Acta Oceanol. Sin., 2017, Vol. 36, No. 6, P. 1–11
DOI: 10.1007/s13131-017-1035-x
http://www.hyxb.org.cn
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China Argo project: progress in China Argo ocean observations and data applications

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Received 21 October 2016; accepted 20 December 2016

Abstract

This paper reviews the current achievements of the China Argo project. It considers aspects of both the construction of the Argo observing array, float technology, and the quality control and sharing of its data. The developments of associated data products and data applications for use in the fields of ocean, atmosphere, and climate research are discussed, particularly those related to tropical cyclones (typhoons), ocean circulation, mesoscale eddies, turbulence, oceanic heat/salt storage and transportation, water masses, and operational oceanic/atmospheric/climatic forecasts and predictions. Finally, the challenges and opportunities involved in the long-term maintenance and sustained development of the China Argo ocean observation network are outlined. Discussion also focuses on the necessity for increasing the number of floats in the Indian Ocean and for expanding the regional Argo observation network in the South China Sea, together with the importance of promoting the use of Argo data by the maritime countries of Southeast Asia and India.

Key words: China Argo, ocean observation, float development, Argo data, data application

Citation: Liu Zenghong, Wu Xiaofen, Xu Jianping, Li Hong, Lu Shaolei, Sun Chaohui, Cao Minjie. 2017. China Argo project: progress in China Argo ocean observations and data applications. Acta Oceanologica Sinica, 36(6): 1–11, doi: 10.1007/s13131-017-1035-x

1 Introduction

In January 2002, China announced its intention to join the international Argo program (Argo Science Team, 1998), becoming the ninth Argo member state following the USA, France, Japan, UK, Korea, Germany, Australia, and Canada. The China Argo project has two primary objectives: (1) to construct an ocean observing network comprising 100–150 Argo profiling floats in the adjacent northwestern Pacific Ocean and the Indian Ocean, and (2) to become an important member of the Argo program, providing global Argo data and associated data products for oceanic research, marine resources development, marine management, and other related activities in China (Xu, 2002). In the same year, the China Argo project was launched as part of a research program (supported by the Ministry of Science and Technology, China) called the “New generation of ocean real-time observing system—an experiment of Argo observing network”. As of November 2016, China Argo had deployed 374 profiling floats in the Pacific and Indian Oceans and in the Mediterranean Sea (Fig. 1). Among these floats, 198 were Argo equivalent floats (i.e., floats purchased and deployed by national scientific research programs, whose principal investigators have agreed to share data with other Argo members). Overall, about 40 193 temperature and salinity profiles and more than 6 000 dissolved oxygen profiles have been obtained, which accounts for about 2.4% of the global Argo data.

China Argo project is a project intended to have close international collaboration, long duration, and unlimited timely data sharing, and it has promoted the progress of sharing of oceanic data in China. Over the past 15 years, Argo data have become the primary source of oceanic climatological information and they have been used widely in many fields of ocean/atmosphere/climate research, including air–sea interaction, ocean circulation, mesoscale eddies, turbulence, oceanic heat/salt storage and transportation, as well as seawater properties and water masses (Xu, 2006, 2010, 2014; Chen, 2011, 2012). Furthermore, Argo data have also been used in operational forecasts and predictions in the above fields (refer to http://www.argo.org.cn/index.php?m=content&cindex&flists&catid14).

2 Argo data management and product development

At the beginning, the China Argo Real-Time Data Center (C-ARDC) was established in Hangzhou (China), which started to build the Argo data receiving, processing, and distributing system (http://www.argo.org.cn/). This system was intended to handle the different types of profiling float data, and it has been operational for 15 years with considerable and continuous improvement. After decoding and quality control, the data obtained from Chinese floats are all submitted in real time (~24 h) to the two global Argo data assembly centers (GDACs), which are located in France and USA, and then they are made available to users. China is one of nine countries (the others comprise USA, France, UK, Australia, Japan, Korea, India, and Canada) with the capacity to submit quality-controlled Argo observations to the GDACs in real time.

Foundation item: The National Natural Science Foundation under contract No. 41621064; the Science and Technology Basic Work of the Ministry of Science and Technology of China under contract No. 2012FY112300; the Public Science and Technology Research Funds Projects of Ocean under contract No. 201005033.

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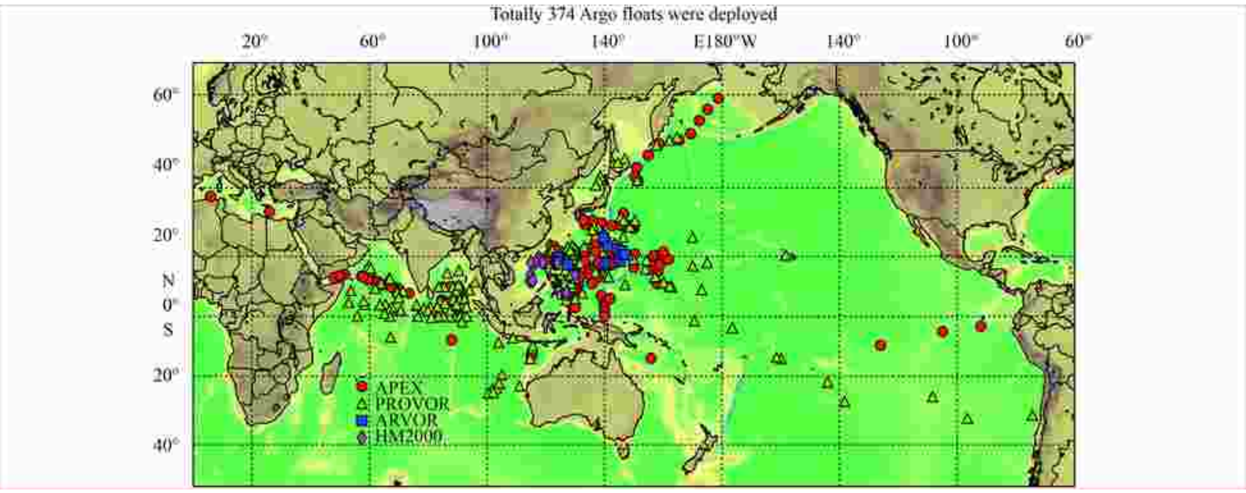

Fig. 1. The launch positions of Chinese Argo profiling floats in period of 2002–2016.

