Perspectives for China Argo ocean observation network

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For most of the 20th century, scarce ocean subsurface observational data hindered an in-depth understanding of the ocean's role in climate change and climate prediction. Traditional shipborne and mooring ocean observations are expensive and sparsely distributed, and sample errors across observational instruments always produce large biases and uncertainties in data used to assess the state and variability of the global ocean. At the turn of the millennium, the application of innovative technologies in float and conductivity–temperature–depth (CTD) sensors initiated continuous, real-time, subsurface observation of the global ocean. This development prompted the original design of the Argo Program in 1998, conceived as a global array of autonomous profiling floats deployed to collect temperature (T) and salinity (S) profiles of the upper ocean (0–2,000 m) in real time.[1] During the past two decades, a network of approximately 3,900 operating Argo floats has been established and maintained over the ice-free open ocean by more than 30 countries. So far, global Argo has obtained more than 2,000,000 T–S profiles over the past 20 years, i.e., four times more than all ship-based T–S measurements acquired over the past 150 years. Additionally, an innovative and reliable data management system has been created that ensures the availability and sharing of Argo data globally within 24 h of collection. Argo's near-global coverage has revolutionized the acquisition and accuracy of global ocean T–S data, and reduced uncertainty in estimates of the Earth's heat budget. This has enabled scientists to estimate that the ocean has absorbed ~30% of the CO_2 emitted from the burning of fossil fuels since the Industrial Revolution and 93% of the extra heat generated within the Earth system.[2]

Recently, the global Argo network has been expanded into seasonal ice zones, many marginal seas, and the deeper ocean (below 2,000 m). Floats equipped with biogeochemical (BGC) sensors allow measurement of BGC variables such as dissolved oxygen, chlorophyll, suspended particles, nitrate, pH, and downwelling irradiance, supporting investigation of oceanic uptake of carbon, acidification, and deoxygenation.[3] BGC-Argo deployments commenced with regional or basin-scale projects such as the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) project, but have recently expanded to the global scale with the Global Ocean Biogeochemistry (GO-BGC) array. Both projects, supported by the National Science Foundation of the United States, focus on the roles of the ocean carbon cycle and ecosystem dynamics. Half of the global ocean is deeper than 2,000 m, and innovative design of floats and CTD sensors has enabled Argo to

