Mid-scale RI-2 Consortium: Biogeochemical-Argo: A global robotic network to observe changing ocean chemistry and biology

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SUMMARY

Directorate of Geosciences (Divisions of Ocean Sciences (OCE), Polar Sciences (OPP))

Overview

The ocean provides critical services to life on the planet, absorbing 93% of the heat from anthropogenic warming and a quarter of human carbon dioxide (CO_2) emissions each year. However, rising ocean temperatures and CO_2 levels also change the marine environment: pH and oxygen levels fall, ocean currents change, and nutrient fluxes and concentrations are shifting, all with large effects on ecosystems and the cycles of oxygen, nitrogen, and carbon throughout the ocean and atmosphere. Observing these biogeochemical (BGC) processes across remote ocean areas with seasonal to interannual resolution has been impractical due to the prohibitive costs associated with ship observations. Yet such observations are essential to understand the natural and perturbed systems.

Robotic profiling floats, proven in the Argo program, with BGC sensors provide a transformative solution to this need. BGC profiling floats are capable of observing chemical and biological properties from 2000 m depth to the surface every 10 days for many years. The NSF-funded Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) program serves as a basin-scale pilot for a global array; its 138 operating BGC floats demonstrate that the major challenges associated with operating a large-scale, robotic network have been overcome and that there is a substantial user base for the data.

This proposal will expand the BGC-Argo observing system to achieve global coverage by deploying 500 BGC floats carrying oxygen, nitrate, pH, and bio-optical sensors. The network will deliver data to an established data system where it will be freely available to all stakeholders in real-time.

Intellectual Merit

This proposal stems from extensive planning by the oceanographic community for an open ocean biogeochemical observing system. Computer and statistical models indicate that large float arrays would provide a transformative view of the biological, chemical, and physical events that impact carbon cycling (air-sea exchange, biological productivity, and carbon export), ocean acidification, deoxygenation, and nutrient supply. Data from the global array would illuminate the mechanisms controlling these processes and their interactions. Such a system would also enable a new generation of global ocean prediction systems in support of carbon cycling and the management of living marine resources. The array would address key questions identified in “Sea Change: 2015-2025 Decadal Survey of Ocean Sciences” such as:

- What is the ocean’s role in regulating the carbon cycle?
- What are the natural and anthropogenic drivers of open ocean deoxygenation?
- What are the consequences of ocean acidification?
- How do physical changes in mixing and circulation affect nutrient availability and ocean productivity?

The importance of global BGC observations has been affirmed by the Subcommittee on Ocean Science and Technology of the National Science and Technology Council and the G7 Science and Technology ministers. A global BGC-Argo array has been placed within the framework of global observing systems in reports by the National Research Council, National Academy of Sciences, the US Office of Science and Technology Policy, and the Global Climate Observing System of the WMO.

Broader Impacts

The proposed array will make biogeochemical data of unprecedented resolution freely available at the global scale in real time, providing equal access to oceanographic researchers at all levels and all institutions, as well as policymakers, resource managers, and other stakeholders. An outreach program will work to diversify the workforce through undergraduate, graduate, and postdoctoral programs, scientific training workshops, and curricula building with educators. Additionally, a partnership with the Marine Advanced Technology Education program will focus on preparing the US workforce for ocean occupations. A continuation of the successful SOCCOM Adopt-A-Float program will incorporate profiling float deployments into school science curricula.

PROJECT DESCRIPTION

Intellectual Merit

A. Science Drivers

A1. Vision. To implement an innovative and sustained robotic network of profiling floats carrying chemical and biological sensors. The unprecedented data stream will drive a transformative shift in scientific and public understanding of chemical and biological (biogeochemical) cycling in the ocean and its dynamics at the global scale.

A2. Technical & Science Goals. We will deploy an array of 500 robotic profiling floats (Figure 1), thereby transforming the US Biogeochemical Argo (BGC-Argo) fleet to a global reach as outlined in the Biogeochemical Argo Science and Implementation Plan (BAPG, 2016). These floats will be equipped with chemical and biological sensors and will be distributed globally in open ocean waters deeper than 2000 meters. The resulting US BGC-Argo array will be a major extension of the highly successful Argo network of ~4000 robotic floats (Riser et al., 2016). The Core-Argo array, sustained in the US by long-term support from NOAA, has fundamentally transformed our understanding of ocean heat content and sea level rise by measuring the temperature and salinity of the upper half of the global ocean; its data have been used in over 3600 papers in refereed journals since the beginning of the program, and are incorporated in all major operational analyses of the ocean's physical state. Together, Core-Argo and BGC-Argo, as well as Deep-Argo which extends physical observations to the ocean bottom, now operate as a unified system termed Argo2020 (Roemmich et al., 2019).

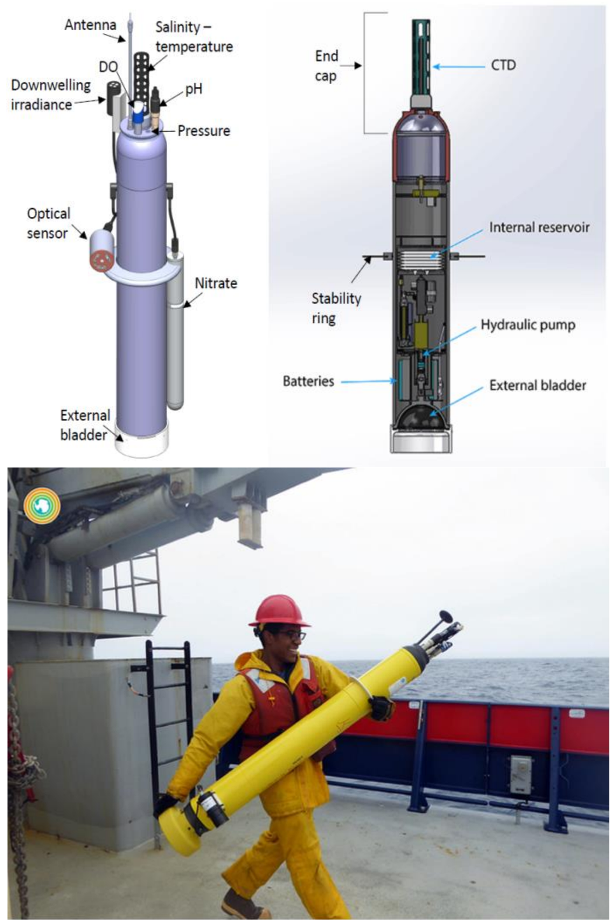


Figure 1. Top) A BGC-SOLO II/S2A float carrying 6 BGC sensors. Bottom) UW grad student (now CalTech postdoc) Earle Wilson preparing to deploy a BGC-APEX float.

Through the continuous, real-time observation of global ocean chemistry and biology, the BGC-Argo array proposed herein will similarly ***revolutionize our understanding of the ocean's role in anthropogenic carbon uptake, acidification and deoxygenation of the global ocean, and ocean productivity and health***. The NSF MSRI program provides the opportunity to establish this essential observing system now, opening a window to observing and understanding the global-scale functioning of an already changing ocean that will be subject to increasing future change.

Argo floats drift freely at 1000 meters depth and profile from 2000 meters depth to the surface every 10 days (Figure 2). At the surface, the profile data and the float position are transmitted to shore via satellite communication systems, and are publicly available within 24 hours. The BGC-Argo floats will carry a suite of proven sensors for oxygen, pH, nitrate, chlorophyll fluorescence, particle abundance (optical backscatter), and irradiance in addition to the standard temperature, salinity, and pressure sensors (BAPG), 2016). Each of these corresponds to an Essential Ocean Variable or Essential Climate Variable identified by the Global Ocean Observing System (GOOS, 2019). The array will be deployed with relatively even spacing (~1000 $\times$ 1000 km separation for a 500-float array) through close coordination with other agencies and nations. A detailed plan for float deployments is given in section C. Floats will carry sufficient batteries for over 200 profiles from 2000 m to the surface (> 5.5 year life at a 10 day profiling interval). The data will be processed and delivered by Internet to the US Argo Data Assembly Center in near real-time (typically <24 hours) with simultaneous quality control to yield a product suitable for research. These data will be freely available immediately.

The unprecedented calibrated, global data set we aim to produce will capture, for the first time, the variability of ocean biogeochemistry at seasonal to interannual time scales across the world's ocean. This capability is vital if we are to understand and predict the biogeochemical and physical responses to the fundamental changes affecting our oceans, including the atmospheric carbon dioxide gas (CO_2) invasion and accompanying ocean acidification caused by human activities, increases in heat content and shifts in wind that drive altered circulation, declining oxygen content, and decreasing sea ice.

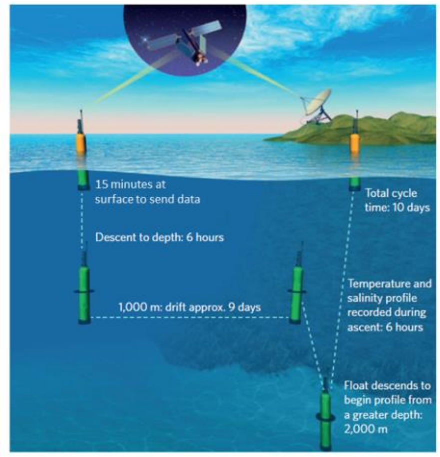


Figure 2. Typical profile operations for an Argo float. Adapted from Riser et al. (2016).