Figure 2 shows the Argo data flow at C-ARDC. Floats using the ARGOS satellite system send their observations to Collecte Localisation Satellites (CLS; Toulouse, France) in hexadecimal format. C-ARDC receives these encoded messages from CLS via the Internet and then performs the appropriate decoding. A unique real-time quality control procedure, specified by the Argo Data Management Team (ADMT) (Wong et al., 2014), is applied to verify the quality of each profile and a quality flag is awarded for each measurement. Then, the data are submitted to the GDACs in a unique format specified by the ADMT (Thierry et al., 2015). Floats using the Iridium satellite have a similar data processing procedure, except their data are delivered via CLS America (Maryland, USA) in a slightly different format. Data from Chinese BeiDou profiling floats are received by a special antenna installed at the "BeiDou Profiling Float Data Service Center" (BDS-PDSC) in Hangzhou, China. It should be noted that the World Meteorological Organization allocates a unique number to each float, which is an identification number for data sharing within the Global Telecommunication System (GTS) and among the GDACs. Since October 2015, data from the floats deployed by China have been submitted to the GTS via the node at the China Meteorological Administration. Prior to this, all data had been submitted to the GTS via CLS.

The goal of the international Argo program is to obtain profiles of temperature and salinity over the global oceans to accuracy of 0.005°C and 0.01, respectively. To guarantee the quality of Argo observations, a delayed-mode quality control that uses historical shipboard conductivity–temperature–depth (CTD) data was proposed at the beginning of the program (Wong et al., 2003; Böhme, 2003; Owens and Wong, 2009). C-ARDC originally established a delayed-mode quality control system for Argo salinity data based on the OW method (Owens and Wong, 2009) and then improved on it in practice (Xu and Liu, 2007; Tong et al., 2004; Liu et al., 2007; Lu et al., 2014). To promote the use of global Argo data among the institutions and universities of China, C-ARDC aperiodically downloads global Argo data from the GDACs and provides it to users in a uniform legible format after performing a posteriori quality control. As of December 2015, approximately 1 400 000 temperature and salinity profiles (partly including dissolved oxygen and chlorophyll) had been collected, processed, and provided to users via the Internet (http://www.argo.org.cn/). Meanwhile, an Argo data sharing platform has been constructed based on distributed database, web services, and OpenGIS technologies to satisfy the requirements for rapid inquiry, display, and downloading of Argo data and its derived products (http://101.71.255.4:8090/flexArgo/out/argo.html).

To address the problem of the irregular spatiotemporal distribution of Argo data, as well as its inadequacies and short time series from the early stages of the Argo program, some research institutions and operational agencies in China have developed various gridded Argo products in combination with historical observations, e.g., expendable bathythermograph (XBT), CTD, ARGOS satellite-tracked drifters, and moored buoys (Wang et al., 2006, 2010; Yang et al., 2008; NMDIS, 2011; Li et al., 2012, 2013, 2014, 2015; Mao et al., 2013; Zhang et al., 2013a). These Argo data products are available online and they have been widely used

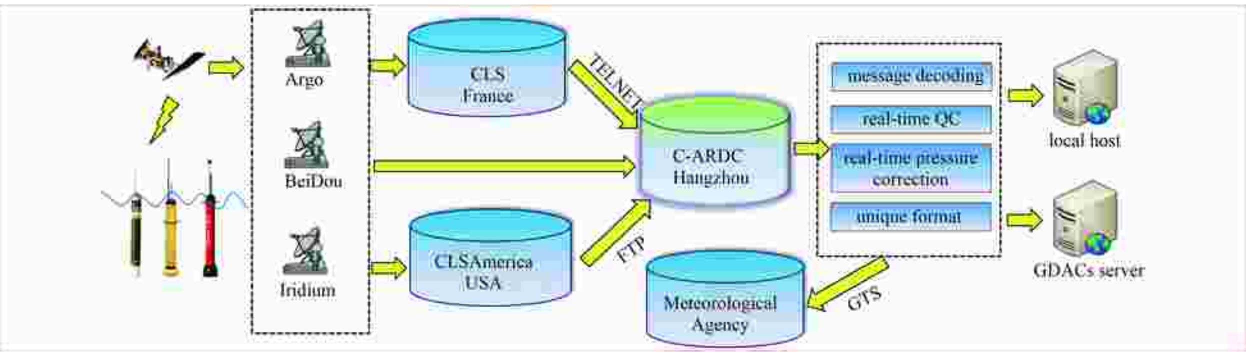

Fig. 2. Data flow of processing at China Argo Real-time Data Center.

(e.g., Jiang and Chen, 2012; An et al., 2012; Zhang et al., 2013b; Gao et al., 2014; Han and Zhou, 2015; Chen and Yu, 2015; Chen and Chen, 2015; Chen and Wang, 2016; Zhang and Xu, 2014, 2015). Based on a simple and effective successive correction method, combined with a mixed-layer model (used to derive sea surface temperature and salinity, because most Argo profiling floats are unable to sample water temperature and salinity above 5 m), C-ARDC developed a monthly global Argo gridded dataset during 2004–2015 with 1°×1° spatial resolution and 58 vertical levels (Li et al., 2016, 2017; Zhao et al., 2016). This dataset was updated at the end of each year and it has been used widely in oceanic research (e.g., Han and Zhou, 2015; Chen and Yu, 2015; Chen and Chen, 2015; Chen and Wang, 2016).

3 Development of profiling floats in China

Since 10th Five-year Plan, the National Ocean Technology Center has started to develop profiling float (called as "COPEX"), and solved the key problems on sealing and pressure proof of the float shell, hydraulic-driven system, autonomous diving and ascending, depth control, satellite communication, and float ballasting method (Yu et al., 2001; Zhang and Lin, 2005; Zhang et al., 2011). An autonomous profiling float that gets satellite fixes and transmits data with BeiDou (BDS) was then manufactured. From 2007 the 710 institute of China Shipbuilding Industry Corporation (CSIC) started to develop their profiling float (called as "HM2000"), and achieved a set of invention patents and technology productions with independent intellectual property rights in terms of the satellite data transmitting terminal, control modules, pressure proof of the float shell, descending and ascending adjustment module. Now an autonomous profiling float using BDS for positioning and transmission is also developed. Owing to a limited coverage of BDS, the BDS profiling floats can only be deployed within the regions including the west of the second island chain in the north Pacific, the SCS, and the Bay of Bengal.

