

Eos

Bringing Biogeochemistry into the Argo Age

Plans are underway to integrate and augment a collection of regional programs to form a global biogeochemical monitoring network.

By K. S. Johnson and H. Claustre

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Crew members prepare to launch a biogeochemical profiling float from R/V *Nathaniel B. Palmer* in the Pacific sector of the Southern Ocean. Credit: Veronica Tamsitt, Scripps Institution of Oceanography

As they drift silently across the world's oceans, the thousands of sensors in the Argo network constantly gather physical data on water conditions as deep as 2 kilometers below the surface. Evolving technology now presents an opportunity for the Argo floats to provide even more information, with the potential to drive a transformative shift in our ability to observe and predict the effect of climate change on ocean ecology, metabolism, and carbon uptake. The new data could also dramatically improve our models of marine resources.

[Argo](#), an international program to measure changes in the ocean's heat content and salinity, was launched in 1999 [Roemmich *et al.*, 2015; Riser *et al.*, 2016]. The initial objective of the Argo program was to operate 3200 profiling floats in the ice-free waters from 60°N to 60°S to measure pressure, temperature, and salinity in the upper 2000 meters of the ocean.

The program began deploying floats in 2000, and as of October 2016, [more than 3700 floats cover most of the world's oceans](#). These platforms have proven to be robust and cost-effective, and they have gained many more capabilities as technology has evolved. Reflecting this, the Argo program has recently approved planning efforts for extensions that include operations at depths below 2000 meters, operations in ice-covered waters at higher latitudes, and focused operations in equatorial waters and western boundary currents.

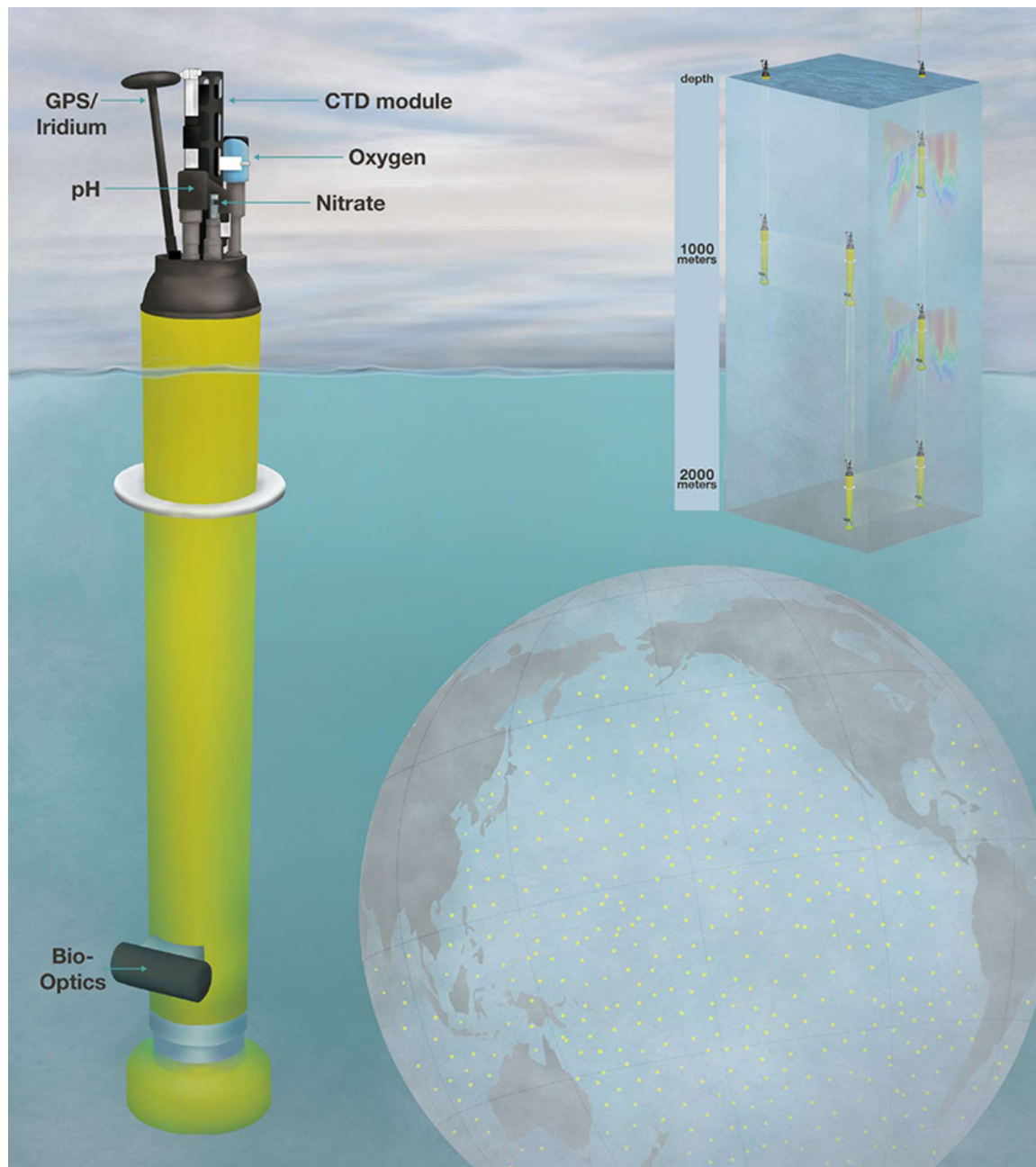
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Biogeochemical-Argo would equip floats across the entire Argo network with a standard set of biogeochemical sensors.