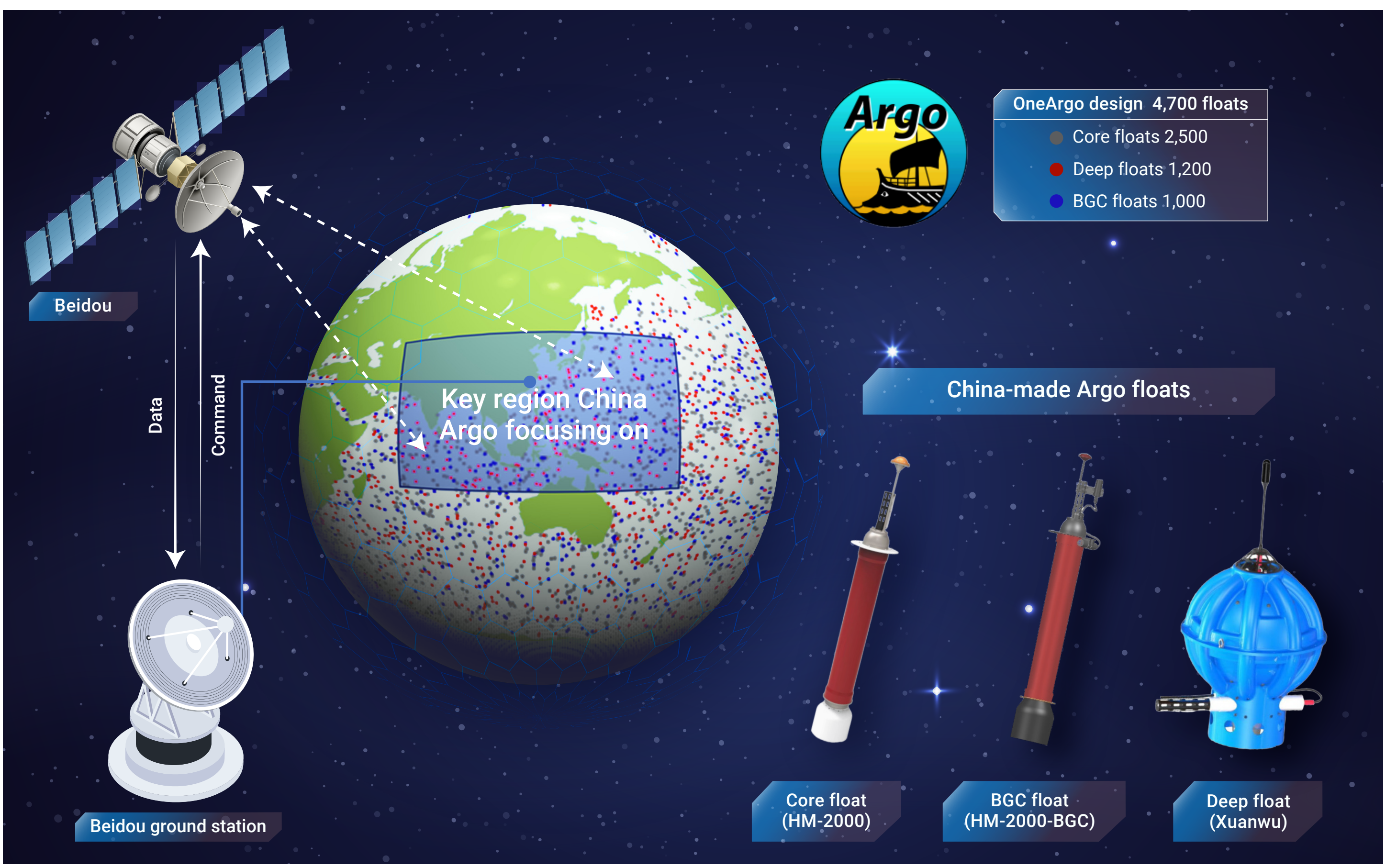

Figure 1. Design for the "OneArgo" array (2,500 core floats, 1,200 deep floats, and 1,000 BGC floats). Shading indicates the key region for future China Argo deployment where a fleet comprising 400 active floats is expected. Prototypes of China's HM-2000, HM-2000 BGC, and Xuanwu floats are superimposed.

measure the water column to depths of 6,000 m. Consequently, a 1,200-float Deep Argo array has been designed, which is considered necessary for tracking deep ocean environmental change and variability, and for completely accounting for the Earth's heat budget.[4] Today, the proposed "OneArgo" array, which is intended as a fully global, full-depth, and multidisciplinary ocean observing system, has been endorsed by the "United Nations Decade of Ocean Science for Sustainable Development" (i.e., the UN Ocean Decade).

In 2002, with State Council approval, China formally joined the Argo Program (hereafter, China Argo). The initial goal of China Argo was to construct and maintain a regional Argo fleet comprising 100–150 floats in the Northwest Pacific and Indian Oceans, and to become an important member of the Argo Program. By the end of 2022, mainly through sponsorship of diverse research projects, China Argo had deployed approximately 550 profiling floats in the global ocean, with the majority in the Pacific and Indian oceans (average yearly deployment: ~27 floats, maximum yearly deployment: 91 floats in 2014), accounting for approximately 3% of the global total float deployment. Various float models and communication systems (i.e., ARGOS, Iridium, and Beidou) have been used. As early as 2009, China Argo deployed two basic BGC floats, each mounted with a dissolved oxygen sensor. Subsequently, an additional 55 BGC floats have been deployed, 2 of which are fully equipped 6-sensor floats that are among the best BGC-Argo floats in the world. From 2015, the Chinese HM (Haima)-2000 float that uses either the Beidou or the Iridium satellite system for data transmission has been adopted by China Argo. Recent pilot deployments of HM-2000 floats equipped with an oxygen sensor obtained satisfactory oxygen profiles in both the Bay of Bengal and the Northwest Pacific, which have supported scientists in investigations of oxygen dynamics. In the past five years, deep floats with a maximum profiling depth of 4,000/6,000 m, including the ARVOR_D (NKE Deep float product, France) and two deep float models (HM-4000 and Xuanwu) developed by Laoshan Laboratory (Qingdao, China), have been deployed to verify the accuracy and stability of different deep CTD sensors. Driven by a buoyancy adjustment system and a buoyancy compensation model, the HM-4000 and Xuanwu floats proved able to profile to depths of 4,000–6,000 m, conducting approximately 130 3-day cycles. Through the Argo data processing system established in Hangzhou, approximately 71,370 T–S profiles and 18,062 BGC profiles had been obtained and processed by the end of 2022 (data can be downloaded from https://www.argo.org.cn/).