During October–December 2014 C-ARDC deployed two COPEX floats and one HM2000 float in the northwest Pacific for a field comparison. The result from the comparison with shipboard CTD, APEX profiling float and historical nearby Argo data indicates that the observations from BDS profiling floats are reliable (Lu et al., 2016). However the two types of BDS float still need to be improved to meet the requirements of the ADMT to the sampling of measurements and data storage for Argo.

In September 2015, the manufacture of the HM2000 float and technicians from the C-ARDC, in according to the requirement of the ADMT, carried out a standardization of observing information, sampling of measurements, and data storage, which was tested on the 5 HM2000 floats deployed by Institute of Oceanology, Chinese Academy of Sciences in the western boundary current region of the northwestern Pacific. Consequently, the HM2000 float has been accepted by Argo Information Center (AIC) after the AST-16 meeting (Brest, France, 2015). The observations from those floats have been partly shared with international Argo and WMO member states via Internet and GTS, after a strict real-time quality control.

4 Scientific applications of Argo data

Data exchange between China and the other Argo member states provides scientists in China with abundant observations of the open oceans with which they are able to perform leading scientific research. Argo data have become the principal source of ocean climatological information, and they have been used widely in many fields of ocean/atmosphere/climate research, including tropical cyclones (typhoons), ocean circulation, mesoscale eddies, turbulence, oceanic heat/salt content and transportation, as well as seawater properties and water masses.

4.1 *Tropical cyclones*

As early as November 2010, China started to deploy Iridium Argo profiling floats in the northwest Pacific Ocean. Given the high transmission rate and two-way communication of the Iridium satellites, China has been able to undertake intensive investigations during the typhoon season in the northwest Pacific Ocean, and has obtained a large amount of upper-ocean (0–500 m) profile data around typhoon tracks. Those profiles were obtained by Iridium Argo floats with shortened cycle times (2–3 days), which provided abundant in situ observations for studies investigating the response of the upper ocean to typhoons.

The combination of model simulations and data collected by Argo profiling floats and satellites in the northwest Pacific Ocean has allowed considerable research to be undertaken on the upper-ocean response to typhoons (Sun et al., 2014; Wang et al., 2014; Cheng et al., 2015). Satellite data are used to describe the response of the sea surface to tropical cyclones, whereas Argo data are mostly used to reveal the response in the upper ocean. Using subsurface temperature and salinity profiles from Argo floats in the Western Pacific Warm Pool (WPWP), Xu et al. (2005) found that most typhoons caused a decrease in sea surface salinity when they passed over the WPWP, and they argued that freshwater delivered by the tropical cyclones was the reason for the salinity reduction. A statistical analysis of in situ Argo observations from the northwest Pacific Ocean (Liu et al., 2006) showed that typhoon-induced salinity changes within the mixed layer present an almost symmetrical distribution along typhoon tracks. A three-dimensional structure of ocean cooling induced by tropical cyclones in period of 1996–2012 was estimated with Argo temperature profiles over the northwest Pacific for the first time, which indicated the importance of initial oceanic conditions to upper ocean response to tropical cyclones (Wang et al., 2016). Using intensive observations collected by Iridium Argo profiling floats during Typhoon Bolaven, Liu et al. (2014) found that surface and subsurface temperature and salinity exhibited different variations on different sides of the track (Fig. 3). Numerical modeling combined with Argo and satellite data indicated that a typhoon causes deepening of the mixed-layer depth, increases heat flux to the atmosphere from the ocean, and encourages strong upwelling of cold water below the typhoon's center (Pei et al., 2015). Lin et al. (2013a, b, 2014) also used Argo data in their research into the influence of ocean heat content on tropical cyclone intensity and storm surge prediction. They investigated the relationship between the global subsurface ocean warming hiatus and Super-Typhoon Haiyan and proposed a new index called the "ocean coupled potential intensity" for tropical cyclone forecasting.

4.2 *Ocean circulation, mesoscale eddies, and turbulence*

Yuan et al. (2014) derived the absolute geostrophic flow based on Argo data, and revealed a westward geostrophic current below the North Equatorial Current, which was named the North Equatorial Subsurface Current. Wu et al. (2014) also used Argo data to calculate geostrophic currents in the Western Pacific, and they analyzed the variations in the volume of water that flows in and out of the WPWP. Using positioning information from Argo floats, Chen et al. (2006) estimated and analyzed the seasonal and interannual changes of mid-depth currents in the tropical Pacific Ocean (such as the Mindanao Eddy, Equatorial Current, and Equatorial Counter Current). Xie et al. (2005) compared mid-depth currents calculated from Argo positioning information with those obtained from National Centers for Environmental

