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The Argo Program

Present and Future

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NEMO float deployed in the Arctic
from R/V Polarstern. Photo from [http://
www.argo.ucsd.edu/pictures.html](http://www.argo.ucsd.edu/pictures.html)



“ The Argo Program is the example of how autonomous and Lagrangian platforms and sensors (ALPS) technology can be the basis of a global ocean observing system. ”

ABSTRACT. The Argo Program has revolutionized large-scale physical oceanography through its contributions to basic research, national and international climate assessment, education, and ocean state estimation and forecasting. This article discusses the present status of Argo and enhancements that are underway. Extensions of the array into seasonally ice-covered regions and marginal seas as well as increased numbers of floats along the equator and around western boundary current extensions have been proposed. In addition, conventional Argo floats, with their 2,000 m sampling limit, currently observe only the upper half of the open ocean volume. Recent advances in profiling float technology and in the accuracy and stability of float-mounted conductivity-temperature-depth sensors make it practical to obtain measurements to 6,000 m. The Deep Argo array will help observe and constrain the global budgets of heat content, freshwater, and steric sea level, as well as the full-depth ocean circulation. Finally, another extension to the Argo Program is the addition of a diverse set of chemical sensors to profiling floats in order to build a Biogeochemical-Argo array to understand the carbon cycle, the biological pump, and ocean acidification.

BACKGROUND

Science writer Justin Gillis of the *New York Times* recently described Argo as “one of the scientific triumphs of the age” (Gillis, 2014). Since its inception, the primary goal of the Argo Program has been to create a systematic global network of profiling floats that can be integrated with other elements of the Global Ocean Observing System. The float network provides freely available upper-ocean data within 24 hours of data transmission. The observations are used in a broad range of applications that focus on examining climate-relevant variability on seasonal to decadal time scales, multidecadal climate change, improved initialization of coupled ocean/atmosphere climate models, and constraining ocean analysis and

forecasting systems. Use of Argo data has been remarkably successful in observing climate variability and change in the ocean, and the program is now evolving to become part of a more comprehensive observing system.

The original plan set by the Argo Steering Team in 1998 was to “provide an enhanced real-time capability for measurement of temperature and salinity through the upper 2,000 m of the ocean and contribute to a global description of the seasonal cycle and inter-annual variability of the upper ocean thermohaline circulation” (Argo Steering Team, 1998). The original goal of the Core Argo Program was, and remains, a nominal coverage of one float per each 3° longitude by 3° latitude box in the

global ice-free ocean in the band from 60°N to 60°S (excluding marginal seas). Deployments were begun in 1999, with the goal of a 3,000-float array achieved in November 2007. Argo observed its one-millionth profile on October 30, 2012. Today, it is taken for granted that systematic observations of the global upper-ocean (0–2,000 m) are obtained by around 3,800 Argo floats (Figure 1), and made available in near-real time. The cost per Argo profile is less than \$200, compared to over \$10,000 for a shipboard hydrographic profile. The Argo Program has collected roughly 1.8 million hydrographic profiles that are archived in the Global Data Assembly Center (GDAC) repository and are freely available to the public. Prior to Argo, there were about 535,000 hydrographic profiles to depths greater than 1,000 m in the World Ocean Database 2009 (Boyer et al., 2009), with large seasonal and geographical sampling biases (Riser et al., 2016). Enhanced sampling by Argo of the upper ocean has significantly improved the ability to estimate the ocean’s heat content (Palmer, 2017) and the monitoring of Earth’s energy imbalance (von Schuckmann et al., 2016).

Riser et al. (2016) recently reviewed the scientific achievements of the first 15 years of the Argo Program. Highlights of that review include that since the beginning of Argo, the data have found widespread use throughout the