The multi-parameter global data stream proposed here will enable the community to address crucial scientific questions that to date have remained intractable due to the dearth of appropriate observations. Many of these directly relate to the priority research questions identified in the National Research Council (NRC) report "Sea Change: 2015-2025 Decadal Survey of Ocean Sciences" (NRC, 2015): "<u>*How have ocean biogeochemical and physical processes contributed to today's climate and its variability, and how will this system change over the next century?*</u>" The data generated by a global BGC-Argo array will transform our understanding of numerous sub-questions outlined in the "Sea Change" report, including:

● *What is the ocean's role in regulating the carbon cycle?* The ocean plays a major role in regulating atmospheric CO_2 concentration by removing about 26% of the anthropogenic CO_2 released into the atmosphere each year (Le Quéré et al., 2018; Sabine and Tanhua, 2010). The surface partial pressure of CO_2 gas (pCO_2), which is the major driver of this process, is controlled by the often-opposing forces of seasonal temperature change and mixing versus biological productivity (Fassbender et al., 2018; Henson et al., 2016; Takahashi et al. 2002) (Figure 3). In a warming ocean, physical processes (reduced solubility of CO_2, enhanced vertical stratification, changing Revelle buffer factor [Fassbender et al., 2017]) and biological processes (changing carbon uptake and timing of uptake) may interact differently, leading to altered surface pCO_2 and hence air-sea carbon fluxes. These processes are not well characterized because of incomplete data sets at the seasonal scale over large regions, few contemporaneous sub-surface observations, and models that often do not accurately reproduce the relative contributions of physics and biology. Furthermore, interannual variability in carbon cycling is not observed or adequately sampled except at a handful of regions around the world (circles in Figure 3). A global BGC float array will completely transform our ability to understand and model the present day and future trajectory of oceanic carbon cycling (Williams et al., 2017, 2018; Gray et al., 2018; Bushinsky et al., 2019) (Section B4).

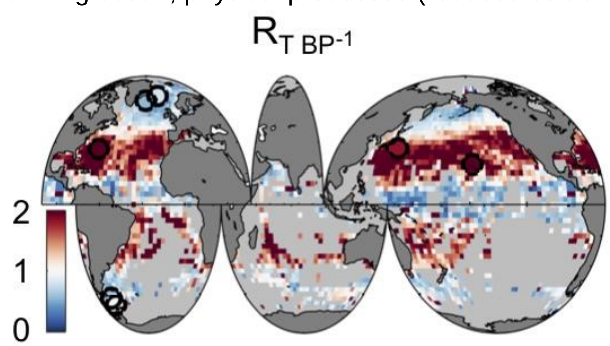


Figure 3. Ratio of thermal (T) to biophysical (BP) controls on seasonal pCO_2 variations for SOCATv4 sea surface data (Bakker et al., 2016) with at least 4 months of climatology (Fassbender et al., 2018). Note the climatology was compiled over 60 years and few regions have full annual cycles in one year, limiting trend detection..

● *What are the natural and anthropogenic drivers of … open ocean deoxygenation, and how can the two drivers be distinguished?* Warming-related decreases in oceanic oxygen are expected and observed (Keeling et al., 2010) as warming reduces the solubility of gases, slows circulation, and increases the rate of bacterial respiration (Oschlies et al., 2018). Oxygen minimum zones, where nitrate is consumed by denitrification, may be expanding (DeVries et al., 2012; Deutsch et al., 2014), with concurrent declines in ocean nitrate (Deutsch et al., 2011), an essential nutrient that supports productivity. The proposed array will enable direct measurement of the extent of oxygen minimum zones (Wojtasiewicz et al., 2018) and the rates of oxygen and nitrate loss (Johnson et al., 2019) globally for the first time.

● *What are the consequences of ocean acidification and the impact of decreasing pH on ocean biogeochemistry?* Based on the few existing ship-based time series (Bates et al., 2014), upper ocean pH ($-\log_{10}([H^+])$) is generally decreasing as atmospheric CO_2 increases (Dore et al., 2009). However, the observed rates of pH decrease are spatially variable (Sutton et al., 2014), with high-latitude waters being most sensitive (Orr, 2011; Fassbender et al., 2017). Many ocean regimes remain unobserved. Profiling float pH measurements will provide direct observations of pH decline (Swart et al., 2018) throughout the surface and interior ocean. These data will also be used to determine changes in carbonate mineral saturation state (Williams et al., 2018), a metric vital for assessing vulnerability to dissolution of calcifying organisms that are a key component of the marine food web (Bednarsek et al., 2012).

● *How do physical changes in mixing and circulation affect nutrient availability and ocean productivity?* Open ocean productivity is determined by the interplay of light levels and nutrient availability, which is in turn driven by the strength and depth of ocean mixing and circulation (Fischer et al., 2014; Mignot et al., 2018). Biological production and the subsequent export of organic carbon from the surface ocean to depth reduces atmospheric CO_2 by about 200 ppm relative to a modeled, abiotic ocean (Parekh et al., 2006; Watson and Orr, 2003). This process, referred to as the “biological pump”, transports organic material vertically, strengthening the vertical gradient of inorganic carbon in the ocean. The depth to which organic carbon is exported prior to remineralization exerts a fundamental control on climate (Kwon et al., 2009) but is difficult to model due to a dearth of systematic observations across the global ocean. BGC-Argo floats will provide direct observations of the net community production that drives the biological carbon pump (Plant et al., 2016; Johnson et al., 2017a; Yang et al., 2017) and the depth at which the organic carbon is consumed (Hennon et al., 2016). This improved knowledge will significantly reduce the present 100% uncertainty in the modeled global biological pump magnitude and allow for a more accurate quantification of potential climate feedbacks associated with marine carbon cycling. Additionally, the duration and magnitude of phytoplankton blooms, and thus potentially the amount of carbon sequestered by the biological pump, appears to be linked to the timing of the bloom (Friedland et al., 2016). Variations in phenology and productivity are also known to have significant impacts on marine fisheries (Stock et al., 2017). Near the sea surface, changes in phytoplankton bloom timing and strength can be observed by ocean color satellites (Racault et al., 2012), but in situ observations are required to understand the processes responsible for these changes. Profiling floats provide the direct measurements needed to enable this mechanistic understanding (Boss and Behrenfeld, 2010; D’Ortenzio et al., 2014; Gittings et al., 2019).

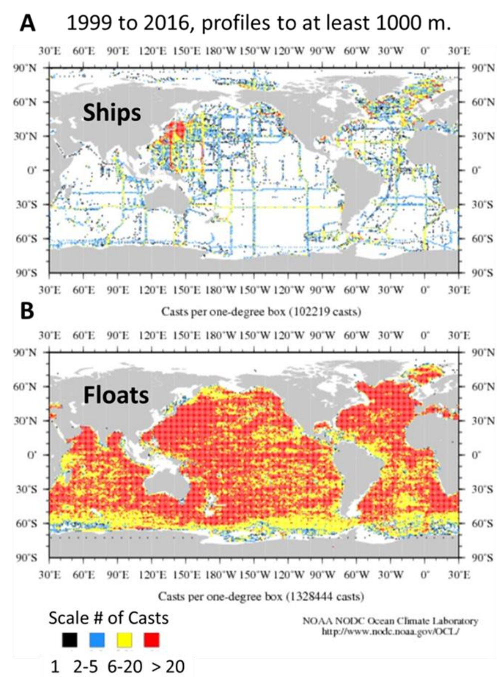


Figure 4. A) Number of ship-based profiles, and B) Core-Argo float profiles of temperature that reach 1000 m in each 1x1 degree square for 1999 to 2016. Figures from the National Oceanographic Data Center.

A3. Situational Analysis. Our best efforts to predict the impacts of climate change on the drivers of marine life are blunted by limited observations. Traditional ship-based oceanography provides only coarse-grained temporal and spatial snapshots of biogeochemical properties. Figure 4 compares the number of ship-based profiles for temperature to a depth of at least 1000 m in each 1° × 1° geographic square with the number of temperature and salinity profiles collected by the Argo network from 1999 to 2016. The ship-based map is predominantly white, with many regions unsampled, or sampled only a few times during this period. In contrast, the Argo program, utilizing robotic floats, has turned the map red with dozens of high-quality profiles in each square. There is no seasonal bias in these measurements, while the vast majority of ship-based profiles are from summer months. The coverage for ship-based biogeochemical properties is far worse than for temperature, which precludes quantifying a seasonal cycle in most regions. Ocean color satellites measure at a higher resolution than ships but detect a limited number of ecosystem properties, and only for the top few tens of meters of the water column. A global BGC-Argo array would transform our understanding of ocean biogeochemistry, just as the Argo array has done for ocean physics. *Establishing this network now, through the MSRI program, is essential to understanding the trajectory of ongoing biogeochemical changes in the ocean and their ecosystem and human impacts.*

The urgent need to adequately observe the global ocean was recently highlighted by the Executive Branch of the Federal Government through the Subcommittee on Ocean Science and Technology (SOST) in the National Science and Technology Council report "Science and Technology for America's Oceans: A Decadal Vision" (SOST, 2018). This report identifies a set of priorities that are well matched to our proposal. These priorities include:

- *Sustain critical ocean monitoring, maintain time-series data collection, and support new observations and discovery in the world's ocean to provide the continuous information streams that inform research, advance forecasts, and support responsible resource management decisions.*
- *Prioritize new observing methods focused on processes that lack fundamental understanding, …*
- *Identify and expand observations ... in under-sampled areas of the global ocean, such as the deep-sea, offshore frontiers, the Southern Hemisphere, and key continental margins.*
- *Increase and sustain the ocean community's access to usable Big Data ….*
- *Encourage unclassified, releasable data, particularly Big Data, to be easily accessible…*

Furthermore, data from a global BGC-Argo array will contribute substantially to the "10 Big Ideas" identified by NSF. Most obviously, our proposed array addresses "Mid-scale Research Infrastructure", but has direct relevance to others: (i) For example, these data address "Navigating the New Arctic". Our group has successfully deployed BGC floats up to 78°N with full data return for temperature, salinity, nitrate, oxygen, and bio-optical properties (no pH on these floats) (Mayot et al., 2018). The data have enabled a novel view of processes controlling plankton production and carbon export in seasonally ice-covered regions of the Arctic Ocean. (ii) Data generated by the BGC float array will significantly advance the goal of "Harnessing the Data Revolution", which envisions real-time sensing of the atmosphere, land, and water to address key questions with social relevance. BGC-Argo data are highly synergistic with ship- and space-based ocean and atmospheric measurements, greatly increasing the value of these large community investments. In addition, the multivariate data produced by a global BGC-Argo array will provide invaluable input for data-assimilating Earth system models that serve to integrate the various data streams arising from global atmospheric, terrestrial, and oceanic observing systems. (iii) The proposed array will contribute to "Growing Convergence Research" which promotes the merger of diverse fields to address topics such as understanding the interplay between food, energy, and water. The ocean provides critical services, such as supplying 20% of the animal protein consumed by 3.1 billion people. Data from a global BGC array will be a nexus between social science, climate science, and technological solutions.

