Biogeochemical-Argo Science & Implementation Plan

The Biogeochemical-Argo Planning Group

Edited by Ken Johnson & Hervé Claustre

The Scientific rationale, design and Implementation Plan for a Biogeochemical-Argo float array

The extension of the Argo array of profiling floats to include biogeochemical sensors for pH, oxygen, nitrate, chlorophyll, suspended particles, and downwelling irradiance.

To be cited as:

Biogeochemical-Argo Planning Group. 2016. The scientific rationale, design and Implementation Plan for a Biogeochemical-Argo float array. Edited by Ken Johnson and Hervé Claustre. doi:10.13155/46601

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Preface

This document describes an implementation plan for a global network of biogeochemical sensors on Argo profiling floats, termed Biogeochemical-Argo. The concept of global biogeochemical measurements was first articulated in a Community White Paper [*Gruber et al.*, 2007] that was supported by the International Ocean Carbon Coordinating Project (IOCCP) and the US Ocean Carbon and Biogeochemistry Program (US-OCB). This was followed by a Scoping Workshop funded by the US Ocean Carbon and Biogeochemistry Program on 28 to 30 April 2009 [*Johnson et al.*, 2009] and an International Ocean Color Coordinating Group (IOCCG) supported working group [*IOCCG*, 2011]. Extensive discussions were held at the OceanObs 09 Workshop on 21 to 25 September 2009 in Venice. This led to two subsequent community White Papers, published in 2010 ([*Gruber et al.*, 2010a]; [*Claustre et al.*, 2010b]).

Recommendations from these meetings were for the implementation of integrated deployments of larger numbers of profiling floats with biogeochemical sensors to demonstrate the feasibility of operating biogeochemical arrays. Following these reports, a variety of regional arrays have been developed with great success. In parallel with these regional efforts, great strides have been made in sensor operation and calibration. This prior work demonstrates the feasibility of operating a global system in order to address fundamental science questions and needs for ocean resource management.

These efforts culminated in a workshop that was held from 11 to 13 January 2016 at the Laboratoire d'Océanographie de Villefranche-sur-mer, France. This document is a summary of the discussions at the Villefranche workshop and has been reviewed by attendees. Review by the Argo Steering Team and community input have been solicited next.

A summary of the report has also been presented at a variety of scientific meetings. These include:

- Global Climate Observing System Science Meeting, Amsterdam, 2-4 March 2016
- Argo Steering Team, Yokohama, 22-24 March 2016
- US OCB Summer Meeting, Woods Hole, 25-28 July 2016

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SUMMARY

Biogeochemical-Argo is the extension of the Argo array of profiling floats to include floats that are equipped with biogeochemical sensors for pH, oxygen, nitrate, chlorophyll, suspended particles, and downwelling irradiance. Argo is a highly regarded, international program that measures the changing ocean temperature (heat content) and salinity with profiling floats distributed throughout the ocean. Newly developed sensors now allow profiling floats to also observe biogeochemical properties with sufficient accuracy for climate studies. This extension of Argo will enable an observing system that can determine 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 CO_2. Biogeochemical-Argo will drive a transformative shift in our ability to observe and predict the effects of climate change on ocean metabolism, carbon uptake, and living marine resource management.

Presently, vast areas of the open ocean are sampled only once per decade or less, with sampling occurring mainly in summer. Our ability to detect changes in biogeochemical processes that may occur due to the warming and acidification driven by increasing atmospheric CO_2, as well as by natural climate variability, is greatly hindered by this undersampling. In close synergy with satellite systems (which are effective at detecting global patterns for a few biogeochemical parameters, but only very close to the sea surface and in the absence of clouds), a global array of biogeochemical sensors would revolutionize our understanding of ocean carbon uptake, productivity, and deoxygenation. The array would reveal the biological, chemical, and physical events that control these processes. Such a system would enable a new generation of global ocean prediction systems in support of carbon cycling, acidification, hypoxia and harmful algal blooms studies, as well as the management of living marine resources.

In order to prepare for a global Biogeochemical-Argo array, several prototype profiling float arrays have been developed at the regional scale by various countries and are now operating. Examples include regional arrays in the Southern Ocean (SOCCOM[1]), the North Atlantic Sub-polar Gyre (remOcean[2]), the Mediterranean Sea (NAOS[3]), the Kuroshio region of the

[1] SOCCOM – Southern Ocean Carbon and Climate Observations and Modeling (www.soccom.princeton.edu)
[2] remOcean – Remotely-sensed biogeochemical cycles in the Ocean (www. remocean.eu)
[3] NAOS – Novel Argo Ocean Observing System (www. en.naos-equipex.fr)

North Pacific (INBOX[4]), and the Indian Ocean (IOBioArgo[5]). For example, the SOCCOM program is deploying 200 profiling floats with biogeochemical sensors throughout the Southern Ocean, including areas covered seasonally with ice. The resulting data, which are publically available in real time, are being linked with computer models to better understand the role of the Southern Ocean in influencing CO_2 uptake, biological productivity, and nutrient supply to distant regions of the world ocean.

The success of these regional projects has motivated a planning meeting to discuss the requirements for and applications of a global-scale Biogeochemical-Argo program. The meeting was held 11-13 January 2016 in Villefranche-sur-Mer, France with attendees from eight nations now deploying Argo floats with biogeochemical sensors present to discuss this topic. In preparation, computer simulations and a variety of analyses were conducted to assess the resources required for the transition to a global-scale array. Based on these analyses and simulations, it was concluded that an array of about 1000 biogeochemical profiling floats would provide the needed resolution to greatly improve our understanding of biogeochemical processes and to enable significant improvement in ecosystem models. With an endurance of four years for a Biogeochemical-Argo float, this system would require the procurement and deployment of 250 new floats per year to maintain a 1000 float array. 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 about $25,000,000 annually. In the present Argo paradigm, the US provides half of the profiling floats in the array, while the EU, Austral/Asia, and Canada share most the remaining half. If this approach is adopted, the US cost for the Biogeochemical-Argo system would be ~$12,500,000 annually and ~$6,250,000 each for the EU, and Austral/Asia and Canada. This includes no direct costs for ship time and presumes that float deployments can be carried out from future research cruises of opportunity, including, for example, the international GO-SHIP program (www.go-ship.org).

The full-scale implementation of a global Biogeochemical-Argo system with 1000 floats is feasible within a decade. The successful, ongoing pilot projects have provided the foundation and start for such a system.

[4] INBOX – Western North Pacific Integrated Physical-Biogeochemical Ocean Observing Experiment (www.jamstec.go.jp/ARGO/inbox/index.html)
[5] IOBioArgo – Australia-India Joint Indian Ocean Bio-Argo Project (www.research.csiro.au/iobioargo)

1. INTRODUCTION AND OVERVIEW

1.1. Scientific rationale

Society faces a suite of challenges driven by change in the ocean. These challenges are global in scale and may have large effects on climate and ocean ecosystems. Increasing atmospheric CO_2 warms the earth and 93% of the added heat is estimated to be stored in the ocean [*Wijffels et al.*, 2016]. This heats surface waters, melts ice, and, when combined with changing winds, these processes may alter large scale ocean circulation [*Meredith et al.*, 2012]. Impacts on ocean productivity are unclear due to limited observations, but major shifts may occur. Increased stratification caused by warmer surface waters will likely reduce upward nutrient fluxes in some regions and produce a negative effect on ocean productivity [*Riebesell et al.*, 2009]. In contrast, increased stratification due to warmer waters may extend the phytoplankton growing seasons in other ocean regions as deep mixing into low light waters is reduced [*Steinacher et al.*, 2010]. An additional complexity is that increased winds at high latitudes may alter phytoplankton production [*Rodgers et al.*, 2014]. The net effect of all these processes on plankton growth will remain unclear without a broad suite of observations to assess change.

Increasing CO_2 is driving a decrease in surface ocean pH ([*Dore et al.*, 2009]; [*Bates*, 2015]) with the potential for negative effects on organisms that produce calcareous shells and indirect effects on ecosystem processes in all regions of the ocean [*Kroeker et al.*, 2013]. Decreasing pH and carbonate ion concentration, and subsequent effects including diminished ballast production that drives the sinking flux of organic carbon, are likely to reduce the oceans ability to remove anthropogenic CO_2 from the atmosphere [*Landschützer et al.*, 2015]; [*Riebesell et al.*, 2009].

Observations show that oxygen minimum zones (OMZ) have expanded in recent decades ([*Stramma et al.*, 2008]; [*Keeling et al.*, 2010]]) and models predict OMZs may further expand in warmer, future climates. However, it is not clear yet whether the observed changes are due to climate change or climate variability (e.g. [*Frolicher et al.*, 2009]). Recent studies suggest that these oxygen minimum zones may change volume on a decadal time scale, in response to climate forcing [*Deutsch et al.*, 2014; *Deutsch et al.*, 2011]. Associated with the changes in OMZ volume are decadal scale changes in denitrification and ocean stocks of nitrate, a major plant nutrient [*Deutsch et al.*, 2011]. However, the few direct observations that are available sometimes suggest behaviors that are contradictory to expectations. For example, despite increasing acidification, the Continuous Plankton Recorder observations show an increase in $CaCO_3$ containing Coccolithophore abundance in the North Atlantic [*Rivero-Calle et al.*, 2015]. The increased CO_2 that drives acidification was hypothesized to increase growth rates of Coccolithophores, outweighing the impact of lower pH.

The effects of warming, acidification and deoxygenation on biogeochemical processes are difficult to predict with numerical models or remote sensing observations only. While the concentrations of phytoplankton pigments detected by remote sensing have decreased [*Boyce et al.*, 2010] the influence on oceanic primary productivity is not clear [*Behrenfeld et al.*, 2016].

The changes produced by warming, acidification, and deoxygenation will influence ocean ecosystem functioning, and these changes may result in significant economic and non-economic costs to society ([*Hoegh-Guldberg and Bruno*, 2010]; [*Doney et al.*, 2012]). Understanding and forecasting the changes in ocean ecosystems will require observations throughout the year over the entire ocean (McKinley et al., 2015). Ocean observing systems, however, have not kept pace with these challenges. Our primary resource for ocean biogeochemical observations is classical ship-board measurements. As the need to observe the ocean increases, the number of observations made from ships is decreasing dramatically (Fig. 1) while the observations made through autonomous platforms and especially with profiling floats are rapidly increasing and now comprise the majority of the data that is collected.

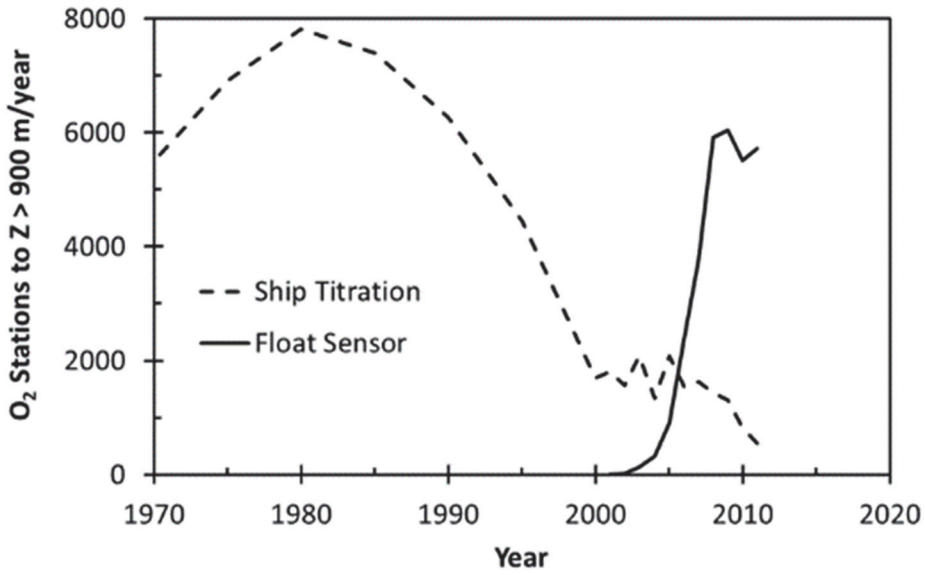

Figure 1. Number of oxygen profiles to a depth (Z) of at least 900 m per year in the US NODC World Ocean Database 2013. "Ship Titration" denotes the Winkler titration measurements made on board ship, while "Float Sensor" values are data reported by profiling floats (from [*Johnson et al.*, 2015]). In 2015, the number of float O_2 profiles approached 12,000.

Without profiling float data, our direct knowledge of the temporal variability of biogeochemical processes comes from satellite ocean color measurements, a few ship-based time series programs (e.g. HOT near Hawaii and BATS near Bermuda) where sampling is repeated roughly monthly [*Ducklow et al.*, 2009], a few moorings instrumented with biogeochemical sensors, and measurements of surface water pCO_2 made over broad regions from volunteer observing ships

and transiting research vessels. Ship-based sampling at time series stations cannot resolve mesoscale and higher frequency processes (e.g. eddies, tropical storms) and gives little sense of change over broad areas [*Henson et al.*, 2015]. Volunteer Observing Ships may sample processes over greater areas [*Palevsky et al.*, 2016] but don't resolve processes in the vertical dimension and often repeat their sampling sporadically.

Satellite observations have helped to overcome such spatial and temporal limitations, but the suite of directly observable biogeochemical parameters is limited to ocean color during cloud-free periods in the upper one fifth of the euphotic zone, typically less than 40 m. Environmental factors, such as temperature, may alter the relationship between color and more fundamental properties such as chlorophyll and particulate organic carbon ([*Graff et al.*, 2015]; [*Graff et al.*, 2016]; [*Mignot et al.*, 2014]). The result is that we have only limited understanding of how ocean biogeochemistry is changing in response to natural climate variations such as El Niño or to anthropogenic climate changes driven by the accumulation of greenhouse gases in the atmosphere, let alone how these changes will propagate through marine ecosystems and the services they provide.

An expanded in situ observing system is needed to assess and predict the future trajectory of ocean biogeochemistry. The observing system must act in synergy with our existing observing assets. The physical oceanographic community has overcome the limitations on observing ocean heat and salt content by developing the Argo array of profiling floats. There are now over 3900 profiling floats deployed in the ocean, collecting over 100,000 profiles of temperature and salinity to 2000 m depth each year. Here we argue that the Argo array should be expanded globally with biogeochemical sensors to produce an analogous, revolutionary improvement in our understanding of ocean biology and chemistry, as has occurred for ocean physics.

1.2. Biogeochemical-Argo is a mature technology

The Biogeochemical-Argo array will be based on the proven profiling float technology used in the Argo array ([*Riser et al.*, 2016]). Profiling floats are free drifting, battery powered platforms that park at 1000 m for 5 to 10 days, then descend to 2000 m before they rise to the surface. Physical and biogeochemical measurements are collected during the ascent and reported at specified depth intervals (typically 60 depths throughout the water column for chemical measurements, every 2 m for physical measurements, and up to 0.2 m for some optical measurements). Once at the surface, float position is determined by GPS and the observed data are then transmitted via the Iridium communication system to a shore-based server. The data are immediately made available through publicly accessible databases on the Internet, following the Argo data policy. The float then returns to its parking depth to repeat the cycle 200 to 300 times.

In 2003, a workshop held at Scripps Institution of Oceanography on "Autonomous and Lagrangian Platforms and Sensors" [*ALPS*, 2003] set the

foundations for developing robotic observation capabilities for ocean biogeochemistry. At that time the Argo program had already started with ~ 1000 operational floats at sea and some case studies had begun to demonstrate the potential of monitoring ocean biogeochemistry through floats equipped with biogeochemical sensors (e.g. [*Bishop et al.*, 2002]). Since this meeting, and in parallel with profiling float improvement and maturation, there has been a major evolution in the development and use of novel biogeochemical sensors.

Dissolved oxygen concentration was one of the first biogeochemical variables to be observed from profiling floats. Early deployments highlighted deep convection and associated ventilation in winter in the Labrador Sea [*Körtzinger et al.*, 2004], a site and season where shipboard measurements have rarely been collected; other deployments allowed quantification of net community production over annual cycles in various oceanic provinces regimes ([*Riser and Johnson*, 2008] ; [*Martz et al.*, 2008]). This development of O_2-float research was paralleled by the promotion of such measurements within the Argo program by the so-called "Friends of Oxygen on Argo" group ([*Gruber et al.*, 2007]). Continuous records of oxygen from profiling floats now exceed a decade in length in some areas of the ocean (Fig. 2).

