cruises constitute additional valuable information.

Data from CTD/LADCPs and moorings have helped to identify the heat storage in shelf regions and to explore its impact on ice shelf melt, which is critical to ice sheet variability. Accumulated XBT/XCTD sections deployed in the Southern Ocean can help in the analysis of the long-term evolutions of heat content and freshwater under the impact of climate change. Repeated cross-slope sections can be used to identify isopycnal variations and changes in the upwelling of circumpolar water to analyze the overturning circulation responses to global climate change. Repeated observations in specified regions can contribute to research on ocean–ice interactions because sea ice shows strong regional trends in both extent and duration. Mooring data deployed at the Antarctic slope front and in the Antarctic coastal current region in Prydz Bay can contribute to the exploration of interbasin circulations and cross-shelf exchanges of material and energy. Overall, the CHINARE and its collected data can function as part of an integrated observing system in the SO and make a considerable contribution to the monitoring of environmental changes in Antarctica.

5 Advice for future investigations

The Chinese Antarctic investigation has been relatively successful in recent years, largely because of the systemic and efficient organization. Here, a few notes of experience and advice are summarized, which should prove helpful for future investigations.

(1) It is very important to establish a consummate plan before a cruise. Sometimes, several plans are required to cope with unexpected emergencies. The more details considered at the outset, the more efficient and productive the cruise will be.

(2) All the Antarctic cruises of CHINARE were organized during the austral summer, and they were too involved in the transportation of material. It would be advantageous to try to commission an austral winter cruise via international cooperation or by hiring another research vessel, in order to achieve additional observations during the cold season.

(3) Based on analyses of the sea ice and air conditions, the optimum window for hydrographic observations around Antarctica is in January and February. Therefore, it would be better to plan oceanic investigation for this period.

(4) Given the lack of shipboard time and the sparse datasets in the SO, we advise the enhancement of long-term observations, such as buoys and mooring arrays, to increase the spatial and temporal series of Antarctic data.

(5) There are some outstanding Chinese oceanographers focusing on polar research but a talent shortage remains, especially among younger scientists in the fields of physical oceanography and meteorology. It is vital that greater numbers of younger scientists be encouraged to attend CHINARE and to contribute their strengths to the polar enterprise.

6 Summary

The first phase of the Chinese Polar Programs commenced in 2012, and it almost coincided with the period of the 12th Five-Year Plan (2011–2015). It constituted China’s first comprehensive large-scale polar investigation. All the scientific subjects, team sizes, observational areas, and instrumentation were highly improved compared with earlier research campaigns. Four Antarctic cruises (28th–31st) conducted around Prydz Bay and the Antarctic Peninsula region demonstrated that Chinese polar investigation was becoming a serious systemic operation.

Various instruments were used in the physical oceanographic and meteorological research during the four cruises, e.g., SBE 911plus CTDs, LADCPs, VMP-200s, air sounding balloons, XBTs, XCTDs, SBE21s, shipborne ADCPs, moorings, sea surface drifters, ice drifting buoys, and instrumented elephant seals. Overall, 248 CTD/LADCP stations, 66 turbulent observations, 507 XBT/XCTDs, 181 air sounding balloons, 58,000 TGM concentrations, 452 aerosol samples, 294 atmospheric samples, 11 moorings, and 28 surface drifters have been acquired or deployed. The extensive collection of observations has proven invaluable in the study of the underlying physical processes of the Antarctic region. Chinese scientists have achieved some new and notable accomplishments and scientific results in the fields of Antarctic physical oceanography and meteorology, and interdisciplinary subjects. Such studies, based on improved scientific techniques and instrumentation, have elucidated various aspects of ocean circulation, water mass formation, energy transformation, and carbon uptake. Indeed, some of the results have clarified long-term controversies in Antarctic science.

Finally, some observations of field experience were summarized, and advice for future CHINARE campaigns offered regarding plan preparation, austral winter cruises, oceanic observation optimization, deployment of buoys and mooring arrays, and the cultivation of scientific talent. Data collected during the 12th Five-Year Plan (2011–2015) and the associated scientific achievements will provide Chinese scientists and their international colleagues greater opportunities for future collaborative research.

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