Here we report on the activities under way to prepare for an Argo extension to include biogeochemical observations. If approved, Biogeochemical-Argo would be an extension of the Argo array that aims to equip floats across the entire network with a standard set of biogeochemical sensors.

These sensors would provide real-time data for pH, oxygen, nitrate, chlorophyll, suspended particles, and measurements of the amount of the

penetrating sunlight (downwelling irradiance) that drives photosynthesis. Data from these sensors would be accessible to the public.



Drawing of a profiling float equipped with biogeochemical sensors. (CTD is conductivity, temperature, and depth.) Insets show (top) a typical float mission as it descends to 2000 meters and (bottom) the global array at the proposed density.

Credit: Kelly Lance, Monterey Bay Aquarium Research Institute

Biogeochemical-Argo Array

A global Biogeochemical–Argo array would enable direct observation of the seasonal to decadal–scale variability in net community production (the rate at which life–forms capture and store chemical energy as biomass), the supply of essential plant nutrients transported from deep waters to the sunlit surface layer, ocean acidification, hypoxia (low oxygen levels), and ocean uptake of carbon dioxide. Bio–optical sensors would supplement satellite observations of the ocean’s color by providing measurements of chlorophyll, light, and light scattering deep into the ocean interior throughout the year, in cloud– and ice–covered areas, or during the dark of polar winter.

Development of a global Biogeochemical–Argo array is proceeding on two tracks.

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Scientists produced a document outlining the system requirements, and the science ministers from the G7 nations endorsed the concept last May.

First, a set of regional and smaller–scale programs is in operation around the world. These programs have already equipped almost 10% of the Argo array with [biogeochemical sensors](#). Although these programs are sponsored by various organizations and they operate independently, they must make their data available to the Argo community and process their data according to Argo standards.

The second track involves the planning needed to scale the various regional projects into an integrated, global program. Scientists from eight countries met in January to formalize the planning process. They produced a document outlining the system requirements, and the science ministers from the Group of Seven (G7) nations endorsed the concept last May. This effort includes a variety of data analyses to determine the appropriate array size.

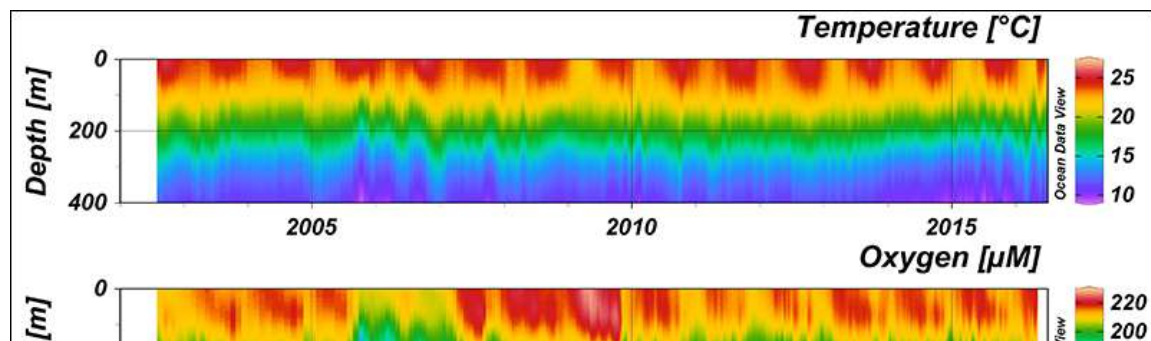
Regional Biogeochemical Arrays

The regional arrays provide a sampling of ocean conditions around the world that is designed to produce an integrated data set that can be used to address questions related to physical–biogeochemical coupling in eddies,

phytoplankton phenology (cyclic and seasonal phenomena), nutrient supply, and climate effects on ocean carbon cycling in selected regions. Some of these arrays include