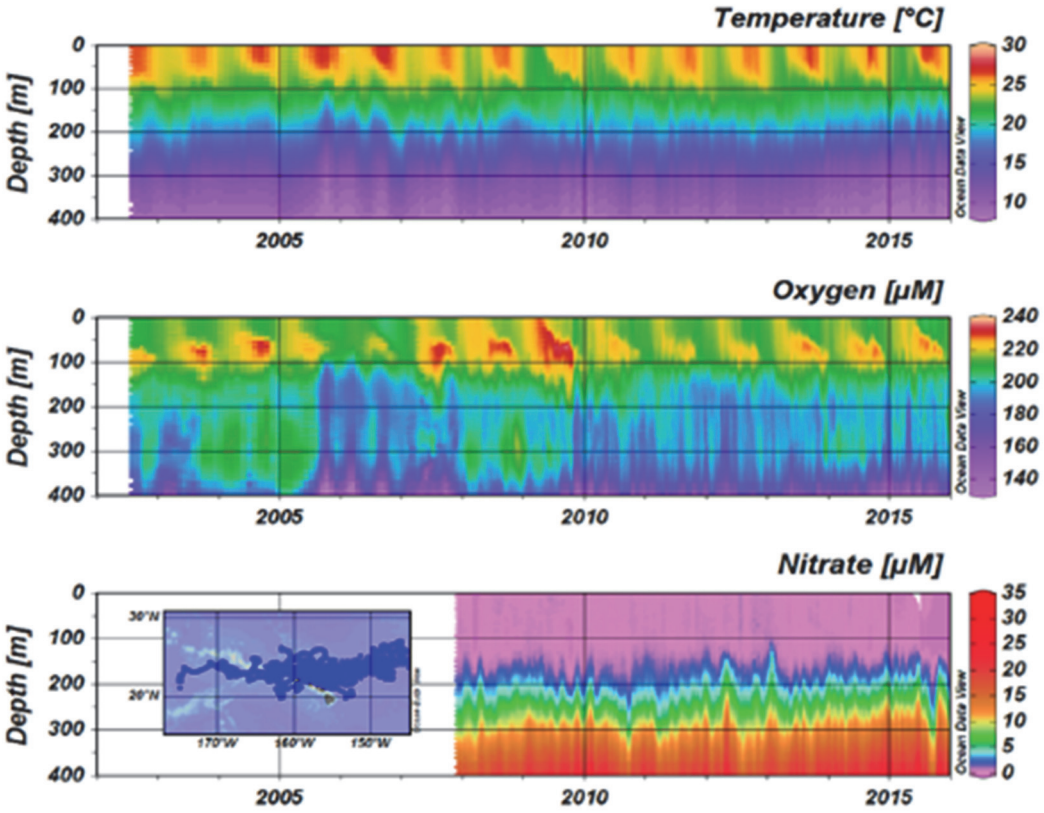

Figure 2. Temperature, oxygen, and nitrate measured from profiling floats deployed at the Hawaii Ocean Time-series station ALOHA since 2002. The inset map shows the profile locations as the floats disperse from HOT. Adapted from data previously reported ([*Riser and Johnson*, 2008], [*Johnson et al.*, 2010], [*Johnson et al.*, 2013a]) and subsequent measurements.

Subsequently, implementation of optical sensors measuring chlorophyll *a* fluorescence and backscattering made it possible to characterize phytoplankton seasonal dynamics ([*Boss et al.*, 2008a; *Boss et al.*, 2008b] [*Mignot et al.*, 2014]) and at the same time supported more conceptual and theoretical studies related to the onset of phytoplankton blooms in temperate latitudes (e.g. [*Boss and Behrenfeld*, 2010]). These approaches were further strengthened by investigations addressing the link between upper layer particle and phytoplankton dynamics and resulting particle flux at depth ([*Estapa et al.*, 2013], [*Bishop and Wood*, 2009], [*Dall'Olmo and Mork*, 2014]). The use of radiometric sensors onboard floats represented an additional refinement for a better quantification of chlorophyll concentration [*Xing et al.*, 2011] or colored dissolved organic matter [*Xing et al.*, 2012]. Furthermore bio-optical measurement realized by profiling floats can now be synergistically used with their ocean color remote sensing counterparts, for developing three-dimensional views of some key variables (e.g. particulate backscattering coefficient, a proxy of particulate organic carbon (POC) in the open Ocean, [*Sauzède et al.*, 2016])

The integration of UV (ultraviolet) optical nitrate sensors onto profiling floats was sparked by the University of Washington/MBARI partnership that formed at the ALPS meeting in 2003. This work led to the first deployments of nitrate sensors on profiling floats in late 2007 at the Hawaii Ocean Time-series station (Fig. 2). Results from this work led to a new understanding of the variability in nitrate within the euphotic zone near Hawaii, where nitrate values are usually depleted to near zero concentrations ([*Johnson et al.*, 2010]). This work has led to the deployment of nearly 90 floats with nitrate sensors in waters from the Greenland Sea to the Weddell Sea ([*Johnson et al.*, 2013a]; [*Omand and Mahadevan*, 2013]; [*Takano et al.*, 2014]). The system has since been adapted to an array of floats in the Mediterranean ([*D'Ortenzio et al.*, 2014] ; [*Pasqueron de Fommervault et al.*, 2015]).

The development of stable Ion Sensitive Field Effect Transistor (ISFET) pH sensors ([*Martz et al.*, 2010]) enables the direct measurement of ocean acidity from profiling floats [*Johnson et al.*, 2016]. More than 30 float years of experience with pH measurements now exist (Fig. 3). The combination of pH measurements with estimates of total alkalinity allow accurate estimates of dissolved inorganic carbon, carbonate ion concentration, and CO_2 partial pressure (pCO_2). Total alkalinity can be estimated throughout the water column based on the profiling float temperature, salinity, oxygen and nitrate measurements and various interpolation methods that are built on the high accuracy database collected by global repeat hydrography programs (WOCE, CLIVAR, and now GO-SHIP) ([*Lee et al.*, 2006]; [*Velo et al.*, 2013]; [*Carter et al.*, 2016]). These interpolation methods allow total alkalinity to be estimated with a global error <10 µeq kg^{-1} [*Carter et al.*, 2016].

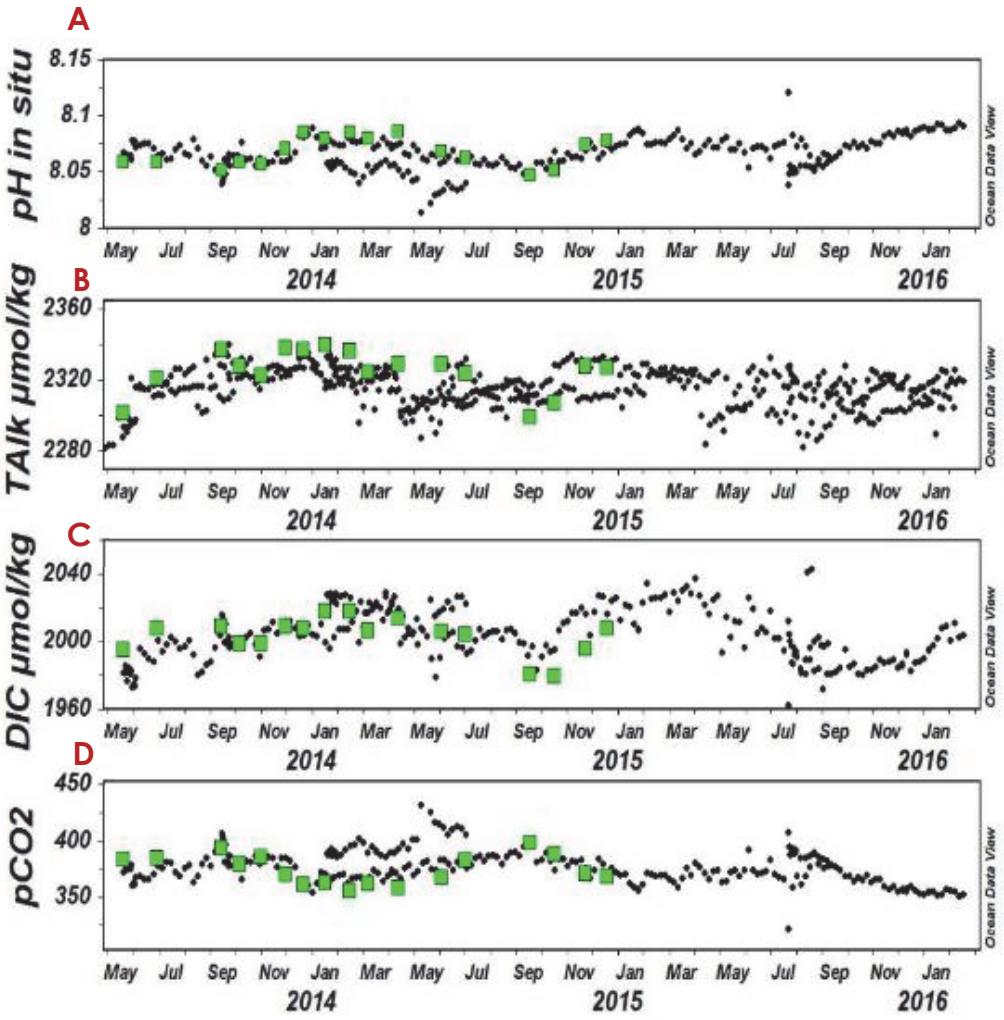

Figure 3. A) pH measured by 3 profiling floats deployed at the Hawaii Ocean Time-series, Station ALOHA (black dots) and pH reported by the HOT program (green squares) in the upper 10 m. All values at in situ temperature on the Total Proton Scale. B) Alkalinity estimated from float data using a regression equation in temperature, salinity and pressure fitted to GLODAP data near Hawaii (black) and observed by HOT (green). C) Dissolved Inorganic Carbon (DIC) computed from float pH and estimated alkalinity (black) and DIC measured by HOT (green). D) pCO_2 at in situ temperature computed from float pH and estimated alkalinity (black) and pCO_2 reported by the HOT program (green). From [*Johnson et al.*, 2016] and unpublished data.

As a result of this sensor development work, there is now a core of chemical and bio-optical sensors that have been tested for many profiling float years. These sensors enable observations of a suite of key biogeochemical variables, including some of the so-called Essential Ocean Variables (EOVs), Ecosystem EOVs (eEOVs), or Essential climate variables (ECVs) (Table 1) that define the biogeochemical cycles of carbon, oxygen, nitrogen, and biomass. These variables are the fundamental measurements that are required to address significant scientific and societal ocean/climate-related issues (e.g. [*Claustre et al.*, 2010a; *Claustre et al.*, 2010b]; [*Gruber et al.*, 2010a; *Gruber et al.*, 2010b]).

Table 1. Autonomous sensors for key oceanic biogeochemical variables

Variable (EOV type)	Sensor Type	Accuracy/Precision	Reference
Oxygen (1,3,4)	Lifetime optode	1% of surface O_2 / 0.2 µmol kg^{-1}	[*Körtzinger et al.*, 2004]; [*Bittig et al.*, 2015]; [*Johnson et al.*, 2015]
Nitrate (1,4)	Ultraviolet photometer	1 µmol kg^{-1} / 0.1 µmol kg^{-1}	[*Johnson et al.*, 2013a]
pH (1,4)	Ion Sensitive Field Effect Transistor	0.01 pH / 0.0005 pH	[*Johnson et al.*, 2016]
Chlorophyll (2,3,4)	Fluorometer	Max (30%,0.03 mg Chl *a* m^{-3})/0.025 mg Chla m^{-3}	[*Boss et al.*, 2008b]
	Radiometer	Max (24%,0.03 mg Chla m^{-3})/0.025 mg Chla m^{-3}	[*Xing et al.*, 2011]
Suspended particles (3)	Optical back-scatter	Suspended particles: Max (50%, 1.5 µg kg^{-1}) /1 µg kg^{-1})	[*Boss et al.*, 2015]
		Backscattering coefficient: Max (10%, $10^{-5} m^{-1}$) / 4 x$10^{-6} m^{-1}$	[*Sullivan et al.*, 2013]
		POC : Max (30%, 20 mg m^{-3}) / 10 mg m^{-3}	[*Cetinic et al.*, 2012]
		PC: Max (30%, 6 mg m^{-3})/ 3 mg m^{-3}	[*Graff et al.*, 2015]
Downwelling irradiance (3,4)	Radiometer	PAR: Max (3%, 5 µmol photons $m^{-2} s^{-1}$)/1 µmol photons $m^{-2} s^{-1}$	Manufacturer web site
		Spectral: Max (3%, 5 X10^{-3} µW cm^{-2} nm^{-1}) / 2.5 X10^{-3} µW cm^{-2} nm^{-1}	

1 An Essential Ocean Variables (EOV)

2 A Biological Ecosystem Ocean Variables (eEOV): Table 1 at http://www.geowow.eu/downloads/GEOWOW-WP6-DEL-D6.2.pdf

3 A Biogeochemistry Ecosystem Ocean Variables: Table 3 at http://www.geowow.eu/downloads/GEOWOW-WP6-DEL-D6.2.pdf

4 An Essential Climate Variables (ECV), either oceanic or atmospheric: https://www.wmo.int/pages/prog/gcos/index.php?name=EssentialClimateVariables

As noted in Section 3, the quality controlled observations made using the sensors in Table 1 have sufficient accuracy and stability for climate-quality observations. Climate-quality requires that the sensors provide a "time series of measurements of sufficient length, consistency and continuity to determine

climate variability and change" [*National Research Council*, 2004]. Such a record requires a sensor that is well-characterized and calibrated to the property of interest before deployment. The calibration should be assessed at deployment with high quality hydrographic measurements, and possibly with mid-deployment or post deployment calibration. It must be possible to assess sensor stability and degradation with sufficient accuracy to allow the desired climate signal to remain detectable. More detail on sensors is provided in section 3. No additional new sensors are required to initiate a global program, but additional sensors added at a later stage in a programs lifecycle could bring even greater breadth to the program.

1.3 Rationale for a Biogeochemical-Argo network

In parallel to the technological developments and associated scientific achievements with biogeochemical profiling floats, extensive planning for a global Biogeochemical-Argo network has taken place. A US Ocean Carbon and Biogeochemistry Program Scoping Workshop was held in Monterey in 2009. This meeting was the first to outline the prospect for a global Biogeochemical-Argo float array [*Johnson et al.*, 2009]. Subsequently, the International Ocean Color Coordinating Group set up a working group dedicated to "*Bio-optical sensors on Argo floats*" [*IOCCG*, 2011], while various white and plenary papers related to a prospective Biogeochemical-Argo network were presented at the OceanObs09 Conference [*Claustre et al.*, 2010a]).

These reports summarize a consensus view that biogeochemical float arrays provide an effective and affordable mechanism for observing the global ocean. Biogeochemical float arrays provide important capabilities that complement other observing systems in synergistic ways. For example, floats with bio-optical sensors can extend the global view of the surface ocean, obtained with ocean color satellites, into the ocean interior. Floats with chemical sensors can extend the highly accurate, but infrequent repeat hydrography cruises that form the core of the GO-SHIP program[6] into the domain of time at the seasonal and interannual scales over the entire ocean. Floats with carbon system parameters, such as pH, would extend the surface pCO_2 observations obtained by the SOCAT global, volunteer observing ship (VOS) network to the third dimension, i.e., the interior ocean.

A common theme from these planning documents has been the need for regional- to basin-scale demonstration projects. The initial experimental projects using biogeochemical floats were based on the deployment of one or few floats (e.g. [*Körtzinger et al.*, 2004]) to address a few key processes. Regional/basin scale experiments have been implemented and include the Southern Ocean (SOCCOM[7]), the North Atlantic Sub-polar Gyre (remOcean[8]),

[6] GO-SHIP (www.go-ship.org/)
[7] OCCOM (www. soccom.princeton.edu)
[8] remOcean (www.remocean.eu)

the Mediterranean Sea (NAOS[9]), the Kuroshio region of the North Pacific (INBOX[10]; [*Inoue et al.*, 2016a]; [*Inoue et al.*, 2016b]; [*Kouketsu et al.*, 2016]), and the joint Australia/India project in the Indian Ocean[11]. Experience from these large scale projects demonstrates the added value in long-term monitoring of key biogeochemical variables at large scales as compared to "spotty" (spatially and temporally biased) observations derived from ship-based platforms.

Within the Argo program, a Biogeochemical-Argo task team was set up in 2014 to coordinate the progressive development of the biogeochemical network. This team has worked closely with the Argo program, in particular with the Argo Data Management Team, to establish the guidelines and rules that should govern data management and quality control of data acquired by biogeochemical profiling floats. The technology is now mature and the system to manage the data and deliver real-time and delayed-mode quality controlled data is nearly operational.

The success of these pilot studies demonstrate that the scientific community is now ready to scale up to the implementation of a long-term global Biogeochemical-Argo network. Indeed, the present maturity in float technology together with its cost-effectiveness (~$400 per 2000 m profile) comes at a time where scientific and societal questions of global relevance are becoming more pressing and acute. It would seem that such a global biogeochemical float network should be closely coordinated with the Argo network, so that it complements Argo with respect to temperature and salinity, while widening the application of Argo towards a better understanding of physical-biogeochemical coupling in the ocean.

In addition to the primary science questions and societal objectives that a global network would address, there are many additional advantages and benefits. First, such a network would resolve poorly understood processes at the regional as well as global scale. By analogy to process study cruises, where various experts share a research vessel to synergistically conduct their observations, a float can be a shared, multidisciplinary platform used to conduct remotely-operated process studies. The global array would also provide an infrastructure that makes ship-based process studies more effective by providing background data for focused studies. The adjustable temporal and vertical resolution of the float mission offers the flexibility required for such type of studies.