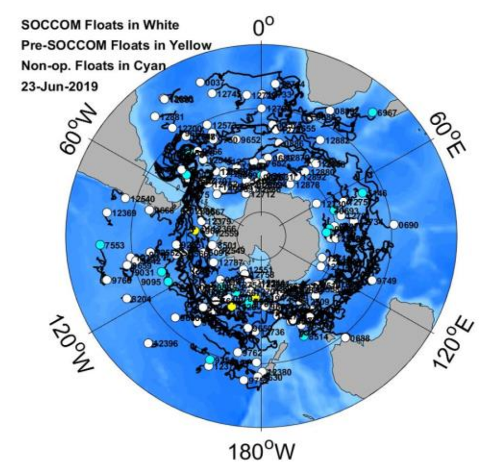
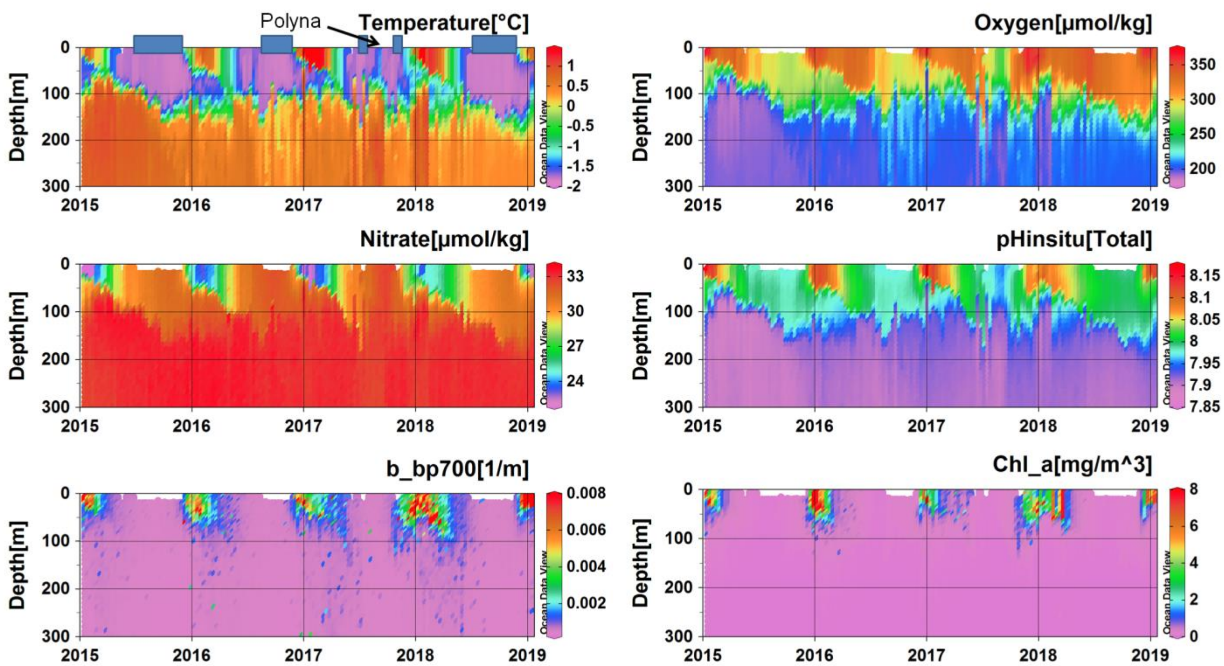


Figure 5. Location of 136 operating floats in the SOCCOM array (white circles). 2 floats with a new micro-controller were recently deployed near Hawaii to expedite testing and are not shown. Only 19 additional floats have failed (cyan symbols).

B. Pre-Implementation Activities Accomplished

B1. Sensors on profiling floats. A novel set of BGC sensors capable of operating on floats is now available, having been used in the basin-scale Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) program, a pilot project funded by NSF Polar Programs (Figures 5, 6), as well as a variety of international projects (BAPG, 2016). Oxygen is measured with luminescence lifetime optode sensors (Bittig et al., 2018a). Nitrate is measured by direct UV spectrophotometry (Johnson et al., 2013). pH is measured by Ion Sensitive Field Effect Transistor (Johnson et al., 2016). Particle abundance (primarily phytoplankton and their detritus in the open ocean) is measured by optical backscatter (Graff et al., 2015). Chlorophyll fluorescence is measured by in situ fluorometry (Roesler et al., 2017). Wavelength resolved irradiance and photosynthetically available radiation (PAR), is measured by radiometry (Organelli et al., 2017). These sensors are all capable of operating for years through the pressure and temperature extremes seen by Argo floats (Johnson et al. 2017b). Figure 6 shows one example of BGC sensor data spanning four years on a float operating in the seasonal ice zone of the Weddell Sea. During the winter of 2017, this float made the first detailed winter observations of BGC properties in the ice-free waters of the Weddell Polynya (Campbell et al., 2019).



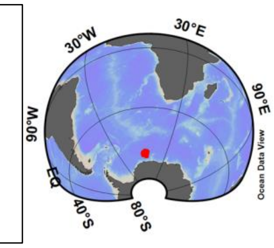


Figure 6. Measurements of Temperature, Oxygen, Nitrate, pH (in situ values on Total Proton Scale), optical backscatter by particles at 700 nm (b_bp700) and chlorophyll fluorescence in the upper 300 m of each 1700 m deep profile from 2015 to 2019 by SOCCOM float 5904468. Map shows location of profiles in the eastern Weddell Sea. Boxes on the Temperature plot and near surface data gaps on other plots indicate periods when the float detected ice. From Claustre et al. (in press).

In combination with international projects, the SOCCOM floats and sensors have initiated a transformation for ocean biogeochemistry similar to that shown in Figure 4 for ocean physical observations. BGC profiling floats now return 4 to 8 times more open ocean data each year than ship-based observations (Johnson et al., 2017b). These tools have been operated at the ocean basin scale to produce high quality assessments of the biogeochemical cycles of oxygen (Bushinsky et al., 2017), nitrate (D'Ortenzio et al., 2014; Johnson et al., 2017a, b), pH (Johnson et al., 2017b; Williams et al., 2018), carbonate mineral saturation state (Williams et al., 2018), chlorophyll (Haentjens et al., 2017; Ardyna et al., 2019), optical backscatter and particulate carbon (Poteau et al., 2017; Mignot et al., 2018), air-sea CO_2 flux (Williams et al., 2017; Gray et al., 2018; Bushinsky et al., 2019), and light attenuation (Organelli et al., 2017). These data are assimilated into ocean biogeochemical state estimate models (Verdy and Mazloff, 2017) to provide a realistic assessment of the current ocean state.

B2. Sensor Data Quality. The quality of chemical observations from profiling floats has been assessed in a variety of ways within SOCCOM. All raw sensor data are passed through a series of quality control checks and assessed for any required adjustments using protocols developed in SOCCOM and documented by the Argo Data Management Team. Chemical sensor data are adjusted using methods that do not require collection of discrete samples when floats are launched; this is an enabling and key component for a global array. The oxygen sensor data are calibrated by applying a gain multiplier based on air measurements made when the float surfaces (as the oxygen partial pressure of air provides a known reference that varies only in proportion to local sea level atmospheric pressure; Johnson et al., 2015; Bittig et al., 2018a). pH and nitrate data are adjusted by applying an offset based on a deep, stable reference field (Johnson et al., 2013; 2016; 2017) predicted with global algorithms fitted to high quality ship data (Carter et al., 2018; Bittig et al., 2018b). Raw and adjusted sensor data are reported in all cases.

The accuracy of the adjusted and quality-controlled data collected by SOCCOM floats has been assessed by comparing sensor values from the first float profile with data from standard laboratory analysis methods applied to water samples collected during a conventional hydrocast coincident with the float deployment (Figure 7; updated from Johnson et al., 2017a). Histograms of the sample-minus-sensor concentrations indicate an initial fleet-wide oxygen concentration bias of 0.5 µmol/kg and a precision of better than 2 µmol/kg; nitrate bias is 0.1 µmol/kg and precision of better than 0.7 µmol/kg; and the pH bias is 0.004 pH and precision of better than 0.013 pH units. The precision estimates reflect one standard deviation of the bottle sample minus sensor variability. The observed differences include both sensor imprecision and ocean changes between the two sets of observations, which may be offset in time by as much as 18 hours. These initial estimates of fleet-wide bias and precision for each variable match closely with the corresponding requirements for the accuracy of Essential Ocean Variables observed on autonomous platforms (GOOS, 2019). Very similar results for bottle minus sensor differences have been obtained for Argo-France BGC floats deployed in the Mediterranean Sea (Mignot et al., 2019).

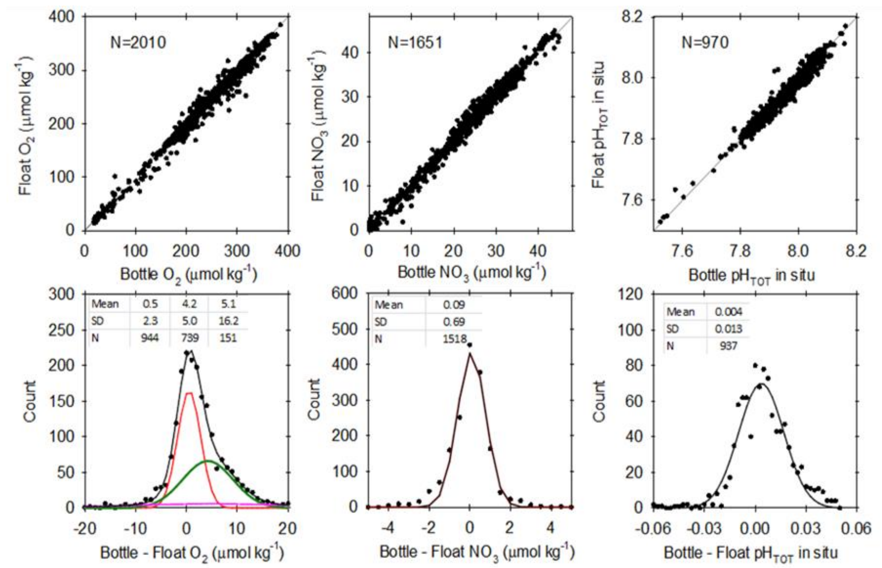


Figure 7. SOCCOM quality-controlled float sensor to bottle data comparison for oxygen, nitrate and pH. Updated from Johnson et al. (2017b). Histograms of the differences are shown in lower panel with normal distributions fitted to values. Oxygen data were fitted with two normal distributions. The first distribution (red line) reflects basic accuracy of data in low vertical gradients. The second distribution reflects an accuracy bias in steep gradients due to relatively slow sensor response time. Algorithms to correct for the slow response are being implemented.