- the Southern Ocean Carbon and Climate Observations and Modeling ([SOCCOM](#)) project
- the Remotely Sensed Biogeochemical Cycles in the Ocean ([remOcean](#)) project in the North Atlantic subpolar gyre
- the Novel Argo Ocean Observing System in the Mediterranean Sea ([NAOS](#))
- the Integrated Physical-Biogeochemical Ocean Observation Experiment ([INBOX](#)) in the Kuroshio region of the North Pacific
- the Australia-India Joint Indian Ocean Bio-Argo Project ([IO Bio-ARGO](#))

Smaller-scale deployments have occurred at a variety of locations, particularly such well-studied sites as the University of Hawai‘i at Mānoa’s Hawaii Ocean Time-series ([HOT](#)) station, where long biogeochemical records from floats (Figure 1) can be calibrated against shipboard measurements. The number of vertical oxygen profiles collected by all of these floats, reaching depths near 1000 meters, now greatly exceeds the number that ships collect each year in the open ocean [*Johnson et al.*, 2015].



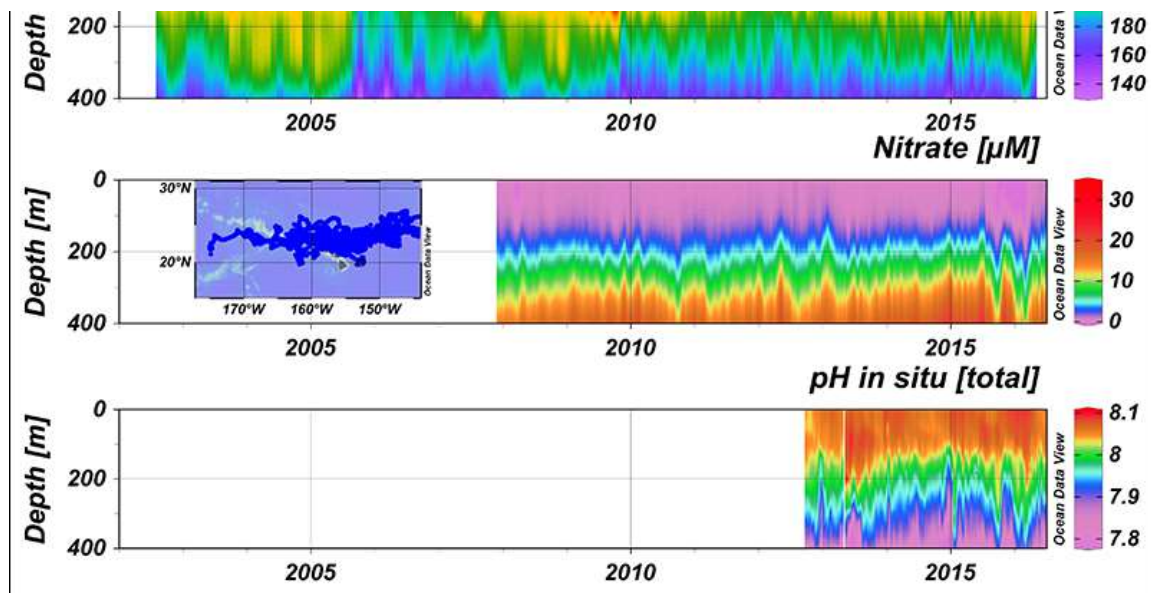


Fig. 1. Temperature, oxygen, nitrate, and pH data measured from profiling floats deployed at the HOT station ALOHA since 2002. The inset map shows the profile locations as the floats disperse from HOT. Adapted from data reported by *Riser and Johnson* [2008] and *Johnson et al.* [2010, 2013, 2016].

These regional programs and such international collaborations as the Scientific Committee on Oceanic Research (SCOR) [Working Group 14.2](#) have laid the foundation for a global observing system by validating sensor operation and developing software tools. The regional programs are also building the expertise needed to operate a global network that interacts with other components of the global ocean observing system, including satellites [*Claustre et al.*, 2011], shipboard programs like the international Global Ocean Ship-Based Hydrographic Investigations Program ([GO-SHIP](#)), and various time series stations.

Data Analysis and Management

The regional programs and international collaborations are



enabling regional- to global-scale analyses of data. Using oxygen sensors on more than 100 profiling floats distributed globally, scientists have assessed, for the first time, oxygen consumption rates in the mesopelagic zone beneath the ocean's surface, where too little sunlight penetrates to support photosynthesis, and the carbon export that fuels this respiration [Hennon *et al.*, 2016].



