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Twenty years of ocean observations with China Argo

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Abstract

The international Argo program, a global observational array of nearly 4 000 autonomous profiling floats initiated in the late 1990s, which measures the water temperature and salinity of the upper 2 000 m of the global ocean, has revolutionized oceanography. It has been recognized one of the most successful ocean observation systems in the world. Today, the proposed decade action "OneArgo" for building an integrated global, full-depth, and multidisciplinary ocean observing array for beyond 2020 has been endorsed. In the past two decades since 2002, with more than 500 Argo deployments and 80 operational floats currently, China has become an important partner of the Argo program. Two DACs have been established to process the data reported from all Chinese floats and deliver these data to the GDACs in real time, adhering to the unified quality control procedures proposed by the Argo Data Management Team. Several Argo products have been developed and released, allowing accurate estimations of global ocean warming, sea level change and the hydrological cycle, at interannual to decadal scales. In addition, Deep and BGC-Argo floats have been deployed, and time series observations from these floats have proven to be extremely useful, particularly in the analysis of synoptic-scale to decadal-scale dynamics. The future aim of China Argo is to build and maintain a regional Argo fleet comprising approximately 400 floats in the northwestern Pacific, South China Sea, and Indian Ocean, accounting for 9% of the global fleet, in addition to maintaining 300 Deep Argo floats in the global ocean (25% of the global Deep Argo fleet). A regional BGC-Argo array in the western Pacific also needs to be established and maintained.

Key words: Argo program, China Argo, ocean observation, core Argo, Deep Argo, BGC-Argo

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1 Introduction

In 1998, scientists from the United States (U.S.), Australia, France, and Japan proposed a design for a global array of autonomous profiling floats to strengthen the capability of researchers to obtain temperature and salinity measurements of the upper ocean (Argo Science Team, 1998). This array, known as Argo, was initially named as an abbreviation of "Array for Real-time Geostrophic Oceanography". The initial design of Argo required the deployments of over 3 000 profiling floats in a 300 km× 300 km array covering the ice-free regions of the world ocean (Argo Science Team, 1998), and is known as "core Argo"; this array only measures the water temperature and salinity of the upper 2 000 m of the global ocean. The profiling floats used in Argo are freely drifting instruments that achieve descent and ascent by changing their buoyancy. When a float is deployed at the sea surface, it dives to a nominal depth of 1 000 m (known as the parking depth) and drifts freely with the ocean current for ~9 days. It then dives another 1 000 m, reaching 2 000 m depth, and ascends to the sea surface at a speed of ~10 cm/s. During its ascent, it measures water temperature and salinity with the mounted CTD sensor (Table 1). When the float reaches the sea surface, the data are transmitted to land stations via satellite, and the float then descends to the parking depth to begin another cycle (Roemmich et al., 2009).

By the end of 2007, the initial design of 3 000 core Argo floats was reached through the joint efforts of more than 30 countries

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Table 1. Comparison of abbreviation and full name

Abbreviation	Full name
ADMT	Argo Data Management Team
ACC	Antarctic Circumpolar Current
AOML	Atlantic Oceanographic Meteorological Laboratory
AST	Argo Steering Team
BGC	biogeochemical
BUFR	binary universal form of the representation of meteorological data
CAS	Chinese Academy of Sciences
CLS	Collect Localisation Satellites
CMA	Chinese Meteorological Administration
CSIO	Second Institute of Oceanography, MNR, China
CTD	conductivity-temperature-depth
DAC	Data Assembly Center
DIN-EOF	data interpolating empirical orthogonal function
DMQC	delayed-mode quality control
FNMOC	Fleet Numerical Meteorology and Oceanography Center
GDAC	Global Data Assembly Center
GDCSM	gradient-dependent correlation scale method
GOOS	Global Ocean Observing System
GTS	Global Telecommunication System
GTSPP	Global Temperature and Salinity Profile Programme
HSOE	Qingdao Hisun Ocean Equipment Co., LTD
IAP	Institute of Atmospheric Physics
IPRC	Research at International Pacific Research Center
ISAS	*in situ* analysis system
JAMSTEC	Japan Agency for Marine-Earth Science and Technology
MBT	mechanical bathythermograph
MLP	mixed layer pump
MOST	Ministry of Science and Technology
MNR	Ministry of Natural Resources
NMDIS	National Marine Data and Information Service, MNR, China
NMEFC	National Marine Environmental Forecasting Center, MNR, China
NOAA	National Oceanic and Atmospheric Administration
NOTC	National Ocean Technology Center, MNR, China
OHC	ocean heat content
OI	Optimal Interpolation
OUC	Ocean University of China
POGO	Partnership for Observation of the Global Oceans
QC	quality control
RUDICS	Router-Based Unrestricted Digital Internetworking Connectivity Solutions
SBD	short-burst data
$SDSL_{EOF}$	sterodynamic sea-level estimated by EOF method
$SDSL_{TG}$	sterodynamic sea-level estimated by tide-gauge residuals
SHOU	Shanghai Ocean University
SOA	State Oceanic Administration
SSS	sea surface salinity
TESAC	temperature, salinity and current report
UN	United Nations
WMO	World Meteorological Organization
XBT	expendable bathythermograph
ZJU	Zhejiang University

worldwide. Now, with ~3 900 active floats across the global ocean, the Argo program has become a major component of the GOOS, which provides a description of the mean state and variability of the upper 2 000 m of the global ocean on seasonal to decadal timescales (Roemmich and Owens, 2000; Riser et al., 2016; Wong et al., 2020; Johnson et al., 2022). An open data policy at all levels of processing was implemented when the array was initially designed. Data acquired by this array are publicly and freely available via the two GDACs, which makes the Argo program a pioneer in scientific ocean data delivery (Wong et al., 2020).

Over the past decade, new sensors have been installed onto the profiling floats that allow BGC variables (e.g., dissolved oxygen, chlorophyll, backscattering, nitrate, pH, downwelling irradiance) to be measured in real time (Johnson et al., 2009; Claustre et al., 2010; Biogeochemical-Argo Planning Group, 2016). In addition, new ice-detection algorithms have been developed that greatly increase the survival rate of floats in regions with seasonal ice cover (Wong and Riser, 2011, 2013). The development of Deep Argo has been recognized as a crucial step in the evolution of the Argo program (Riser et al., 2016). An initial design of the Deep Argo array (5°×5°×15-day target) of ~1 200 floats has been proposed by Johnson et al. (2015) to provide the capacity to resolve global decadal trends in ocean heat content and thermosteric sea level anomalies, which is considered to be necessary for a complete accounting of the Earth's heat budget (Hakuba et al., 2021; von Schuckmann et al., 2020). Since that proposal, pilot deployments of hundreds of 4 000-m and 6 000-m profiling floats have been implemented by countries such as the U.S., Japan, and France, and the performances of Deep Argo CTDs are being tested and improved. Today, the renamed international Argo program, "OneArgo", has been endorsed by the "United Nations Decade of Ocean Science for Sustainable Development (2021–2030)," which is expected to transform the revolutionary core Argo array into one with truly global reach, including the polar oceans and marginal seas, extending to the full ocean depth and including ocean biogeochemical measurements (Roemmich et al., 2019a; Johnson et al., 2022).

China's participation in the Argo program was suggested at the 14th joint working group meeting of the U.S.-China Marine and Fishery Science and Technology Protocol (Hangzhou, China, 1999). As early as 2002, China formally joined the international Argo program with the State Council's approval, becoming the ninth country to participate in this program (Xu, 2002; Xu and Liu, 2007; Liu et al., 2017). The initial objectives of China Argo were to construct a real-time observation network comprising 100–150 Argo floats in the adjacent northwestern Pacific Ocean and Indian Ocean, and to become an important member of the international Argo program, providing global Argo data and related data products for oceanic research, weather and climate forecasts, marine resources development and protection in China (Xu, 2002). After two decades, the objectives of China Argo have been fully realized. The Argo data have become a primary data source of fundamental research and operational forecast and prediction of ocean states, weather, and climate.

This paper reviews the progress achieved in the first two decades of China Argo since 2002, including float deployment, data acquisition, data QC, product development, float technology development, and extension of China Argo. Finally, some perspectives on the future development of China Argo are also provided.

2 Implementation status of China Argo

2.1 *Float deployment*

The first China Argo float deployment (led by Weidong Yu, First Institution of Oceanography, SOA) took place in March 2002 in the tropical eastern Indian Ocean. In January 2003, a pilot project supported by the MOST, China Argo deployed the first set of 13 floats (seven PROVOR and six APEX floats) in the Philippine Sea, symbolizing the initial implementation of China Argo. The float deployment of China Argo has been sponsored by the MOST, SOA (incorporated into the MNR in 2017), and other government agencies. By the end of 2021, 544 floats had been deployed in the Pacific Ocean, Indian Ocean, Atlantic Ocean, and Southern Ocean, and some of them were deployed in marginal seas such as the South China Sea, Sea of Japan, Mediterranean Sea, and Bering Sea (Fig. 1), accounting for approximately 3% of the global deployment. These floats were provided by 16 scientists from the three institutions of oceanography and the NMEFC of the MNR, the two institutions of oceanography of the CAS, OUC, SHOU, and ZJU. Unlike countries such as the U.S., Japan, France, the United Kingdom (U.K.), Canada, and India, whose national Argo programs are typically funded by the budget in each fiscal year, China Argo is mainly sponsored by research programs, leading to notably unstable yearly deployment over the past two decades (Fig. 2). The maximum yearly deployment (91 floats) occurred in 2014; however, most yearly deployments have been fewer than 40 floats. The deployment of China Argo has focused on regions such as the northwestern Pacific Ocean, South China Sea, and Indian Ocean, which have important impacts on China's climate and weather, disaster forecasts and prevention, and marine transportation.