The initial performance specifications found for profiling float sensors do not degrade over the lifetime of a float. The primary evidence for this comes from comparisons of SOCCOM profiling float data to conventional hydrographic data in GLODAPv2 (Global Ocean Data Analysis Project; Olsen et al., 2016) when the floats pass within 20 km of a station in the GLODAPv2 database (Figure 8). There is no systematic difference for nitrate between observations in GLODAPv2 and all of the float sensor data, the subset of float data from at least 6 months after deployment (Figure 8E), and the subset of float data from at least 2 years after deployment (Figure 8H). There is a mean difference between the GLODAPv2 data and float sensor data of 5 µmol/kg O_2 at depths below 500 m where seasonal variations are minimized.

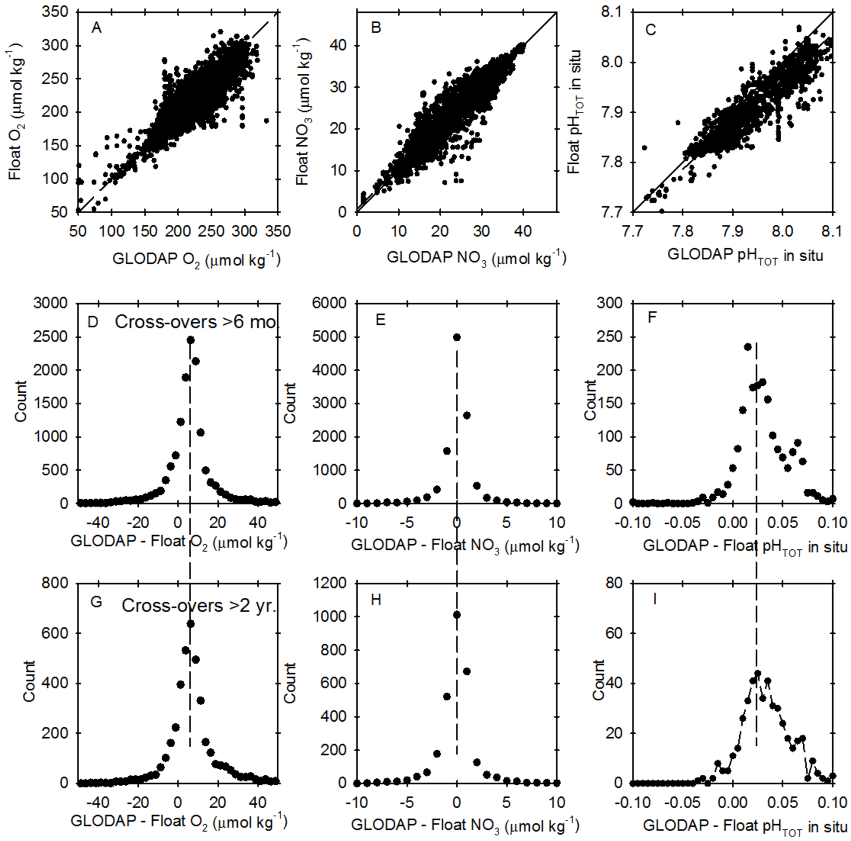


Figure 8. Comparison of quality-controlled float oxygen (A), nitrate (B), and pH (C) data to GLODAPv2 measurements (Olsen et al., 2016) when a float profile occurs within 20 km of a GLODAPv2 station. Histograms of the differences are shown in D-F only for data after floats that have been in the water at least 6 months. Panels G to I are similar histograms, but only for data after floats have been in the water at least 2 years.

The difference does not change as floats age (Figure 8D and 6G), suggesting that this is a systematic bias between GLODAPv2 and the SOCCOM float data and not an artifact due to aging sensors. The bias increases with the time difference between the GLODAPv2 station date and the SOCCOM float profile date (Johnson et al., 2017b). Presently, the mean age difference between the GLODAPv2 station data and the profiling float data is 17 years. A decrease of 5 µmol/kg O_2 in two decades is consistent with reported rates of oxygen change in the Southern Ocean that are based on shipboard data (Helm et al., 2011). This systematic difference is likely due to a decrease in ocean oxygen content of Southern Ocean waters in recent years. Thus, no significant decrease in oxygen sensor performance with age of the float is apparent.

The float pH sensor data have a mean offset from the bottle data of 0.03 near the surface, which does not change if the comparison is made with float data more than 6 months after deployment (Figure 8F) or more than 2 years (Figure 8I). Similar to $O_{2,}$ the offset increases with the mean age difference between the GLODAPv2 station time and the profiling float measurement time (Johnson et al., 2017b; Swart et al., 2018). The observed rate of change is consistent with expected and observed rates of ocean pH decrease due to increasing atmospheric CO_2 (ocean acidification; Swart et al., 2018). There is, therefore, no evidence of a decrease in pH sensor performance with time.

The bio-optical sensors on profiling floats provide an important metric for plankton biomass. Figure 9 shows the relationship between the particulate organic carbon (POC) collected on a GF/F glass fiber filter (standard ship-board method) and optical backscatter due to particles at 700 nm. Data come from three environments: the North Atlantic (NABE; Cetinic et al., 2012), the Southern Ocean (SOCCOM; Johnson et al., 2017b and additional data), and profiling floats launched at the Hawaii Ocean Time-series site (HOT; unpublished data). The relatively consistent relationship between POC and backscatter across a broad range of environments demonstrates the capabilities and limitations of using backscatter to observe the accumulation of plankton biomass (Organelli et al., 2018). This program will continue to collect ship-board POC data to understand the features of such empirical relationships.

One factor contributing to the consistent performance of the sensors on SOCCOM profiling floats is the lack of biofouling when floats cycle at 10-day intervals. Profiling floats in the SOCCOM array, and Argo floats in general, park at 1000 m depth for 9 days before profiling. They spend approximately 15 minutes at the surface to transmit data after each profile. As a result, there is little time for fouling organisms to settle when the float is at the surface, and conditions at depth do not support significant growth. The lack of fouling is consistent with the historical behavior of Argo salinity sensors, which show relatively little degradation in performance over time. Shorter profile times (~1 d) do lead to biofouling.

While profiling floats could be recovered to further test sensor performance and long-term degradation, we believe these results would not be definitive. Statistically significant numbers of comparisons would have to be made, which means recovering many floats, at considerable expense. More problematic, it may take up to 6 months to send a float back to the laboratory for recalibration. It would not be clear whether any observed changes in sensor performance occurred in situ or during the period after recovery.

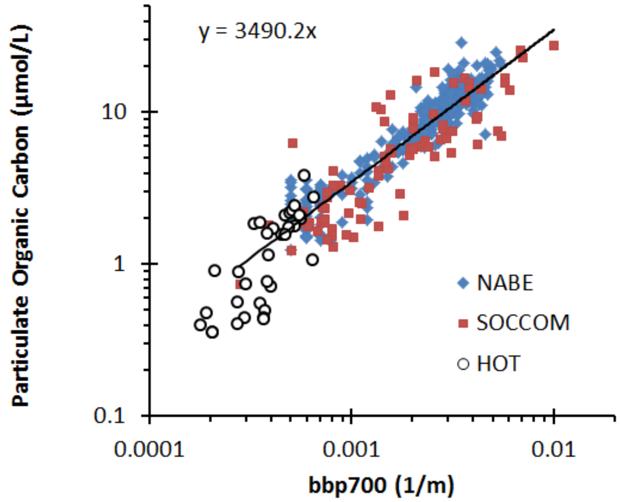


Figure 9. Comparison of Particulate Organic Carbon collected on a GF/F filter with backscatter by particles at 700 nm (bbp700) with an FLBB sensor for samples from NABE, SOCCOM, and HOT. The NABE samples were corrected by adding back a DOC blank to make all results comparable.

B3. Reliability. As is true for Core-Argo, some percentage of BGC floats will suffer premature failures due to mechanical and electronic faults. SOCCOM deployed 159 floats and at this time 138 are operational. A survival rate near 95% each year is slightly lower than that seen for Core-Argo floats deployed by the partners in this project (Figure 10). The slightly higher losses result from some of the SOCCOM floats operating in harsh, high latitude, ice-covered conditions and early losses of commercially prepared floats that required additional development. The commercially prepared floats are now more mature and reliable.

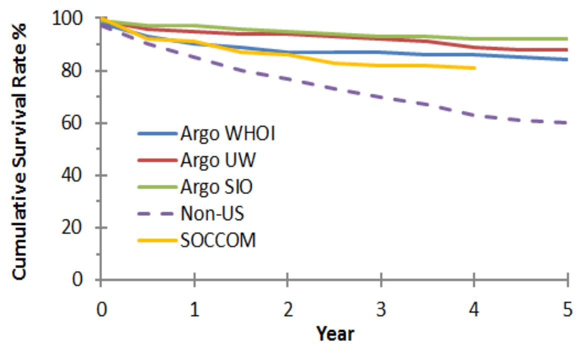


Figure 10. The cumulative survival rate for Core-Argo floats from WHOI, UW, and SIO, as well as for BGC floats in the SOCCOM program. After 4 years, 82% of SOCCOM floats have survived and are operating. This corresponds to a mean annual survival rate of 95% each year (0.95^4 = 0.82). The cumulative survival rate for all non-US Argo floats is also shown. Data are from 2014 to present, downloaded from the JCOMMOPS web site (JCOMMOPS, 2019).

In addition to float losses, individual sensor malfunctions may also occur. Survival rates for oxygen sensors and bio-optical sensors are close to 100% (Figure 11a). Nitrate sensors suffer malfunctions, at about 5%/year (Figure 11b). The primary mechanism for malfunction appears to be water penetration into the optics of the sensor probe. Efforts are underway to improve performance of these components.