Three crew members prepare a profiling float for launch near the ice edge in the Southern Ocean. In an international collaboration, the float is being deployed for the U.S. Southern Ocean Carbon and Climate Observations and Modeling program from the Australian R/V *Investigator*. Credit: Melissa Miller, Scripps Institution of Oceanography

Bio-optical measurements of chlorophyll from these floats show no significant bias with satellite remote sensing products [Xing *et al.*, 2011]. These measurements enable scientists to study many fundamental aspects of phytoplankton ecology [Boss and Behrenfeld, 2010]. Combining bio-optical measurements from floats and satellites also enables scientists to create a three-dimensional reconstruction of the particulate organic carbon distribution [Sauzède *et al.*, 2016].

Nitrate sensors on the floats [Johnson *et al.*, 2013] enable researchers to study the bottom-up influence of nutrient supplies on ecosystems. For example, the NAOS array of profiling floats in the Mediterranean Sea, equipped with nitrate sensors, shows seasonal variability that was previously unobservable [Pasqueron de Fommervault *et al.*, 2015].

Profiling floats deployed at the HOT station (Figure 1) have produced pH readings at the sea surface over the course of several years that agree with the shipboard observations to 0.004 ± 0.007 pH units [Johnson *et al.*, 2016]. This precision exceeds the Global Ocean Acidification Observing Network's [requirements for pH measurements](#).

In parallel with these pilot projects, the community has begun to develop shared data management procedures. The successful data management system of the existing Argo program serves as a basis for adapting the system for biogeochemical parameters. The [Argo Data Management Team](#) has developed a parallel file structure for the core temperature, salinity, and

pressure data and for associated biogeochemical data. Annual meetings of the Argo Data Management Team and members of the regional biogeochemical float programs are optimizing this new data management and distribution system.

Global Planning

The success of these regional projects has led to the second track of the project: preliminary planning for the transition to a global-scale Biogeochemical-Argo program. Planning includes several OceanObs'09 reports [Gruber *et al.*, 2010; Claustre *et al.*, 2010] and a U.S. Ocean Carbon and Biogeochemistry Scoping Workshop [Johnson *et al.*, 2009].

To formalize planning for Biogeochemical-Argo, scientists gathered for a meeting on 11–13 January 2016 in Villefranche-sur-Mer, France, with attendees from Australia, Canada, China, Japan, France, Germany, the United Kingdom, and the United States. On the basis of observing system simulation experiments and analyses of global ocean data sets presented at the meeting, an array of about 1000 biogeochemical profiling floats would provide the needed resolution to greatly improve our understanding of biogeochemical processes on a global scale and would reduce the uncertainties of major ocean carbon fluxes. Such an array would significantly improve marine resource models.

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The science ministers of the G7 nations have indicated their support for this effort. They issued a [communiqué](#) and appendix (Attachment 2) after their 15–17 May 2016 meeting in Tsukuba, Japan, that endorses the development of a global ocean, biogeochemical observing system through the Argo network.

Costs

At the January planning meeting in Villefranche, attendees formulated estimates of the costs of implementing and maintaining the proposed additions to the Argo network.

A Biogeochemical–Argo float lasts for about 4 years, so this system would require the annual procurement and deployment of 250 new floats to sustain it. The lifetime cost for a Biogeochemical–Argo float, including capital expense, calibration, data management, and data transmission, is about \$100,000. A global Biogeochemical–Argo system would thus cost nearly \$25,000,000 annually [National Research Council, 2015].

In the present Argo paradigm, the United States provides half of the profiling floats in the array while the European Union (EU) and Australia/Asia/Canada share most of the remaining half. If this continued, the U.S. cost for the Biogeochemical–Argo system would be about \$12,500,000 annually, and the EU and Australia/Asia/Canada would each pay about \$6,250,000.

By way of comparison, the annual cost of the proposed U.S. share is about one quarter of the annual cost of either the U.S. Ocean Drilling Program or the U.S. Ocean Observatories Initiative, and it is similar to the annual operating cost of one Global Class research vessel in the U.S. fleet.

This presumes that float deployments can be carried out on research cruises already planned, particularly the international GO–SHIP program, which provides essential validation data.

A New Age for Ocean Biogeochemistry

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A global Biogeochemical–Argo system would provide an integrated picture of the systems that drive the world’s ocean ecosystems.

A global Biogeochemical–Argo system would enable a transformation in our understanding of ocean biogeochemistry, climate interactions, and marine resources. It would provide data from regions and under conditions not accessible to satellites, and the global coverage would provide an

integrated picture of the systems that drive the world's ocean ecosystems.

The [summary document](#) from the Villefranche meeting, "The Rationale, Design and Implementation Plan for Biogeochemical-Argo," is available from the [program website](#), and we encourage the public to contact us with their comments at johnson@mbari.org or claustre@obs-vlfr.fr.

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