Secondly, a global network measuring a consistent set of bio-optical properties would be of great benefit for the ocean color community. It has been argued that algorithms used to retrieve bio-optical properties from space may suffer from regional bias. For example, chlorophyll values determined from ocean color that is remotely sensed from satellites over the Southern Ocean are

[9] NAOS (www.en.naos-equipex.fr)
[10] INBOX (www.jamstec.go.jp/ARGO/inbox/index.html)
[11] Joint Australia/India project (www.research.csiro.au/iobioargo)

believed to be too low (e.g. [*Johnson et al.*, 2013b]). Developing a network with well-calibrated and consistent bio-optical sensors would help in rapidly identifying such regions. In return, these areas could be investigated though dedicated bio-optical cruises to better characterize the nature of anomalies and potentially to improve algorithms for space-based observations at a regional scale.

A Biogeochemical-Argo program would also provide developing countries interested in setting up observation capabilities in their own waters with a cost-effective way of mounting an observation program that does not heavily depend on research vessel infrastructure and shore-based laboratory capabilities. A clear definition of best practices, an open sharing of knowledge within the community and training opportunities for interested researchers from around the globe will be key for such countries to join and for Biogeochemical-Argo to reach this important potential user group.

Finally, it is anticipated that the creation of a Biogeochemical-Argo program will foster increased collaboration between the physical and biogeochemical oceanic research communities. The historical communities with biological and chemical foci can also interact in novel ways. An example is the long-standing debate on the role of eddies in supporting high levels of Net Community Production in the sub-tropical ocean [*Kähler et al.*, 2010]. The in situ statistics on nutrients and biomass distributions from a large number of platforms would provide an important constraint on this process. This might be considered as the most cost-effective way to better understand key processes in a changing ocean.

2. GRAND CHALLENGES FOR FUTURE OCEANS

Biogeochemical-Argo is poised to address a number of grand challenges in ocean science and in the management of ocean and global resources, topics that are difficult, if not impossible, to address with our present observing assets. Further, these are topics of immediate importance to society in the face of a changing climate and the need for greater protection of ocean resources. The observing system described here will enable significant advances to be made in these areas.

2.1 Ocean science research

2.1.1 Carbon uptake

Will ocean carbon uptake continue at the same relative rate as the ocean warms?

The ocean plays a major role in regulating the CO_2 concentration of the atmosphere. Time series observations from nine ocean stations have verified that the uptake of anthropogenic CO2 by the ocean led to increased seawater CO_2 concentrations and decreased pH in seawater in the Pacific and Atlantic Ocean [WMO, 2013 and references cited therein]. About 26% of

the anthropogenic carbon released to the atmosphere is currently taken up in the ocean [*Le Quere et al.*, 2015]. The long-term CO_2 measurements also show the importance of further observations for seasonal and interannual variability on ocean CO_2 concentration and uptake. Numerical models suggest relatively little change in ocean carbon uptake, while the sparse observational data indicate greater variability ([*Wanninkhof et al.*, 2013]; [*Landschützer et al.*, 2015]; [*Landschützer et al.*, 2014]). [*Landschützer et al.*, 2015] noted that the Southern Ocean "sink for anthropogenic CO_2 is more variable than previously suggested and that it responds quite sensitively to physical climate variability." As a result, "the Southern Ocean might lose its recently regained uptake strength, leading to a faster accumulation of CO_2 in the atmosphere and consequently an acceleration of the rate of global warming". Similarly, [*Watson et al.*, 2009] were able to demonstrate that the CO_2 sink in the North Atlantic, one of the most prominent sink regions of the world ocean, shows interannual variability by more than a factor of two. A major advance has been the development of the SOCAT database for shipboard pCO_2 measurements, which now allows annual estimates of ocean carbon uptake [*Le Quere et al.*, 2015]. However, the data are still relatively sparse and often lack a well-defined seasonal record in most areas. Profiling floats equipped with pH sensors can make a significant contribution to reducing the uncertainty that is introduced by sparse, temporal resolution in most ocean areas when the float data are merged with shipboard observations of pCO_2 (Fig. 4). In return, the more accurate pCO_2 measurements performed by equilibrator-based pCO_2 systems on "volunteer observing ships", forming the backbone of the SOCAT database, have the potential to provide crucial quality control to float-based carbon observations.

2.1.2 Biological carbon pump

What are the interannual variations in the biological carbon pump? Will its strength be reduced in a warmer ocean?

Net Community Production (NCP) of organic matter, defined as primary production minus respiration at all trophic levels in the upper ocean, removes dissolved inorganic carbon from surface waters and converts it into particulate organic carbon. These particles are removed from the surface by sinking or migrating organisms. This process, known as the biological pump [*Buesseler and Boyd*, 2009], reduces the surface ocean CO_2 partial pressure resulting in a lowering of atmospheric CO_2. Numerical models indicate that the biological pump reduces atmospheric CO_2 by about 200 ppm, relative to the value expected for an abiotic ocean ([*Sarmiento et al.*, 2011]; [*Watson and Orr*, 2003]; [*Parekh et al.*, 2006]). The IPCC found "It is difficult to project how the pump might be altered and whether it would represent a positive or negative feedback to climate change" [*Portner et al.*, 2014]. [*Riebesell et al.*, 2009] illustrated the various sensitivities of marine carbon fluxes and highlighted the fact that the sign and magnitude of the various responses and feedbacks in the biological systems are largely unknown. In situ observations are required throughout the ocean to constrain variability in the biological pump. Profiling

floats equipped with nitrate, oxygen and pH sensors will allow direct measurement of NCP and the biological pump ([*Riser and Johnson*, 2008]; [*Alkire et al.*, 2012]; [*Plant et al.*, 2016]). Chemical and biooptical sensors allow estimates of the carbon export component ([*Martz et al.*, 2008]; [*Dall'Olmo and Mork*, 2014]), changes in the timing of phytoplankton blooms [*Boss and Behrenfeld*, 2010], and influence of nutrient transport events ([*Johnson et al.*, 2010]; [*D'Ortenzio et al.*, 2014]; [*Pasqueron de Fommervault et al.*, 2015]).

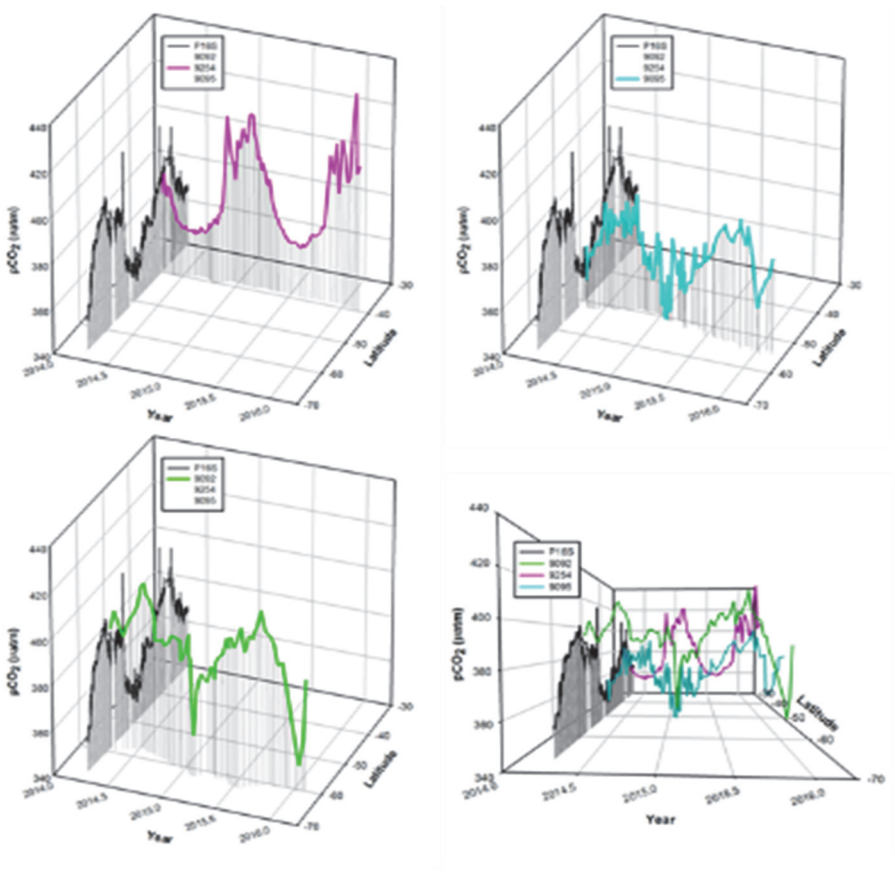

Figure 4. pCO_2 at in situ temperature measured with a shipboard system on the 2014 P16S GO-SHIP cruise (black line), and pCO_2 computed from measured pH in the upper 10 m along with estimated alkalinity [*Carter et al.*, 2016] for three SOCCOM floats deployed on the cruise that have operated for two years.

2.1.3 Oxygen Minimum Zones and Nitrate cycling

How does the volume of Oxygen Minimum Zones change in time? How does this affect the cycling of nitrate?

Concentrations of dissolved oxygen are decreasing in many areas of the ocean interior ([*Stramma et al.*, 2008]; [*Keeling et al.*, 2010]) and oxygen minimum zones (OMZs) may be expanding. Evidence now suggests that the area and volume of OMZ regions may oscillate on a decadal to centennial time scale, linked to variability in trade winds ([*Deutsch et al.*, 2014; *Deutsch et al.*, 2011]). As oxygen is depleted in OMZs, nitrate is consumed by processes

such as classical denitrification and anammox. In addition, respiration of sedimenting particulate material in an OMZ may slow down, resulting in an enhanced flux of carbon to greater depth [*Roullier et al.*, 2014]. The available data sets suggest that nitrate stocks may show multi-decadal scale oscillations, as well [*Deutsch et al.*, 2011]. Long-term decreases in oxygen may reduce ocean productivity as a result. However, oxygen measurements at the very low concentrations found in OMZs are difficult and the historical data are often suspect [*Bianchi et al.*, 2012]. Oxygen sensors on profiling floats are now capable of producing high quality data that rival the consistency of the best shipboard data when sensors are calibrated in the atmosphere on each profile ([*Bittig and Körtzinger*, 2015] [*Johnson et al.*, 2015]). Global arrays of floats with oxygen and nitrate sensors could produce unparalleled records of variability in OMZs ([*Stanev et al.*, 2013]; [*Whitmire et al.*, 2009]; [*Prakash et al.*, 2012]). They would help elucidate the mechanism of deoxygenation within the intermediate waters of the ocean, such as that occurring in the North Pacific [*[Emerson et al., 2004]; [Whitney et al., 2007]; [Sasano et al., 2015]*], and its linkage to climate

2.1.4 Ocean acidification

What is the variability and trend in ocean pH? How does the changing carbonate saturation state affect biogeochemical processes?

Seawater pH is one of the fundamental chemical properties of the ocean. It is affected by a variety of natural processes such as net primary production and respiration, formation and dissolution of biogenic calcium carbonate minerals, net air-sea CO_2 exchange, as well as mixing and circulation. In addition, the pH of seawater is being reduced over the upper layer of the oceans as a consequence of anthropogenic CO_2 invasion into the ocean, which reacts to form carbonic acid. This process is termed ocean acidification. The effect of ocean acidification has already been observed in marine and coastal organisms such as corals in low latitude, bivalves in mid-latitude, and pteropods and krill in high latitudes. At the current rate of anthropogenic CO_2 emission, a wide variety of organisms that produce $CaCO_3$ skeletons may be at an existential risk by the end of this century with subsequent impacts on ecosystems and the services they provide [*Gattuso et al.*, 2015]. The serious threat by ocean acidification calls for our better understanding of its status and progress. There is an urgent need for spatially and temporally resolved measurements of biogeochemistry and physics in order to optimize modeling for future projections and adequate actions for protection and adaptation [*Newton et al.*, 2012].

pH measurements provide essential information on all of these processes and they are key to understanding subsequent effects on ecosystems that result from the changing pH and calcium carbonate saturation state [*Bednaršek et al.*, 2012]. pH reductions will lead to the entire water column in some ocean areas becoming undersaturated with respect to the mineral aragonite in just a few decades [*Gruber et al.*, 2012]). This could lead to a variety of ecosystem

changes that are now only poorly monitored. For example, a decrease in aragonite production may lead to a weakening of the biological pump ([*Riebesell et al.*, 2009]; [*Hofmann and Schellnhuber*, 2009]). Until recently, the observing network for ocean pH was comprised of ship-based repeat hydrographic surveys, VOS pCO_2 tracks for near-surface observations, and high-frequency time-series stations by ships or moorings. Accordingly, the array of Biogeochemical-Argo floats with pH and other biogeochemical sensors could resolve the spatial and vertical patterns and short-term variations such as seasonal and interannual dynamics in essential variables of CO_2 chemistry, including fluctuations and trends of aragonite saturation depth, net community production as well as the acidity of seawater globally.

2.1.5 Phytoplankton communities

What is the composition of phytoplankton communities? How will it affect higher trophic levels and carbon cycling?

Phytoplankton are at the base of the marine food web and are responsible for about half of the biological uptake of CO_2 on Earth through the process of photosynthesis. They comprise very diverse organisms with a wide range of shape, size, pigmentation, photosynthetic efficiency, nutrient uptake, or temperature tolerance, all resulting in different biogeochemical and ecological functionality in marine ecosystems. To assess phytoplankton community composition is therefore of crucial interest for improved biogeochemical characterization (e.g., improved primary production and carbon export estimates) and to better understand and potentially predict the ecosystem responses to current and future changes in environmental drivers. Important progress has recently been made in developing a capability for retrieving information on the composition of phytoplankton communities using bio-optical observations acquired in situ (field cruise, moorings) or derived from remote sensing of ocean color ([*IOCCG*, 2014] and references therein).

Such a capability, applied to profiling floats equipped with bio-optical and biogeochemical sensors, will provide invaluable information on the vertical distribution of relevant proxies. For instance, the shape of the vertical profile of chlorophyll *a* as well as its magnitude can be used to derive quantitative information on the size structure of the phytoplankton assemblage (relative contributions of pico-, nano-, and micro-phytoplankton to the total chlorophyll *a* concentration) ([*Uitz et al.*, 2006]; [*Sauzède et al.*, 2015]), which is known to be an important driver of, e.g., energy transfer to upper trophic levels or sinking of organic carbon to the deep ocean. The ratio of the chlorophyll *a* fluorescence to the particulate backscattering coefficient, a proxy for POC, has proved to be a useful indicator of phytoplankton composition with low values associated with a dominance of diatoms in bloom conditions [*Cetinic et al.*, 2015]. Such conditions have strong impact on the export and potential sequestration of carbon. The chlorophyll *a* concentration-to-particulate backscattering ratio also provides information on the photoacclimation status of phytoplankton (e.g., [*Behrenfeld et al.*, 2005]; [*Mignot et al.*, 2014]), which

induces horizontal and vertical variability in the chlorophyll *a* concentration decoupled from that of carbon biomass with consequences for primary production modeling (e.g. [*Uitz et al.*, 2008]; [*Westberry et al.*, 2008]; [*Graff et al.*, 2016]).

Biogeochemical-Argo will be the first observation network to provide such depth-resolved proxies of phytoplankton community composition and photoacclimation over large spatial and temporal scales in the world's oceans.

2.2 Ocean Management

Oceanic primary production is of fundamental importance for sustaining life on planet Earth. Half of the oxygen that has accumulated in the atmosphere has been produced by oceanic plankton. These phytoplanktonic organisms now underpin nearly all marine food webs by fixing CO_2 and essential nutrients dissolved in seawater and capturing solar energy to turn these raw materials into complex organic molecules (carbohydrates, lipids, proteins) that provide the essential food sources to fuel marine ecosystems. Organisms from zooplankton and anchovies to tuna, sharks, whales and seabirds ultimately rely on phytoplankton for their energy, as do the bacteria that recycle waste organic material back into nutrients to maintain the system. Excess organic particles formed from dying cells sink through the ocean depths to the seabed providing further nutrition to deep-sea and seabed organisms. Oxygen depletion, when acute as in OMZs, limits the space available for these organisms [*Gilly et al.*, 2013]. In this way, these processes directly modify the biogeochemical nature of the marine environment to structure habitats in which organisms interact as an ecosystem. Thus it is clear that to understand and manage marine ecosystems to any degree it is essential to be able to track changes in the activity and distribution of these primary producers and their associated biogeochemical environment.

2.2.1 Living Marine Resources

Does real time data improve management of living marine resources?

Ensuring healthy marine ecosystems and sustainable harvest of living marine resources are of considerable economic, social and cultural significance [*Reimer et al.*, 2015]. Dramatic changes have already occurred in higher trophic levels of the marine food web due to anthropogenic influences, primarily overfishing [*Worm and Branch*, 2012]. Other anthropogenic environmental stressors influence marine ecosystems including rising temperatures and acidity and decreasing oxygen availability ([*Pinsky et al.*, 2013]; [*Doney et al.*, 2012]). The effects of these changes will manifest themselves more drastically over the coming century. The need to anticipate and mitigate the potentially dramatic effects of the rapidly changing marine environment on ecosystems and marine resources is urgent and is increasingly recognized [*FAO*, 2013; 2014]. For example, legislation mandating ecosystem-based approaches for the management of living marine resources in Europe [*Union*, 2014] and in Canada [*Oceans Act*, 1996], and recently announced

increases in Marine Protected Area in the US [*House*, 2014] are reflections of a growing recognition that marine ecosystems and their resources are threatened and along with a willingness to take action.