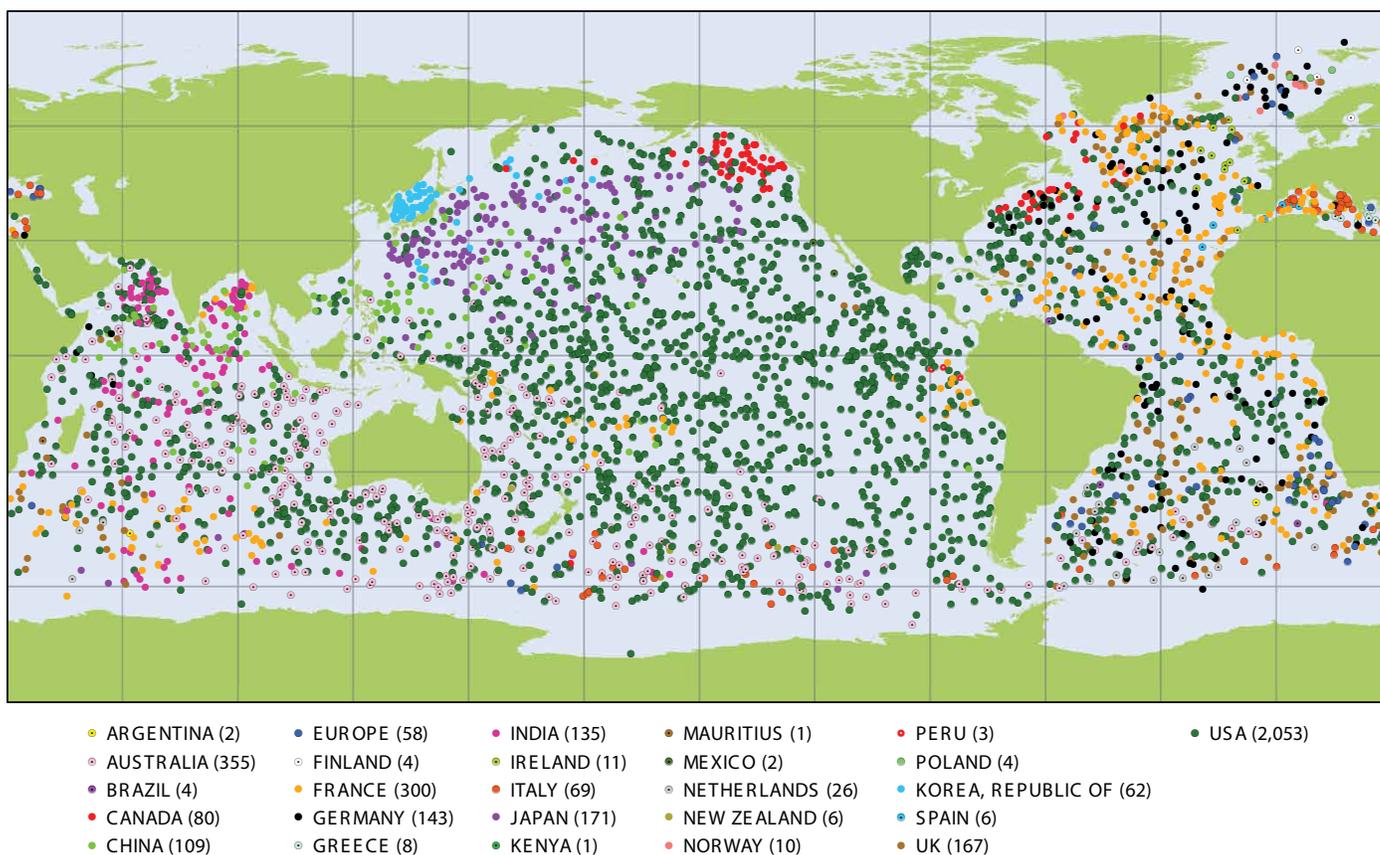


FIGURE 1. Dots colored to represent the contributions of 26 countries show the worldwide Argo array as of July 2017, with a total of 3,790 operational floats. *Source: JCOMMOPS*

oceanographic community and are associated with over 2,800 publications on diverse topics, from mesoscale variability and air-sea interaction to water mass formation, ocean circulation, and more. The contribution of Argo to the global ocean observing system is synergistic with satellite altimetry and is assimilated to constrain ocean reanalyses and forecasts (Chang et al., 2013). The Argo data set puts strong constraints on the uptake of heat by the ocean due to anthropogenic climate change (Desbruyères et al., 2016). Argo has also significantly reduced the uncertainty in decadal rates of ocean heat uptake above 2,000 m (G.C. Johnson et al., 2016). Interannual heat content variations from at least one Argo analysis are even well correlated with top-of-the-atmosphere global energy fluxes from satellites (G.C. Johnson et al., 2016), providing insight into global energy budget variations with El Niño (G.C. Johnson

and Birnbaum, 2017). Argo observations have made it possible to examine the variability of salinity in ways never before possible, given the scarcity of ship measurements, and the Argo data set has allowed scientists to observe the intensification of the global water cycle due to climate change (Durack et al., 2012).

The Argo Program is based on profiling float technology, including its continuing innovations. The history of neutrally buoyant floats in oceanography began with short-range acoustic tracking by John Swallow in the 1950s (Swallow, 1955). Floats were transformed into global ocean circulation tools during the World Ocean Circulation Experiment, (WOCE) when Russ Davis and Doug Webb equipped them with a pumping system and satellite navigation so they could cycle repeatedly from 800 m to the sea surface for tracking purposes (Davis et al., 1992). Subsequently,

conductivity-temperature-depth (CTD) sensors were added to collect profiles of temperature and salinity during ascents (Davis et al., 2001). Then, the new profiling float technology was adapted and globalized for the Argo Program (Roemmich and Gould, 2003, and Gould, 2005, provide thorough reviews of the development of float technology).

As Argo has matured over the past 17 years, it has expanded into new areas of research that were not envisioned in the original planning for the program (Argo Science Team, 1998). Technology advances have continued, with Iridium communication improving by over tenfold the vertical resolution of profiles (reduced from ~10 m to 1 m in the near surface, and from ~50 m to 2 m in the deep ocean), allowing better sampling of the mixed layer, and reducing dangers for floats in regions that would have been perilous for deployment of early

models, including marginal seas and seasonally ice-covered areas. By limiting the amount of time the floats are exposed to light in the euphotic zone from 12 hours to 15 minutes (Figure 2), the use of Iridium greatly reduces biofouling. Also, by shortening the surface time, the use of Iridium reduces advection by surface currents, grounding, and sea ice hazards to the floats. Two-way Iridium messaging also permits a float's profiling mission (i.e., profiling frequency, drift depth, and sensor sampling rates) to be changed after the float has been deployed.