The most significant sensor losses in SOCCOM occurred in early generation pH sensors manufactured by MBARI and by Sea-Bird Electronics (Figure 11c). Malfunctions in the first generation MBARI sensors included 10% loss at deployment and a subsequent annual loss rate near 11%/year. Despite this, approximately 50% of the first generation sensors from MBARI are still operating after four years in the Southern Ocean. The early malfunctions occurred due to seawater leaks across O-ring seals on the ISFET chips. Significant improvements to the mechanical designs have been implemented in revised designs from both producers (MBARI and Sea-Bird) in second and third generations of the ISFET pH sensor. There are now few losses at deployment, and annual loss rates appear to be <5%/year. Additional design improvements are underway at MBARI to further improve reliability and manufacturability. The newest MBARI pH sensor design greatly reduces the number of components, O-rings, and steps in assembly, which creates a more robust sensor and minimizes the possibility of inadvertent human manufacturing error, particularly as new technical staff are brought in to build sensors. Success rates with the second and third generation pH sensors, currently deployed, are sufficient to move forward. We expect to achieve even more reliable, precise, and robust pH sensors as part of our focus on continuous improvement.

Note that none of these individual sensor malfunctions endanger the overall operation or lifetime of a float. Malfunction of a single sensor results in a fractional decrease in float capability, but the float and remaining sensors still provide significant contributions to the observing system. The observed survival rate for SOCCOM floats of 95% per year can be used to predict the population of operational floats versus time. With a 95% annual survival rate, 500 floats deployed at the rate proposed here will reach total population near 457 floats. A substantial number of these predicted 'failed' floats will operate for multiple years before they are lost.

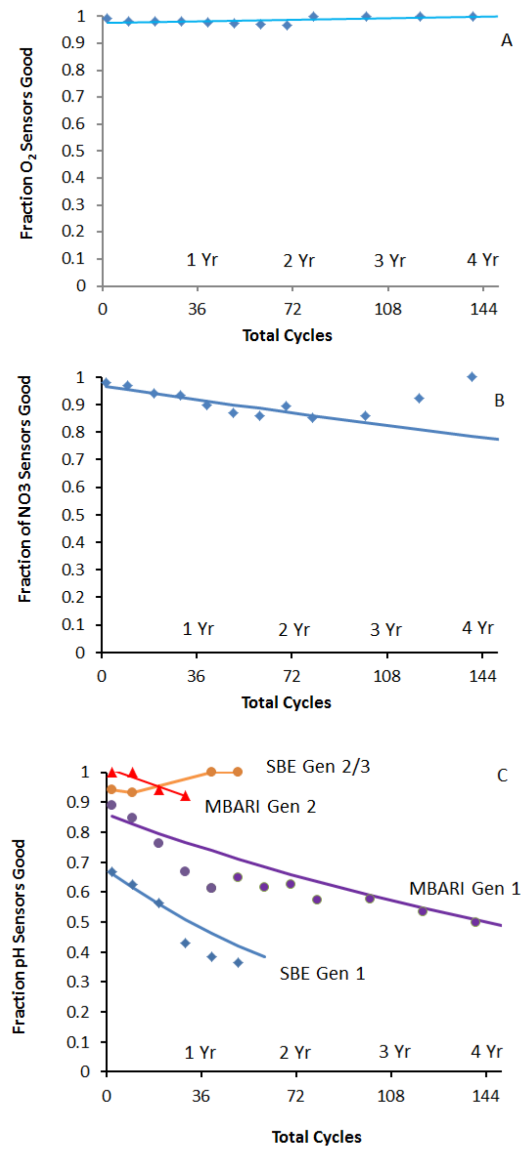


Figure 11. Cumulative survivial rates for oxygen (A), nitrate (B), and pH (C) sensors. Panel C shows survivial rates for first generation sensors from MBARI and from Sea-Bird Electronics (SBE) and for second and third generation sensors from these sources.

B4. A Science Example. A period of 5 years will be required to deploy the entire 500 float array. However, transformative science will be enabled shortly after the initial floats are deployed. As the BGC-Argo array grows, the depth and richness of the science will greatly expand. To illustrate this, we present one case study from the SOCCOM project. Soon after the first SOCCOM floats began to return data, efforts began to validate estimates of surface ocean pCO_2 derived from the pH observations, based on comparison to existing ship-based pCO_2 gridded products (Williams et al., 2017). While good agreement was found in most regions, this early look at the data identified significant discrepancies at high latitudes in wintertime. Building on this finding, Gray et al. (2018) used data from 35 SOCCOM floats spanning three years to compute the annual mean and seasonal cycle of air-sea CO_2 flux across the Southern Ocean. The results showed a surprisingly strong outgassing of CO_2 just to the north of the seasonally-ice covered portion of the Southern Ocean. This observation was in sharp contrast to existing ship-based estimates that find negligible air-sea CO_2 exchange in this region. The difference of 0.23 Pg C/yr amounts to a local ocean CO_2 emission that is about 10% of the global estimated net ocean CO_2 uptake. Gray et al. (2018) suggested that this CO_2 emission was detected because the year-round float data were able to capture the wintertime signal that remains unmeasured by ships.

The growing SOCCOM float coverage now enables a more in-depth examination of the spatial variability in the float-based estimates of CO_2 fluxes as well as decadal-scale changes in the carbon content of the interior ocean. Preliminary findings based on comparison to historical data indicate significant increases in subsurface carbon concentrations relative to those observed prior to the year 2000 (Chen et al, in prep), underscoring both the importance of depth-resolved float data in understanding drivers for changing ocean processes and the synergy with other global datasets. Furthermore, float-based pCO_2 estimates are now being merged with ship-based measurements using sophisticated interpolation methods (Bushinsky et al., 2019). The resulting flux estimates not only demonstrate that the primary cause of the differences between the two data sets is their differing spatiotemporal coverage, but also provides a regional estimate of oceanic carbon uptake that takes full advantage of both data sets. We note these efforts were all led by SOCCOM researchers who were Ph.D. students and postdoctoral associates at the time, the majority of whom have since become Assistant Professors at major universities.

A complete bibliography of papers using BGC-Argo data is available at the Biogeochemical-Argo organization website (Biogeochemical-Argo, 2019).

B5. Community Planning for BGC-Argo. The scientific successes from relatively small arrays of BGC floats have led to extensive planning for a global, BGC-Argo system. It is apparent that a global array is the only tool available to observe basic biogeochemical processes in the ocean at the global scale from the surface through the mesopelagic zone with seasonal and annual resolution. Initial planning through community workshops focused on array design and capabilities (Gruber et al., 2007, 2010; Claustre, 2010, 2011; Johnson et al., 2009). Efforts focused on the complementary nature of BGC-Argo floats with platforms such as ocean color satellite-based remote sensing. By extending observations from the surface to 2000 m and by providing in situ rate measurements not accessible from satellites, the merged satellite and BGC float arrays offer highly synergistic views of oceanographic biological processes (Claustre, 2011; Hostetler et al., 2018). These design studies culminated with a Biogeochemical-Argo Science and Implementation Plan that was produced by an international group of scientists (BAPG, 2016). Public comment on the draft plan was solicited (Johnson and Claustre, 2016) and incorporated in the final report. This proposal builds directly from that plan.

Assessments by the National Research Council (2011), National Academy of Sciences (2017), and the Subcommittee on Ocean Science and Technology of the US Office of Science and Technology Policy (SOST, 2018) place a BGC-Argo array within a broader US ocean science framework. Significant international planning has also occurred (GCOS, 2016; Fennel et al., 2017; CLIVAR, 2018). Action O38 of the 2016 Global Climate Observing System Implementation Plan of the World Meteorological Organization is “Development of a biogeochemical Argo array” (GCOS 2016). In 2016, the G7 Science and Technology Ministerial meeting reported on the need for enhanced ocean observations, with a particular recommendation for “increasing the capability of the global Argo network to include more biological and biogeochemical observation” (G7, 2016). One outcome of this planning was unanimous approval by the Intergovernmental Oceanographic Commission Executive Council for the operation of BGC sensors on Argo floats within the same framework that enables temperature and salinity observations in the 40% of the ocean area that lies within Exclusive Economic Zones (Decision IOC-XXIX/6.1.1, July 2018). The IOC is the competent organization for marine research within the United Nations and represents 149 Member States.

As a proof of concept for the global array, the SOCCOM program has spent the last five years creating a basin-scale BGC-float network. Funded by the NSF Office of Polar Programs with significant contributions from NOAA and NASA, this prototype network is working well. More than 130 floats are currently operating in the Southern Ocean and reporting oxygen, nitrate, pH, and bio-optical properties in real time (Figure 5). Floats sample waters from the Southern subtropics to the continental slope of Antarctica, including seasonally ice-covered waters of the Ross and Weddell Seas (Figure 5). Data are posted to the Argo Data Assembly Centers, as well as the SOCCOM website (SOCCOM, 2019), within 24 hours of satellite telemetry of each float profile. The real-time data from SOCCOM are of research quality, freely available, and have been used in many of the more than 80 SOCCOM papers (see References for a list) as well as numerous papers by the broader community. In addition, other nations are operating float arrays in regions such as the Mediterranean Sea and Indian Ocean.

B6. Planning for a Global BGC-Argo Array. Successful implementation of regional prototype float networks such as SOCCOM demonstrates the capacity to build a global system. The BGC-Argo Science and Implementation Plan calls for an array of 1000 floats globally distributed relatively evenly throughout ocean waters deeper than 2000 m (BAPG, 2016). The size requirements for this array were determined by a variety of assessments, including observing system simulation experiments (OSSE; Majkut et al., 2014; Kamenkovich et al., 2017), evaluation of correlation length scales of biogeochemical variables (BAPG, 2016; Mazloff et al., 2018), and reconstruction of ocean chlorophyll fields (BAPG, 2016). In the formal OSSE experiments, the accuracy in reconstructing a particular BGC property, given observations from a specific number of floats, was assessed by simulating the float array in a high-resolution model.