Longer term oceanic changes over interannual (e.g. ENSO) to decadal and climatic time frames tend to be manifested as shifts in the timing of seasonal and sub-seasonal processes. Such phenological changes can lead to mismatches in ecosystem coupling. For example, vertical migrating zooplankton may be missing the spring phytoplankton bloom that is their key food source. Resolving this coupling across scales cannot be achieved except through sustained high-frequency observing of the interior ocean biogeochemistry. Understanding these coupling modes will provide insights needed to assess ecosystem tipping points ahead of full-scale regime shifts, such as have been associated with the collapse of some major fisheries.

The Biogeochemical-Argo network would provide an important underpinning for the observation of changes occurring at the base of the food web, for the attribution of changes in higher trophic levels to environmental stressors, and for the development of predictive capabilities for marine living resources. The network would, for the first time, enable monitoring, on a global scale, for environmental conditions such as acidity (pH) and oxygen concentrations, which directly affect physiological functions and fitness of various important species, and nitrate concentrations and plankton biomass, which determine productivity at the base of the marine food web. Observations of variability and trends of these properties are necessary for proper attribution of changes at higher trophic levels to environmental conditions. The Biogeochemical-Argo observations would also provide much needed information to constrain, validate and improve lower trophic level models – improvements in realism of these models has been severely hampered thus far by a lack of global, depth-resolved biological and chemical observations. Such models can interface between the ocean's biochemical environment and higher trophic levels [*Bianucci et al.*, 2016].

2.2.2 Carbon budget verification

Does an improved ocean carbon budget lead to greater constraints on terrestrial carbon fluxes and a better understanding of global actions to reduce atmospheric CO_2?

Today, the primary estimate of the net terrestrial carbon flux (the sum of fluxes due to land use change and terrestrial carbon sinks) is the difference between anthropogenic carbon emission (fossil fuels and cement) and the atmospheric CO_2 growth and ocean CO_2 sink [*Le Quere et al.*, 2015]. In this scheme, improvements in our understanding of the ocean carbon sink will lead to an improved understanding of the net terrestrial carbon flux [*NRC*, 2010]. Such improved estimates are a key step towards understanding the success of global carbon agreements such as the Paris Agreement reached at the UN COP21 Conference.

The authors of the Global Carbon Project report [*Le Quere et al.*, 2015] note that an important recent development in constraining ocean carbon fluxes, and subsequently the net terrestrial carbon flux, is the yearly estimate of the ocean carbon sink now produced by the SOCAT project. While the primary estimate of the temporal trend in the ocean sink is model-based, the yearly, observational estimates provide an assessment of the confidence in the trend. Today, the uncertainties in the observational estimates are relatively large, due to the scarcity of pCO_2 measurements in any one year. The observations of pH on profiling floats can be combined with estimates of total alkalinity [*Carter et al.*, 2016] to provide assessments of surface ocean pCO_2 over complete annual cycles (Fig. 3). These float-based observations provide complete annual cycles of pCO_2, and can do so throughout the ocean (Fig. 4). A system of profiling floats throughout the ocean would substantially improve our estimates of air-sea CO_2 exchange derived from the SOCAT program by providing accurate estimates of the amplitude of the annual pCO_2 cycle. This, in turn, could lead to greater confidence in the terrestrial carbon flux, which cannot be measured directly.

2.3 Emergent phenomena

Beyond the explicit phenomena described above, a Biogeochemical-Argo system would provide a unique data set that might reveal unanticipated, emergent phenomena. Our prior history of atmospheric CO_2 observations has shown a variety of such phenomena that are now well accepted, but which were not anticipated. These include the discovery of seasonal cycles of CO_2 in the atmosphere due to the seasonal changes in photosynthesis and respiration on land and the effect of El Niño climate oscillations on atmospheric CO_2 concentrations.

Areas of concern might include the effects of deoxygenation and ecosystem shifts that might result from acidification or warming. Recent analyses of climate records and numerical models suggest that interactions of wind and ocean circulation have the potential to produce large, rapid climate shifts ([*Mayewski et al.*, 2015]; [*Rodgers et al.*, 2014]) that may ripple into ecosystem processes and carbon cycling.

3. THE DESIGN OF BIOGEOCHEMICAL- ARGO NETWORK

3.1 Biogeochemical Sensors

The suite of sensors to be used in a global observing system that will be deployed in the near future must be operational now. These sensors must provide robust measurements of the core Biogeochemical-Argo variables that include several essential (ocean, ecosystem or climate) variables. They must also provide data that directly addresses the research and management needs of the network (Table 2). Here we briefly summarize the sensors that meet these criteria.

Table 2. Major research and management topics and sensors applicable to topics. ✓indicates direct relevance and • indicates indirect relevance through a calibration function or other related function.

Research and management topic	O_2	NO_3	pH	Chla	Suspended particles	Downwelling irradiance
Carbon cycle						
Anthropogenic carbon uptake by the ocean	•	•	✓			
Variability in the biological pump	✓	✓	✓	✓	✓	✓
Variability in NCP	✓	✓	✓	✓	✓	✓
Mesopelagic respiration	✓		✓	✓	✓	
Particulate export				✓	✓	
Ocean deoxygenation/ denitrification	✓	✓	•	✓	✓	
Ocean acidification variability	•		✓		•	
Effects of changing carbonate saturation state.	•	•	✓		•	
Marine resource management	✓	✓	✓	✓	✓	✓
Reducing error in ocean carbon budget	•	•	✓		•	
Ocean Color validation				✓	✓	✓

3.1.1 Oxygen

Oxygen sensors have been deployed on more than 600 profiling floats since 2002 [*Takeshita et al.*, 2013]. Fig. 2b shows a record of oxygen from floats deployed at the Hawaii Ocean Time-series (HOT) Station ALOHA since 2002. They have produced an uninterrupted time-series that now spans 13 years. Measurements of dissolved oxygen directly address the needs of the Biogeochemical-Argo system (Table 2). This data has been used to study the metabolic balance between autotrophy and heterotrophy [*Riser and Johnson*, 2008] as well as nutrient supply mechanisms [*Johnson et al.*, 2010]. Measurements made by the Hawaii floats on the 27.0 σ_θ density surface are consistent with the shipboard measurements made by the HOT program (Fig. 5). From 2002 to 2015, the mean difference between these two data sets on the 27.0 density surface is about 2 µmol kg^{-1}.

The data shown in Figs. 2 and 5 are just one example from hundreds of oxygen sensors that have been implemented on floats and have recorded time series. Numerous papers have described results collected in such a way ([*Körtzinger et al.*, 2004]; [*Körtzinger et al.*, 2005]; [*Martz et al.*, 2008]; [*Whitmire et al.*, 2009];

[*Kihm and Körtzinger*, 2010]; [*Johnson et al.*, 2010]; [*Prakash et al.*, 2012]; [*Ulloa et al.*, 2012]; [*Stanev et al.*, 2013]; [*Bushinsky and Emerson*, 2015]).

The first oxygen sensors deployed on profiling floats were Clark-type oxygen electrodes [*Edwards et al.*, 2010]. These have largely been replaced by optical oxygen sensors (lifetime optodes) that measure the fluorescence lifetime of a platinum porphyrin complex embedded in a plastic film [*Körtzinger et al.*, 2005]. The Aanderaa optode sensor used on the majority of floats is quite stable when deployed in the ocean ([*Takeshita et al.*, 2013]; [*Bittig and Körtzinger*, 2015]; [*Johnson et al.*, 2015]; [*Bushinsky et al.*, 2016]). Also the response time and pressure response characteristics are well documented [[*Bittig et al.*, 2014]; [*Bittig et al.*, 2015]]. However, it suffers from a poor factory calibration and, possibly, sensor drift while exposed to light or warm temperatures. A similar long-term drift pattern has been shown for the Sea-Bird oxygen optode and Rinko FT oxygen sensor. The drift and accuracy problems are overcome by recording the atmospheric oxygen value when the float surfaces and using this value to recalibrate the sensor ([*Körtzinger et al.*, 2005]; [*Bittig and Körtzinger*, 2015]; [*Johnson et al.*, 2015]; [*Bushinsky and Emerson*, 2015]). This produces a well calibrated sensor that has an accuracy of 1% or better. The data produced by these sensors, after calibration with atmospheric oxygen, is of a quality equivalent to the shipboard Winkler titrations made in multi-national observing programs [*Johnson et al.*, 2015]. The data are suitable for climate research that is focused on detecting trends in ocean oxygen content.

3.1.2 Nitrate

Nitrate is determined using a UV optical sensor ([*Johnson and Coletti*, 2002]; [*Johnson et al.*, 2010]; [*Johnson et al.*, 2013a]). The optical nitrate sensor has been deployed on more than 100 profiling representing several hundred float years of accumulated experience (e.g., ([*Johnson et al.*, 2010]; [*Johnson et al.*, 2013a]; [*D'Ortenzio et al.*, 2014]; [*Ascani et al.*, 2013]; [*Omand and Mahadevan*, 2015]; [*Takano et al.*, 2014]; [*Pasqueron de Fommervault et al.*, 2015]; [*Plant et al.*, 2016]), including >20 years of data from the Southern Ocean with some under ice deployments. Fig. 2c shows a record of nitrate obtained since 2008 with floats deployed near Hawaii. The nitrate sensor is precise to ± 0.2 µmol kg^{-1} over the entire concentration range seen in the ocean [*Johnson et al.*, 2013a]. However, the sensors can have drift or offsets over multiple years, typically on the order of 0.5 µmol kg^{-1} y^{-1} ([*Johnson et al.*, 2010]; [*Johnson et al.*, 2013a])., while seasonal variability is 4 to 6 µmol kg^{-1} y^{-1}. Careful examination of changes in deep nitrate concentration over multiple years allows the data to be corrected for drift in much the same way that salinity data is corrected in the Argo program (Wong et al., 2003). The seasonal variability in high nutrient surface waters of the Southern Ocean and North Pacific, due to biological cycles, (4 to 12 µmol kg^{-1} y^{-1}; [*MacCready and Quay*, 2001]) is readily detectable and quantifiable [*Plant et al.*, 2016]. In low nutrient areas, the sensor clearly shows events that entrain nitrate into surface waters ([*Johnson et al.*, 2010]; [*D'Ortenzio et al.*, 2014]; [*Pasqueron de Fommervault et al.*, 2015]).

3.1.3 pH

pH measurements are made with the DuraFET pH sensor ([*Martz et al.*, 2010]; [*Hofmann et al.*, 2011]; [*Johnson et al.*, 2016]). The Deep-Sea DuraFET version of the sensor is capable of operating to 3000 m depth, and this has been demonstrated on CTD rosettes and over 50 profiling floats [*Johnson et al.*, 2016]. The sensor can be calibrated in the lab to determine its temperature, pressure, and pH response and deployed in the ocean to obtain results consistent to better than 0.015 pH with spectrophotometric pH measurements throughout the water column (Fig. 3; [*Johnson et al.*, 2016]). Correction of small drifts in the sensor reference potential are possible by comparison to interpolation equations fitted to deep pH observations in high quality data sets [*Williams et al.*, 2016].

3.1.4 Chlorophyll fluorescence

Chlorophyll pigment biomass is routinely assessed at high vertical resolution using chlorophyll fluorometers (excitation in the blue with emission in the red part of the visible spectrum). Conversion from fluorescence to chlorophyll involves a variety of corrections and assumptions [*Cullen*, 1982], but given its relationship to light attenuation (measured with radiometers in daylight) and ocean color, the value can be constrained with an error of about 30%. Given the large dynamic range of chlorophyll in the ocean (0.01-50 mg Chla m^{-3} in the surface oceans) this parameter has been found to be extremely useful for studies of net primary production and phytoplankton population dynamics.

3.1.5 Suspended particles

Particulate abundance will be measured with a sensor measuring light scattered from particles in the backward direction. This backscattering measurement constrains particulate mass [*Boss et al.*, 2009], the total organic mass of particles ([*Cetinic et al.*, 2012], [*Graff et al.*, 2015]), as well as general particle dynamics [*Ohde et al.*, 2015]. These parameters are critical to study and constrain phytoplankton dynamics and production [*Behrenfeld et al.*, 2005], net community production [*Alkire et al.*, 2012], export to depth [*Dall'Olmo and Mork*, 2014] and riverine sediment input to the oceans.

Chlorophyll *a* fluorescence and backscatter measurements are often used conjointly to address the temporal and vertical dynamics of both phytoplankton biomass and suspended particles and their dependence on physical forcing (generally indexed on mixed layer dynamics). Such analyses have been undertaken in various areas like the North Atlantic ([*Boss et al.*, 2008b], [*Boss and Behrenfeld*, 2010]), the North Pacific [*Westberry et al.*, 2016], the oxygen minimum zone of the Eastern South Pacific [*Whitmire et al.*, 2009], the Arabian Sea [*Ravichandran et al.*, 2012], and in the austral ocean [*Bishop and Wood*, 2009]. Focused studies of particle dynamics using profiling floats in artificially iron-enriched areas [*Bishop et al.*, 2004] or naturally iron enriched areas (e.g. island plumes of the Kerguelen plateau; [*Grenier et al.*, 2015]) have also take place.

3.1.6 Downwelling irradiance

Radiometers implemented on floats allow the measurement of downwelling irradiance at specific wavelengths as well as Photosynthetically Available Radiation, PAR [*IOCCG*, 2011]. Simultaneous measurements of backscattering, Chla fluorescence, and irradiance allowed to develop a mechanistic understanding of the seasonal linkage between upper layer phytoplankton dynamics to the fluctuations (by up to 50 m) of the deep chlorophyll maximum in subtropical gyres [*Mignot et al.*, 2014]. New methods have been recently developed to identify cloud-free irradiance profiles [*Organelli et al.*, 2016] that are required to derive the diffuse attenuation coefficient, a key optical property that is insensitive to any sensor drift and that can be used to better constrain the estimation of Chla concentration from fluorescence measurements [*Xing et al.*, 2011] (see Fig. 6). Primary production studies often infer vertical structure of phytoplankton and the subsurface light field from surface measurements (e.g. [*Uitz et al.*, 2006], [*Uitz et al.*, 2010]). Floats will allow a global evaluation of these methods and improvements of their parametrizations.

3.2 Float performance

The addition of biogeochemical sensors to profiling floats has been facilitated by two primary upgrades to the float design: the change from slow, one-way Service Argos communications to faster, two-way Iridium communications, and the change from alkaline to lithium primary batteries. The first Argo floats equipped with Iridium were deployed by the University of Washington in 2003; since that time the use of Iridium in Argo has grown to the point that over 60% of the floats in the Argo array now use Iridium, and the deployment of older-type Service Argos floats has dwindled. The use of Iridium has increased the effective data upload speeds reducing to several minutes (from many hours) the time floats spend on the ocean surface, and it has allowed two-way communication between shore-based labs and the floats, making it possible to reconfigure float missions after the floats are deployed and to confirm that information has been transferred and received.

The increased data capacity has allowed for additional measurements by biogeochemical sensors to be made on the floats with only a modest increase in communication time. For example it is now possible to record, the Chla and backscattering signal with a vertical resolution of 1 m. This enables robust detection of spikes in the optical signals that are due to large sinking particles (e.g. [*Briggs et al.*, 2011]).