A new generation of Argo floats is smaller, lighter, easier to handle, more robust, and longer-lived than its predecessors. Continuous advances in CTD sensors (Sea-Bird SBE 41 and 41cp) have made the Argo data set more accurate and consistent than seemed possible 20 years ago when Argo was conceived. Argo floats capable of profiling in areas seasonally covered in sea ice

have been developed (Klatt et al., 2007). In recent years, the Argo Steering Team has called for enhanced float coverage in western boundary regions, marginal seas, and polar regions; in addition, two new parts of the Argo Program have begun (Roemmich et al., 2009; Riser et al., 2016): Argo is no longer constrained to the upper 2,000 m and to measuring only temperature and salinity (and less often oxygen).

As Argo has developed, data quality control and archiving techniques have evolved and improved along with it, assuring the scientific value of the data collected. Because of the need to deliver data to the real-time users within 24 hours, questionable data are initially flagged by a series of automatic checks (Wong et al., 2015). Delayed-mode quality control follows, with an operator further reviewing questionable data and making corrections for sensor drift, in particular, in the salinity sensor (Owens and Wong, 2009).

With the Argo Program's value proven, it has become apparent that enhanced sampling is needed to cover highly energetic regions (particularly western boundary currents), the deep ocean, and biogeochemical processes. Deep Argo is designed to sample the global ocean water column below 2,000 m, the present limit of Argo profiling (G.C. Johnson et al., 2015). The deep floats and their accompanying new Sea-Bird SBE 61 CTDs are capable of profiling to 6,000 m depth while achieving the accuracy in temperature, salinity, and pressure needed to resolve decadal variability and change in the deep water masses of the world ocean. Biogeochemical-Argo is being developed to include new low-power, long-lived sensors for pH, nitrate, and optics that promise to add valuable multidisciplinary dimensions to the program in the future (Biogeochemical-Argo Planning Group, 2016). In the following sections, we summarize the

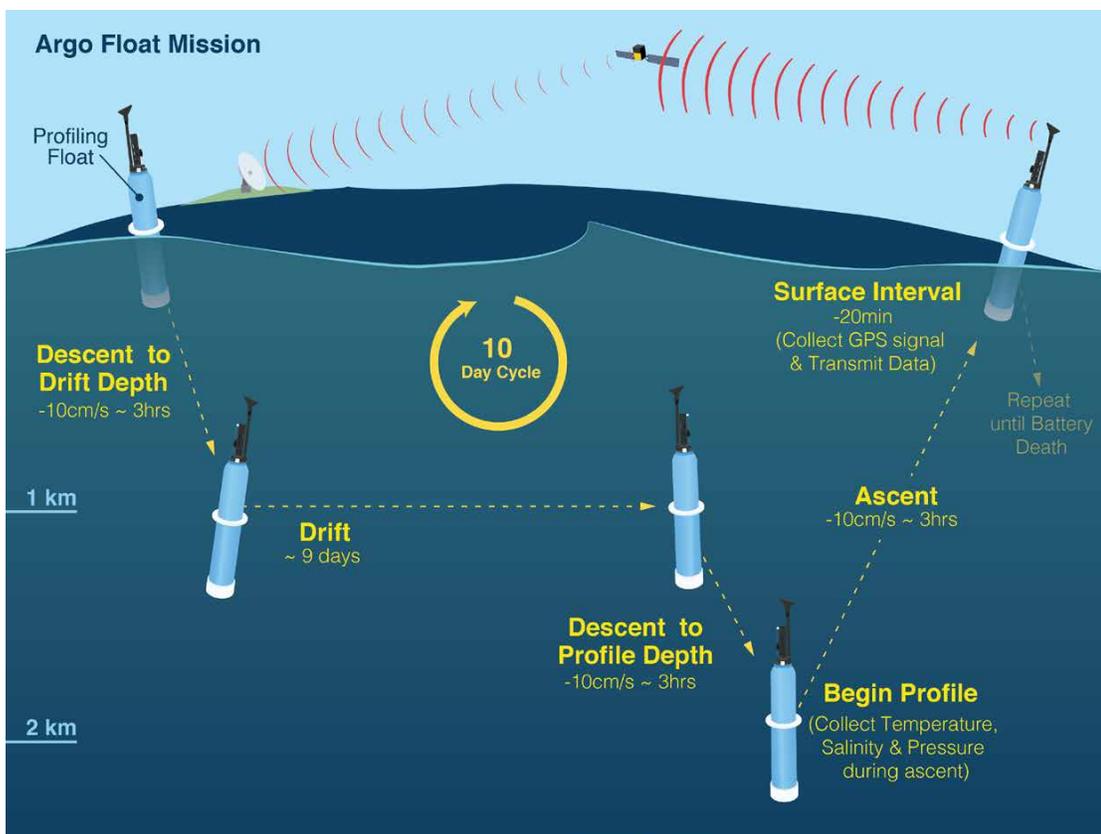


FIGURE 2. The typical profiling mission that Argo floats repeat every 10 days over their nominal five-year lifetimes is illustrated here.