APEX (Teledyne Webb Research, U.S.), PROVOR (NKE Instrumentation, France), and HM2000 (HSOE, China) are the principal float models used in China Argo, accounting for ~92% of the floats that China has deployed. In the past five years, with the development of float and sensor technology, BGC and Deep Argo floats such as PROVOR_IV, NAVIS_BGCi, and ARVOR_D have been used by China Argo (Fig. 3). For each float used by the Argo program, temperature and salinity (core variables) are the two elemental and necessary variables that a float must observe; in other words, the core Argo is the basic mission of the Argo program. In addition to temperature and salinity, more than 50 BGC floats deployed by China Argo have enabled us to obtain data on dissolved oxygen concentration, chlorophyll, particulate backscattering, downwelling irradiance, nitrate, and pH profiles in the upper 1 000 m or 2 000 m.

2.2 *Data acquisition*

Of the 544 floats deployed by China Argo, 539 have reported and transmitted data successfully via satellites (ARGOS, Iridium, and Beidou). As of December 2021, approximately 70 353 core profiles and 15 311 BGC profiles had been observed and processed (see Table 2), accounting for 2.8% of the total core (temperature and salinity) profiles collected by the Argo program.

In the early period of Argo, almost all floats transmitted their data via the ARGOS satellite system operated by CLS (Toulouse, France). This is a one-way and low-bandwidth satellite system, with data throughput of no more than 1 bit/s. To guarantee error-free data reception and location in all weather conditions, it takes at least 10 h for floats to transmit data at the sea surface. At present, approximately 89% of the active floats in the China Argo float array use the Iridium satellite constellation for data transmission. For this satellite system, users often receive data via RUDICS when large quantities of data are to be transmitted, such as those from BGC-Argo floats with multiple sensors and high-resolution sampling schemes. Another method is to use SBD for data transmission; for instance, data (SBD messages) from several PROVOR and PROVORDOI (with additional dissolved oxygen sensor) floats deployed by China are transferred to users via e-mail. The Iridium satellite system is a two-way communication system, users are able to send commands to modify the mission configuration of a float. In recent years, the Beidou navigation system has been adopted for profiling floats manufactured by China (e.g., the HM2000 float). In addition to positioning, the Beidou satellite system has the capacity to transmit short messages (~1.25 bytes/s). Like the Iridium system, the Beidou satellite system is also a two-way communication system.

2.3 *Data assembly centers*

To process (including data decoding, quality control, and data encapsulation and distribution) the data obtained by the floats in the global Argo fleet, countries such as the U.S., U.K., Australia, Japan, Korea, India, Canada, and France have established DACs. All the data assembled by DACs are immediately submitted to the two GDACs: the Coriolis Data Center in France and the U.S. Navy's FNMOC. In China, there are two DACs: CSIO DAC, the China Argo Real-time Data Center at the Second Institute of Oceanography, MNR, and NMDIS DAC, the China Argo Data Center of the NMDIS, MNR. CSIO DAC processes data from the majority of China Argo floats (97% of the floats deployed as of December 2021), and NMDIS DAC processes data from the remaining floats.

CSIO DAC was established in 2002 with the support of the MOST and SOA, and submitted the first core profile from Float 5900019 to the GDACs. The Argo processing procedure was initially developed in 2002, by two young CSIO technicians whom

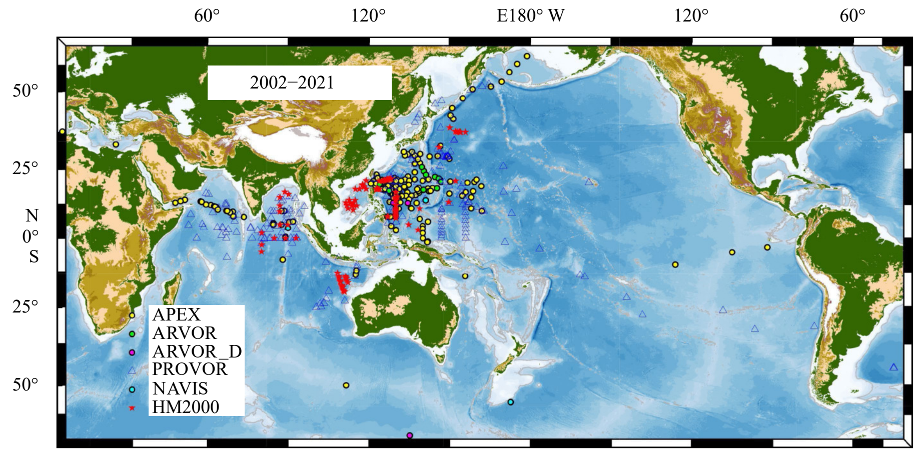

Fig. 1. Launch positions of all China Argo floats since 2002 (various float models are denoted by different markers).

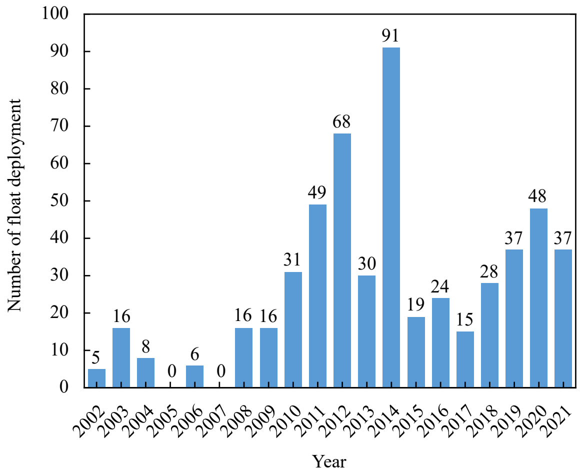

Fig. 2. Number of float deployments by year from March 2002 to December 2021.

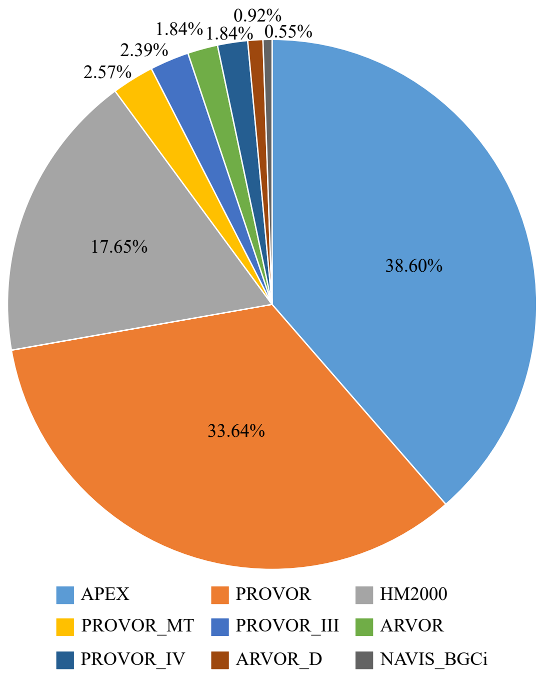

Fig. 3. Percentages of the float models deployed by China Argo.

received POGO-sponsored technical training at NOAA's AOML in Miami. Because of the application of diverse new firmware versions of various float models, this procedure could no longer satisfy the needs of automatic data processing. Therefore, CSIO developed a new Argo data processing system in 2014 (Fig. 4). Allowing data from the majority of profiling floats (including BGC-Argo floats with fully equipped sensors) used by the Argo program to be processed automatically in real time, this system has been operating for the last seven years. In addition, the profile data are encoded into TESAC or BUFR messages, and over 90% of the profiles have been inserted into the GTS within 12 h via the GTS node at the CMA (Tran, 2019).

Table 2. Numbers of profiles observed grouped by variables (2002–2021)

Variables	Number of profiles observed
Temperature and salinity	70 353
Dissolved oxygen	2 635
Chlorophyll *a*	2 148
Particulate backscattering (700 nm)	2 148
FDOM (fluorescent dissolved organic matter)	1 811
Downwelling irradiance (412/443/490 nm)	3 618
PAR (photosynthetic available radiation)	1 206
Nitrate	1 373
pH	372

2.4 *Data quality control*

Upon the operation of the China Argo DACs, the unified data QC procedures specified by the ADMT have been applied. At the beginning of the Argo program, an initial design of Argo CTD QC, including a set of automatic quality tests, was drafted based on the QC tests of the GTSPP. Each DAC is required to apply these QC tests and assign quality flags to each core profile within 24 h after the data are received. That is called Argo Real-Time QC, and through this process, grossly bad data that may result from sensor malfunction or corrupted satellite transmission can be detected (Wong et al., 2020, 2022).