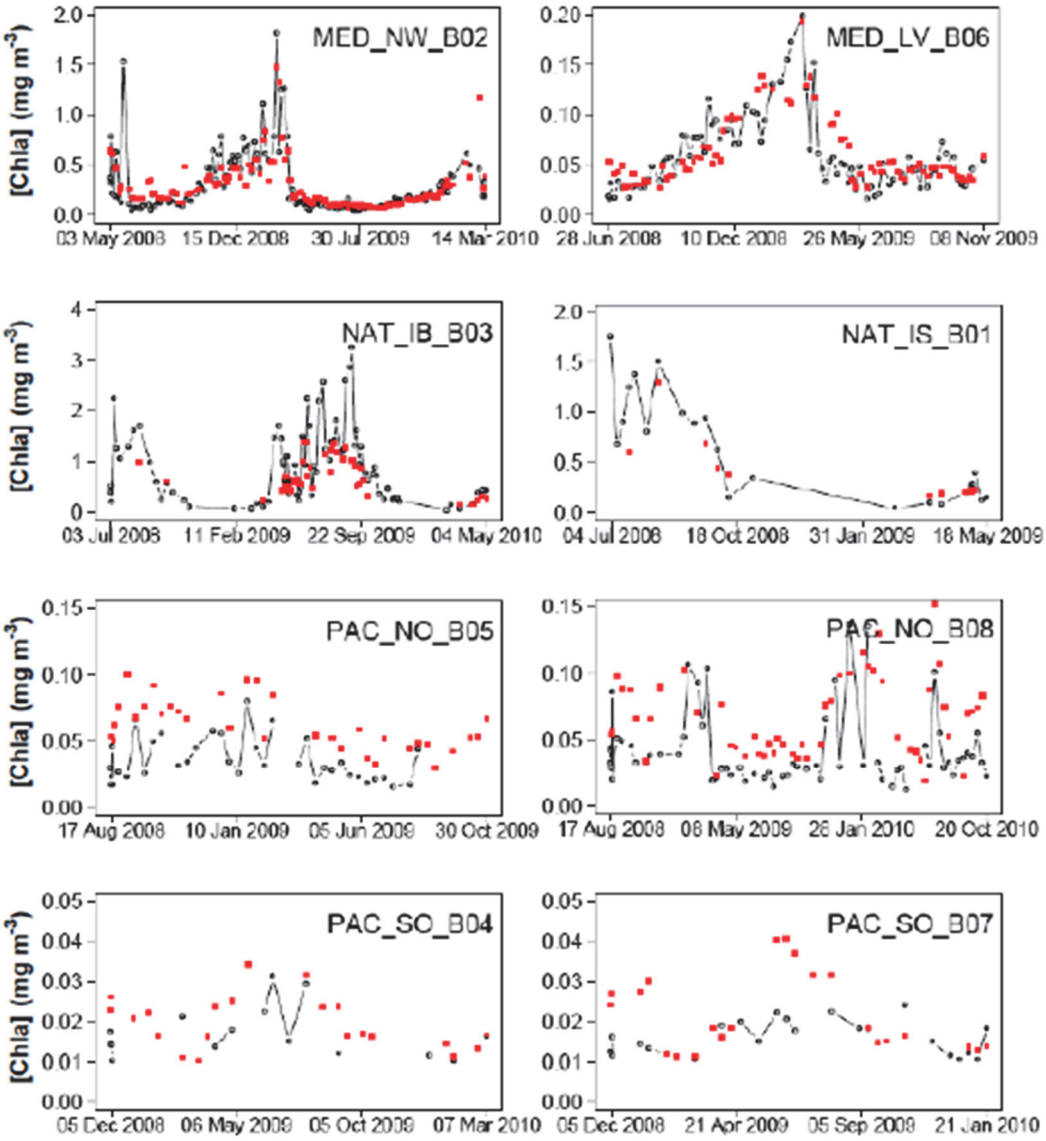

Figure 6. Comparison of MODIS surface Chlorophyll a concentration (red points) with Chla concentration retrieved from floats equipped with a fluorescence sensor and a radiometer at 490 nm (black points) in various open ocean areas. Med NW stands for North Western Mediterranean Sea, MED-LV for Mediterranean Levantine Basin, Nat_IB for North Atlantic Irminger Basin, NA-IS for North Atlantic Icelandic Basin. Pac_NO and PAC_SO for North Pacific subtropical gyre and South Pacific Subtropical gyre, respectively. After [*Xing et al.*, 2011]

The conversion from alkaline to lithium batteries increased the available energy in a float by four times and also significantly increased reliability because lithium batteries are produced with greater attention to quality control. The increased energy allows for more sensors and higher data density. Biogeochemical sensors typically consume about 25% of the float power budget. This means that the lifetime of the float can be extended from about 150 profiles in a standard Argo float with alkaline batteries to 250 profiles in a float with a full suite of biogeochemical sensors.

3.3 Sensor payload

The major science and management questions outlined in Section 2 will require a suite of sensors to address them. The floats that are envisioned will carry oxygen, pH, nitrate, chlorophyll fluorescence, backscattering and downwelling irradiance sensors. This set of sensors is termed the biogeochemical sensor suite. The biogeochemical sensor suite has significant impact on the program cost, which is outlined in Section 4.2. However there are substantial reasons to equip biogeochemical floats with the full sensor suite. This topic was discussed extensively at the Villefranche meeting. In the end, the consensus was to strive to deploy floats with a sensor package as similar as possible to the biogeochemical sensor suite. Here we explain the rationale for this decision.

There are three major arguments in support of the biogeochemical sensor suite. First, the biogeochemical sensor suite greatly expands the breadth of the science and marine resource management topics that can be addressed. econd, the biogeochemical sensor suite enables different aspects of a question to be analyzed and it also allows some redundancy in approaching questions (Table 2). The third relates to the validation of sensor performance.

The grand challenge questions related to ocean science and ocean resource management that are discussed in Section 2 span a breadth of topics. Many, if not all, of these processes are interlinked and occur over a broad range of temporal and spatial scales. Ocean carbon uptake is driven in large part by net community production, which drives the biological pump. The effectiveness of the biological pump will be determined to some extent by the depth to which particulate organic carbon is exported before it is remineralized ([*Kwon et al.*, 2009] [*Passow and Carlson*, 2012] [*Guidi et al.*, 2015]). Changing net community production alters the potential of ecosystems to support fisheries. Changing the extent of Oxygen Minimum Zones may change the intensity of the biological pump, while changing ocean carbon uptake alters acidification rates, and in turn varies ecosystem impacts. These ocean processes can be studied in isolation, and in fact that has been the tendency in the past for ocean science. However, the interlinked nature of the processes means that interpreting cause and effect can be difficult, perhaps impossible, unless a comprehensive approach is taken to understanding a broad range of interactions [*Gattuso et al.*, 2015]. Hence, studying the full suite of questions will often require the full set of sensors in the biogeochemical sensor suite (Table 2). The science and management research done with the biogeochemical sensor suite will be much stronger than that which could be accomplished with one or a few sensors.

Second, the different properties measured with each sensor allow individual processes to be addressed by several methods. This enables different components of the same process to be addressed through a multifaceted and synergetic approach. For example, carbon export may be assessed by using the seasonal nitrate depletion observed in the mixed layer with a nitrate sensor to determine the amount of carbon available for export (Plant et al., in press).

An oxygen sensor can be used to examine the depth profile of respiration rates to assess processes that remove carbon below the mixed layer [*Martz et al.*, 2008]. Optical backscatter sensors detect the penetration of particles to great depth ([*Dall'Olmo and Mork*, 2014], [*Briggs et al.*, 2011]).

In another example, measurement of both chlorophyll fluorescence, light scattering and downwelling irradiance enable assessments of phytoplankton physiology through changes in the ratios of optical properties, such as carbon/chlorophyll ratios (e.g. [*Xing et al.*, 2014], [*Mignot et al.*, 2014]). Such multi-faceted and multidisciplinary approaches will allow much greater understanding of the processes at play.

Finally, simultaneous operation of multiple sensors enables more robust assessments and corrections for possible sensor drift. For example, the optical oxygen sensors are extremely stable. Possible small drifts (order of a few tenths of a percent per year) can be detected and corrected by air oxygen measurements ([*Johnson et al.*, 2015]; [*Bittig and Körtzinger*, 2015]; [*Bushinsky and Emerson*, 2015] [*Bushinsky et al.*, 2016]). The stable oxygen measurements are then key tools to detect and subsequently correct small drifts in the pH sensor ([*Johnson et al.*, 2016]; [*Williams et al.*, 2016]) or nitrate sensor ([*Johnson et al.*, 2013a]; [*Pasqueron de Fommervault et al.*, 2015]). The Chla fluorescence sensor drift and calibration can be well constrained using the diffuse attenuation coefficient derived from radiometric measurements and that is insensitive to sensor drift of bad calibration [*Xing et al.*, 2011].

The discussions in Villefranche concluded that the negatives (cost primarily) to operating floats with the full biogeochemical sensor suite were far outweighed by the positive aspects. It is inevitable that some floats will be operated with only one or two biogeochemical sensors to address focused research or management topics. Quality control of the data will be more difficult for these floats and they will have more limited scientific utility. Such floats and data should nevertheless be incorporated into the Biogeochemical-Argo system. However, because of the limitations of these data sets they will not be considered as Biogeochemical-Argo floats but as Biogeochemical-Argo equivalents.

Arguments have also been made to proceed towards implementation of a global biogeochemical observing system by initially equipping a large portion of the Argo array with only one biogeochemical sensor, such as oxygen [*Gruber et al.*, 2010a], or bio-optics [*Claustre et al.*, 2010b], rather than the full biogeochemical sensor suite. If the entire Argo array were equipped with a single sensor such as oxygen, this could be an effective strategy to predict values of other biogeochemical parameters using multiple linear regressions ([*Carter et al.*, 2016]; [*Williams et al.*, 2016]) or using Neural Network techniques similar to those developed by [*Sauzède et al.*, 2016]. However, such techniques are not effective in finding emergent processes not encapsulated in the MLR's or Neural Networks. Such a strategy should not be the primary approach

utilized by Biogeochemical-Argo, but it could be a very effective complement if sufficient funds were available.

3.4 Defining the array size and distribution

The size of the global array and the distribution of the floats (evenly dispersed or more heavily concentrated in some areas) are fundamental questions for operation of the system. Here we consider three approaches to answering these questions. These approaches include Observing System Simulation Experiments (OSSE), assessments of decorrelation length scales of biogeochemical variables, and bioregionalization of ocean ecosystems.

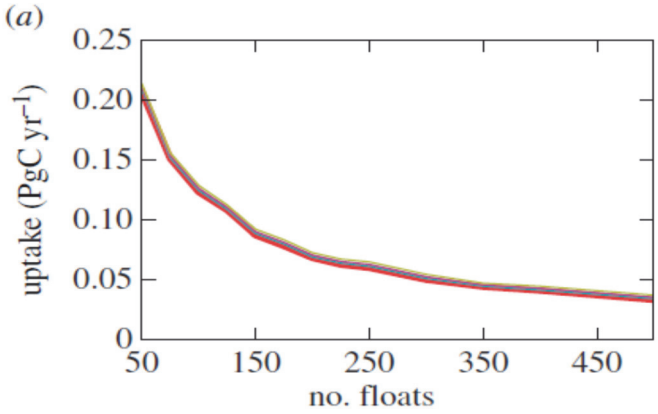

Figure 7. Error estimate for the annual reconstruction of Southern Ocean CO_2 uptake for varying number of floats. Southern Ocean (beyond 30°S) CO_2 uptake is ~0.8 PgC yr^{-1}. The fractional error at 200 floats is near 10%. From [*Majkut et al.*, 2014].

3.4.1 OSSE-related approaches

OSSE's for a Southern Ocean carbon observing system have been published by several groups ([*Lenton et al.*, 2006]; [*Majkut et al.*, 2014]). Both of these studies assessed the number of observing nodes required to constrain the CO_2 flux in the Southern Ocean. Here, we focus on the results from [*Majkut et al.*, 2014] who examined a strategy using Biogeochemical-Argo floats in waters south of 30°S, comprising 30% of the ocean area. They subsampled a 2°x2° fully coupled ocean-atmosphere biogeochemical model for air-sea CO_2 flux with simulated arrays of profiling floats. The error in reconstructing the air-sea CO_2 flux simulated by the coupled model (0.76 Pg C yr^{-1}) is shown in Fig. 7 as a function of the number of floats in the sampling array. The error begins to level out near 200 floats with a value of 0.075 PgC yr^{-1}. Given a Southern Ocean CO_2 uptake of 0.76 PgC yr^{-1}, this amounts to a ~10% error in the CO_2 flux, equivalent to the targeted uncertainty. Extrapolating these results to the globe would yield ~700 floats (200 /30% * 100%) if similar conditions prevailed.

The approach used by [*Majkut et al.*, 2014] were extended by the SOCCOM group using the global output of the much higher resolution (~1/10°) CM2.6

model [*Delworth et al.*, 2012]. Fig. 8 shows a global map of the modeled air-sea CO_2 flux and the reconstructed map, obtained by subsampling the model at 1000 randomly distributed locations in water deeper than 1000 m, similar to 1000 randomly distributed profiling floats. The errors (reconstruction – model) for randomly distributed arrays of 500, 1000, and 2000 floats are also shown. The decrease in error is largest from 500 to 1000 floats (not shown). There is diminishing return for an array larger than 1000 floats. It should be noted that this experiment was performed for the Biogeochemical-Argo carbon observatory alone. If combined with the existing carbon VOS observatory, the overall error of the estimation of the CO_2 sink can be further reduced.

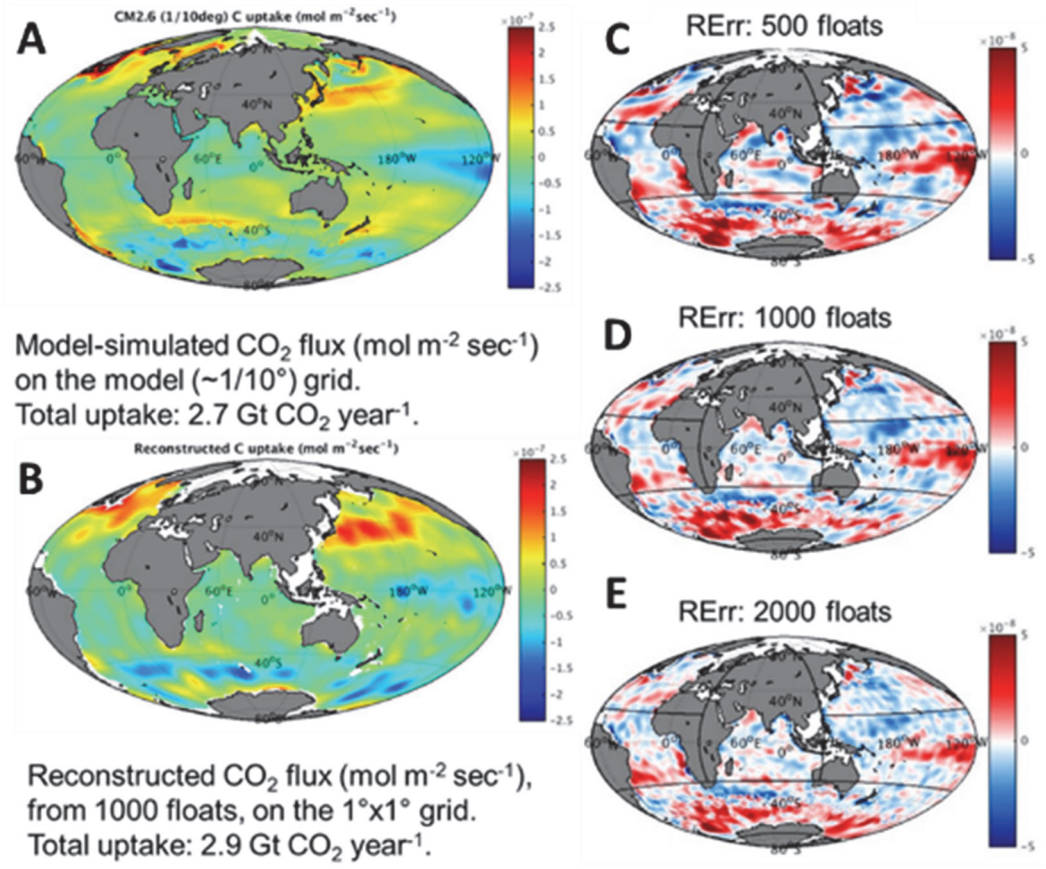

Figure 8. (A) Simulated air-sea CO_2 flux using the CM2.6 coupled ocean-atmosphere model. B) Reconstructed air-sea CO_2 flux with 1000 simulated profiling floats. Difference between the reconstructed air-sea flux and the CM2.6 modeled flux for 500 (C), 1000 (D) and 2000 (E) simulated floats.

3.4.2. Satellite ocean chlorophyll reconstruction

Chlorophyll concentration (Chl) that is derived from ocean color satellites is the only highly resolved (spatial and temporal) biogeochemical data set with a global extent that is now available. These data can be used to directly assess the effectiveness of profiling float arrays of various sizes at sampling the global

distribution of chlorophyll. Here, we determine the relative error in the global mean chlorophyll concentration defined as:

$$\Delta Chl = \frac{\overline{Chl}_{bin} - \overline{Chl}_{ref}}{\overline{Chl}_{ref}}$$

where $\overline{Chl}_{ref}$ is the global mean of the Chl surface concentration calculated from the 15-years long, MODIS data set (monthly composites at 0.5 degree resolution) and $\overline{Chl}_{bin}$ is the mean of the Chl concentrations obtained from the same monthly climatology, although using a decreasing number of sub-samples, extracted at *n* different locations. These points are considered to be the equivalent to a profiling float sample. The *n* points are selected using an equidistant distribution.

Results of this analysis are shown in Fig. 9. The mean relative error decreases rapidly with increasing number of profiling floats. The curve levels out near 1000 floats with a mean relative error of 5%. One standard deviation (calculated over the monthly means) with 1000 floats is about 3.5%. As a result, 15% of simulated global float arrays producing errors larger than 10%.

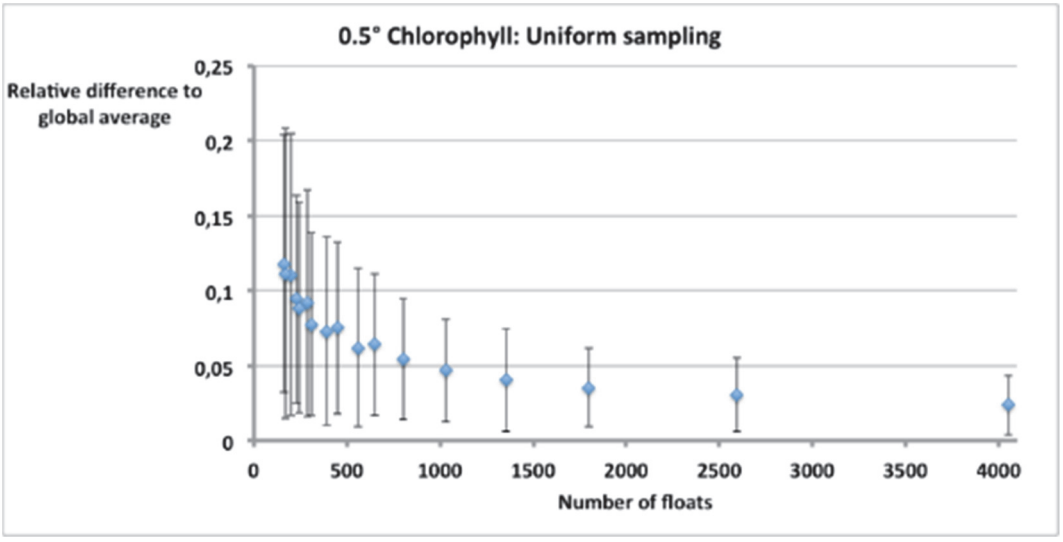

Figure 9. Relative uncertainties of global chlorophyll as function of number of float based on 10,000 simulations (circles). Lines denote +/- 1 standard deviation over all the simulations.