Argo 2020 (Sketch) — 4,410 Floats

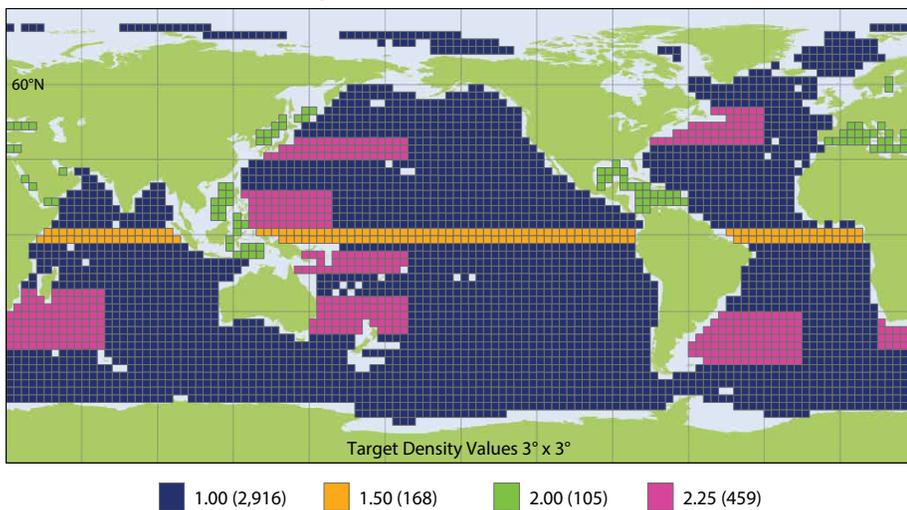


FIGURE 3. This map of potential enhancements to the Argo array shows extensions poleward of 60° latitude, increased float densities in western boundary current extension regions (magenta), marginal seas (green), and the equatorial region (orange). *Source: JCOMMOPS*

technical status and future plans of the Argo Program as well as the Deep Argo and Biogeochemical-Argo extensions.

The Argo Program is the example of how autonomous and Lagrangian platforms and sensors (ALPS) technology can be the basis of a global ocean observing system. For understanding the broad visions for ALPS technology, capabilities, infrastructure, and user base, this discussion of Argo’s present status and future is illustrative. Argo is perhaps the most internationally collaborative effort in the history of oceanography, and could not have been implemented and sustained without broad multinational participation. We gratefully acknowledge the large and essential contributions of our international partners while describing Argo’s brief history, its present status, and its future evolution from a US perspective.

THE FUTURE OF CORE ARGO

As originally envisioned, Argo was to provide uniform coverage over the ice-free ocean basins. However, as the understanding of the ocean and its variability has evolved, enhancements to the Core Argo array have been suggested to improve the observation of certain energetic regions. In particular, around western boundary current extensions

(such as those of the Gulf Stream, the Kuroshio, and the Agulhas), a doubling of the float array density has been proposed (Figure 3), and a doubling in the equatorial region is also being discussed (Cravatte et al., 2016).

As noted, the addition of Iridium satellite phone communications has enabled floats to spend only minutes on the ocean’s surface rather than the nearly full day of transmitting that was required when using ARGOS telemetry. This change almost entirely eliminates the loss of floats by beaching on the coast, which has permitted the expansion of Argo into marginal seas, such as the Gulf of Mexico, where previously high float mortalities due to beaching made it unfeasible to maintain the array in these areas. Thus, a target float resolution of two floats per 3° × 3° box to cover the marginal seas is proposed (Figure 3).

Another geographic area outside the Core Argo domain that is beginning to be addressed is seasonally ice-covered seas that occur in the Arctic and Antarctic (e.g., extension of the array poleward of 60° latitude; Figure 3). There is a relative dearth of ocean observations in these remote polar regions, and the rapid climate changes there are driving the need for adequate Arctic and Antarctic

observing networks. Profiling floats must surface to report their data and provide position information, but sea ice makes this difficult and hazardous as floats on the surface can easily be crushed or otherwise damaged by sea ice. When sea ice is present, the floats can seek to determine the conditions before attempting to surface (Klatt et al., 2007; Wong and Riser, 2011). During ice-free periods, the floats function as normal profiling floats, periodically surfacing, sending back their data, and returning to the parking depth. The expansion of the profiling float array into the polar regions presents technological challenges, such as positioning under ice, but this has been tested in the Antarctic’s Weddell Sea (Klatt et al., 2007), and additional acoustic geolocation engineering and feasibility studies are underway for the Arctic (Lee et al., 2010; Nguyen et al., 2017, in this issue).

DEEP ARGO Motivation

The average ocean depth is 4,000 m, so at present Argo samples only the upper half of the ocean volume. Recent advances in profiling float technology and in the accuracy and stability of float-mounted CTD sensors have made it practical to obtain profiling measurements to 6,000 m. By sampling from the sea surface to the bottom, global budgets of heat content, freshwater, and steric sea level can be closed, and the full-depth ocean circulation, including deep transports by the meridional overturning circulations (MOC), can be observed systematically. International partners in the Argo Program are now deploying regional pilot arrays of Deep Argo floats in the North Atlantic, the Southwest Pacific, and the Indian/Southern Ocean to demonstrate the technical readiness and scientific value of the platforms and sensors, with at least one more regional array planned for the western South Atlantic. In the coming years, these regional demonstration arrays will expand to form a global array of 1,228 Deep Argo floats with a nominal 5° × 5° spacing (G.C. Johnson et al., 2015).