Because Argo floats are disposable instruments, retrieving floats for sensor recalibration is nearly impossible; thus, float data, especially salinity measurement, can be affected by sensor drift caused by biological fouling and biocide leakage into the conductivity cell (Wong et al., 2003, 2020). To calibrate the data affected by sensor drift, DMQC methods and toolkits were developed (Wong et al., 2003; Böhme and Send, 2005; Owens and Wong, 2009), which are typically conducted for the first time 12 months after float deployment (Wong et al., 2020). The effect of adjustment relies upon the quality and quantity of the nearby CTD reference data set; therefore, it is critical to collect recent

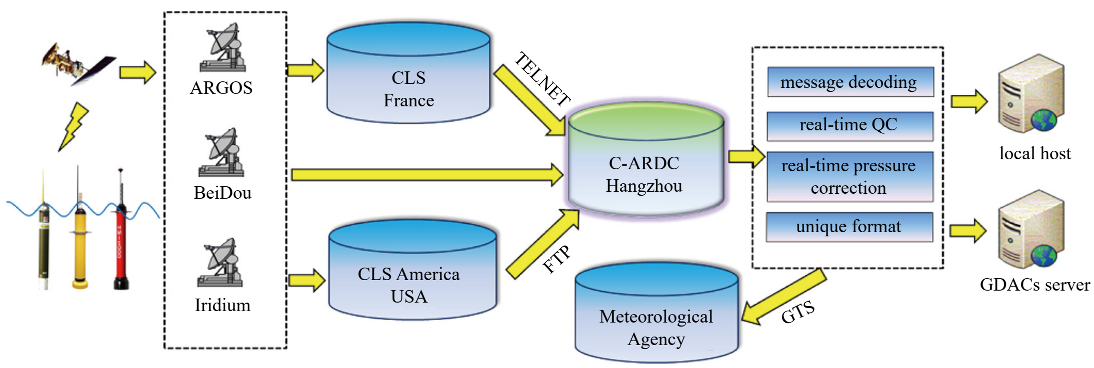

Fig. 4. Diagram of the Argo data processing system operating at CSIO (Liu et al., 2017). Note that C-ARDC is the same as CSIO DAC.

high-quality shipboard CTD casts for Argo DMQC. At present, China Argo is making use of the OWC toolkit (https://github.com/ArgoDMQC/matlab_owc) for DMQC of all floats. The DMQC operator typically sends the results of comparisons between float data and the historical time-series to the scientists or experts from the DAC, who will then determine whether the adjustment will be adopted based on their knowledge of the regional oceanography. As of December 2021, approximately 75% of the core profiles acquired by China had been subjected to DMQC.

When a core profile is submitted to the Coriolis GDAC, a statistical procedure (Gaillard et al., 2009) and a daily MIN/MAX test (Gourrion et al., 2020) for detecting outliers are performed. If a profile fails these tests, a warning e-mail is sent to the associated DAC, where further examination will be implemented and anomalies flagged.

Of the 544 floats deployed by China Argo, 59 are BGC-Argo floats with a range of biogeochemical sensors. Because QC methods and procedures for all BGC variables are still under development, in the early stage, CSIO DAC did not conduct any QC tests for BGC variables. In 2019, CSIO DAC began to conduct delayed-mode bio-fouling tests on the dissolved oxygen profiles from 14 PROVORDOI floats deployed by OUC in 2014, to identify and flag oxygen measurements suspected of contamination by bio-fouling. Recently, standard RTQC procedures for oxygen and chlorophyll profile data have been determined by the BGC-ADMT; thus, CSIO has begun to follow these procedures to produce adjusted data in real time.

2.5 *Global Argo data set repository*

By the end of 2021, the Argo program has obtained more than 2.5 million core profiles from over 17 000 profiling floats. Various data quality problems still exist in the global data set because of uneven levels of data processing by different DACs and anomalous profiles resulting from sensor drift without timely adjustment. Therefore, CSIO developed a fast reception and post_QC system for global Argo data based on the QC method used by the ADMT combined with the practices and improved methods proposed by various DACs (Li et al., 2020b; Liu et al., 2021). With this system, the local host at CSIO is able to synchronize with the remote host at the Coriolis GDAC four times a day; the updated data are then added to the post_QC system, and anomalies in each core profile are detected and re-flagged. The ISAS13 climatology (Gaillard, 2012), a high-quality temperature and salinity climatology data set, is employed as a reference field to detect sensor drift in Argo core profiles. If a temperature or salinity measurement falls beyond ±6.5 times the standard deviation derived from the nearby climatology values, the measurement is flagged as a suspicious point (the whole profile is flagged if more than 1/3 points are beyond the threshold). Finally, the post_QC data are subjected to visual examination by oceanographic experts and re-flagged when necessary. The data set is expected to be updated quarterly and made freely available via the CSIO's FTP site (ftp://ftp.argo.org.cn/pub/ARGO/global/core). Approximately 2 551 028 temperature and salinity profiles were downloaded from the GDACs, ranging from July 1997 to December 2021, 2 411 825 of which were retained after QC, accounting for approximately 94.5% of the total profiles (Fig. 5). The daily post_QC Argo data set provided by CSIO (excluding the visual examination) has been transferred to several departments and institutions for application in their operational forecast and reanalysis systems. The data set has also been used to evaluate the quality of remotely sensed sea surface salinity (SSS) (Yan et al., 2021), and the results indicated the high quality of this data set.

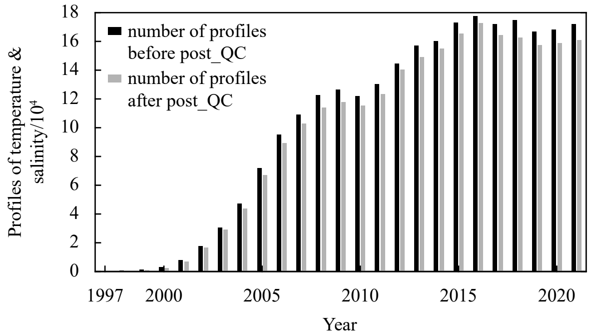

Fig. 5. Numbers of temperature and salinity profiles provided by the GDACs from 1997 to 2021. Gray indicates the number of profiles after QC; black shows the number of profiles before QC.

In addition to temperature and salinity, the BGC profiles provided by the GDACs are also synchronized daily to the local host. To date, the QC procedures for most BGC variables are still under revision, and the original quality flags assigned by the associated DAC are used, no BGC measurements will be re-flagged in our present system before they are written in a readable txt file.

2.6 *Development of Argo products*

The Argo fleet, comprising over 3 500 floats, provides more than 120 000 temperature and salinity profiles each year across the global ocean, although these floats are unevenly distributed both in time and space. To facilitate the usage of the Argo data in the oceanographic and atmospheric realms, different groups around the world have developed various products based on Argo data in addition to other data sources. These products are typically monthly averaged fields, and include measurements such as temperature, salinity, and mixed layer depth (Ridgway et al., 2002; Hosoda et al., 2008; Roemmich and Gilson, 2009; Good et al., 2013; Gaillard et al., 2016; Holte et al., 2017).

The first gridded product of China Argo was developed by Wang et al. (2006) based on a data interpolating empirical orthogonal function (DIN-EOF) method. It contains a three-dimensional temperature, salinity, and ocean velocity data set across the Pacific Ocean. Subsequently, related products were developed, which have been particularly useful in investigations of physical oceanography and climate change (Li et al., 2013, 2017; Liu et al., 2017; Cheng et al., 2017; Li et al., 2020a). Some gridded products combine Argo data with other observations (such as data from gliders, CTD probes, XBTs, and MBTs) and extend back to 1940–1960 (Cheng et al., 2017; Li et al., 2020a). However, the products developed in the early stage were generally regional in scale and rarely updated, which greatly limited their further usage. In this context, we introduced the applications of products with global coverage and that are routinely updated: BOA_Argo (Li et al., 2013, 2017; Lu et al., 2020), IAP data (Cheng and Zhu, 2016; Cheng et al., 2020; Li et al., 2020a), and GDCSM_Argo (Zhang et al., 2013).

2.6.1 *BOA_Argo data set*

BOA_Argo, a global gridded Argo data product developed by CSIO in 2012 (ftp://data.argo.org.cn/pub/ARGO/BOA_Argo/) (Li et al., 2013, 2017), is a monthly product containing data on temperature, salinity, isothermal layer depth, mixed layer depth, and composite mixed layer depth, with 1°×1° horizontal resolution and 58 vertical levels from the surface to 1 975×10^4 Pa, covering a period of 17 years from 2004 to 2020 (Lu et al., 2020). The product was generated based on Argo data only and was first released on the Argo program office's website (https://argo.ucsd.edu/data/argo-data-products/) in 2017. Recently, BOA_Argo has drawn considerable attention in scientific research, such as in studies of the interannual variability of OHC (Liu et al., 2019; Liang et al., 2021; Yang et al., 2021; Lyu et al., 2021), salinity/the hydrological cycle (Tesdal et al., 2018; Cheng et al., 2020; Li et al., 2019; Liu et al., 2019, 2020; Duan et al., 2021; Ponte et al., 2021; Wu et al., 2021), eddy-induced heat transport (Gonaduwage et al., 2021), the Earth's energy imbalance (Hakuba et al., 2021), and sea level change (Amin et al., 2020; Camargo et al., 2020). In addition, it has been adopted in the field of biochemistry (Dilmahamod et al., 2019; Guerreiro et al., 2019; Herr et al., 2019; Park et al., 2020; Wang et al., 2021b) and in assessment of the quality of satellite remotely sensed SSS (Bao et al., 2019, 2021; Liu and Wei, 2021).