Figure 12A shows the error in the estimated annual CO_2 flux in the Southern Ocean (south of 30°S) as a function of number of floats determined in one OSSE (Majkut et al., 2014). Figure12B shows the fraction of the Pacific Sector of the Southern Ocean for which the error in reconstructed oxygen concentration is less than the variability in oxygen, given a particular number of floats throughout the Southern Ocean in another OSSE (Kamenkovich et al., 2017). In both cases, the added improvement in accuracy obtained by increasing the number of floats begins to decline at around 200 floats. Extrapolating these estimates from the Southern Ocean to the globe suggests that an array near 1000 floats is appropriate.

Here we propose to deploy 500 floats, half the desired global number, presuming that an additional 500 floats will be deployed by international partners, as occurs in the Core-Argo program. Even without the anticipated international contribution, the 500-float array will be transformational. As shown in Figures 12A, B the errors in property estimation increase with a smaller array (e.g., 500 versus 1000 floats), but the uncertainty reduction from a smaller array is still substantial. The science example in Section B4 illustrates the types of science that can be accomplished as the array size grows. In contrast to earlier BGC-Argo efforts, our goal is to build an array that spans the global ocean at relatively uniform density, with high quality, consistent data across the entire system. This will enable the community to address an entirely new class of science questions, such as those outlined in Section A2. These questions are global in scope and require a system that observes the world ocean.

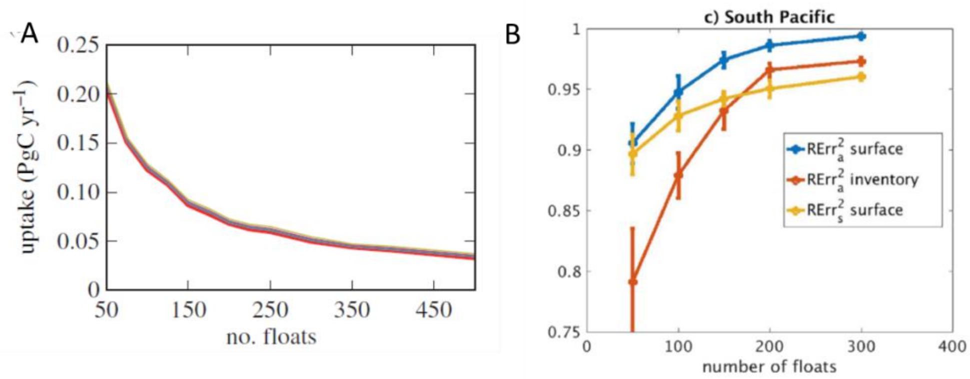


Figure 12. A) Error estimates for the annual reconstruction of the Southern Ocean CO_2 uptake, in PgC, for varying numbers of floats with pH in an array south of 30°S. From Majkut et al. (2014). B) Fractional area of the Pacific Sector of the Southern Ocean with small reconstruction errors (reconstructed field minus CM2.6 coupled climate model field weighted by local spatiotemporal variability) in oxygen concentration for a simulated array of floats south of 30°S. $RErr_A$ is error in annual mean field, $RErr_S$ is error in seasonal variability. From Kamenkovich et al. (2017).

BGC profiling floats typically carry enough batteries to operate for 6 years at a 10-day interval between profiles. However, as noted above, inevitable mechanical or electronic failures reduce the mean BGC float lifetime to 4 to 5 years (Riser et al., 2018). An average 4-year lifetime will require a global replacement rate of 250 floats per year in a 1000 float array. The oceanographic community envisions a system that operates with significant international collaboration (BAPG, 2016). In the Core-Argo system, the US provides half of the Argo profiling float array and this model is expected to continue for BGC-Argo. If the US operates half of the BGC-Argo array (500 floats), then 125 US BGC floats need to be deployed each year. The plan outlined below builds to a maximum annual deployment rate of 125 floats per year.

B7. Results from Prior NSF Support.

Sarmiento/Johnson/Riser/Talley: Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM), PI Jorge Sarmiento, Princeton (PLR-1425989, $22,381,623), K. Johnson Subaward ($5,933,890), S. Riser Subaward ($6,292,995), L. Talley Subaward ($4,372,667), 9/1/2014 to 8/31/2020. **Intellectual Merit**: We proposed to build and deploy 200 profiling floats in the Southern Ocean. We have deployed over 150 floats, of which 138 are currently operating, and are on schedule and budget to reach our target of 200 floats. A data system to process and quality control the observations has been developed and all data are available to the public in real-time at the SOCCOM website (SOCCOM, 2019) and through the Argo data system. Shipboard measurements at the time of float deployment have been collected for nearly all floats and used to validate sensor operation. All shipboard data are available through the CCHDO website (CCHDO, 2019) and links at the SOCCOM website

(SOCCOM, 2019). Over 80 peer-reviewed publications by SOCCOM scientists are available and indicated in the References section with an asterisk. Several highlights from the publications are listed in the "Community Planning" section. In addition, 4 Ph.D. theses have been completed with SOCCOM support (Ellen Briggs, SIO; Nancy Williams, Oregon State; Veronica Tamsitt, SIO; and Earle Wilson, UW) and a number of others are in progress. **Broader Impacts**: A major role in outreach has been support of the SOCCOM Adopt-A-Float program. 90 floats have been adopted by 58 K-12 schools. In addition, SOCCOM has contributed to the training and education of 15 postdocs (11 at least partially funded by SOCCOM), 14 graduate students (12 funded by SOCCOM), and 35 undergraduate students (8 of whom have received some SOCCOM funding) at five different institutions. 54% of these junior researchers have been female and ~9% have been participants from underrepresented groups, with highest participation of underrepresented groups at the undergraduate level.

Wijffels: Tracking Subtropical Water Mass Anomalies to the Tropics and Their Potential for Re-emergence, PI, Susan Wijffels, WHOI (OCE 1830007); 09/01/2018 - 9/1/2021; Award Amount: $760,573 **Intellectual Merit:** We propose to take a globally consistent observational and modelling approach to quantitatively understand the source, fate, and potential re-emergence of subtropical water mass anomalies (spiciness). We will build a more unified view of where and when subtropical variability impacts the far field using Argo data and dedicated ensembles of simulations with controlled regional surface forcing. By focusing on the feeder flows to the equatorial upwelling systems, we will then assess the importance of the proposed 'ocean tunnel' to climate. **Broader Impacts:** Science community: an improved gridded global Argo analysis will be made freely available with particular focus on water mass variability and realistic estimates of resolved scales and errors. Training of the next generation of ocean scientists: via support for a graduate student in the MIT-WHOI Joint Program. The student will learn both numerical modelling (including the analysis of ensembles) and observational analysis techniques, as well as benefit from interactions with the Australian-based ocean forecasting and reanalysis team via collaborator Peter Oke. Improved multi-year forecasting: ocean tunneling is a prime candidate for enabling longer term climate forecasting. We will discuss our results directly with climate forecasting teams in the US and Australia.

C. Implementation Plan

C1. Project Implementation Overview. Our goal is to build a 500-float array that spans all of the major ocean basins (Figure 13), with the exception of the central Arctic Basin (see below). While there are now ~350 profiling floats operating with BGC sensors, about half of these carry only oxygen sensors with the 138 SOCCOM floats comprising the majority of multi-sensor platforms. The deployment plan for our 500 floats (Figure 13) achieves global coverage independent of potential contributions from NOAA and from other countries. If the anticipated cooperation and contribution occur, the plan will be modified on an annual basis towards the ultimate goal of 1000 floats evenly distributed in waters deeper than 2000 m.

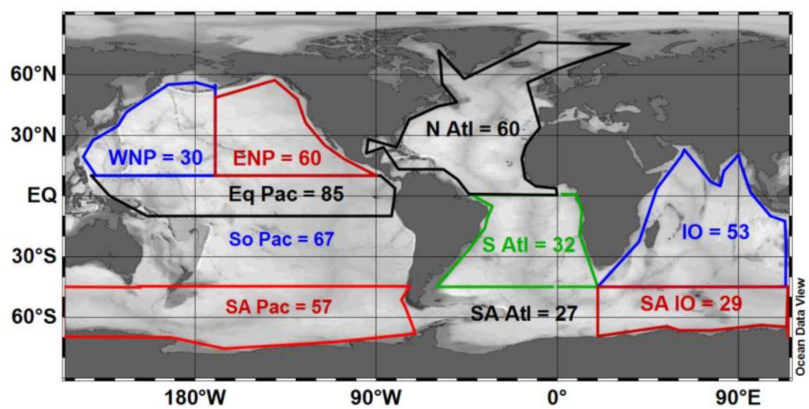


Figure 13. Major ocean areas and proposed number of floats from 500 float array.

The deployment plan is based on the following criteria:

- Maximize science achievements in the 5-year deployment period and over the subsequent operational life of the floats;
- Achieve global coverage, including portions of the Arctic. Year-round ice cover and a large density gradient due to low surface salinity in the central Arctic make profiling float operations difficult. We will deploy floats only in the less stratified Nordic Seas between Iceland and Svalbard, much of which has seasonal sea ice only (Mayot et al., 2018);

- Maintain a slightly higher density in regions where the US has historically dominated float distributions (NE Pacific, Equatorial Pacific, Southern Ocean). This recognizes that contributions of international floats will be higher in other regions;
- Sustain float deployments in the SOCCOM region at a rate of about 30/year to acquire decadal scale observations;
- Maintain compatibility with the Core-Argo mission of ~10-day cycle times and 2000 m deep profiles to ensure that the data from these floats contribute to Argo objectives.

With these objectives in mind, we describe our implementation plan in detail in the following sections.