Deep Argo will deliver global data from the sea surface to 6,000 m as a near real-time product, as well as a delayed-mode quality-controlled research version, via the Argo Global Data Assembly Centers.

Keys to understanding decadal variability and multidecadal change in the ocean and the coupled climate system include observations of regional balances and completion of global budgets of heat, freshwater, sea level, and carbon. In regional balances, deep ocean heat and freshwater content are slowly modified by horizontal and vertical advective processes and mixing. The MOCs span the full water column as the flows of North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW) away from their source regions are balanced by shallower and less dense transports of deep, intermediate, thermocline, and surface waters (Talley, 2013). NADW and AABW fill much of the world ocean (G.C. Johnson, 2008), and as AABW warms and freshens, the steric expansion contributes to sea level rise (Purkey and Johnson, 2013). Integration from the ocean bottom to the surface provides the full steric contribution to sea level as well as completes the ocean inventories of heat and freshwater content.

An example of the high value of global observations is seen in estimates of global ocean heat content. Ocean heat dominates Earth's energy balance over terrestrial, atmospheric, and cryospheric components (Rhein et al., 2013), and its decadal and longer changes are measured more accurately by the complementary combination of Earth's radiation budget and ocean temperature (G.C. Johnson et al., 2016; Palmer, 2017). A significant fraction of the ocean heat gain, perhaps 15% (Purkey and Johnson, 2010), resides in the deep ocean below Core Argo's 2,000 m limit, and warming in the ocean below 2,000 m is expected to increase over time (Collins et al., 2013). Multidecadal changes in properties extend to the sea bottom through the spreading and renewal of AABW and NADW in all oceans. A Global Ocean

Observing System must span the entire volume of the ocean, and we are now overcoming technology limitations that previously made it impractical to collect such data with profiling floats. Line-based shipboard repeat hydrography, which until the present has been the dominant component of deep ocean observations (Talley et al., 2016), can now be complemented with area-based float observations. The combination of high-accuracy, transect-based repeat hydrography and broad-scale coverage by profiling floats is powerful. The hydrography provides the bedrock traceable salinity calibration data for Deep Argo floats, and measures many more key parameters with high accuracy than currently possible using floats. The need for systematic and accurate sampling of the full ocean volume has long been recognized by the scientific community (e.g., Fischer et al., 2010), and this is now a reality for addressing ocean circulation, heat, freshwater, and sea level issues on a genuinely global basis.

Technology Requirements and Progress

Measuring temperature and salinity variability in the deep ocean is technically challenging. Deep ocean properties show significant large-scale trends on decadal time scales in some deep basins, with the strongest anomalies

occurring at high latitudes (Purkey and Johnson, 2010, 2013; Desbruyères et al., 2016) near water mass formation regions. Globally, multidecadal depth-dependent trends below 2,000 m are $4\text{--}8 \times 10^{-3}$ degrees per decade in temperature (Purkey and Johnson, 2010). In salinity, if the global ocean is receiving 2 cm per decade of freshwater from melting ice (e.g., G.C. Johnson and Chambers, 2013), then the depth-averaged salinity is decreasing by 0.0002 per decade. Regional signals are often much larger than these global averages, even at depth (Purkey and Johnson, 2013). The global challenge is substantial, and requires limiting the systematic errors in salinity and pressure to the greatest extent possible for estimation of decadal trends in the vertical structure of temperature and salinity. The Argo Program's international partnership proposes to meet the technical challenge by deploying a new generation of Deep Argo floats and CTDs in a global array to extend sampling to the ocean bottom.

A sustainable multinational Deep Argo Program will not rely on a single float design. Technology advances have provided pumping systems and other float components capable of operation at abyssal pressures. Four models of Deep Argo floats have been developed (Figure 4), including two 6,000 m models, Deep

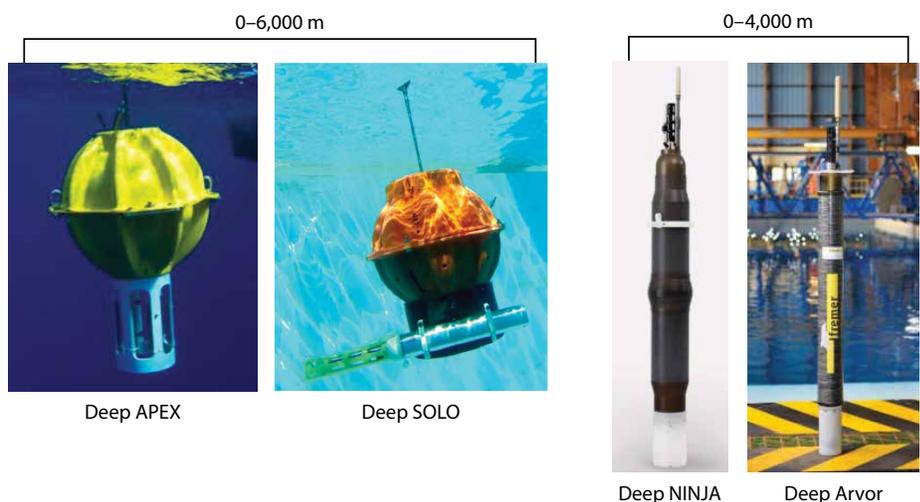


FIGURE 4. The four float models developed for Deep Argo are the 6,000 m Deep SOLO and Deep APEX (USA) and the 4,000 m Deep Arvor (France) and Deep NINJA (Japan).