The previous analysis was done considering a uniformly distributed sub-sampling by an array of sensors, mimicking an evenly distributed Biogeochemical-Argo array. However, there are large regions of the ocean where variance in optical properties is low (e.g., gyres) while at other regions (e.g., polar fronts) the variance is large.

To illustrate these issues, the 15-year long global climatology of chlorophyll concentration observed by the MODIS sensor is analyzed for variability. For each pixel (at 0.5° resolution), the distance at which the concentration is different by 5% from the value observed for that pixel has been evaluated. The resulting distances (in km) are then regrouped in three main classes: < 100 km, in the range 100-300 km, > 300 km (Fig. 10). Most of the high variability regions (smaller distance to find a 5% difference) are coastal. Such regions are not accessible to current profiling float technology.

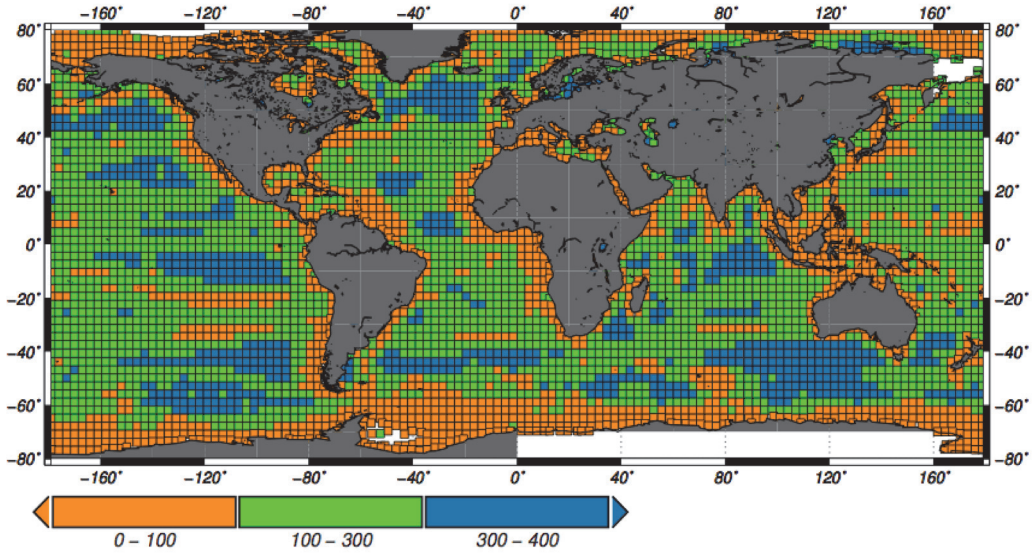

Figure 10. Map of the minimum distances at which, for each pixel, the Chl concentration is 5% greater than the Chl observed at that pixel. Chl concentrations are obtained by the 15-years climatology of MODIS OC sensor.

3.4.3 Decorrelation length scales

In the early stages of planning the deployment of the Argo array, correlation scales were estimated from satellite altimetry and XBT data. The use of these two datasets together yielded estimates of around 300 km for the decorrelation scales of sea surface height and upper ocean temperature. These results were not inconsistent with the general knowledge of the mean and eddy fields at that time and led to the widely-quoted suggestion that about 3000 profiling floats would be a good target for Argo planning. The rationale for this estimate can be found by dividing the area of the world ocean (deeper than 2000 m and equatorward of 60°; about 3×10^8 km^2) by the estimated decorrelation area (a box 300 km × 300 km in size), to yield an estimate of about 3300 floats; this number was widely quoted as "about 3000". In the nearly two decades since the Argo design process was initiated, our best global estimates of these decorrelation scales has probably not changed greatly (a testament to the quality of the design work done at that time) although the Argo Steering Team has recognized that a number of regions of the world ocean (marginal seas, polar seas and boundary currents) require a higher sampling density than the canonical one float per 300 km x 300 km box.

The question arises in designing a biogeochemical float array as to how much different the decorrelation scales for properties such as carbon, oxygen, nutrients, and chlorophyll might differ from those of the basic Argo variables of temperature, salinity, and dynamic height. While there are not yet enough float-based measurements of these biogeochemical quantities to fully determine such length scales, some useful estimates can be made using ship-based data collected during the WOCE years and the later GO-SHIP and CLIVAR repeats of these hydrographic lines. Some results from such an analysis are shown in Fig. 11. In this case, the covariance functions of temperature and nitrate, composited from 32 zonal and meridional hydrographic sections collected between 20° and 40° of latitude in both hemispheres, has been estimated. As can be seen, the zero-crossing of both the east-west and north-south covariance functions does not differ importantly from the 300 km canonical estimate originally used in Argo. The results shown here are similar to results from other depths about 2000 m, and for other variables such as salinity and dissolved oxygen. The result is perhaps not surprising, since the biogeochemical variables strongly co-vary with temperature, and they are strongly linked among themselves through Redfield-type relations. This analysis

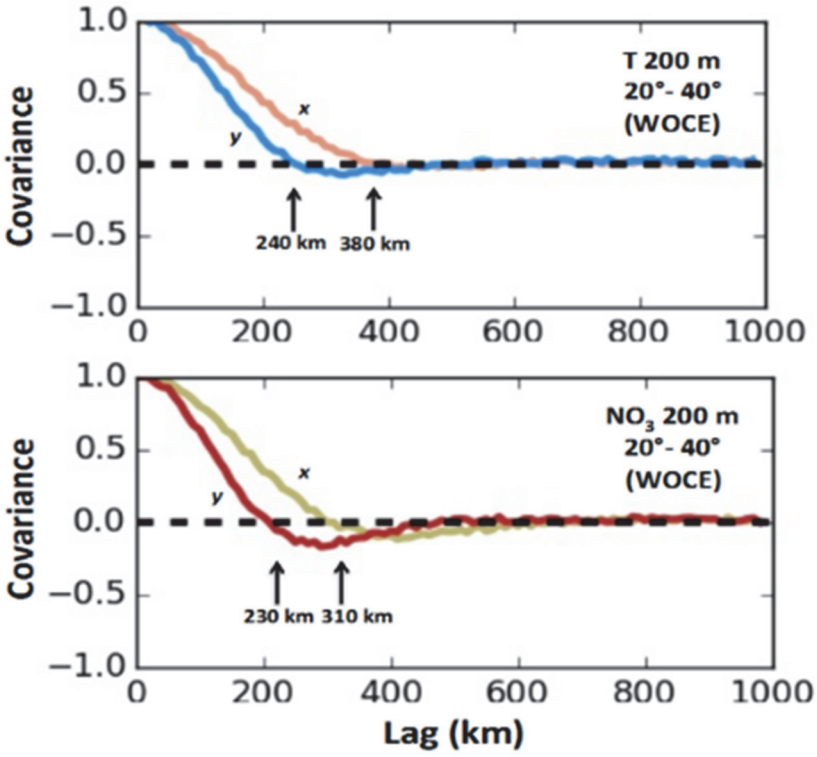

Figure 11. Top: The covariance function of temperature at 200 m estimated from 32 zonal (x) and meridional (y) ship-based hydrographic sections collected between 20° and 40° of latitude (both hemispheres) using data from WOCE and its successor repeat programs. Bottom: A similar covariance estimate for NO3 at 200 m, using the same ship-based section data.

is supported by the work of [*Jones et al.*, 2012], who assess decorrelation length scales for surface pCO_2 in the SOCAT data set. They found median autocorrelation lengths for pCO_2 around 400 km. Such length scales would

lead to an array near 1800 floats (3×10^8 km^2/(400 km × 400 km) = 1875). These results suggest that a fully-implemented Biogeochemical-Argo array might require roughly the same number of floats as Argo itself.

3.4.4 Bioregion analysis

Uniform global coverage by biogeochemical floats might not be the optimal strategy for Biogeochemical-Argo, especially since the regular Argo array is in place and already successfully samples the ocean globally. Deploying floats in specific biogeochemical provinces (e.g., western boundary currents, eastern boundary upwelling regions, and equatorial zonal jet systems), with sparser coverage in places of relatively low biogeochemical activity (e.g., the centers of subtropical gyres) might prove to be a more efficient and cost-effective sampling strategy than opting for uniform global coverage using biogeochemical floats. Again it is recalled here that Biogeochemical-Argo equivalent floats with only oxygen sensors (i.e., the most mature and overall least expensive biogeochemical sensor) in addition to the array of floats equipped with the full biogeochemical suite could represent a cost-effective alternative to constrain some biogeochemical measurements (e.g. NO_3, O_2) with a better resolution spatio-temporal resolution.

Bioregions represent a way to identify ocean areas having similar properties and variability in biological and/or ecological characteristics. Bioregions were introduced by [*Longhurst*, 2010], who partitioned the global ocean surface into provinces, which share common biogeochemical characteristics. Following that work, other bioregionalisations schemes were proposed at global (i.e. [*Reygondeau et al.*, 2013]; [*Hardman-Mountford et al.*, 2008]) and at regional scales [*Henson et al.*, 2006], [*D'Ortenzio and d'Alcala*, 2009]. A common feature of the present approaches for bioregionalisations is the utilization of ocean color observations, which provide the required spatio-temporal resolutions and coverage to identify robust patterns.

For the Biogeochemical-Argo network design, bioregions could provide a powerful tool to objectively determine how to distribute the floats. For example, considering 1000 floats as the fixed global target (see section 3.4.2), an equal number of floats could be assigned to each bioregion, whatever the total surface of the bioregion.

Recently, a bioregion approach was used to define the implementation of a Biogeochemical-Argo array in the Mediterranean (in the framework of the French NAOS project and Argo-Italy). The roadmap for float deployments (goo.gl/XA5d8s) was prepared using a bioregionalisation of the Mediterranean Sea based on ocean color [*D'Ortenzio and d'Alcala*, 2009]. The array was subsequently set up by considering bioregions as the main framework to define the network characteristic (i.e. number of floats, parking depths, profiling frequency).

3.5 Conclusions on array size and distribution

The various assessments of desired array size fall between 700 and 1800 profiling floats. We have selected 1000 floats, in the middle of the range as the target size for a Biogeochemical-Argo array. It should be acknowledged that this selection has considerable uncertainty and may need to be revisited as global results are acquired.

The variability of surface chlorophyll shown in Fig. 10 would suggest higher sampling density in some regions of the ocean, such as high latitude regions. However, the variability in most of the open ocean regions that can be sampled by profiling floats is lower and of a scale comparable to that sampled by the Argo array. It was, therefore, concluded that initial deployments and operations should begin with the premise that a relatively uniform distribution of floats was adequate. Again, this assumption will need to be tested as more experience is obtained.

Table 3. Summary of array size estimates.

Assessment	Global Array Size
Southern Ocean OSSE extrapolated to global scale	700
Global OSSE of air-sea CO_2 flux	1000
Satellite surface ocean chlorophyll reconstruction	1000
Nutrient/pCO_2 decorrelation length scales	1800
Mean of all assessments	1000

4. THE IMPLEMENTATION

4.1. Developing the global array

The number of floats that must be deployed each year depends on 4 factors: desired array size, number of vertical profiles achievable by the float, the cycle time between profiles, and float survival rate each year. The array size was considered in Section 3, and here we use 1000 floats as the desired target size for the system. The other parameters are considered in the following.

The original Argo Implementation Plan [*Argo Science Team*, 1998] foresaw floats achieving only 100 full profiles before battery capacity was expended. The introductions of Li primary batteries and Iridium communications have dramatically changed this. Laboratory-based and in situ estimates of energy consumption by floats equipped with biogeochemical sensors suggest that the biogeochemical sensors account for no more than about 25% of the total energy consumption, still yielding a majority of missions longer than 250 profiles for fully equipped biogeochemical floats.

Float survival rates have also increased. At the beginning of Argo it was hoped that 50% of the floats deployed would last longer than 3 years, equivalent to 80% of the floats surviving each year. As can be seen in Fig. 12, over 50% of floats presently being deployed in Argo by the US are expected to last longer than 5 years. This is a survival rate closer to 90% per year. The experience in SOCCOM largely supports this result. Even floats that operate in ice covered areas do not have unusual failure rates [*Wong and Riser*, 2011]. We use 90% as the expected yearly survival rate. That is, 10% of the surviving floats in each year class will fail prematurely each year due to mechanical, electrical, or software failures, and environmental problems such as grounding.

The float cycle time is a program dependent variable, which must be optimized

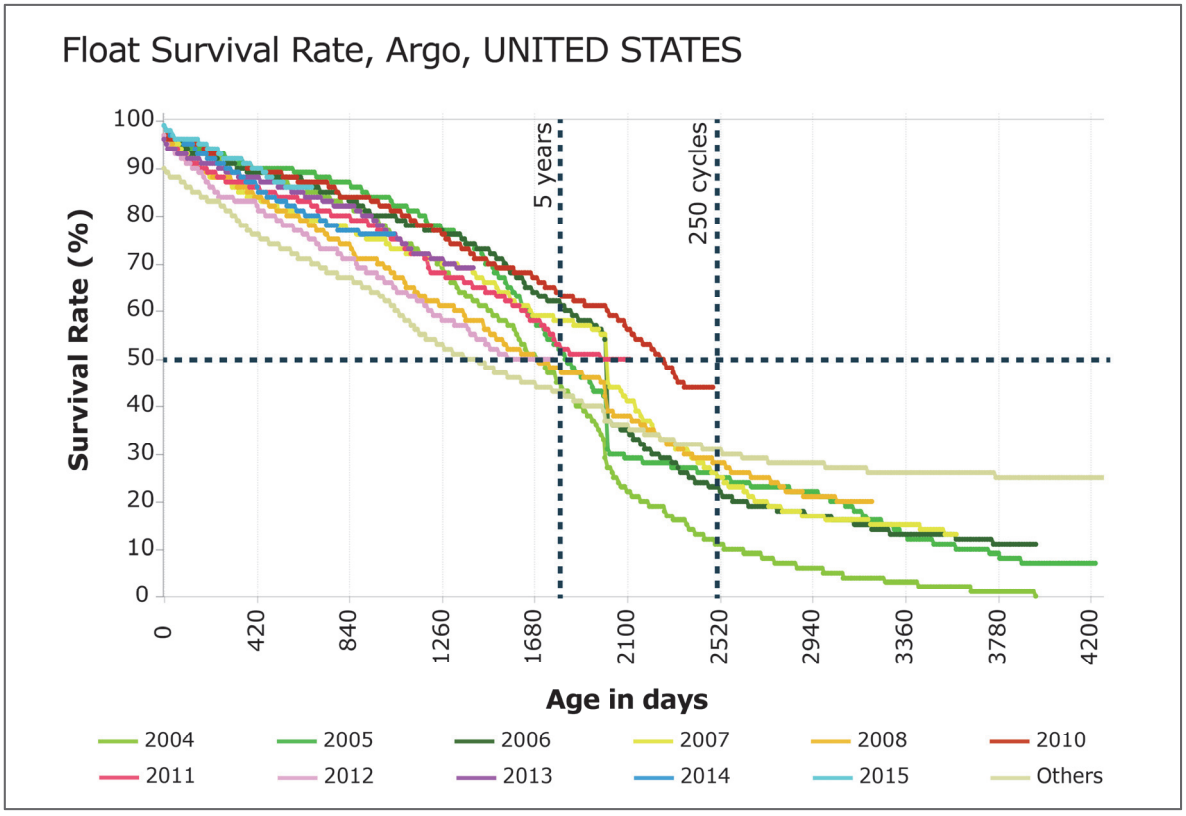

Figure 12. The lifetime of US Argo floats from 2001 through 2015 as a function of the number of profiles collected. The duration (expressed as number of 10-day cycles) generally increases over the years, from 60 cycles (less than 2 years) for floats deployed in 2001 to well over 150 cycles (5 years) for floats deployed in 2010. There are good reasons to project that many floats deployed in 2010 (and after) will survive as long as 250 cycles, or about 7 years. These results are for floats with CTD sensors only; for floats equipped with a full suite of BGC sensors it is projected that the lifetimes will be about 25% less, still implying lifetimes in excess of 4 years or more.

between science requirements for sampling frequency and operational requirements to maintain a float array at a particular size. Discussions at the Villefranche's meeting suggested that the scientifically desirable cycle time was order of 5 to 7 days to capture major biological processes such as spring

blooms. This is a bit shorter than typical core Argo float cycle times of 10 days, but is necessary to adequately observe biological events at the appropriate temporal resolution.