In summary, the extensive usage of BOA_Argo has proven its high quality and reliability. Furthermore, the strict quality control procedures (Li et al., 2017, 2020b) and refined Barnes successive method employed in the generation of BOA_Argo allow mesoscale signals to be accurately captured, compared with other datasets with the same horizontal resolution (Li et al., 2017). For example, the abnormal eddy structure with high SSS in June 2016 from EN.4.2.1 (Good et al., 2013) was invisible both in corresponding satellite observations and BOA_Argo (Bao et al., 2021), indicating the high quality of BOA_Argo. The interannual variability of OHC from BOA_Argo is nearly 50% larger than that of other gridded datasets in regions with active mesoscale signals (e.g., the Antarctic Circumpolar Current (ACC) and western boundary currents) (Liang et al., 2021) (Fig. 6), consistent with the greater portion of mesoscale signals retained in BOA_Argo (Li et al., 2017).

2.6.2 *IAP data set*

The IAP data set (Cheng et al., 2017, 2020; Li et al., 2020a, http://www.ocean.iap.ac.cn/) is another widely used global ocean gridded data set. In contrast to BOA_Argo, other available profiles from various instruments (e.g., XBT, MBT, and shipboard CTD) are also used to produce this data set. It includes 1°×1° monthly temperature fields starting from 1940, from the sea surface to 2 000 m depth. At present, other variables such as salinity, potential density, stratification, and OHC are also estimated (Cheng et al., 2020; Li et al., 2020a). The relatively long time series of the IAP data set gives it advantages in scientific studies associated with climate change and variability (Cheng et al., 2017, 2019, 2020; Frederikse et al., 2020; Li et al., 2020a). The usage of the internationally recommended bias correction scheme for XBT developed by Cheng et al. (2014) and an ensemble optimal interpolation scheme have greatly reduced uncertainty in the estimation of the long-term variability of OHC (Cheng et al., 2017), salinity (Cheng et al. 2020), and stratification (Li et al., 2020a) (Fig. 7). For example, a recent study explicitly stated the advantage of the IAP data set when comparing different products with independent sea level observations: "the $SDSL_{EOF}$ reconstruction based on the ref. 24 dataset has the smallest trend differences to the $SDSL_{TG}$ in most regions (extended data Fig. 5) and also provides the best representation of variability." (Dangendorf et al., 2021). Furthermore, the IAP analysis has been comprehensively evaluated using the knowledge of recent well-observed ocean states during the Argo period (since 2005), but subsampled using the sparse distribution of observations in the more distant past, to show that the method produced a less biased (compared with irregular sampling) historical reconstruction back to 1960. This method provides a new strategy to evaluate data sets and increases the value of Argo data.

The IAP data products have supported many scientific studies and climate services since their initial release in 2016. For example, these products directly supported a key assessment result in an IPCC special report for the ocean and cryosphere: "Critically, the high confidence and high agreement in the ocean temperature data means we can detect discernable rates of increase in ocean heat uptake (Gleckler et al., 2012; Cheng et al., 2019)" (Bindoff et al., 2019). The IAP data are updated every 3–5 months and provide climate information to society (Cheng et al., 2021); for example, they have been used as key climate indicators by several governmental organizations, such as the U.S. Environmental Protection Agency (https://www.epa.gov/climate-indicators/climate-change-indicators-ocean-heat).

2.6.3 *GDCSM_Argo data set*

GDCSM_Argo (ftp://data.argo.org.cn/pub/ARGO/GDCSM_Argo/) is a product developed by CSIO DAC and SHOU. In contrast with BOA_Argo, a method of GDCSM was used to construct the three-dimensional gridded data (Zhang et al., 2013). The development of the GDCSM data set is based on OI and adopts anisotropic correlation scales. This method can be easily derived as a variation problem to find a vector of estimates that minimizes the total error variance of the field being estimated. It deduces the correlation scale function from the Fourier solution of the anisotropic diffusion equation. According to the needs of the objective analysis, the horizontal gradient change of oceanographic elements is evaluated based on climate data (Zhang et al., 2015). The longitudinal and latitudinal correlation scales in the objective analysis are limited by horizontal gradients. By adding the anisotropic background error correlations, the GDCSM can effectively extract shorter wavelength information zonally with a large gradient (Zhang et al., 2015, 2021). Error tests and statistics are used to determine the key parameters, such as correlation scale extrema, the radius of influence, and the relative ratio of background to observation errors.

Following a similar procedure to that of BOA_Argo, a global Argo gridded data set (GDCSM_Argo) is then generated. The product provides monthly three-dimensional temperature, salinity, sound velocity, and thermocline parameters for the global ocean from January 2004 through December 2020. The horizontal resolution is 1°×1°, with 58 vertical layers at depths between 0 m and 1 950 m. The GDCSM_Argo data set was verified based on *in-situ* observations and other gridded data sets. Its temperature and salinity differences relative to TAO/TRITON moored buoy observations are less than ±0.5°C and ±0.02 respectively in the equatorial Pacific (Fig. 8). In general, this data set is in good agreement with other gridded data sets such as WOA18 (Garcia et al., 2019), Roemmich-Argo (Roemmich and Gilson, 2009), JAMSTEC-Argo (Hosoda et al., 2008), EN4.2.1, and IPRC-Argo (http://apdrc.soest.hawaii.edu/projects/argo/). However, in contrast to WOA18 and other gridded data sets estimated by traditional OI, GDCSM_Argo tends to retain more small-scale information (Zhang et al., 2015). The GDCSM_Argo has been applied in the fishery oceanography (Xie et al., 2019; Zhang et al., 2021, 2022), and revealed more accurate environmental characters of fishing ground.

2.7 *Development of float technology*

Two float models have been developed in China during the past two decades, i.e., HM2000 and COPEX float developed by HSOE and NOTC, respectively. Both of them adopt a hydraulic system to change their buoyancy for controlling the descending and ascending of the floats. By SBE 41/41CP CTD sensor that the floats equipped, temperature and salinity profile data are ac-

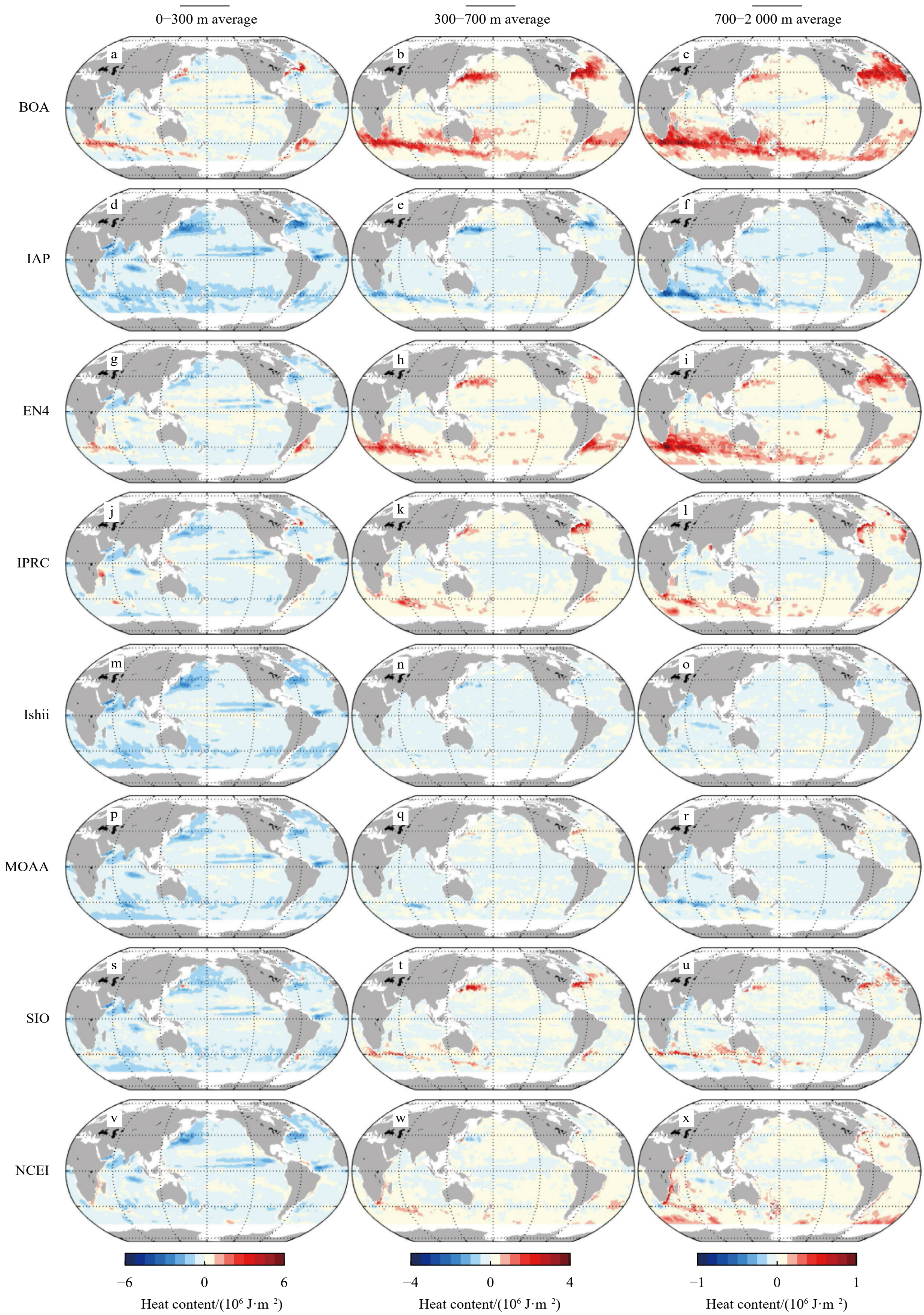

Fig. 6. Differences of interannual variability of depth-averaged ocean heat content between each product and the ensemble mean (unit: 10^6 J/m^2) (Liang et al., 2021).