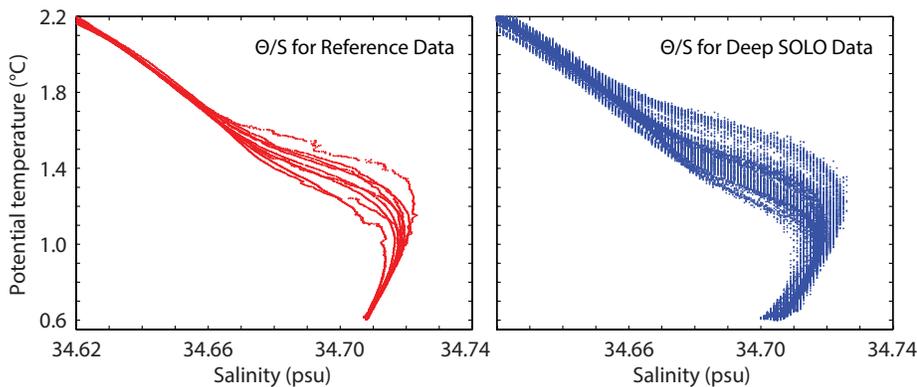


FIGURE 5. (left panel) Deep potential temperature (Θ) vs. salinity (S) relation for CTD reference data (CLIVAR line P15S in 2009) in the southwest Pacific Basin, and (right panel) for 11 Deep SOLO/SBE-61 floats in the southwest Pacific Basin.

Deep Argo National Contributions — 28 Operational Floats — July 2017

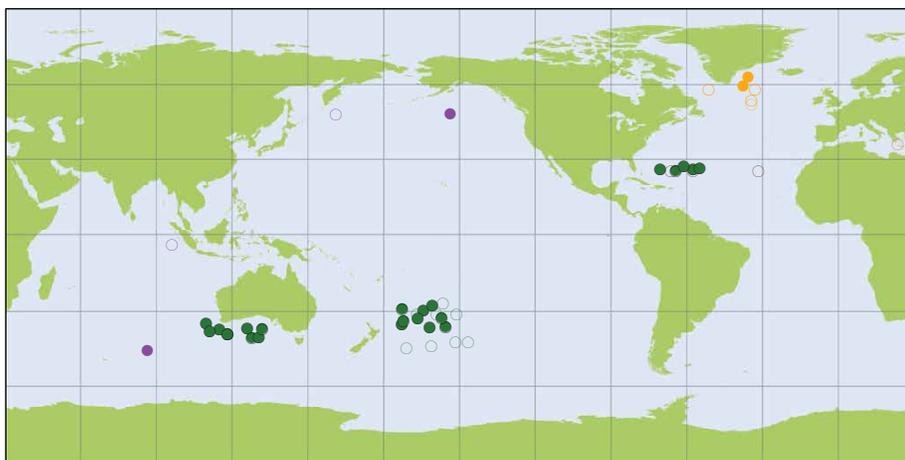


FIGURE 6. Status of the Deep Argo array as of July 2017, with 49 deep floats, including 28 operational and 21 planned in the next few months, deployed toward the goal of 1,228 floats. Source: JCOMMOPS

OPERATIONAL	PLANNED
● EUROPE (0)	○ FRANCE (7)
● FRANCE (2)	○ ITALY (1)
● JAPAN (2)	○ JAPAN (2)
● USA (23)	○ UK (3)
	○ USA (8)

SOLO (USA) and Deep APEX (USA), and two 4,000 m models, Deep Arvor (France) and Deep NINJA (Japan). Deep APEX is designed and manufactured by Teledyne Webb Research. Deep SOLO is designed and produced in limited quantity by the Argo float lab at Scripps Institution of Oceanography, and a commercial version is manufactured by MRV Systems LLC. Deep Arvor (Le Reste et al., 2016) is designed by Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER) and commercialized by NKE-Instrumentation. Deep NINJA (Kobayashi et al., 2013) is developed jointly by the Japan Agency for

Marine-Earth Science and Technology (JAMSTEC) and Tsurumi Seiki Co. Ltd. Comparisons of these Deep Argo float models are ongoing to assess float performance, robustness, and cost-effectiveness.