Despite the minor contribution to the global Argo array, scientists in China have benefited from Argo observations in studies of ocean changes on seasonal–decadal scales. More than 1,000 papers using Argo data have been published by Chinese scientists. Additionally, using BGC observations, studies have examined multiscale biogeochemical cycles and ecosystem dynamics, particularly concerning phytoplankton and oxygen responses to synoptic-scale events (e.g., tropical cyclones and winter storms) and mesoscale eddies. For example, dissolved oxygen has been shown to exhibit three different types of response to tropical cyclones in the Bay of Bengal. Moreover, tropical cyclones passing over oligotrophic oceans have been found to lead to vertical redistribution of phytoplankton, increase in surface biomass, and reduction in subsurface biomass. Studies have also shown that mesoscale eddies in the Northeast Pacific have a substantial impact on the subsurface chlorophyll maximum, which further influences dissolved oxygen in the upper oxygen minimum layer.

Currently, most ocean data assimilation systems, physical and biogeochemical modeling, and operational forecasting in China employ Argo data as the main data source, thereby enhancing capabilities for ocean and weather forecasting. To facilitate the application of Argo data, several products combining Argo T–S profiles with other data sources have been developed. The dataset developed by the Institute of Atmospheric Physics (IAP) is a representative product, covering the period from the 1940s to the present, based on an ensemble optimal interpolation scheme that merges Argo data with data from other ocean observing systems. The Argo profiles with near-global coverage obtained since 2005 have been used as a "synthetic data" product to examine the performance of reconstructions for the historical period, extending Argo's value back in time. The product has been used in many research fields (i.e., climate, oceanography, and biology.), and has supported the development of landmark climate reports from the International Panel on Climate Change (IPCC) and the World Meteorological Organization (WMO).[2] In addition to other datasets, BOA_Argo (https://argo.ucsd.edu/data/argo-data-products/) is another widely used product that has been applied to the evaluation of the global ocean heat content, sea level change, and the hydrological cycle.[5]

In summary, over the past two decades, China Argo has achieved its initial goals and contributed to the regional Argo observational network. However, China Argo has not been incorporated into regular ocean observational programs; consequently, China's contributions (only ~1.5% in December 2022) to the Argo Program have been much smaller than those of the United States, France, Japan, and Australia (accounting for ~75% of the global deployment). Moreover, with impending implementation of the OneArgo program, China Argo still lacks adequate and sustainable support from governmental agencies. A new design of the China Argo regional observation array, proposed in 2017, comprises 400 profiling floats distributed across the Northwest Pacific, South China Sea, and Indian Ocean (Figure 1). To satisfy the requirements of the climate/weather prediction and scientific communities, enhanced deployments in key regions (e.g., boundary currents regions and tropical oceans) should be considered for improving El Niño–Southern Oscillation (ENSO) forecasting. For a better understanding of anthropogenic influences on ocean biogeochemical cycles and productivity, and to inform climate policy makers, installations of various BGC sensors onto a portion of floats are necessary. Additionally, construction of a regional Deep Argo array of 300 deep Xuanwu floats has been proposed by Laoshan Laboratory, which would account for approximately 25% of the global Deep Argo array.

Major challenges must be addressed to achieve the target network of China Argo, and the following initiatives are proposed.

1) Incorporate China Argo into regular ocean observing programs as an effective action as part of the UN Ocean Decade, which would provide sustainable support for long-term maintenance of China Argo.

2) Introduce a special program to construct the new generation of the China Argo regional observing network comprising 400 operating floats within five years (~140 floats per year). Subsequently, maintain annual deployment of 100 floats to fill gaps as a regular ongoing project.

3) Establish a China Argo alliance that includes diverse stakeholders for better coordination and effective use of float resources.

4) Refine key regions from advanced coupled-model output and feedbacks from scientific communities for optimized design of regional BGC and Deep Argo networks.

5) Accelerate float and sensor technology development and testing, and promote adoption of China-made floats in the China Argo observing network. Meanwhile, development of a new generation of communication system such as Iridium or Starlink that could provide high-speed broadband connection between Argo floats and end users is imperative.

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DECLARATION OF INTERESTS

The authors declare no competing interests.