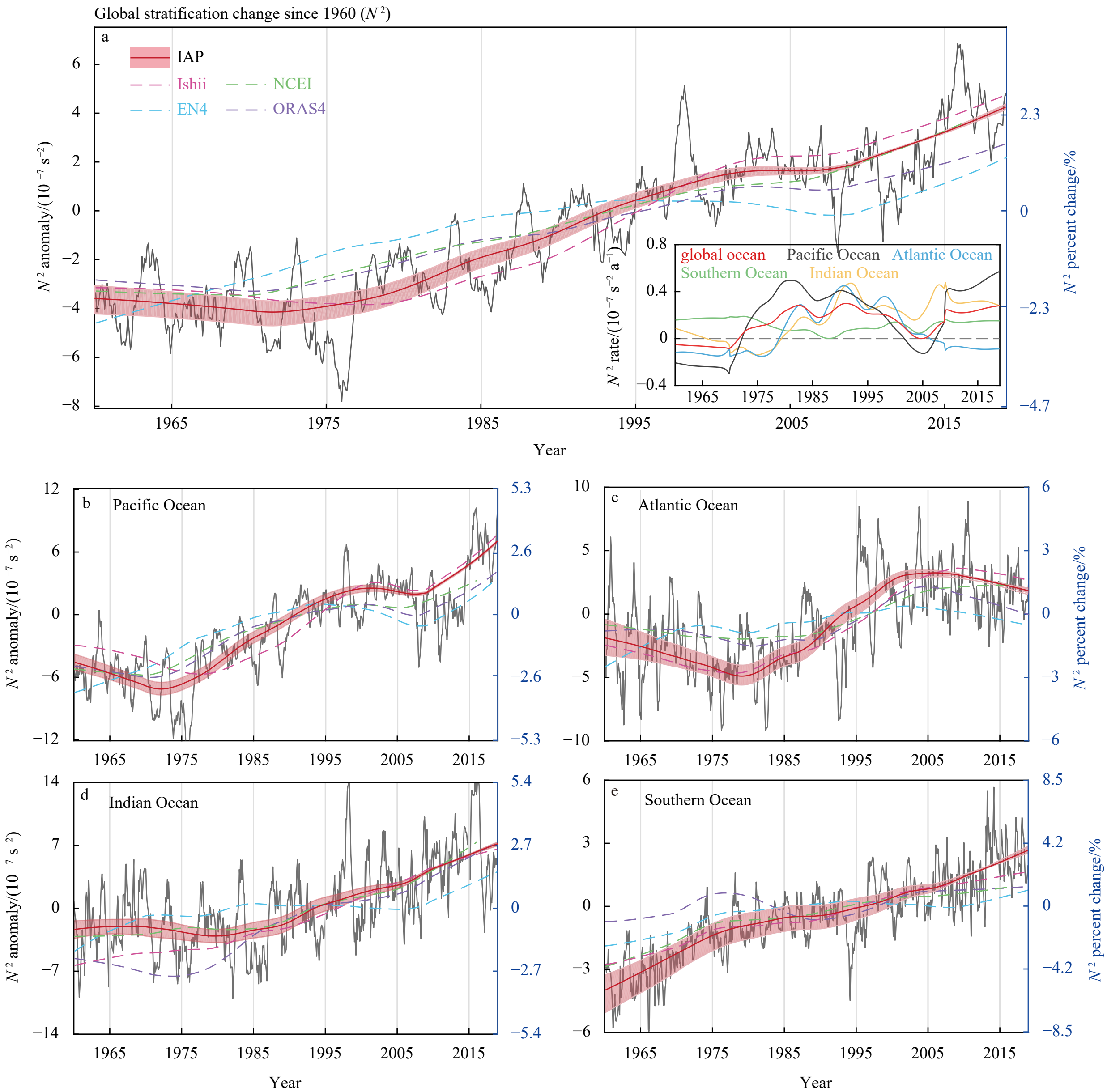

Fig. 7. Time evolution of the 0–2 000 m ocean stratification changes of global (a), Pacific (b), Atlantic (c), Indian (d) and Southern (e) oceans (Li et al., 2020a). The thin gray curves are monthly means with the smoothed time series shown in thin lines. A comparison with other products is provided. The 90% confidence intervals of IAP estimates are shown in red shading.

quired as they ascend to the sea surface. After reaching the sea surface, they transmit data and positions via ARGOS, Iridium or Beidou satellite. In November 2014, CSIO organized a field-testing experiment in the northwestern Pacific, where two COPEX, one HM2000 and two APEX floats were deployed for a comparison of the temperature and salinity profiles between the floats and concurrent shipboard CTD (Lu et al., 2016). Based on the results from this experiment, the HM2000 float was then introduced for the first time to the AST-16 meeting (Brest, France, March 2015), and received certification from the AST. Since then HSOE has continued to develop floats equipped with oxygen sensor.

2.8 *Expansion of China Argo*

2.8.1 *BGC-Argo*

With the rapid technical development of miniaturization and low-power consumption of optical, photochemical, and electrochemical sensors, profiling floats equipped with a wide variety of sensors represent promising technology and platforms for future observations in ocean biogeochemistry and bio-optics (Chai et al., 2020). The BGC-Argo program aims to develop a 1 000-float global array, equipped with biogeochemical and bio-optical sensors, measuring, for example, oxygen, nitrate, pH, chlorophyll, particulate backscattering coefficients, and downwelling irradiance, in support of fundamental research on oceanic biogeochemical cycles and ecosystems and the needs of ocean resource management (Claustre et al., 2020).

As early as 2009, the first two BGC-Argo floats (APEX float equipped with an oxygen sensor) contributed by China were cast in the Luzon Strait and southeast off Taiwan Island, respectively. This could be recognized as an early trial of the BGC-Argo project in China. However, until 2018, BGC-Argo float deployments from

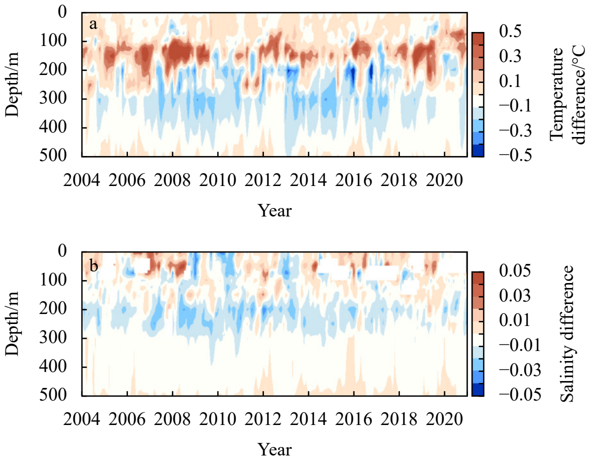

Fig. 8. Temperature (a) and salinity (b) differences between GDCSM_Argo and TAO buoy observations in the equatorial Pacific.

China were very rare, with the exception of 14 PROVORDOI floats deployed in 2014 (mentioned above, but their valid oxygen data only lasted approximately 3 months). Since then, CSIO has deployed 14 additional floats in the northwestern Pacific to build up a regional BGC-Argo array, and nine floats are still operational at the end of 2021 (Fig. 9a). Aside from the northwestern Pacific, some BGC-Argo floats were also deployed in the Bay of Bengal, South Atlantic, and Southern Ocean; these were typically Argo-equivalent floats sponsored by several institutions and universities.

In particular, the first China-made BGC-Argo float (using the Beidou satellite system for data transmission), a HM2000 profiling float equipped with an Aanderaa optode 4330 oxygen sensor (Fig. 9b), was deployed in March 2021 in the Bay of Bengal, and the second one was deployed in August 2021 in the northwestern Pacific (WMO number: 2902757; Fig. 9a). In addition to temperature and salinity measurements, both of these floats reported fairly good dissolved oxygen profiles.