CTD sensors mounted on Deep Argo floats include an extended depth version of the SBE 41 on Deep Arvor and Deep NINJA and the newly developed SBE 61 mounted on Deep SOLO and Deep APEX. Initial results from SBE 61 CTDs in the Southwest Pacific are promising, and indicate that individual sensors are stable in abyssal potential temperature-salinity characteristics for more than a year, to about ± 0.001 PSS-78 at constant potential

temperature. As Figure 5 shows, the ambitious accuracy targets set for these instruments (0.001°C , 0.002 PSS-78, and 3 dbar) have not yet been achieved, but progress is being made in approaching those standards. Additional validation experiments are planned for SBE 41 and SBE 61 CTDs. In Deep Argo, not only are the accuracies of individual instruments important but also, as noted above, systematic errors must be minimized.

Future of Deep Argo

Once it is fully implemented, Deep Argo will consist of about 1,228 floats distributed globally at $5^{\circ} \times 5^{\circ}$ spacing (G.C. Johnson et al., 2015). Deep Argo floats will sample the water column from the sea surface to 4,000 m or 6,000 m, depending on the float model used, every 10–15 days. A strategy for efficient combination of 4,000 m and 6,000 m float models will be developed. Statistical analysis indicates that the $5^{\circ} \times 5^{\circ} \times 15$ day array will greatly reduce uncertainties in the global decadal trends in ocean heat content and in the steric contribution to sea level rise (G.C. Johnson et al., 2015). The standard error of the trend in global ocean heat content on decadal time scales for the 2,000–6,000 m depth range will decrease to ± 3 TW (± 0.006 W m^{-2} averaged over the surface of the globe) using Deep Argo data, down from the present ± 17 TW (± 0.034 W m^{-2}) based on repeat hydrographic transects (G.C. Johnson et al., 2015). With 10- to 15-day cycling, the Deep Argo array will have a refresh time, based on float battery energy capacity and consumption, of about five years, similar to past experience with 2,000 m Core Argo floats. In the pilot phase of Deep Argo, floats from the United States, France, Japan, New Zealand, the UK, Spain, and Italy have been deployed (Figure 6). It is expected that more international Core Argo partners (Figure 1) will join the Deep Argo effort, some during the remaining pilot phase and some in global implementation. The Argo Steering Team will continue its coordination of Core Argo and Deep Argo, which

are considered as a single global Argo array spanning the full ocean depth. As with Core Argo, all Deep Argo data are freely and immediately available from Argo's Global Data Assembly Centers.

BIOGEOCHEMICAL-ARGO

Motivation

Biogeochemical-Argo (BGC-Argo) is designed to examine the biogeochemical variability of the upper 2,000 m of the world ocean using Argo-like profiling floats equipped with a suite of BGC sensors (Figure 7). This extension of Argo will enable observation of the seasonal-to decadal-scale variability in biological productivity, the supply of essential plant nutrients from deep waters to the sunlit surface layer, ocean acidification, hypoxia, and ocean uptake of CO₂ (Biogeochemical-Argo Planning Group, 2016). While Core Argo is designed to examine the climate-scale variability of heat storage and freshwater content, such variability is also related to changes in the global carbon cycle. The ocean contains a sizable portion of both the global biomass and the global inventory of carbon, with both of these having strong links to the physical aspects of ocean circulation. The BGC-Argo array would fulfill the need called out in the first ALPS meeting report to create a global array of profiling floats measuring key parameters to address questions related to primary productivity in the ocean (Rudnick and Perry, 2003).

Early global ship-based BGC surveys were carried out as part of the GEOSECS and WOCE projects undertaken from the 1970s through the 1990s, and this work continues to the present day through GO-SHIP repeat sections (Talley et al., 2016). While GO-SHIP measurements are of very high quality, include key parameters that cannot presently be measured from floats, and provide coast-to-coast top-to-bottom sections useful for studying boundary currents and enforcing mass constraints, ship time is expensive, the observations that can be collected in this way are temporally sparse

and biased to summer months, and the data are generally not available in real time. The BGC-Argo array is planned to be able to address these issues and will provide high-quality BGC data in real time over the global ocean, analogous to the CTD observations provided by Core Argo. These efforts will provide a strong synergy with shipboard programs by extending observations into full seasonal cycles and by providing the real-time data needed for operational models.

Technology Requirements and Progress

Claustre et al. (2010) describe the core biogeochemical variables that profiling floats can measure. Substantial technical effort has been devoted to developing compact, low power sensors with long-term stability to measure these core variables. Recent technical developments have allowed Argo-type floats to carry BGC sensors for dissolved oxygen, nitrate, pH, chlorophyll, and particulate backscatter (K.S. Johnson et al., 2009; Biogeochemical-Argo Task Team, 2016). Some specific examples of new sensor types are: optode oxygen sensors (Körtzinger et al., 2005) and a method for calibrating them (K.S. Johnson et al., 2015), ultraviolet spectrophotometer nitrate sensors (K.S. Johnson et al., 2013), ion sensitive field effect pH sensors (K.S. Johnson et al., 2016), and fluorometers for chlorophyll *a* fluorescence and backscattering for particulate matter (Boss et al., 2015).