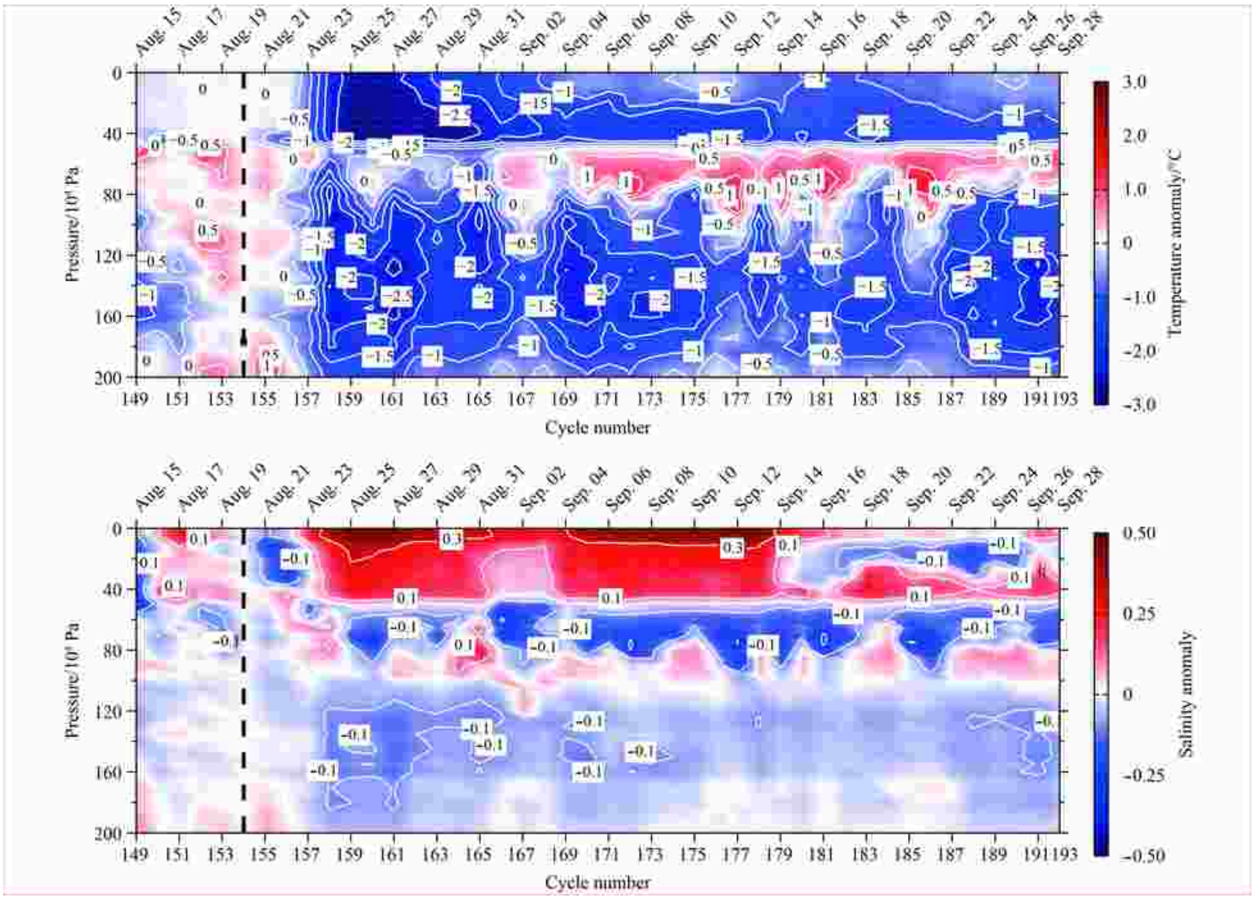

Fig. 3. Vertical section of temperature (a) and salinity (b) anomalies (reference date: August 20) above 200×10⁴ Pa as a function of time (August 15 to September 28) observed by Float 5901989 (Liu et al., 2014).

Prediction (NCEP) reanalysis data. Their results showed that, except for a region near the equator, the velocity of NCEP reanalysis was smaller than that of Argo with an average difference of –2.3 to –1.8 cm/s. In addition, some eddies cannot be resolved correctly because of the dominant zonal currents in the NCEP reanalysis. Xie and Zhu (2008, 2009) also developed a dataset of global ocean surface currents by means of the trajectories of Argo floats. These studies indicate that the dataset derived from Argo floats is a good supplement to the ocean surface current database (Fig. 4). Furthermore, Argo data have been used to calculate the three-dimensional (3-D) flow in the Pacific Ocean, reflecting their suitability in deriving large-scale 3-D ocean currents (Zhang

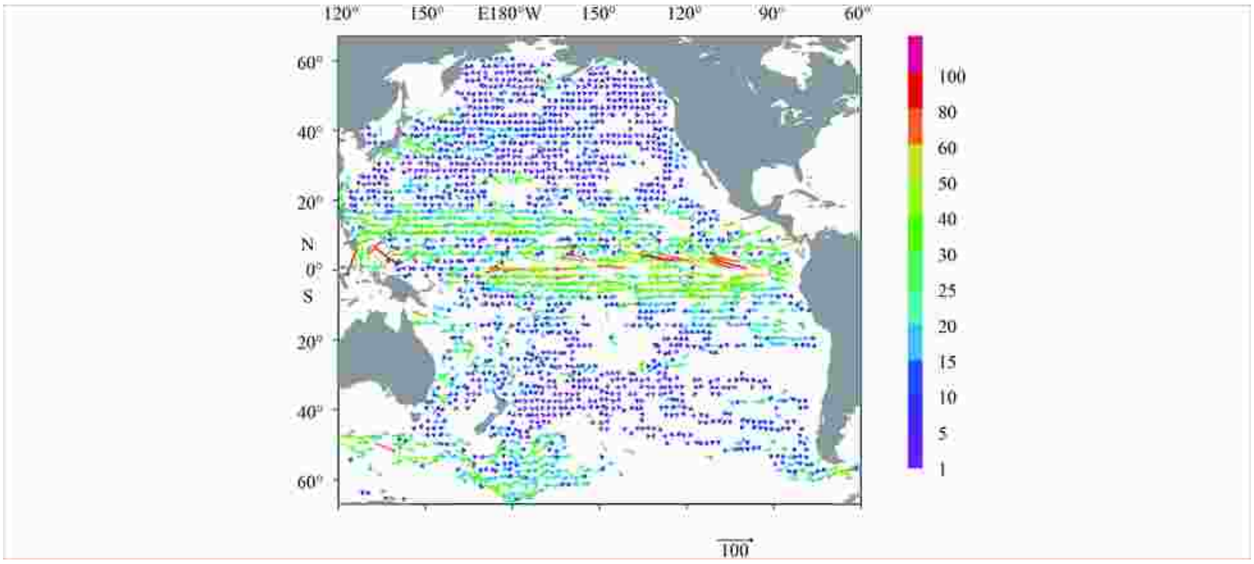

Fig. 4. Mean surface velocity vectors (color scale: cm/s) in the Pacific Ocean obtained using trajectory data of Argo floats (Xie et al., 2009).

et al., 2012).