The observed data from the CSIO northwestern Pacific BGC-Argo array have proven to be extraordinarily valuable to regional

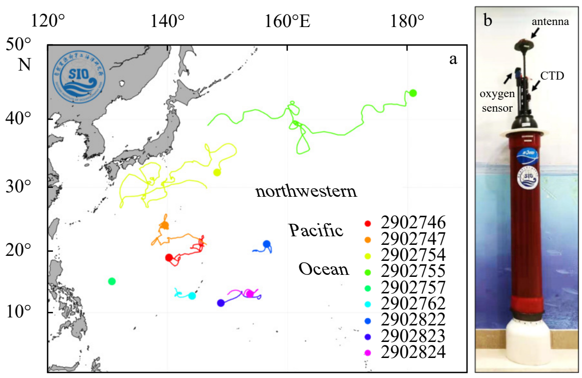

Fig. 9. Present China BGC-Argo regional array in the northwestern Pacific, with nine active floats. The round dots represent their latest profile positions. The legend shows their respective WMO numbers (a); a China-made BGC-Argo float, HM2000-O_2, with a Beidou satellite antenna and an Aanderaa optode 4330 oxygen sensor (b). It was cast in the low-latitude Northwest Pacific (15°N, 130°E, shown in panel a, WMO: 2902757) in August 2021.

ecosystem dynamics studies, including the typhoon-induced response of phytoplankton vertical distribution (Chai et al., 2021), mid-latitude northwestern Pacific winter blooms and fast carbon exports (Xing et al., 2020), seasonal and daily-scale phytoplankton photoacclimation effects (Xing et al., 2021), eddy-induced physical and biogeochemical response (Ding et al., 2022), as well as the neural-network-based regional model of chlorophyll profile estimate (Chen et al., 2022). Particularly, Xing et al. (2020) reported the wintertime fast carbon exports due to the synoptic-scale mixed-layer dynamics driven by the winter storms (Fig. 10), the observed carbon-export process, called as "mixed layer pump (MLP)", was unexpectedly strong in the mid-latitude oceans, substantially extending the window of time where MLP processes can be important. Their findings also indicated that carbon export via MLP processes during winter occurred on time scales too short to be adequately sampled with the 5- or 10-day profiling intervals of regular Argo floats, and highlighted the significance of high-frequency observation for quantifying carbon exports in the mid-latitudes.

2.8.2 *Deep Argo*

The proposed Deep Argo array, with the goal of maintaining a global fleet of 1 200 floats collecting temperature, salinity, and pressure data from the sea surface to near the ocean bottom, will expand Argo's current monitoring capabilities to the full ocean volume, allowing for assessment of year-to-year variability in the deep ocean's heat and freshwater contents, circulation, and contribution to steric sea level rise (Johnson et al., 2015). Recent technological advancements have led to the development of four new float models capable of reaching the deep and abyssal ocean: Deep Arvor, Deep NINJA, Deep SOLO and Deep APEX, with maximum profiling depths of 4 000 m and 6 000 m, respectively (Kobayashi et al., 2013; Petzrick et al., 2013; Le Reste et al., 2016; Roemmich et al., 2019b). By the end of 2021, approximately 320 Deep Argo floats have been deployed by 10 countries, and 188 of these are still reporting data.

In 2016, from the "Wenhai" project that was launched and funded by the Laoshan Laboratory, China began its pioneering development of a 4 000-m profiling float. Several 4 000-m float prototypes developed by OUC, Tianjin University, and Laoshan Laboratory were manufactured and tested in the South China Sea and western Pacific during 2018–2019, and over a thousand 4 000-m temperature and salinity profiles were obtained (Gao et al., 2021). After Phase I of the "Wenhai" project, the HM4000 deep profiling float designed by Laoshan Laboratory was ultimately chosen as the primary model to engage in pilot regional deployment.

Similar to the features of the other deep floats, a HM4000 float can park at depths ranging from 500 m to 4 000 m, with a nominal parking depth of 1 000 m. Users can easily adjust the ascending/descending speed of the float according to their observation requirements via the bidirectional satellite system. Moreover, the HM4000 float has the advantages of self-protection strategies, such as grounding detection and emergent ascending for a timeout or excessively deep profiling. To prolong the float's lifetime, a low-power-consumption strategy in the profiling phase was also designed. At present, the measurement module is compatible with both SBE61 and RBRargo³ deep CTD sensors.

In 2020, the deep float R&D team from Laoshan Laboratory upgraded the existing testing processes and manufacturing for HM4000, based on the results and feedback from field testing in 2019 in the western Pacific. In May and June 2021, nine HM4000 floats were deployed around the region of the Kuroshio and Oyashio Extension in the North Pacific, with eight of them equipped with RBRargo³ deep CTD and one with an SEB61 CTD sensor (Fig. 11). By the end of 2021, seven floats were still reporting data and over a hundred 4 000-m temperature and salinity profiles had been acquired (Fig. 12). To verify the accuracy of the CTD sensors equipped on the floats, a CTD rosette equipped with a SBE 911 plus CTD and a Guildline Autosal 8400B salinometer were taken onboard the research vessel. When a float was deployed, a full-depth CTD cast was conducted and several water samples were taken from the CTD rosette. After collection, all samples were stored in the salinometer laboratory and were analyzed for salinity. The comparisons between observations from the floats, shipboard CTD, salinometer, and climatology indicated that half of the floats were able to obtain fairly good temper-

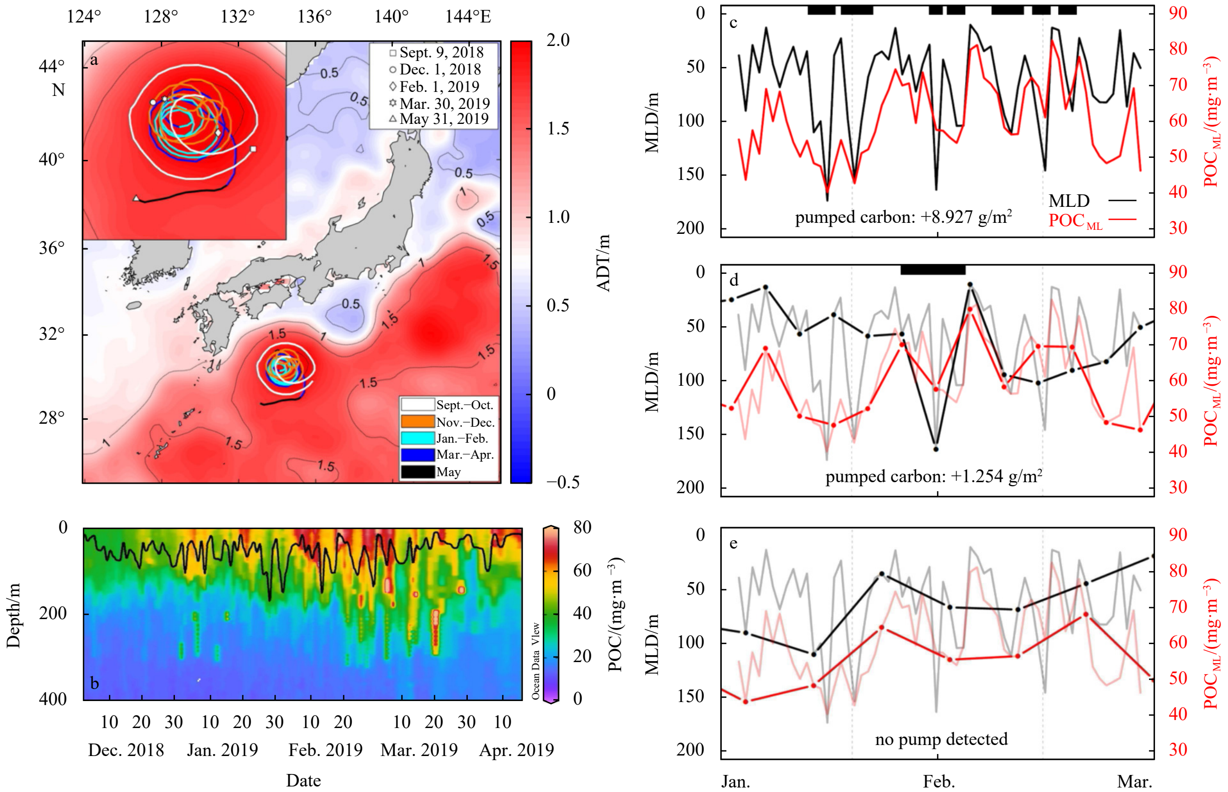

Fig. 10. Trajectory of the BGC-Argo float (WMO: 2902750) in the Northwest Pacific. The colored curves represent the observation times (white: September and October; orange: November and December; cyan: January and February; blue: March and April; black: May). The thin contour represents the absolute dynamic topography (ADT) on 1 December. The locations of the float on specific days are marked by different symbols, with a square and a triangle denoting the first and last profilings of the float, respectively (a); float-observed POC time series, the black curve in each panel represents mixed layer depth (MLD) (b); time series of MLD, surface POC (POC_{ML}), and MLP events captured by different sampling frequencies (c–e). Actual 1-day sampling (c), simulated 5-day sampling (d), and simulated 10-day sampling (e). The black bars represent the detected MLP events, and their lengths represent event durations, with different efficiencies (denoted in each panel). Modified from Xing et al. (2020).

Fig. 11. Schematics of the HM4000 float mounted with two types of CTD sensor.