These sensors are now available commercially and are installed on floats deployed in a number of regions of the world ocean. The most ambitious use of these floats is in the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) project, sponsored by the US National Science Foundation with contributions from the US National Oceanic and Atmospheric Administration and NASA. SOCCOM aims to deploy as many as 200 BGC-Argo floats in the Southern Ocean by 2020, with about 80 floats already deployed

(Figure 8). The floats share many characteristics with conventional Argo floats: 0–2,000 m sampling, 10-day cycle times, and real-time data availability, but they also carry the additional BGC sensors. These sensors use only about 25% of the energy stored in the float batteries, so multiyear missions are possible. Data from these floats have already been used to examine seasonal cycles of primary production in the Southern Ocean as well as the import and export of CO₂ to the ocean in the range of latitudes from the Antarctic Circumpolar Current to the southern edge of the seasonal ice

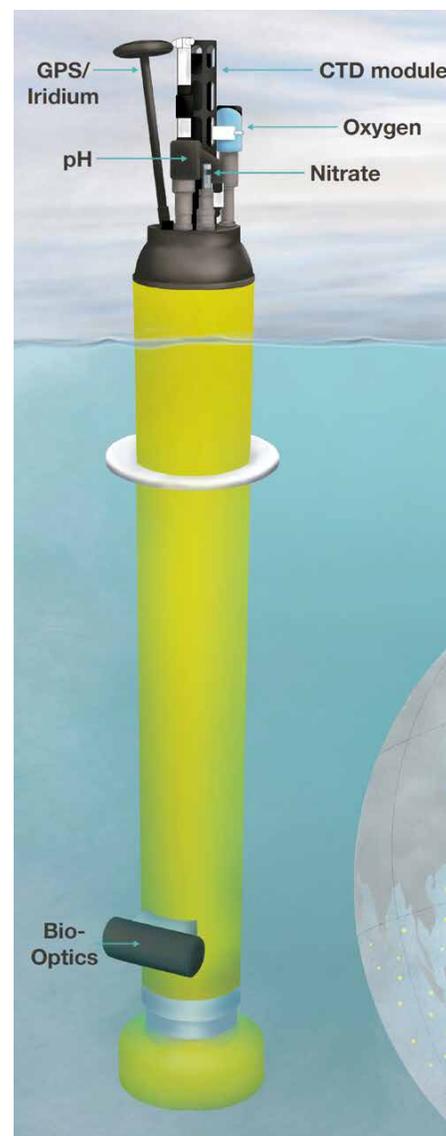


FIGURE 7. Illustration of a profiling float equipped with biogeochemical sensors. Illustration by Kelly Lance, MBARI



FIGURE 8. Status of the Biogeochemical-Argo array by sensor type as of July 2017. Source: JCOMMOPS

- Operational Floats (270)
- Suspended particles (147)
- Downwelling irradiance (55)
- pH (62)
- Nitrate (80)
- Chlorophyll *a* (147)
- Oxygen (253)

zone around the Antarctic continent. The SOCCOM floats are equipped with an ice-avoidance algorithm that allows them to sample under sea ice in winter.

Future of Biogeochemical-Argo

Preliminary plans are underway to expand the SOCCOM BGC float array into the subtropical portion of the Southern Hemisphere, and eventually to deploy a global array consisting of roughly 1,000 BGC-Argo floats (Biogeochemical-Argo Planning Group, 2016). In addition to the SOCCOM deployments sponsored by the United States, France has deployed BGC floats in the Mediterranean and the North Atlantic, and other European countries have plans to participate. Japan, Australia, China, and India have also expressed interest in providing BGC-Argo floats, and it is hoped that other nations will also join. Already, the number of vertical oxygen profiles to near 1,000 m collected by these floats greatly

exceeds the number collected each year by ships (K.S. Johnson et al., 2015).

In the coming years, we can expect important new insights into the carbon cycle, the biological pump, and ocean acidification to come from the BGC-Argo program. New sensors for quantities such as $p\text{CO}_2$ and total alkalinity will be added to the floats, and as a baseline is established for the global distribution of BGC variables, it will be possible to assess decadal and longer changes in these quantities. It seems likely that the development of BGC-Argo will run parallel to the early development of the Core Argo Program.

Planning for the global Biogeochemical-Argo array is ongoing. Roughly 7% of the total Argo array (Figure 8) is now equipped with biogeochemical sensors, with many of these instruments deployed in regional programs (Biogeochemical-Argo Planning Group, 2016). Given an expected lifetime of about four years for a BGC-Argo float,

this array would require the deployment of 250 new floats per year to sustain it (K.S. Johnson and Claustre, 2016).

CONCLUSIONS

The success of Argo is largely built on international cooperation and the free sharing of the data. The program has evolved from modest beginnings to a present that was not then fully envisioned, and with a future that is still evolving. Allowing for evolutionary development of observing systems is essential for their long-term sustainability. Additionally, Argo would not be possible without sustained programmatic support from the sponsoring agencies, the substantial tenacity of many individuals, and community building—there simply would be no Argo without its dedicated community of scientists, technologists, and government representatives.

As technology continues to advance, the scientific value of the Argo array

will only increase as the observational record lengthens, more capable sensors for autonomous platforms become available, and floats are able to profile the full ocean depth. However, there are challenges to the Argo Program: flat or declining budgets in many of the international partner countries make maintaining the number of operational floats difficult, additional data types from new sensors are taxing the delayed-mode quality control and data archiving systems, and there is an ongoing need for the labor-intensive task of improving the quality control of the data and the underlying reference data sets. 

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