The North Equatorial Current bifurcates near 13°N to the east of the Philippines, where it divides into two western boundary currents (i.e., the southward Mindanao Current and the northward Kuroshio Current). The Mindanao Current serves as a link connecting tropical and subtropical circulations. The circulations and eddies in this region are of great importance to the understanding of water exchange between the Southern and Northern Hemispheres. However, the variations of the circulations and eddies are so complex that it is impossible to provide their complete description based on a single or several hydrological surveys. Since 2003, China Argo has focused on this area and a number of floats have been deployed successively, one of which captured a mid-depth anticyclonic eddy to the east of the island of Mindanao. In addition to the Mindanao and Halmahera eddies, this constituted another eddy located below the thermocline that reflects mid-depth ocean characteristics (Zhou et al., 2006). Zhou et al. (2010) further analyzed the features of both cyclonic and anticyclonic eddies to the east of Mindanao at intermediate depths (1 000–2 000 m), and they found that the mean tangential velocities of these eddies were about 10 and >20 cm/s at 2 000 m and 1 000 m, respectively. This indicated that the geostrophic calculation might contain large errors because of the vigorous eddy activity at the reference levels. Modeling studies have suggested that mesoscale eddies strengthen the subduction of mode waters; however, this eddy effect has never been observed in the field. Recently, an experiment on this subject was undertaken using Iridium Argo floats (Xu et al., 2016). In this experiment, 17 Argo floats with enhanced daily sampling were deployed in an anticyclonic eddy. The eddy effects on mode-water subduction were captured to the south of the Kuroshio extension, based on over 3 000 hydrographic profiles following the anticyclonic eddy. It was established that the potential vorticity and apparent oxygen utilization distribution are asystematic outside the anticyclonic eddy core, and that enhanced subduction occurs near its southeastern rim.

Wu et al. (2011a) investigated diapycnal mixing of the upper 2 000 m in the Southern Ocean, using high-resolution hydrographic profiles from Iridium Argo floats. They established that the spatial distribution of turbulent diapycnal mixing in the Southern Ocean at depths between 300 m and 1 800 m is controlled by topography, by means of its interaction with the Antarctic Circumpolar Current (Fig. 5). The seasonal variation of this mixing is remarkable, which is largely ascribed to the seasonal cycle of surface wind stress, which is more pronounced in the upper ocean over flat topography.

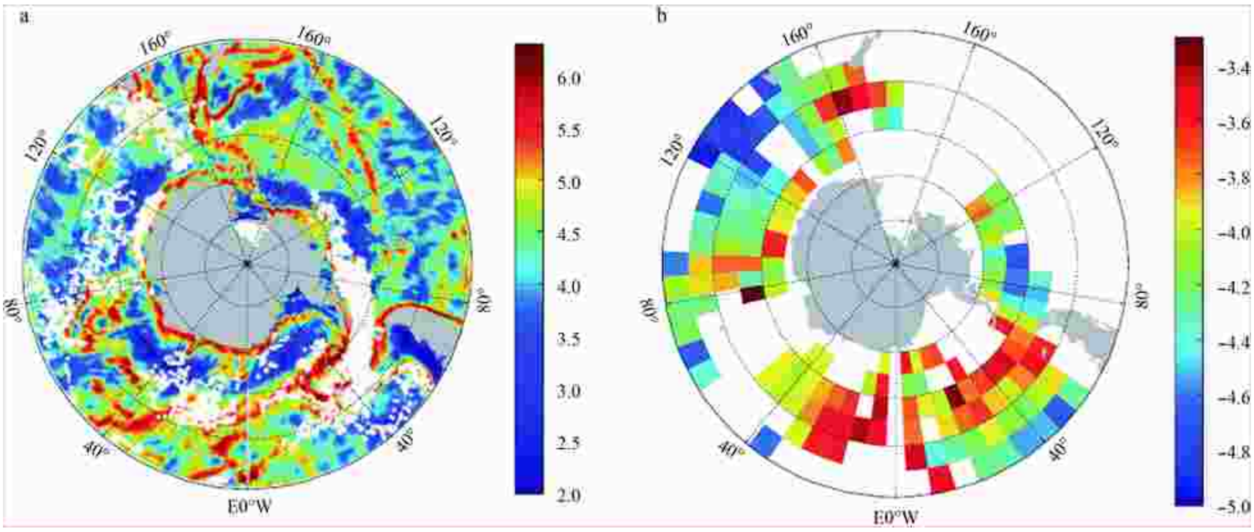

Fig. 5. Horizontal distribution of topographic roughness and diapycnal diffusivity in the Southern Ocean (Wu et al., 2011). a. Topographic roughness and geographic distribution of high-resolution profiles (white dots) obtained from the Argo Iridium floats used in the Southern Ocean and described in this paper. The color scale represents Log_{10}(Roughness) in m^2. b. Horizontal distribution of diapycnal diffusivity vertically averaged over the depth range 300–1 800 m, on a 6°×5° spatial grid. The color scale represents $\mathrm{Log}_{10}K$ in m^2/s).

4.3 *Upper-ocean heat/salt content and transportation*

One of the goals in establishing a global Argo observing network was to estimate the trend of global ocean heat content and freshwater storage. Upper-ocean heat content (OHC) is an important indicator of climate change, and it has a significant influence on global sea level rise. Cheng and Zhu (2014a) indicated that the large jump in OHC during 2001–2003 was real but was an artifact of sample error, reflecting the influence of the transition of the ocean observation network from ship-based observations to the Argo era. Therefore, the selection of the period of climatology and the vertical resolution of a dataset could have considerable influence on the accuracy of OHC estimations (Cheng and Zhu, 2014b, 2015). Wu et al. (2011b) analyzed the temporal and spatial variations of OHC in the tropical western Pacific Ocean, and they found that, except for the well-known east–west antiphase interannual oscillation, the OHC anomaly also has a negative–positive–negative tripole pattern of interannual meridional oscillation. By combining available satellite altimetry and Argo float profile data, Zhang et al. (2014) proposed that eddy-induced zonal mass transport could reach a total meridionally integrated value of up to 30×10^6–$40\times10^6 m^3/s$, and that it occurs mainly in subtropical regions where background flows are weak. This transport is comparable in magnitude to that of the large-scale wind- and thermohaline-driven circulation (Fig. 6).