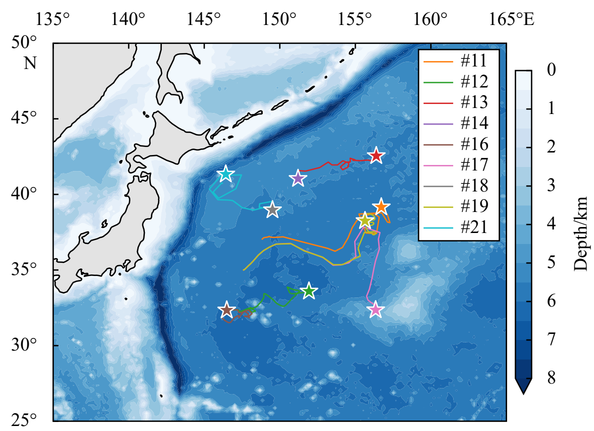

Fig. 12. Trajectories of nine HM4000 floats deployed in the North Pacific Ocean as of December 31, 2021.

ature and salinity profiles at least at the time they were deployed (e.g., float #16 equipped with the RBRargo^3 CTD sensor, shown in Fig. 13), whereas the remainder observed systematic or pressure-dependent salinity errors (e.g., float #18 equipped with the RBRargo^3 CTD sensor, shown in Fig. 14). Data obtained from this field test are very useful for the sensor manufacturers to verify and improve their Deep Argo CTDs.

3 Perspectives on China Argo

3.1 *Future of the China Argo network*

Because the physical and biogeochemical profiles from the global Argo fleet have been widely used in scientific research and ocean forecasts, the value of the Argo program has been fully realized by the scientific community. However, in contrast to the U.S., Australia, France, Germany, U.K., and Japan, China's contribution to the global Argo network was not sufficient during the past two decades. For instance, both the total number of the floats deployed and the current number of operational floats account for no more than 3.5% of the global array. As mentioned in Section 2.1, the majority of float deployments were sponsored by research projects, which is considered to be unsustainable. Figure 15 shows the time evolution of the China Argo fleet over the past decade. The number of the active floats reached a peak of 204 in January 2015, when a large number of floats sponsored by a special project were added into China Argo during 2010–2014, and brought the number of active floats of China Argo to fourth place in the global array (~5.3% of the total number). Since then, float deployment reverted to the previous situation again. As of December 2021, the number of the active floats decreased to 85, only accounting for 2.16% of the total number. It is worth noting that float deployments were greatly affected by the COVID-19 pandemic around the world since the end of 2019, which resulted in a 2% reduction of operational floats globally. Therefore, it is a great opportunity and obligation for China Argo to make a greater contribution to the international Argo program, e.g., "OneArgo", for the next decade.

It has been suggested that China Argo should maintain a fleet of 400 floats in the North Pacific, South China Sea, and Indian Ocean, with a yearly float deployment of approximately 100 floats, and remarkably increase China's contribution to the Argo program. In addition, the percentage of domestically produced profiling floats using the Beidou satellite system for data transmission is expected to be increased. Furthermore, the regional Deep Argo and BGC-Argo observing networks are considered to be crucial to satisfy the needs of multidisciplinary studies and novel discoveries.

3.2 *BGC-Argo*

Presently, China BGC-Argo relies on scattered contributions from several research institutions, without overall planning. Nevertheless, time series of subsurface observations from BGC-Argo

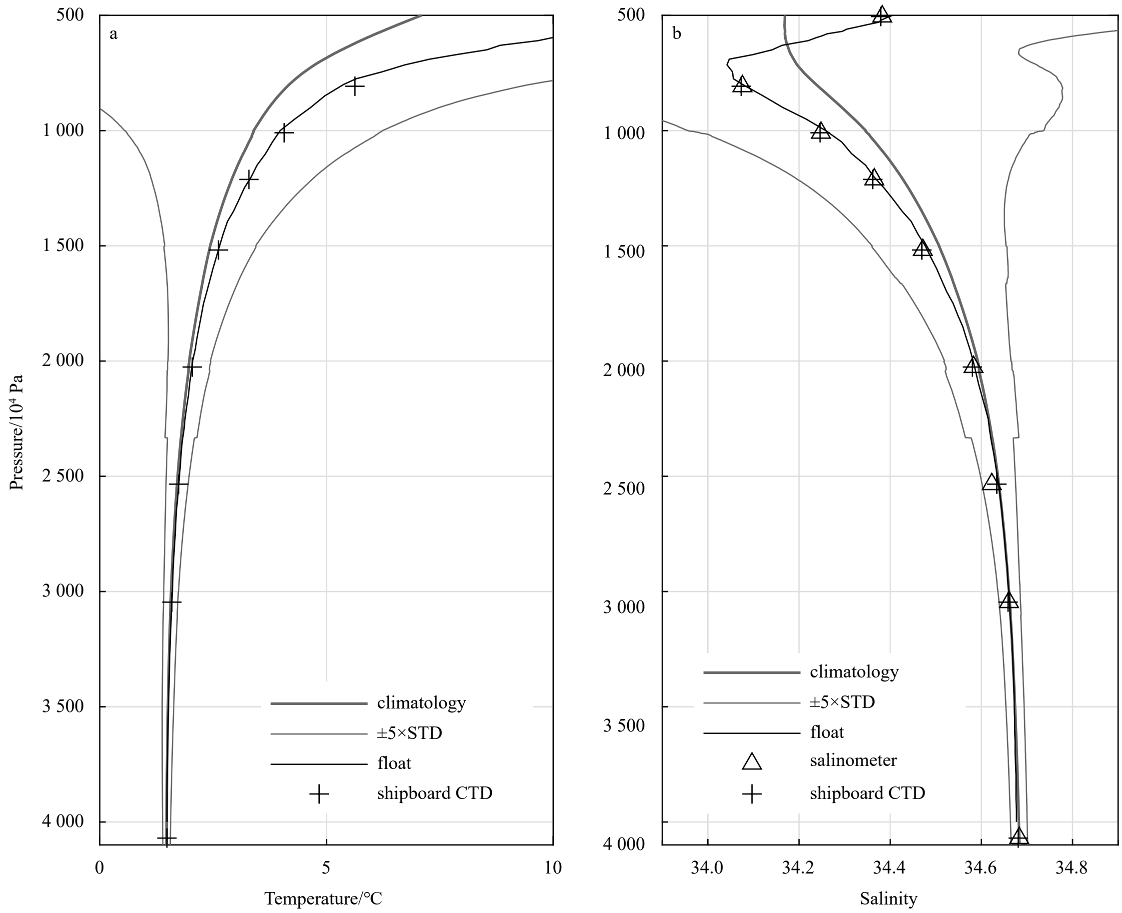

Fig. 13. Temperature and salinity profiles (below 500×10^4 Pa) observed by HM4000 float #16 (equipped with RBRargo^3 CTD sensor) shown in Fig. 11. The thick gray lines are the nearby climatological temperature and salinity profiles derived from the ISAS13 data set, and the thin gray lines are the corresponding ±5 standard deviation (STD) envelopes. Fairly good float temperature and salinity profiles were verified by the shipboard CTD cast, salinities analyzed by salinometer, and the climatological data set.

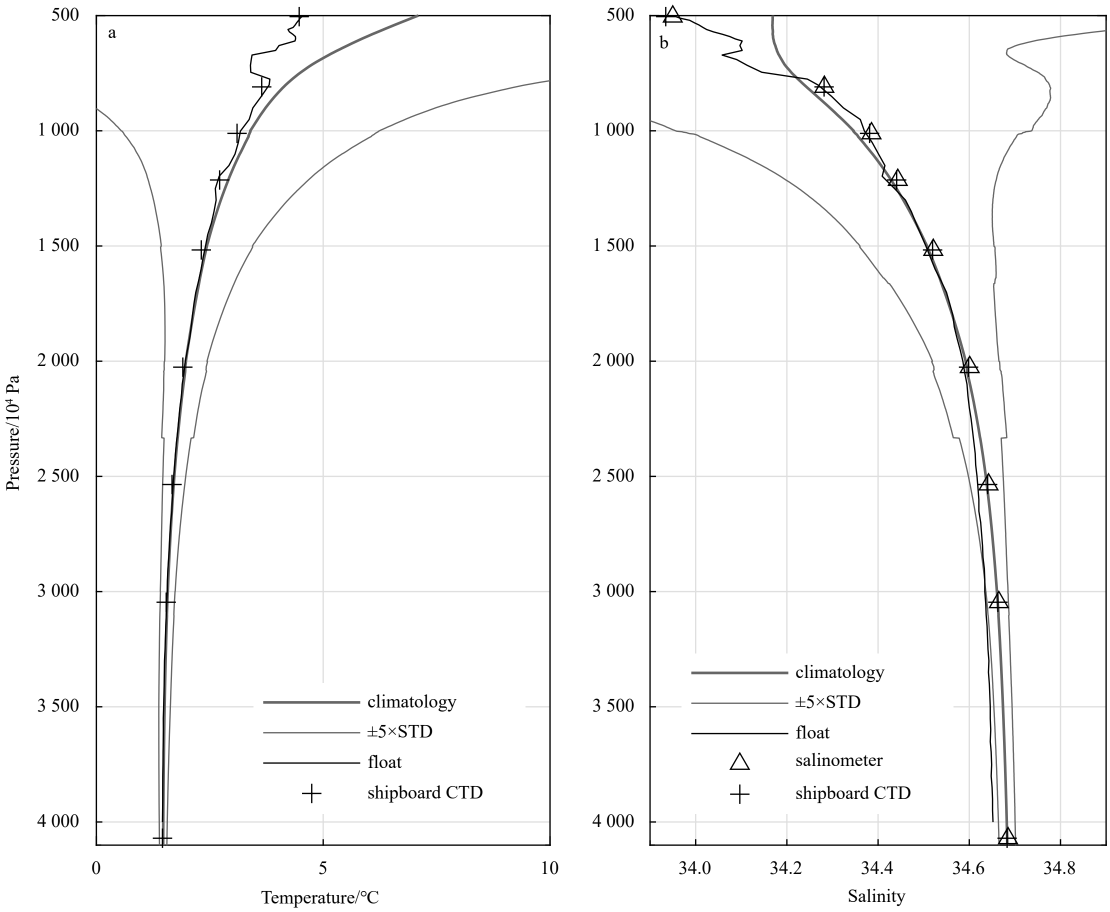

Fig. 14. Temperature and salinity profiles (below 500×10^4 Pa) observed by HM4000 float #18 (equipped with the RBRargo^3 CTD). Pressure-dependent salinity biases against the shipboard CTD cast, salinometer, and climatology are remarkable below $2\,000\times10^4$ Pa .

have proven to be extraordinarily valuable to studies on meso- and submesoscale processes (Wang et al., 2021a) and daily to synoptic-scale ecosystem dynamics (Xing et al., 2020; Chai et al., 2021).