C2. Investigators, Senior Personnel, & Management: The principal investigators are: *Lead-PI: Kenneth Johnson (MBARI); Co-PIs: Stephen Riser (UW), Jorge Sarmiento (Princeton), Lynne Talley (UCSD SIO), Susan Wijffels (WHOI).* The Principal Investigators and Senior Personnel contribute a body of experience that is uniquely suited to bring this project to fruition. PI Johnson is co-Chair of the BGC-Argo Mission Team and is Associate Director of the SOCCOM program. His Chemical Sensor Lab developed the nitrate (Johnson et al., 2013) and pH sensors (Johnson et al., 2016) utilized on profiling floats. He is a former Chair of the UNOLS Academic Research Fleet consortium. Co-PI Riser's Float Lab at UW pioneered the addition of BGC sensors to floats. His lab has undertaken extensive development of profiling floats, including the operating firmware used on many Argo floats. They have deployed more than 2000 Argo floats and several hundred BGC-Argo floats. Co-PI Sarmiento is Director of the successful SOCCOM project. His group has played a central role in previous biogeochemical observation programs and in pioneering developments for ocean biogeochemical modeling. He will ensure the project meets the needs of the BGC research community. Co-PI Talley leads the SOCCOM observations group. She is the co-Chair of the US Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) and is one of the most experienced, sea-going oceanographers in the US. She has successfully led the effort to deploy SOCCOM floats using a national and international suite of collaborators. Co-PI Wijffels led Argo Australia through hundreds of float deployments. She has been Co-Chair of the Argo Steering Team since 2010. Together the UW, SIO and WHOI Argo labs, with which the project personnel are closely connected, currently contribute nearly half of global Core-Argo floats.

Table 1. Senior personnel, institution, and role.

Heidi Cullen	MBARI	Broader Impacts lead
Andrea Fassbender	MBARI	Biogeochemical data QC and dissemination, Data Team lead
George Matsumoto	MBARI	Broader Impacts EARTH workshops and Adopt-A-Float lead
Yui Takeshita	MBARI	Biogeochemical sensor calibration and data QC
Alison Gray	UW	Float production and sensor performance
Sarah Purkey	UCSD (SIO)	Float production oversight and sensor performance
Todd Martz	UCSD (SIO)	Biogeochemical sensor expertise & Makerspace lead
David Nicholson	WHOI	Biogeochemical sensor expertise, sensor performance.

The Senior Personnel associated with the program (Table 1) likewise bring significant expertise and capability at each of the partner institutions. They span a variety of career levels, which helps ensure a sustainable program by involving mid- and early-career scientists in the development, design, and implementation of large-scale projects. The Senior Personnel will be active in float and sensor acquisition and data processing. Senior Personnel Dr. Heidi Cullen and Dr. George Matsumoto will lead the Broader Impacts portion of the project. Matsumoto will be the primary lead for the EARTH educator workshops, provide a liaison with the MATE competition, and work with Steve Riser (UW) and Todd Martz (SIO) on the researcher workshops and the Makerspace components of the project, described in Broader Impacts.

The Project Office will be led by the current SOCCOM project manager, Dr. Roberta Hotinski. She has established tightly coordinated activities in the SOCCOM project using an annually updated Project Implementation Plan and will bring this management expertise to this project. This includes coordinating reviews and reporting obligations. Mr. Gene Massion will act as the System Engineer for the project. Mr. Massion has extensive experience in systems engineering and project management through work at MBARI and in the US defense industry.

C3. Program Management. The project management structure (Figure 14; see Project Execution Plan for a more detailed version) is built on the successful SOCCOM example, but expanded to incorporate production of floats by three separate institutions, rather than one. The project will be led by the Project Director, Ken Johnson with an Executive Team consisting of the PIs and Senior Personnel. The latter are included to ensure broader disciplinary input and to develop the next generation of leaders at each institution. The Project Director and Executive Team will meet weekly by conference call. The task teams (below) will also establish routine teleconference calls, again as in SOCCOM. This will ensure that float production and deployment are occurring as projected each year in the annual Implementation Plan, and that any significant issues are addressed in a timely manner. These might involve developments in NOAA and/or international collaboration, or unexpected opportunities and challenges (technical difficulties, cruise cancellations, newly announced cruises, evolutions in float or sensor technology).

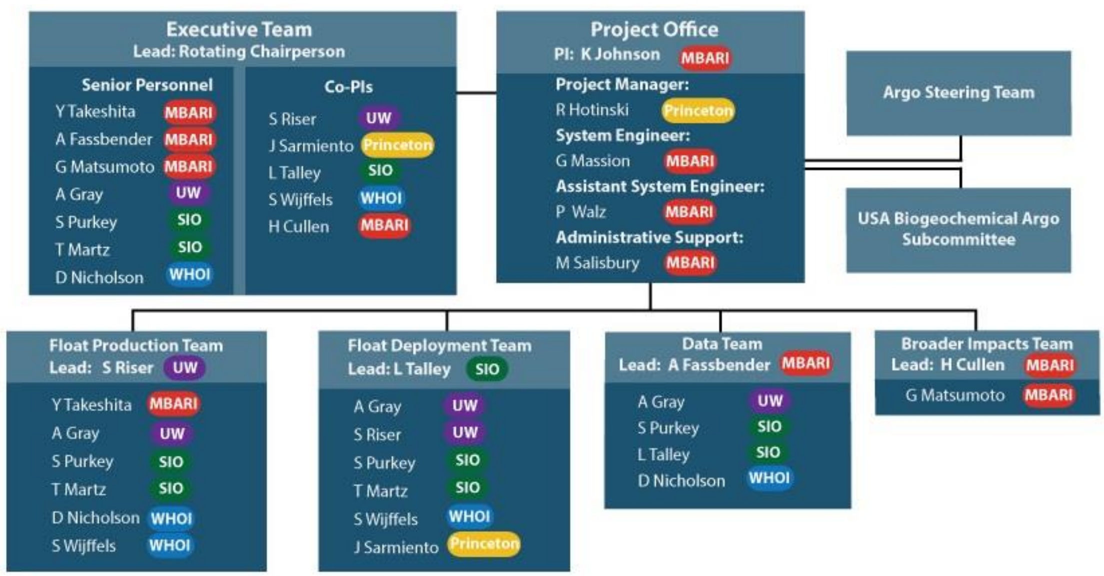


Figure 14. Top level project organization chart. The project is managed by the Project Office located at MBARI in collaboration with the Executive Team. The Argo Steering Team and US-OCB Biogeochemical Argo Subcommittee provide periodic inputs and review.

There will be four project task teams. The *Float Production Team*, led by Co-PI Riser, will coordinate production of floats among the responsible institutions (UW, SIO, and WHOI, as well as pH and nitrate sensor production at MBARI). The Float Production Team will be responsible for creating and assessing float production schedules and communication between the production teams. They will provide preliminary assessments of float and sensor operations and communicate any technical issues that may arise. The *Float Deployment Team*, led by Co-PI Talley, will prioritize geographic subregions for phased deployment and coordinate float deployments and any associated ship-board measurements and data. Much of this activity will involve identifying and coordinating deployment cruises with a priority for cruises with high quality shipboard data for validation of float calibrations. The Deployment Team and Float Production Team leads (Riser and Talley) will coordinate their tasks, through regular teleconferences and meetings of the Executive Team, to ensure that floats can be produced, tested, and delivered to meet cruise schedules. The *Data Team*, led by Dr. Andrea Fassbender and including Senior Personnel and technical staff from all institutions, will ensure complete processing and rapid (within 24 hours) distribution of the Core-Argo and biogeochemical data. Distribution will include the Argo Global Data Assembly Centers (GDACs), global operational forecasting centers, as well as public availability of the integrated data sets through MBARI. The Data Team will assess and report on biogeochemical sensor performance on an annual basis. They will also ensure timely QC, compilation, availability and archiving of the relevant shipboard data sets. Finally, the *Broader Impacts Team*, led by Dr. Heidi Cullen, will coordinate outreach and education activities. All of these teams will include appropriate technical staff from each of the five program institutions. The four project task teams will report to the Executive Team during the weekly conference calls and at annual workshops. The Project Execution Plan denotes the responsibilities and communication paths for these groups in more detail.

If approved for funding, the Executive Team and the task team leads will refine the Integrated Master Schedule (IMS) of the Project Execution Plan (PEP) in a pre-funding phase. The PEP is presented in a preliminary form in the Supplementary Documents and introduced in Section C9. These refinements to the IMS will reflect any budget changes and cruise availability, as well as any evolving technical factors. As a component of the PEP, the Executive Team, in coordination with each of the Task Teams and the Project Office, will develop and circulate an annual Implementation Plan for the following project year to all program personnel. The Implementation Plan will detail the specific goals for each group in terms of float numbers, delivery dates from manufacturing, and the proposed deployment cruises and schedule. The Implementation Plan will set the annual objectives and timeline for the Broader Impacts program.

The Executive Team will solicit periodic webinars by users of BGC-Argo data to better understand the opportunities and needs of the science community. Reflecting the open availability of the data, these webinars will be open to the public. However, because the science community may regard the very latest concepts in development to be proprietary, the Executive Team will also invite occasional “science minutes” during weekly calls to remain abreast of community activities that might affect the development of the operational array.

The overarching goal of a global 1000 BGC-float array mandates that the work conducted here be carefully and thoroughly coordinated with the global Argo program. Therefore this effort is closely integrated with the existing U.S. Argo program funded by NOAA, and with the Core- and international BGC-Argo programs, led by the Argo Steering Team. In particular, developments in data processing and quality control will be collaboratively developed via the international Argo Data Management Team and its BGC-Argo task team. This is essential to the creation and sustainability of a uniform global data set for the broader science community.

C4. Float and Sensor Acquisition. The UW, SIO, and WHOI laboratories are the primary academic US Core-Argo float labs, and they are well-versed in efficient and reliable float production, data handling, and deployments. BGC profiling floats and sensors will be acquired, assembled, and tested by the float groups at UW, SIO, and WHOI, and coordinated by the Float Production Team. Coordination with the Deployment Team will ensure that floats are available in a timely manner for deployment cruises. This distributed model for float production, with multiple centers supplying floats, is based on the successful US Argo program. It maximizes success through internal competition, innovation, and technical exchange. As noted above, it has resulted in US float performance that greatly exceeds that attained by most international Argo partners (Figure 10).

Three profiling BGC float models will be used for this array (Table 2): APEX, Navis, and SOLO-II/S2A. All three, to be built by three different U.S. entities, are based on highly reliable Core-Argo models, all with similarly high reliability and lifetimes that exceed Argo norms (Figure 10).