Yang and Xu (2015) estimated the net meridional heat transport (MHT) through the 15°N section in the Pacific Ocean, and they found that MHT changes occur mainly within 0–800×10^4 Pa. Yang et al. (2015c) analyzed the transportation of heat and salt at-

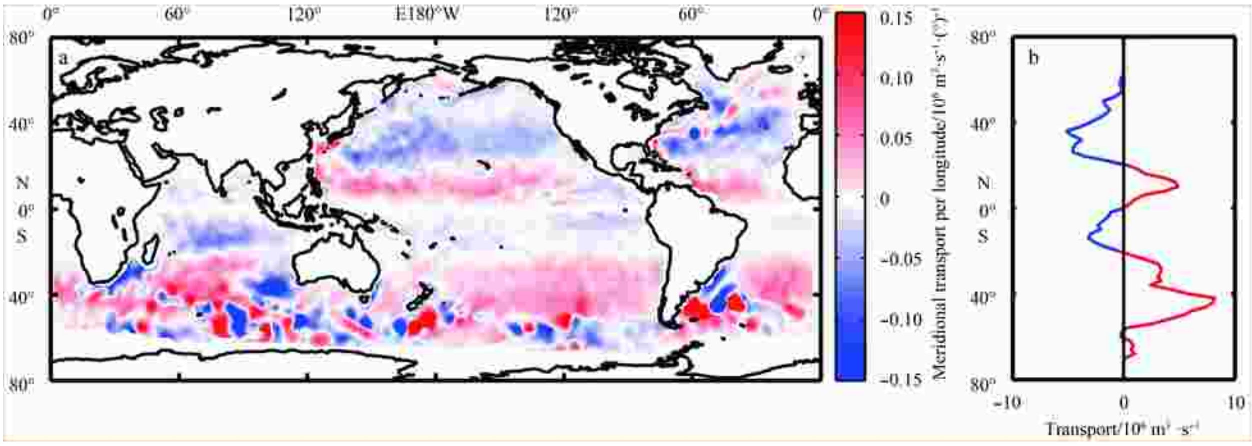

Fig. 6. Global distribution of the meridional transport of fluid trapped by mesoscale eddies (Zhang et al., 2014). a. Eddy-induced meridional transport through a zonal cross section per degree of longitude. b. Distribution of the total zonally integrated meridional transport induced by eddies as a function of latitude.

tributable to mesoscale eddies in the tropical southeastern Indian Ocean. They believed that MHT by cyclonic eddies (anticyclonic eddies) is southward (northward), while salt transport is northward (southward); the meridional heat/salt transportation occurs mainly within 0–300×10^4 Pa.

4.4 *Characteristics of seawater and water masses*

After analyzing the amplitude, phase, and period of interannual variations in the upper-ocean temperature based on the gridded Argo temperature dataset, Chen and Chen (2015) proposed the existence of a “Niño Pipe” between 10°S and 10°N in the Pacific Ocean, the path of which is similar to that of the Equatorial Undercurrent in the Pacific Ocean (Fig. 7). Zheng et al. (2014) and Zheng and Zhang (2015) analyzed the influence of changes in salinity and barrier layer thickness in the Pacific on El Niño–Southern Oscillation (ENSO) events using Argo data. They indicated that interannual change of barrier layer thickness in the Equatorial Pacific presents a “seesaw” zonal pattern of variation during the ENSO cycle, and that salinity would influence the interannual change of barrier layer thickness via adjustment of the mixed-layer depth in the Central Equatorial Pacific. In addition, salinity also plays a very important role in adjusting the sea surface dynamic height in the western tropical Pacific Ocean, and the effect of salinity on sea surface dynamic height is comparable to that of temperature (Zheng et al., 2015). Du et al. (2015) analyzed the decadal (2004–2013) changes of salinity in the tropical Indian–Pacific Ocean using Argo and historical observations. They found that increases in salinity in the western tropical Pacific Ocean and decreases in salinity in the southeastern tropical Indian Ocean are related to enhancement of the Walker Circulation. Argo salinity data have also been used to evaluate the accuracy of Aquarius, SMOS sea surface salinity products (Wang et al., 2015; Yang et al., 2015a).

Argo profile data with high spatiotemporal resolution are convenient for accurate estimations of various parameters of seawater, such as the mixed-layer depth, thermocline, barrier layer, sea surface height, and ocean acoustic field. Using temperature and density criteria, An et al. (2012) calculated the mixed-layer depth of the global oceans and discussed the impact of the barrier layer and compensation layer on the mixed-layer depth. They suggested that the western equatorial Pacific Ocean, Bay of Bengal, and western tropical Atlantic Ocean constitute regions with high incidence of a barrier layer, whereas a compensation layer exists in the subtropical northern Pacific Ocean and the

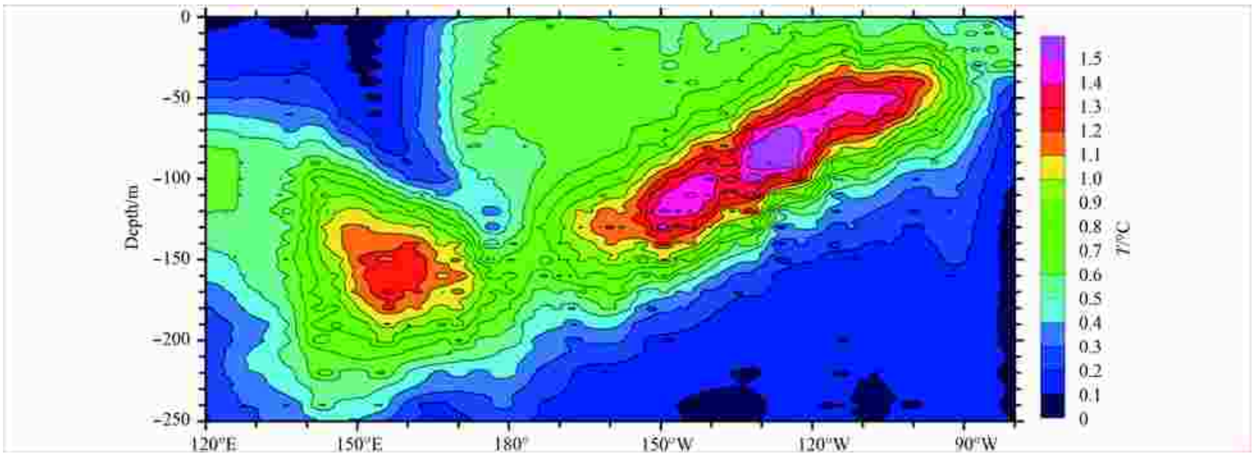

Fig. 7. The Niño Pipe between 10°S and 10°N in the Pacific Ocean (Chen and Chen, 2015). The pipe center gradually deepens from 50 m at 130°E to about 250 m near the date line, after which it then rises to the surface at 85°W. Its path is similar to that of the Equatorial Undercurrent.

northeastern Atlantic Ocean in winter. Yi et al. (2015) calculated the rate of increase of global mean sea level (GMSL) after 2010 using Argo and altimeter data. They highlighted that the GMSL trend is consistent with ENSO fluctuations, and that its rate of increase has been accelerating since 2010. In addition, Argo data have also been used in the analysis of the acoustic field near the Philippine Sea (Zhang et al., 2009), waters east of Taiwan (Zhang et al., 2010), and tropical Indian Ocean.