CSIO expects to maintain the present regional BGC-Argo array in the Northwest Pacific, and to extend it to the tropical and subarctic Pacific, as well as the South China Sea. In addition, more contributions by China in the Indian Ocean, Southern Ocean, and Arctic Ocean have been suggested, supporting more studies of biogeochemical cycles, ecosystem health (e.g., warming, acidification, and deoxygenation), and biological carbon pump processes. In the next decade (2021–2030), it is expected that China will contribute (and maintain) approximately 50–100 BGC-Argo floats in the global array (i.e., 5%–10%), and that China-made BGC-Argo float and sensor technology will be further promoted and developed. As for the BGC data quality control, CSIO has participated in the development of novel QC methods (e.g., on irradiance, chlorophyll, and backscattering data) along with other DACs, towards a better application of BGC-Argo data. Some DMQC procedures (e.g., on oxygen, nitrate, chlorophyll) have begun to be tested, and CSIO expects to achieve the operational application of DMQC procedures of all biogeochemical variables in the near future.

3.3 *Deep Argo*

It is also expected that China will maintain at least 300 Deep Argo floats in the global ocean, particularly in the North Pacific (e.g., the South China Sea, Kuroshio Extension regions, and tropical western Pacific regions) and in the Southern Ocean, building up a regional deep-ocean observation network and providing observations as deep as 6 000 m for the scientific community. This would be approximately 25% of the total floats in the global Deep Argo array, and would require a yearly deployment of approximately 100 floats.

Improvement and upgrading of the HM4000 float will be continued, with a target of at least 100 mission cycles in the sea or a three-year mean float lifetime. At Laoshan Laboratory, the R&D team is developing the 6 000-m float, Xuanwu, which will allow the water column from the sea surface to the sea floor to be measured. In addition, to accommodate the increasing requirements for future deployments of Deep Argo, high-precision CTD sensors are being developed. In the next decade, the 4 000-m (6 000-m) profiling floats are planned to be manufactured industrialized before 2025, and a data center will be established by collaboration between Laoshan Laboratory and CSIO.

4 Summary and discussion

The international Argo program achieved its initial design of a global array comprising 3 000 core Argo floats within seven years after 2000. It took twelve years to collect one million profiles and only six years for another million profiles across the global ocean. The open-data policy adopted by Argo has driven an explosion in ocean and climate research using Argo data. It should be noted that the Argo program would never be successful without the international collaborations of more than 30 countries. Today, "OneArgo" is endorsed by the UN Ocean Decade, aiming to build

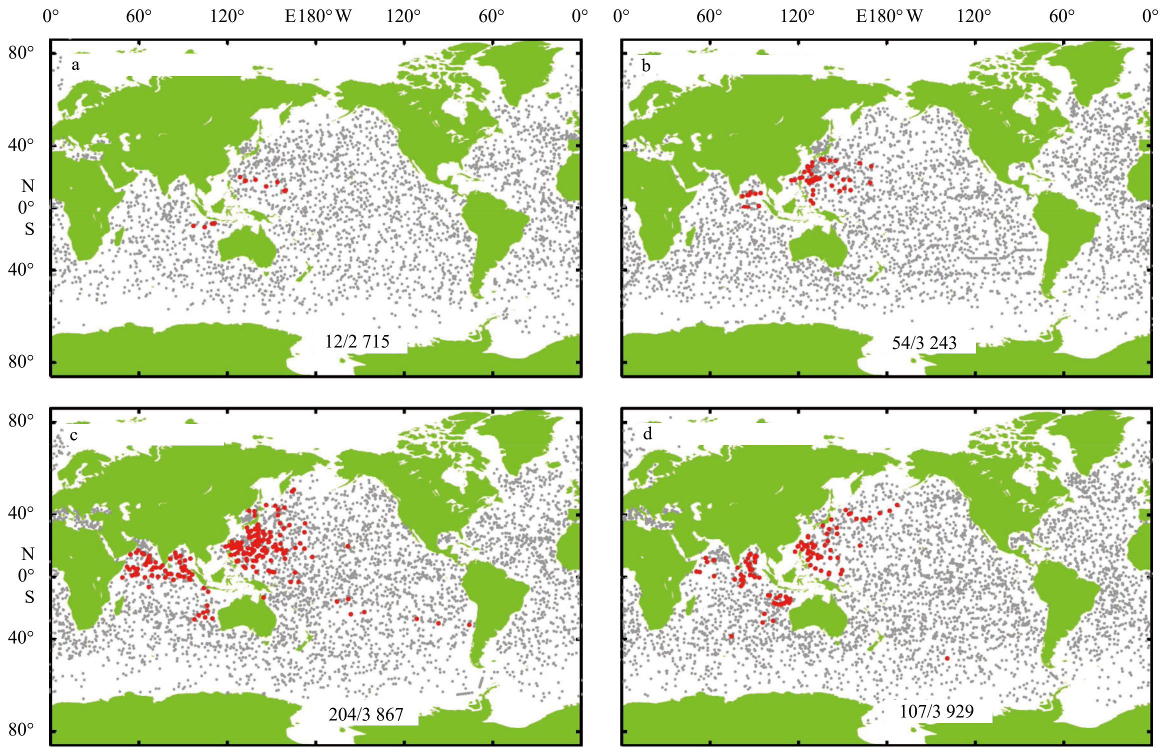

Fig. 15. Locations of operational Argo floats across the global ocean in December 2006 (a), December 2010 (b), January 2015 (c), and December 2020 (d). Red dots are Chinese floats and gray dots represent floats deployed by other member states. The number before and after the slash is the total number of the operational floats deployed by China and other countries, respectively. Note that the number of the operational Chinese floats reached a peak (204) in January 2015.

a truly global, full-depth, and multidisciplinary network beyond 2020. However, to accomplish this goal, sufficient resource investment from each member country and new partners is a challenge we must face.

In this paper, we reviewed the progress achieved by China Argo over the past two decades. Relying on research projects and a few special programs, China has maintained a regional Argo fleet consisting of approximately 100 floats across the Pacific Ocean, South China Sea, and Indian Ocean. These float deployments have been supported by the majority of institutions and universities in China. Data reported by each operational float (via different communication systems) are transmitted to the associated DAC and then submitted to GDACs in real time after automatic data QC with the ADMT-specified QC procedure. Through fast reception and the post_QC system, CSIO DAC is able to provide high-quality global Argo temperature and salinity profiles for operational departments in near real time. Several Argo data products based on different objective analysis methods have been developed and distributed. These gridded data sets may include variables such as temperature, salinity, potential density, sound velocity, OHC, mixed-layer depth, and thermocline depth. Many scientific studies and intergovernmental climate change reports have cited and benefited from these data sets. In China, Argo data have been used and produced over 900 scientific publications, the second most around the world (refer to https://argo.ucsd.edu/outreach/publications/bibliography/).

Expansion of China Argo from core to Deep and BGC has begun recently. This includes establishing the regional BGC-Argo observation array in the northwestern Pacific and pilot deployments of deep floats (4 000 m). Moreover, BGC (equipped with dissolved oxygen sensors) and deep profiling floats (4 000 m) are being developed and tested. Despite the small number of BGC floats being deployed, their time series of subsurface observations have proven to be very useful in studies of multi-scale biogeochemical cycles and ecosystem dynamics. The pilot deployments of the HM4000 float in the North Pacific have obtained valuable 4 000-m temperature and salinity profiles, as well as simultaneous shipboard CTD casts and seawater salinity analyses by salinometer, which are expected to be useful for the sensor manufacturers to improve their CTD products.

In general, China Argo's contribution to the global Argo network over the past two decades is not sufficient in contrast with the outcomes using Argo data. To sustain the growth of the China Argo fleet and respond to the UN decade action of "OneArgo", a regional Argo observation network comprising 400 profiling floats across the northwestern Pacific, South China Sea, and Indian Ocean has been proposed. In addition, the building of a regional Deep Argo fleet of 300 deep floats had been suggested by the Laoshan Laboratory, which would account for 1/4 of the global array. For BGC-Argo, the regional fleet focusing on the western Pacific has been regarded as a promising observation system for studying biogeochemical cycles, ecosystem health, and biological carbon pump processes. For the next ten years, the construction and maintenance of the China regional Argo array should be incorporated into the national fiscal budget. In addition, a China Argo alliance that includes the majority of oceanography institutions and universities needs to be established for better coordination and effectively use of float resources.

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