If 250 floats were deployed each year, an array with 90% survival, 250 profile lifetime, and 6 day cycle time would build to a steady state population near 1000 floats (Table 4). We believe this is a reasonable operational profile for a Biogeochemical-Argo system, and the available data suggests that it can be achieved.

4.2. System cost

There are two approaches to computing the operating cost for a global array. Regional scale programs such as SOCCOM, which deploys 30 to 40 floats per year with a sensor array similar to that desired for Biogeochemical-Argo, provide one end point. This is done by dividing their operating costs by the number of floats. A second approach, outlined in the Friends of Oxygen on Argo report [*Gruber et al.*, 2007], provides a relatively independent reference point. This method requires the capital cost of each sensor and an estimate of the lifetime cost of operating the sensor. Using the methodology outlined in [*Gruber et al.*, 2007], this approach is summarized in Table 5. The capital cost for a Biogeochemical-Argo float is about $80,000 in 2016.

Table 4: Float population that results with 250 floats deployed per year, 250 profile battery capacity, 90% survival each year and a 6 day cycle time

Project Year		**0**	**1**	**2**	**3**	**4**	**5**	**6**
Floats left in year class	0	250	225	202	181	162	0	0
Floats left in year class	1		250	225	202	181	162	0
Floats left in year class	2			250	225	202	181	162
Floats left in year class	3				250	225	202	181
Floats left in year class	4					250	225	202
Floats left in year class	5						250	225
Floats left in year class	6							250
total running/year		250	475	677	858	1020	1020	1020
Cumm. Total Built		250	500	750	1000	1250	1500	1750

Additional costs to prepare sensors and maintain the data stream, including quality control, are estimated to be $27,600 for a total lifetime cost of $107,600. If 250 floats per year are deployed, total cost is about $26,900,000. This does not include the full cost of ship time to deploy floats. A global array would be dependent on using other research programs, particularly the GO-SHIP global

survey program[12] to provide most of the ship time. The budget also does not count the cost of research programs that utilize the data. The results in Table 2 are consistent with the experience of the SOCCOM program, which operates at the scale of 30 to 40 floats per year.

Table 5. Biogeochemical-Argo system costs. Capital costs of components are estimates of current market price. Total cost for a core Argo float was estimated as US Argo budget of $10,000,000/year/300 floats/year. Operating costs for additional sensors were estimated from [*Gruber et al.*, 2007] for O_2, and a similar cost was applied to biooptics and pH. Nitrate is more complex and has a higher power demand. Its operating cost was doubled, relative to oxygen.

Item	Capital cost	Total cost including data processing and QC.
Core Argo T/S float	$22,000	$33,000
Add O_2 to Argo	$7,000	$10,200
Add nitrate	$24,000	$31,000
Add biooptics (Chl, BB, Ed)	$17,000	$20,200
Add pH	$10,000	$13,200
Cost per float	$80,000	$107,600
	Floats/year	**Program Cost/year**
US share if half of array	125	$13,450,000
Global total	250	$26,900,000

4.3. Integration with other components of the observing system

The Biogeochemical-Argo program that is envisioned above will have to form and maintain close relationships with a variety of other ocean programs in order to function as we envision. The relationships must include both observational programs as well as analysis and modeling programs. Some of the necessary partnerships are discussed below.

4.3.1 Partnerships with observational programs

The costs outlined in Table 5 do not include funds for ship time to deploy floats. Biogeochemical-Argo will be much more cost effective if it partners with other global programs that conduct ocean observations. This would allow Biogeochemical-Argo to deploy its floats as a joint program with other shipboard hydrographic programs. Float deployments require only a few minutes of ship time and have little impact on other observations. However,

[12] GOSHIP Program/ (www.go-ship.org)

quality control of biogeochemical float data benefits substantially from having ship-based profiles measured at the time of deployment. Deployment from research vessels is desirable for a large portion of the array. The cruises conducted by the GO-SHIP repeat hydrography program[13]; [*Talley et al.*, 2016]) are a particularly important partnership possibility. GO-SHIP cruises transect complete ocean basins, which can provide unique deployment opportunities. GO-SHIP voyages also take routine observations of most of the biogeochemical variables measured by floats so could provide this important source of quality control data at time of deployment. Other programs that operate, equivalent to the current Geotraces program, are also potential partners.

Partnerships with observational programs are also required to collect high quality data that can be used to validate sensor performance over the lifetime of the float ([*Williams et al.*, 2016]; [*Johnson et al.*, 2016]). Similar to the core Argo program [*Owens and Wong*, 2009], a reference data set of high quality measurements between 1000 and 2000 m depth is needed to provide a background data set that can serve as a reference database to evaluate sensor performance over time. The observations of the GO-SHIP program and the optimized data sets such as GLODAP-2 serve this function admirably.

4.3.2 Production of analytical products

Rapid advances are being made in analyses of near-real time biogeochemical data. A good example from the ocean is the SOCAT (Surface Ocean CO_2 ATlas[14]) data product. This is mostly based on the existing network of volunteer observing ships equipped with pCO_2 systems. SOCAT data products are now routinely used for the annual assessment of ocean CO_2 uptake made by the Global Carbon Project [*Le Quere et al.*, 2015]. One application of the SOCAT annual data is to improve our understanding of the terrestrial CO_2 budget, as discussed above (Section 2.1). The ocean carbon budget is thus an essential contribution to understanding changes on land.

Surface ocean pCO_2 measurements from VOS ships and research vessels are now used to make annual estimates of ocean CO_2 uptake. However, the ocean data is sparse and requires extensive mapping to fill in spatial and temporal gaps. Global Biogeochemical-Argo can contribute directly to the annual estimate of ocean CO_2 uptake by providing a global picture of the annual variability in surface ocean pCO_2. The synergy between highly accurate, but temporally sparse measurements made from ships and the less accurate float measurements that fully resolve annual cycles will result in an improved ocean CO_2 uptake estimate. As the system evolves a variety of other products could be developed. These might include integration with remote sensing to build 3D products of bio-optical parameters, similar to the work of [*Sauzède et al.*, 2016] or maps of carbon export.

[13] GO-SHIP (www.go-ship.org)
[14] SOCAT (www. www.socat.info)

4.3.3 Partnerships with ocean modeling and forecasting programs

The Biogeochemical-Argo budget that is outlined in Table 5 does not include explicit funding for analysis of the data that is produced. This is similar to the core Argo program. It will be incumbent on Biogeochemical-Argo to build partnerships with a variety of modeling programs to supply them with biogeochemical data that can be used to initialize and validate ocean circulation models and coupled ocean-atmosphere models, or assimilated in ocean state estimates. It will also be an essential contribution to marine resource management models. The need is driven by ongoing environmental change and the growing awareness of the potential negative effects on marine ecosystem health and living marine resources. This capability lags behind the well-developed predictive capabilities for weather and ocean physics.

Linkages to operational models are essential for effective utilization of the profiling float data. Forecasts of physical ocean properties and processes, which are now well established in more than a dozen nations, routinely support a range of services from operations at sea and weather forecasts to protection of the coastal environment [*Bell et al.*, 2015]. These operational systems routinely assimilate temperature and salinity profiles from the Argo array and satellite-derived sea level anomalies and sea surface temperatures. Assessments of the value of the different sources of observations and their effect on forecast systems unanimously conclude that Argo profiles are a critical data set (most critical to seasonal prediction skill and equally important as satellite altimetry to the forecast skill of eddy-permitting models; [*Oke et al.*, 2015a; *Oke et al.*, 2015b]). We anticipate that the Biogeochemical-Argo array will play a similar role to satellite ocean color in biogeochemical and ecosystem prediction in terms of reanalyses, short-term forecasts and seasonal predictions.

Operational forecasting centers in several nations have only recently taken on the challenge of biogeochemical and ecosystem forecasts by integrating these processes into their ocean analysis and forecasting systems. However, these efforts remain severely data-limited. While we know from available observations that ocean ecosystems are highly dynamic, their characterization in predictive models is necessarily restricted by parsimony to assumptions of fixed biogeochemical relationships and simple, stationary ecosystem structure and interactions. Ongoing operational activities in Europe and North America encompass global and regional products and range from assessments of ocean primary production and carbon fluxes to optimization of management strategies for living marine resources [*Gehlen et al.*, 2015]. At present these efforts have to rely on satellite ocean color, a proxy for surface ocean chlorophyll concentrations, as the primary source of real-time global biological observations; this is a severe limitation restricting the usefulness and scope of resulting products. Just as the core Argo array has a strong complementarity with satellite altimetry, which has revolutionized our capability to describe and forecast the state of the physical ocean, the Biogeochemical-Argo array in

synergy with ocean color satellites will revolutionize our capability to monitor ocean ecosystems. The Biogeochemical-Argo array will greatly expand the suite of observed parameters and extend observations in surface-only chlorophyll and other bio-optical properties ([*Sauzède et al.*, 2016]; [*Uitz et al.*, 2006]) into the vertical dimension.

Uncertainties in biogeochemical and ecosystem predictions result from three principal sources of error: (1) structural uncertainties in model formulations and parameterizations, (2) errors in initial, boundary and forcing conditions, and (3) errors due to numerical approximations; the first two are deemed to be the most important ones by far. Biogeochemical-Argo will provide an unprecedented source of information for addressing structural uncertainties in models and for improving their realism, which to-date has been severely hampered by insufficient observations. Biogeochemical-Argo observations would also greatly improve the accuracy of initial and boundary conditions for biogeochemical and ecosystem models.

As the scope of ocean forecasting expands to include marine biogeochemistry and ecosystems, there is an increasing focus on services for shelf and coastal waters. Coastal and shelf seas are among the world's most productive and diverse environments, account for up to 30% of marine primary productivity, serve as historically rich fishing grounds and play important roles in global biogeochemical cycles ([*Watson and Pauly*, 2001]; [*Liu et al.*, 2010]; [*Doney*, 2010]). With their high exposure to human influence, these systems are particularly vulnerable to the multiple stressors of eutrophication, acidification, temperature increases, and expanding hypoxia. They are exposed to harmful algal blooms, events of mass mortality, disease, extensive fishing, and other forms of habitat degradation. Dynamical, biogeochemical and ecological interactions between coastal/shelf seas and the adjacent deep ocean are two-way, which motivates the strategic goal of a seamless prediction framework linking coastal forecasting systems to larger scale systems [*Kourafalou et al.*, 2015]. Coastal prediction systems will directly benefit from Biogeochemical-Argo providing accurate open ocean boundary conditions that will supply the evolving large-scale context for more robust characterization of local changes in living marine resources.

The data from Biogeochemical-Argo will also play a critical role in the development of high-resolution state estimate models that incorporate biogeochemical parameters. As an example, consider the work that is now underway in Japan to incorporate biogeochemical data in carbon models. JAMSTEC has developed a 4-D physical and biogeochemical ocean state estimate (ESTOC[15], that covers the full depth range ([*Doi et al.*, 2015]; [*Osafune et al.*, 2015]). The state estimate was created with an ocean data assimilation system based on a 4-D variational technique (4D-VAR) with a biogeochemical model. The state estimate was developed to understand the processes and

[15] ESTOC - Estimated State of Global Ocean for Climate Research (www.godac.jamstec.go.jp/estoc/e/top)

depict accurate global distribution of carbon cycle with dissolved inorganic carbon (DIC) and its transport in four dimensions.

The global distribution of DIC based on the ESTOC resolves well the seasonal and interannual variations, estimating absorption of the anthropogenic CO_2 into the global ocean. Thus, such 4D-VAR system is surely a powerful tool to investigate short/long-term changes in carbon cycle, representing ocean circulation with physical process based on global Argo observation. Since the amount of biogeochemical data is quite small at this time, the accuracy of the carbon cycle in the 4D-VAR system is still not enough. To improve the performance, the 4D-VAR system with NPZDC model requires more Biogeochemical-Argo profiles, including dissolved oxygen, nitrate, Chl-a, and pH data. Such improvement will also make it possible to diagnose the appropriate Biogeochemical-Argo array with OSSE for global carbon cycle investigation. To investigate further detailed mechanism of the carbon cycle, input of new observational parameter for 4D-VAR system would be effective such as pCO_2 (Fig. 3).

4.3.4 Supporting the utilization of data by ocean researchers

The data generated by the Biogeochemical-Argo array will serve as an important data resource for the ocean research community. Achieving the scientific goals that are described above, as well as entirely unanticipated outcomes, will require the active involvement and utilization of the data set by graduate students, postdoctoral researchers, academic scientists, and scientists in government agencies and private institutions. The budgets outlined in this paper do not include funds for these analyses. The budget described in Section 4.2 includes only the capital costs, data system and associated program management. It will be essential for funding agencies to recognize that, in addition to direct funding for the array, there will be a need to support analysis of the data.

4.4 Integration with remote sensing

Profiling floats equipped with bio-optical sensors provide an important extension to ocean color observations by satellite. Remote sensing of the ocean surface covers spatial scales ranging from kilometers to the global scale and temporal scales ranging from days to the decadal scale. However, the satellite optical measurements only provide information in a layer defined by one optical attenuation length, generally less than the upper 40 m. Profiling floats sample the water column between the surface and 2 km (with vertical resolution for up to 1 m). As a result, floats can extend remote sensing observations into the ocean interior, providing essential information on carbon export and the fate of algal blooms ([*Dall'Olmo and Mork*, 2014]; [*Siegel et al.*, 2016]), as well as on the deep chlorophyll maximum that is ubiquitous at ~100m depth in all the subtropical gyres (2/3 of the ocean area).

The intersection between the spatio-temporal domains covered by both remote sensing and profiling floats also encompasses the mesoscale processes

and the seasonal cycle of mixed layer dynamics and its impact on biomass cycles. Studying these is pivotal for improving our understanding of the impact of physical forcing on ocean biology and the biogeochemical cycle of elements, in particular of carbon. These processes have been poorly studied to date, because of the lack of appropriate observational strategies. The design of observational strategies based on the combined use of both approaches would improve our knowledge of these fundamental oceanic processes. An example of such synergies is the extension of surface remote sensing products to depth [*Sauzède et al.*, 2016], allowing for a direct measure of the vertical fields of carbon pools (e.g. particulate organic carbon, phytoplankton biomass) and their dynamics [*Boss and Behrenfeld*, 2010]. Among other benefits, improved estimates of primary production are expected.

The calibration and validation of remotely-sensed satellite data is another area that would benefit strongly from the development and deployment of bio-optical floats ([*Claustre et al.*, 2010b]; [*IOCCG*, 2011]). Comparing each individual float's relevant sensor to the remote sensing product is a means to check the stability of biogeochemical sensors such as chlorophyll and backscattering [*Boss et al.*, 2008b].

In addition, comparing a long term and distributed database comprised of measurements by biogeochemical floats with a remote sensing product will contribute to validation of remote-sensing algorithms and it could be used to assess performance of the remote sensor instrument [*Werdell et al.*, 2007]. Identification of regions where improvement of bio-optical product retrievals is needed will lead to the deployment of multi- or hyper-spectral CAL/VAL floats [*Leymarie et al.*, 2016] as well as to planning of dedicated oceanographic cruises. These strategies will complement biogeochemical float-provided knowledge on bio-optical properties and will support current (e.g., NASA's MODIS-Aqua, ESA's Sentinel 3) and future (e.g., NASA's PACE) satellite missions.

The profiling float data may also exhibit a strong complementarity with remote sensing of atmospheric CO_2 concentrations from satellites such as GOSAT and OCO-2. The ocean CO_2 uptake computed from inversions of global satellite CO_2 data sets may reflect significant errors from the estimated terrestrial flux [*Deng et al.*, 2016]. A more complete constraint on the ocean uptake produced by combining shipboard pCO_2 data and profiling float pH data would reduce these biases.

4.5. Sensor calibration / cross-calibration

Continuous assessment of sensor performance is a key component of any observing system. This is an important part of the delayed mode data sets that are created by core Argo. Argo maintains and updates a reference data base of high quality shipboard CTD measurements. This data set is used to quality control and adjust float sensor data through statistical comparisons of each floats data between 1000 and 2000 m depth with the reference data set [*Owens and Wong*, 2009]. Such assessments of biogeochemical sensor

performance are critical to obtaining data that is of suitable quality for climate studies.

Initial efforts in regional-scale programs have focused on obtaining a hydrocast with high quality biogeochemical data to verify sensor calilbration. This has been critical in demonstrating sensor performance and understanding sensor calibration issues. For example the initial calibration casts have been used to show that errors in oxygen sensor calibration occur mainly as a gain correction ([*Bittig et al.*, 2015]; [*Johnson et al.*, 2015]), while errors in nitrate and pH occur primarily as constant offsets over the entire sensor range ([*Johnson et al.*, 2013a]; [*Johnson et al.*, 2016]). However, a high quality reference data set is also essential. The reference data set is used to predict analyte concentrations in the depth range from 1000 to 2000 m, where there is much less temporal variability than in the upper ocean. These predictions can be done using multiple linear regressions equations that are fitted to hydrographic data using parameters observed by the float [*Williams et al.*, 2016], or they may be fitted using Neural Network techniques (unpublished work, R. Sauzède and O. Pasqueron de Fommervault). As the float data diverge from the predicted values at depth, the sensor calibration is corrected using a knowledge of sensor error performance [*Johnson et al.*, 2016].