The temperature and salinity distributions and water mass characteristics in the northwestern Pacific Ocean were analyzed by Xu et al. (2006) and Sun et al. (2008) based on Argo data, and the identification indicators of North Pacific Tropical Water, North Pacific Intermediate Water, and North Pacific Deep Water were given. Based on Argo data collected near the Luzon Strait during 2003–2009, Liu et al. (2011) found that the intrusion of North Pacific Tropical Water into the South China Sea (SCS) peaks in winter. During their study, no obvious intrusion of North Pacific Intermediate Water into the SCS was observed; however, they found a trend for the movement of low salinity SCS intermediate water into the Pacific Ocean. Based on the seasonal variation of Argo temperature and salinity data in the core area of the mode water in the northwest Pacific Ocean, Song et al. (2009) proposed a salinity criterion for determining mode water. Combined with the sea level anomaly, they found that eddies could only temporarily influence the temperature and salinity structure of mode water, before it would return to its initial state. From model simulations, a dual-core low-salinity water mass was found to the west of Luzon Island in the SCS, which appears in July and disappears in October, with its lowest salinity in September (Yan et al., 2015). It is closely related to the precipitation brought by the summer monsoon, and the change of the mixed-layer depth is the principal factor contributing to the formation of the dual cores. This conclusion has been verified by *in situ* data collected by Argo floats with 4-day temporal resolution.

5 Application of Argo data in operational forecasts and predictions

Current data assimilation techniques have been able to integrate a great quantity of conventional data (e.g., shipborne, XBT, CTD, TAO, and Argo) and unconventional data (e.g., various remote sensing satellites and radars) into oceanic numerical models, to obtain physical variables (e.g., temperature, salinity, sea surface height, and currents) that can truly reflect the state of the oceans. These parameters can be used to provide initial and open boundary conditions that are more accurate for ocean circulation and ocean–atmosphere coupled models, which can improve the accuracy of climate predictions.

As early as 2004, Argo data have been used in the optimization of physical processes in data assimilation and model simulation (Zhang et al., 2004), as well as in the improvement of ENSO and the enhancement of summer precipitation predictions in China (Zhang et al., 2006, 2013c) (Fig. 8). Argo data can provide initial signals of significant oceanic abnormalities for short-term climate predictions of the Global Ocean Data Assimilation Operational System of the National Climate Center of China (Liu et al., 2005). This system, which is transitioning into its second generation (Wu et al., 2013; Zhou et al., 2016), plays an important role in improving ENSO predictions as well as enhancing the capability of operational global climate predictions. Furthermore, it has demonstrated improved capability in capturing interannual and interdecadal changes in the sea surface height of the tropical Pacific Ocean, as well as the signals that indicate two types of El Niño.

The team led by Zhu Jiang of the Institute of Atmospheric Physics, Chinese Academy of Sciences, developed a 3-DVAR-based Ocean Variational Analysis System (Zhu et al., 2006), which is able to effectively assimilate Argo, TAO, XBT, ship-based observations, and sea surface height anomalies obtained by altimeters. After assimilation, both temperature and salinity accuracies are greatly improved than priority. This system has been installed in the operational assimilation system for the tropical Pacific Ocean, at the National Marine Environmental Forecasting Center, to release real-time temperature and salinity reanalysis products of the tropical Pacific Ocean. It makes China one of the countries with the capacity to release temperature and salinity reanalysis products, and to provide powerful support for the prevention and reduction of natural disasters, weather forecasts, and sudden incident handling. Another data assimilation system (China Ocean Reanalysis) for China's seas, developed by the Na-

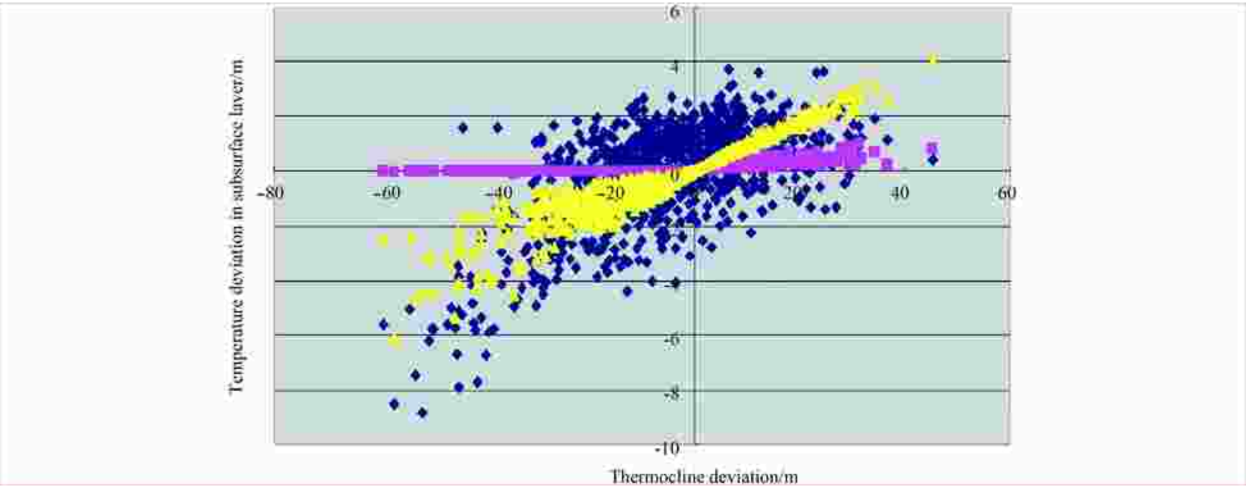

Fig. 8. Comparison of observed relationship between subsurface temperature anomaly and mixed-layer depth in the tropical western Pacific Ocean and that calculated by the parameterization scheme in the Zebiak–Cane oceanic model. The blue color represents observations, and the pink and yellow colors represent the original parameterization scheme and that improved with Argo data, respectively (Zhang et al., 2013).

tional Marine Data and Information Center, has been extended to the global oceans (Han et al., 2011, 2013). This system is based on a multiscale 3-DVAR and combined POM model, which provides better estimations of heat content, Atlantic Ocean meridional overturning currents, and equatorial Pacific Ocean subsurface currents.

The Argo program provides continuous and unprecedented data for ocean data assimilation, and the advantages it offers for data assimilation and operational predictions and forecasts have been widely reported. In addition, Argo data have also been applied successfully in the field of marine fishery (Zhang et al., 2014; Yang et al., 2015b). With further extension and maintenance of the global Argo network, Argo data are expected to play an increasingly important role in optimizing assimilation methods, improving the parameterization schemes of numerical models, and enhancing the capability of operational ocean and climate predictions.

6 Challenges and prospects

Argo has not only become the principal data source for physical oceanographic research from basin to global scales, but Argo data have also been used widely in operational oceanic and atmospheric forecasts and predictions. The future development of the Argo program is described in the article “Fifteen years of ocean observations with the Argo array, ” which was co-authored by 27 scientists from 18 countries early in 2016 (Riser et al., 2016). In that article, it was stated “It is possible that a decade or two from now the science community will barely recognize the deployment strategies or the instruments being used by Argo or its successor programmes at that time”. For this reason, the international Argo Steering Team has suggested continuing with the current long-term plan for the next few years, stressing the importance of maintaining the existing array over the longer term, while moving in new directions by deploying floats (and adding new sensors) in new and special regions, and designing and testing floats capable of operation in the abyss. The goals are to sustain the present level of systematic observation of the global oceans and to improve the assessment of the ocean’s role on climate. The article also stressed that the development of deep Argo is likely to be a particularly crucial step in the evolution of the program. The present array has demonstrated its value in providing estimates of the change in heat content of the upper 2 000 m of the global oceans over the past few decades, but these have been somewhat smaller than the predictions of model-based global heat budgets. Some studies have indicated that the deeper waters of the global oceans, currently beneath the present limits of Argo sampling (~2 000 m), could act as a repository of the increased heating necessary to close the global heat budget. The implementation of deep Argo observations and observations of the oceanic carbon cycle from floats will help improve forecasts of ENSO and the Indian Ocean dipole, and increase our understanding of the circulation of the ocean and its role in the climate system (Castelao, 2014).

In the future, the international Argo program will be sustained and its goals developed from those of “Core Argo” to “Global Argo” (http://www.argo.ucsd.edu/). Although certain achievements have been realized in the application of Argo data in China, many aims of leading international science remain to be addressed, e.g., the estimation of global ocean velocity with Argo trajectories and its application in the validation of ocean currents (Ollitrault and Rannou, 2013; Ollitrault and de Verdière, 2014; Gray and Riser, 2014), improvement on studies of complex spatial variations using Argo data (Castelao, 2014), construction of North Atlantic meridional overturning circulation, and high-resolution 3-D temperature time series based on sea surface height anomaly derived from Argo *in situ* observations combined with satellite altimeter data (Mercier et al., 2015; Guinehut et al., 2012). Argo subsurface temperature data have been assimilated in many newly developed climate models, leading to evident improvement in the predictability of atmospheric intraseasonal oscillations, monsoon activity, and air–sea interaction (e.g., ENSO) (Chang et al., 2013). The Kuroshio, strong western boundary current transports heat from the tropics and subtropics to the high latitudes; thus, considerable heat exchange with the atmosphere occurs along its path. Furthermore, some currents separate from the boundaries into the ocean interior or coastal waters, which would probably affect the tracks of storms or ameliorate continental climate (Kwon et al., 2010). Currently, floats with sensors that can detect dissolved oxygen, nitrate, chlorophyll, and pH are able to monitor the effects of the ocean circulation on key climatological and biogeochemical process (e.g., the carbon cycle, oceanic hypoxia, and ocean acidification) from a physical perspective (Johnson et al., 2009). Moreover, the observations recorded by these newly developed floats will enhance the capability of biogeochemical modeling (Brasseur et al., 2009). In addition, recent studies have investigated waters deeper than 2 000 m, especially in the high latitudes of the Southern Ocean, and they have made considerable contributions to studies of global sea level rise (Fukasawa et al., 2004; Johnson et al., 2008; Purkey and Johnson, 2010, 2013). Thus, it is evident there are many further challenges in basic research and operational applications to be addressed with Argo data.

In the past 15 years, although China has deployed over 360 Argo floats, this accounts for only 3% of the total number of floats distributed over the global oceans, a contribution that is far behind that of USA (>50%), Australia, France, and Japan. Although the global Argo observing network is currently maintained by more than 30 countries and its data are made freely available, countries in Southeast Asia and around the Indian Ocean, who suffer the effects of typhoons, storm surges, ocean waves, and tsunamis, benefit little from this network. Although China and India joined the international Argo program early after its inception, their number of floats account for only 6% of the total. In addition, the number of floats in the Indian Ocean is much smaller than in the Pacific and Atlantic Oceans and currently, it does not meet the initial target of the Argo program. The SCS regional Argo observing network is being constructed but it is maintained by a country outside the region. It is imperative that the floats in the Indian Ocean and of the SCS regional Argo observing network be operated by countries within the region, and that Argo data applications are promoted by and for the countries of Southeast Asia and around the Indian Ocean. Therefore, China should grasp the successful development of the BeiDou profiling float, and the extension of the international Argo program from “Core Argo” to “global Argo” (Riser et al., 2016), as an opportunity to construct a regional Argo observing network in the western boundary current region (typhoon genesis region) and SCS, with planned gradual extension to the Bay of Bengal and Arabian Sea. The ultimate target is to construct a regional Argo observing network composed of at least 400 profiling floats (mostly Chinese BeiDou profiling floats) that will cover the region of the “Maritime Silk Road”. This would become an important component of the “global Argo” program, enhance cooperation and exchange between China and other countries along the “Maritime Silk Road”, and promote Argo applications in basic research and operational forecasts and predictions in the region.

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