A global program is possible with a balance between deployments with high quality calibration hydrocasts at float deployment and those that would occur without such calibrations. Deployments without calibration casts will depend on predictions at depth to verify sensor calibration, while deployments with a calibration cast can be used to assess the uncertainty introduced by the vicarious calibration. As a result a global program can likely proceed with a careful balance between sensors deployed with rigorous calibration casts, such as those obtained on GO-SHIP cruises, and sensors deployed without calibration on volunteer research ships.

4.6. Data management

As for core Argo, Biogeochemical-Argo must be committed to real-time public access to high quality data. This will require a flexible and efficient system. The Biogeochemical-Argo system has been developed as an add-on activity to the Argo data system given the commonality of the data stream and the data distribution requirements. The diversity and the measurement complexity of biogeochemical variables has made the inclusion of the biogeochemical-Argo data stream into the existing Argo system a challenge as the core system had not been defined and sized for the additional complexity of the data stream from biogeochemical sensors. Several Bio-Argo workshops with the Argo Data Management team have been required to define the proper structure of a joint Argo and Biogeochemical-Argo data management system.

As a result of these interactions, the historical core Argo data management was not changed. A core-Argo (C-Argo) profile still contains the CTD sensor parameters (pressure, temperature, salinity, conductivity) that are measured with the same vertical sampling scheme and at the same location and time.

Additional parameters from other biogeochemical sensors are now stored in a so-called B-Argo profile file, which is very similar to the core-Argo profile file. Data flagging as well as data distribution mode (Real-time and Delayed-mode) of B-Argo rely on the same principles as for C-Argo. The settings of such a data system allow taking into account the specificity of each type of measurement and at the same time do not affect the highly effective Argo data management system. In summary, both Core-Argo and the relevant variables of the B-Argo profile file are merged into a so-called Merged-Argo file (M-Argo), which is the file dedicated to end-users. These radical changes were accompanied by a change in the format of the distributed netcdf files, from format 2.2 to format 3.1 [*Carval et al.*, 2014]. In the meantime the Bio-geochemical community is progressively establishing the good practice procedures for data management and quality control of each variables (e.g. [*Organelli et al.*, 2016] [*Schmechtig et al.*, 2014; *Schmechtig et al.*, 2015a; *Schmechtig et al.*, 2015b; *Schmechtig et al.*, 2016]).

The Biogeochemical-Argo data management system can henceforth be considered as well sized and adapted for an efficient management of Biogeochemical-Argo data. Furthermore this new structure has been generically established in a way it might be able to cope with the inclusion of new variables in the future (e.g. pCO_2, other nutrients than NO_3^-). The revisions to the Argo system should greatly reduce future challenges in management of Biogeochemical-Argo data. The essential point will be the sizing of the human resources that Biogeochemical-Argo will dedicate to optimally operate this data management system.

Presently, the Biogeochemical-Argo group involved in the data management meet every year in phase with the Argo Data Management Team meetings (see section 5.1). These joint meetings have been essential for developing the new Argo data system encompassing Biogeochemical-Argo. Such yearly joint meetings will continue and will be reported to a steering team that oversees global operation of the system (Section 5.1).

5. PROGRAM COORDINATION AND PLANNING

5.1. Overall governance of system.

The Biogeochemical-Argo Scientific Steering Committee (SSC) has the primary responsibility for coordination and management of international activities. Main duties include:

- Develop and update the Biogeochemical-Argo science plan with respect to a global network on a periodic basis;
- Coordinate the implementation plan, in particular to optimize the various national efforts;
- Interact with other task teams (e.g. "marginal seas", "polar areas") to prepare and coordinate the possible implementation of a Biogeochemical-Argo component to these new developments of Argo;

- Elaborate "good practice" recommendations with respect to float and sensor preparation, calibration, deployments and associated in situ simultaneous measurements;
- Provide advice regarding the scientific relevance for the addition of new variables into the Biogeochemical-Argo data stream, in particular based on an evaluation of the degree of readiness of their sensors;
- In close interaction with the Argo Data Management Team coordinate and organize the Biogeochemical-Argo data management;
- Establish and /or strengthen interactions and exchanges with international programs (IMBER, SOLAS) or group of experts (IOCCP, IOCCG) and promote partnership;
- Seek, in partnership with national committees, financial resources from national and international funding agencies to support the implementation of Biogeochemical-Argo;

The Biogeochemical-Argo co-chairs have the additional responsibilities to:

- Ensure the international promotion of the program;
- Represent Biogeochemical-Argo at scientific conferences and in meeting with other scientific programs. In some cases, the co-chairs may ask an SSC member to serve in their place.

The Biogeochemical-Argo SSC is expected to meet once a year, before the Argo Science Team meeting and will report to it.

5.2. International coordination

The primary coordination mechanism for Biogeochemical-Argo is achieved through interactions with the Argo Steering Team, which is a broadly international group[16]. However, Biogeochemical-Argo would also maintain international coordination through a variety of other, related activities. Global carbon observing is coordinated, at the international scale, by the Global Climate Observing System (GCOS[17]), which was established to support the United Nations Framework Convention on Climate Change (UNFCCC). The GCOS Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (GCOS, 2010) contains several action items relevant to Biogeochemical-Argo. These include Action O30, "Deploy a global pilot project of oxygen sensors on profiling floats". The 2016 update to the plan will include additional Action items related to development of a global biogeochemical observing system. Biogeochemical-Argo will need to maintain close ties to this community to ensure that it is responsive to the needs of international community for climate observing.

A variety of other international coordinating activities are underway. These include SCOR Working Groups such as WG142, "Quality Control Procedures for

[16] (www.argo.ucsd.edu)
[17] GCOS (www.wmo.int/pages/prog/gcos/index.php?name=AboutGCOS)

Oxygen and Other Biogeochemical Sensors on Floats and Gliders"[18]. The International Ocean-Colour Coordinating Group (IOCCG) also sponsors a Working Group on "Bio-optical Instrumentation on Argo Floats", which facilitates international collaboration and standards on interactions with ocean color remote sensing[19]). Active interactions with the International Ocean Carbon Coordination Project[20] are also maintained for better communications and interactions with ocean carbon and biogeochemical community as well as wider science community and policy and decision makers.

5.3. Coordination of deployment

The budget envisioned in Table 5 does not include direct funding for the ship time needed to deploy floats. Active, international collaboration will be required. Regional scale programs such as SOCCOM, which also does not include ship time for float deployments, are demonstrating the issues that are involved in coordinating float deployments. Close coordination with shipboard science programs is essential. But if that coordination is maintained, then a reasonable array of deployment options are available, even in remote areas such as the Southern Ocean. An international meeting, the "GO-SHIP/Argo/IOCCP Conference 2015" (GAIC2015[21]) was held to foster discussion of many of these issues.

5.4. Future integration of new variables and improved sensors

As noted above, the sensor suite that is now available and tested is sufficient to address the grand challenge topics described above. These biogeochemical sensors are a relatively recent development. This reflects the rapid expansion of technological capabilities that has been enabled by the rapid development of electronics and optics. It is likely that new sensors will be developed that would enable significant extensions to the Biogeochemical-Argo capabilities. It is also possible that the existing sensors may be improved significantly. This has already happened for dissolved oxygen. Early biogeochemical floats used oxygen sensors based on Clark-type oxygen electrodes [*Edwards et al.*, 2010]; [*Riser and Johnson*, 2008]). These have subsequently been replaced with optical sensors based on fluorescence lifetimes, which have improved stability and a capability for calibration in air [*Körtzinger et al.*, 2005]. The Biogeochemical-Argo system must be capable of responding to such technical advances.

Possible new sensors that might be available in the future include pCO_2. The current state of optode-based pCO_2 sensors [*Atamanchuk et al.*, 2015] has not yet reached float-readiness. We do expect, however, that there will be significant improvements of this technology over the next few years. We see the pCO_2 sensor as a prospective second carbon system parameter that may

[18] www.scor-int.org/SCOR_WGs_WG142.htm
[19] IOCCG (www.ioccg.org/groups/argo.html
[20] IOCCP (www.ioccp.org/)
[21] GAIC (www.gaic2015.org)

mature quickly and become an alternative to the pH sensor allowing direct observation of the CO_2 saturation state at the sea surface. This sensor would also link directly with the pCO_2 measurements provided by the global carbon-VOS (Voluntary Observing Ship) network. The ship-based observations would serve as an important quality control measure for float-based pCO_2 observations and at the same time add the much-needed vertical dimension to the carbon-VOS observatory.

Other examples might include the development of particulate inorganic carbon (PIC) sensors [*Guay and Bishop*, 2002] or fast repetition rate fluorometers. The highest accuracy pH measurements are generally made by spectrophotometry using well characterized indicator dyes [*Clayton and Byrne*, 1993]. Spectrophotometric pH profiles have been measured in situ [*Liu et al.*, 2006] and such systems may become alternate approaches for pH determination if they are proven to have the appropriate performance needed for long-term deployments. As new sensors are proven robust and effective, they may be considered for addition to the system based on performance, cost, and scientific merit.

In addition to new sensors, it is possible that the performance of existing sensors may be extended. One example might be application of the UV nitrate sensor to also observe dissolved nitrite in OMZ regions. The nitrite ion has a UV spectrum that is moderately distinct from that of nitrate [*Johnson and Coletti*, 2002] and quantification of the higher nitrite concentrations that result from denitrification in OMZ regions may be feasible. Such a capability would greatly add to interpretation of nitrate loss processes in OMZ regions. To facilitate such work, it will be necessary to ensure that low-level sensor data, such as UV spectra, are archived and available to the community.

5.5. Early career scientists

The future success and the sustainability of a Biogeochemical-Argo program rely on a strong end-user community. One of the challenges of a major science program is to ensure that the data is accepted and used by a broad range of community members. A particular goal would be to attract early career scientists to build research programs focused on utilization of Biogeochemical-Argo datasets. Access to diverse, well-calibrated data sets is a challenge for early career scientists, who do not have the resources to build a large research program. A Biogeochemical-Argo system will provide data sets in unique areas that have the required properties of calibration, and diverse observations. We find with the graduate students and postdocs associated with the regional biogeochemical float programs, that they are among the most innovative users of the data. It should be a focus of the Biogeochemical-Argo to ensure that such access is maintained across the ocean science community, so that young scientists can find the required research resources. This is also an important element of capacity building. It will be essential to ensure that early career scientists are involved in system development and operation. Fostering

the work of early career scientists is one of broader impact activities that are envisioned for the program.

5.6. Education and outreach

A new generation of scientists will be prepared and trained as the future operators and end-users of the network. In this context, dedicated Biogeochemical-Argo summer schools will be organized. Beside the specificities of the Biogeochemical-Argo network, these summer schools will also focus on a broader context (e.g. GOOS) identifying the network as a component of the future global integrated system of observation dedicated to biogeochemistry and ecosystems and involving other in situ networks (e.g. Go-Ship, carbon-VOS, Ocean Site, gliders) as well as satellite and modeling components.

With respect to public outreach, regional pilot programs like SOCCOM or remOcean have already a strong outreach component to their science and serve in developing future programs. In particular, the "adopt a float" concept, dedicated to children in primary and secondary education, relies on the appropriation of the Biogeochemical-Argo float by a school or a group of pupils. The scientific journey of the float serves as entry to diverse topics related to ocean science. With the help of science communicators (who can be PhD students joining outreach training), ocean literacy is enhanced. Thanks to scientific outcomes of first biogeochemical-Argo pilot projects, the Biogeochemical-Argo network is beginning to attract a new community of end-users (modelers, data analysts at the global scale). This is largely due to ease of data access, as well as the overall interoperability of data acquired by a fleet of floats. Hence, a continuous effort to facilitate the access to Biogeochemical-Argo datasets is necessary to promote the network and contribute to its sustainability over the long-term.

In parallel, capacity-development actions will have to be undertaken on all the aspects of the network including technology (knowledge on floats, sensors) float preparation, sensor calibration, deployment procedures, float mission control and change as well as data access and data management. These capacity-building actions will primarily concern technical and engineering staff that are involved in Biogeochemical-Argo related activities. Some of these actions will be performed using web-based interfaces (e.g. on line video hands-on), some others will require dedicated workshops. The capacity building component will need to pay particular attention to potential new users in developing countries for which Biogeochemical-Argo may be a cost-efficient way of mounting their own regional observation program.

6. SUMMARY AND RECOMMENDATIONS

Biogeochemical-Argo will revolutionize our understanding of ocean biogeochemistry and the management of marine resources. This report provides an overview of the science and management topics that can be addressed with a global array of profiling floats that are equipped with biogeochemical sensors and it outlines the size and configuration of the array needed to address these questions.

Based on the discussions at the Villefranche-sur-Mer meeting and subsequent community review of this document we recommend that an array with the following configuration would be required.

- A 1000 float array;
- Global deployment with a relatively even distribution;
- Sensor suites for pH, oxygen, nitrate, chlorophyll fluorescence, suspended particles, and downwelling irradiance;
- Transparent and public protocols and procedures for all aspects of the system;
- Real-time data access;
- Real-time products;
- International coordination;
- Entrainment of early career scientists;
- Outreach and capacity development;

A system with these characteristics will enable much greater understanding of ocean processes and it will provide the foundation for informed ocean management.

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Appendix 1: Biogeochemical-Argo task team terms of reference

Within the Argo program, the Bio-Argo task team acts as a scientific committee of Bio-Argo national representatives, which provide recommendations and guidance for the progressive development and implementation of a Bio-Argo program. More specifically, its terms of reference are to:

- Develop and update the Bio-Argo science plan with respect to regional pilot projects and to a global network.
- Coordinate the implementation plan, in particular to optimize the various national efforts.
- Interact with other task teams (e.g. "marginal Seas", "polar areas") to prepare and coordinate the possible implementation of a Bio-Argo component to these new developments of Argo.
- Elaborate "good practice" recommendations with respect to float and sensor preparation, calibration, deployments and associated in situ simultaneous measurements.
- Provide advice regarding new variables in the BIO-Argo data stream, in particular based on an evaluation of the degree of readiness of their sensors.
- In close interaction with ADMT coordinate and organize the Bio-Argo data management.
- Establish and /or strengthen interactions and exchanges with international programs (IMBER, SOLAS) or group of experts (IOCCP, IOCCG).
- Establish and develop interactions with the operational oceanography community (e.g. Marine Ecosystem Analysis and prediction task team of GODAE OceanView)

Appendix 2: List of participants, Villefranche meeting

- Barbier, Michèle, Ocean Synergies / Laboratoire d'Océanographie de Villefranche, France
- Belbeoch, Mathieu, Joint Commission on Oceanography and Marine Meteorology Operations (JCOMMOPS), France
- Bittig, Henry, Laboratoire d'Océanographie de Villefranche, France
- Boss, Emmanuel, University of Maine, USA
- Briggs, Nathan, Laboratoire d'Océanographie de Villefranche, France
- Claustre, Hervé, Laboratoire d'Océanographie de Villefranche, France
- Dall'Olmo, Giorgio, Plymouth Marine Laboratory, UK
- Doi, Toshimasa, JAMSTEC, Japan
- Dortenzio, Fabrizio, Laboratoire d'Océanographie de Villefranche, France
- Fennel, Katja, Dahlhousie University, Canada
- Fujiki, Tetsuichi, JAMSTEC, Japan
- Gehlen, Marion, Laboratoire des Sciences du Climat et de l'Environnement, France
- Gray, Alison, Princeton University, USA
- Hardman-Mountford, Nick, CSIRO, Australia
- Hosoda, Shigeki, JAMSTEC, Japan
- Ishi, Masao, Japanese Meteorological Agency, Japan
- Johnson, Kenneth, Monterey Bay Aquarium Research Institute, USA
- Körtzinger, Arne, GEOMAR Helmholtz-Zentrum für Ozeanforschung, Germany
- Le Traon, Pierre-Yves, IFREMER & Mercator Océan, France
- Leymarie, Edouard, Laboratoire d'Océanographie de Villefranche, France
- Obolensky, Grigor, Laboratoire d'Océanographie de Villefranche, France
- Organelli, Emanuele, Laboratoire d'Océanographie de Villefranche, France
- Paqueron de Fommervault, Orens, Laboratoire d'Océanographie de Villefranche, France
- Piotrowicz, Steve, NOAA, USA
- Poteau, Antoine, Laboratoire d'Océanographie de Villefranche, France
- Riser, Stephen, University of Washington, USA
- Roesler, Colin, Bowdoin College, USA
- Russell, Joellen, Arizona State University, USA
- Sarmiento, Jorge, Princeton University, USA
- Sauzède, R, Laboratoire d'Océanographie de Villefranche, France
- Uitz, Julia, Laboratoire d'Océanographie de Villefranche, France
- Wang, Haili, Xiamen University, China

Invited, excused

- Brasseur, Pierre, Laboratoire des Écoulements Géophysiques et Industriels, France
- Deutsch, Curtis, University of Washington, USA
- Dunne, John, NOAA, USA
- Feely, Richard, NOAA, USA
- Gruber, Nicolas, ETH, Switzerland
- King, Brian, NOC, UK
- Prakash, Sataya, INCOIS, India
- Ravichandaran, Ravi, INCOIS, India
- Talley, Lynne, Scripps Institution of Oceanography, USA
- Wanninkhof, Rik, NOAA, USA

Appendix 3: Group photo of Villefranche meeting attendees

Biogeochemical-Argo Network - Group photo