(1) The *BGC-APEX float* is an established platform that constitutes 90% of the SOCCOM array. These floats are supplied by the UW Float Laboratory, which purchases APEX float components from Teledyne Webb Research and does the final assembly and sensor integration at UW. Thorough pre-deployment testing protocols have led to high reliability for this float model. Utilization of the BGC-APEX float is an effective risk mitigation strategy, as it is a proven platform. However, the APEX float also has some weaknesses as the oldest (but thoroughly-tested) technology. Limited vertical stability of the float in its current configuration prevents it from carrying a radiometer, so BGC-APEX floats can be deployed only in the configuration now used in SOCCOM with oxygen, pH, nitrate, fluorescence, and optical backscatter. In addition, the float has a relatively small volume change and requires an expensive carbon fiber hull to reach the full 2000 m depth range in areas with large vertical density gradients such as in the tropical oceans. The current BGC-APEX production rate for SOCCOM (~40 BGC-APEX Argo floats/year)

will continue under the proposed funding, but is the maximum rate that the UW Argo laboratory can sustain. It is thus necessary to have other BGC float sources, preferably with full capabilities.

(2) WHOI and UW will deploy *Sea-Bird Scientific Navis* floats. Fully assembled, tested, and deployment-ready BGC-Navis floats can be purchased now from Sea-Bird Scientific. These BGC floats have been deployed in limited quantities during SOCCOM. Initial Core-Argo Navis float deployments revealed problems in the hardware and software that led to high levels of float profiling failure. However, these problems have been identified and remedied and the Core-Argo Navis floats are now amongst the most reliable in the Argo fleet (Figure 10). The next step is extending this reliability to BGC-Navis models. Recent deployments are demonstrating significantly improved reliability of both the profiling hardware and the sensors. A National Oceanographic Partnership Program (NOPP) project at UW and Sea-Bird is currently underway to further improve the reliability of BGC-Navis floats by developing a robust pre-deployment testing protocol based on the BGC-APEX floats. Additionally, the NOPP project is carrying out design revisions to enable air-oxygen observations from the Sea-Bird oxygen sensor as well as vertical stability enhancements required for the float to carry a radiometer in addition to the other 5 BGC sensors and extra batteries for longer endurance. Through this effort, we anticipate BGC-Navis floats will soon attain similar levels of reliability as the UW BGC-APEX.

(3) SIO will deploy *MRV Systems BGC-SOLO-II/S2A* floats. For many years, MRV has been producing a high quality, Core-Argo float (the MRV S2A) that is based on the SOLO-II float developed at SIO. The SOLO-II floats deployed in the Core-Argo program by SIO have the highest reliability of any float model in the Argo program (Figure 10). Currently, 97.5% of the SOLO-II/S2A US Argo floats deployed between 2016-2018 are active, compared to 94.7% of the APEX floats and 93.2% of the Navis floats. SOLO-II floats are extremely efficient and theoretically operate for nearly 10 years. A NOPP-funded effort to adapt the SOLO-II/S2A for BGC applications is currently underway (Figure 1). It will result in commercial availability of the MRV BGC-S2A that is capable of carrying all six BGC sensors. These BGC floats will provide a reliable, versatile, and long-lived option for global BGC-Argo.

Table 2 shows our proposed annual float production schedule, which has been used to create the program budget. The majority of floats deployed in Years 1 and 2 will be the UW BGC-APEX to mitigate risk. There will be a ramp up of both BGC-SOLO-II/S2A and BGC-Navis float contributions over succeeding years to grow the array to maturity. We have allowed one year before significant ramp up of Navis float acquisitions and two years for SOLO-II/S2A. This will allow the NOPP-funded refinements for these platforms to be fully tested, it will allow the two commercial manufacturers sufficient time to increase production efficiently, and it will allow the SIO and WHOI groups to build experience with BGC-floats and data management integrated with MBARI (Section C5) before deploying large numbers. Utilizing three float models from different sources mitigates the risk of a significant fault in any one model. A detailed deployment strategy is outlined in the next section.

Table 2. Nominal float production schedule

Lab	Float	Year 1	Year 2	Year 3	Year 4	Year 5
UW	APEX	40	40	40	40	40
UW	Navis	6	24	25	25	25
WHOI	Navis	10+3*	15	25	30	30
SIO	SOLO-II	3 to 5**	5	15	30	30

*floats funded by NOAA OOMD and contributing to this program.
**floats funded by NOPP and contributing to this program.

The majority of the BGC sensors will be obtained from Sea-Bird Scientific, which is the sole commercial supplier for qualified CTD, nitrate, pH and bio-optical sensors on Argo floats. Previous models of Sea-Bird oxygen sensors have not been capable of making the air oxygen measurements used to assess sensor accuracy and drift. For this program, we will require that all oxygen sensors make air oxygen observations when the float surfaces. Air oxygen calibrations have the potential to reduce error in absolute error oxygen concentrations to less than 0.5% of surface oxygen concentrations (Bittig et al., 2018a) over the entire deployment period. Sea-Bird is making the necessary adaptations via the NOPP grant mentioned above to accommodate this requirement of air oxygen calibration.

A subset of nitrate and pH sensors will be built by the MBARI Chemical Sensor Lab, as is currently done in SOCCOM. Construction of a subset of sensors at MBARI will mitigate the risk of a sole commercial sensor source. Although Sea-Bird and MBARI nitrate and pH sensors differ in mechanical design, they operate on identical principles and deliver identical data streams. The BGC sensor suite on each of the three float platforms are, therefore, essentially the same. These sensors have been well-tested in the SOCCOM program where extensive validation efforts have been made. We will continue more limited validation efforts encompassing all three float types (Section C6).

C5. Float Deployment and Operation. The global array will be implemented in phases. A steady buildup of deployments allows for faults in components or software to be identified and corrected before they impact the entire array. The Float Deployment Team will be responsible for implementing the phased deployments. Coordination with international and NOAA Argo efforts will be conducted through the annual planning meetings of the BGC-Argo and Core-Argo programs. Co-PIs Wijffels, Riser and Johnson are members of the International Argo Steering Team, which coordinates the international planning.

It should be noted that our program is not planning to directly fund most of the ship time required for deployments. Rather, our intent is to collaborate with other seagoing research projects to deploy floats and collect validation samples, or use vessels of opportunity to reach the regions we are targeting. SOCCOM experience to date suggests that a significant number of deployments (~50%) should be from research cruises making high quality BGC observations (see C6). Further, there are significant synergies to be obtained by coupling float deployments with high quality ship-based observations such as the GO-SHIP program for repeat hydrographic sections (Talley et al., 2016; Sloyan et al., 2019) (Figure 15). Given a typical transit speed near 20 km/hr for research vessels, a ship would deploy only one float every 2 days with an array spacing of 1000 km. At an operating cost for US global class research vessels of about $50,000 per day, directly funding the ship time would greatly increase the cost of this program.

The feasibility of using vessels of opportunity for most float deployments has been successfully demonstrated during the global implementation of Core-Argo, which has only a small amount of funded ship time. Due to our strong preference for validation samples on deployment for a significant portion of our floats, collaboration with the GO-SHIP program is essential. Co-PI Talley, as Co-Chair of the US GO-SHIP program, is well placed to achieve close coordination and scheduling of float deployments.

We note that the US GO-SHIP program is funded through 2020 and is currently completing a program review prior to submission of a proposal for the next 6 years of operation (Figure 15). Given the prominent role and longstanding success of GO-SHIP in US ocean science, we expect the program to continue. In the unlikely case that it does not continue, GO-SHIP partners including Australia, Japan, and Germany support half of the global GO-SHIP program and have routinely deployed SOCCOM floats. We also would utilize other regularly scheduled research cruises, including the Atlantic Meridional Transit, conducted from the UK to the Falkland Islands each year, or US Antarctic Program cruises in the Southern Ocean, as well as cruises scheduled by UNOLS and international research fleets.

Finally, funds for a modest number of additional days of ship time on the New Zealand vessel R/V Kaharoa are included. Kaharoa is used for most Core-Argo deployments in the subtropical South Pacific and Indian Oceans. Day rates on Kaharoa, which carries only 7 crew and no scientists, are less than $10,000 per day. The net effect of an unanticipated reduction of US GO-SHIP would be an increase in complexity of cruise scheduling and a reduction in the percentage of floats deployed with complete shipboard BGC sample collection and validation (see Section C7), but it would not lead to failure of the proposed program.

A notional deployment plan for the first year is shown in Figure 15 along with the 5-year US GO-SHIP plan. About sixty floats will be produced in Year 1, which includes the first half of 2021 (August 2020 start). One of our deployment planning priorities is to sustain the SOCCOM array in the Southern Ocean, which will begin to enable decadal-scale assessments of BGC variability and the processes that drive it. Approximately 30 floats will be deployed per year in waters south of 30°S, replacing SOCCOM floats as they expire. This proposal would replace the floats now included in a SOCCOM renewal proposal.

These floats will be deployed using the same strategy that has worked successfully in SOCCOM. This includes collaboration with Australian, British, Japanese, and German cruises in the Southern Ocean, as well as US Antarctic Program cruises. The remaining floats would be deployed on GO-SHIP lines. The US GO-SHIP program is planning to occupy the A16 meridional transect in the Atlantic, the P2 zonal section across the North Pacific, and I05 zonal section across the Indian in our proposed Year 1. Approximately 20 and 10 floats would be deployed on these cruises, respectively, accounting for half of the floats available in 2020-2021, including support for continuation of SOCCOM on the southern end of A16 and along I05.

The number of floats to be deployed in each year is approximate due to a number of external factors. Research cruises may be cancelled or delayed due to a variety of reasons. If this occurs, we will always seek alternate opportunities or accept the delay; the latter option may move a set of floats into another year for deployments. Past experience has shown that occasionally floats fail their pre-deployment tests once received at the port of embarkation. In most cases, this occurs because of rough handling during shipping or poor storage conditions of the float crate. If profiling float components or BGC sensors fail pre-deployment tests, the floats will be returned to the originating laboratory or manufacturer for diagnosis. Once repaired, the floats will be deployed at a later opportunity. The net effect will be some adjustment to the plan summarized in Table 2 each year. In some cases, a yearly target may be exceeded if floats from an earlier year are moved to a later date.

Floats will "park" at 1000 m depth for 9 days before profiling, which is consistent with the Argo protocol (see Fig 2). The full sampling profile will be 2000m-surface which enables sampling of deeper waters used to assess sensor stability and drift.

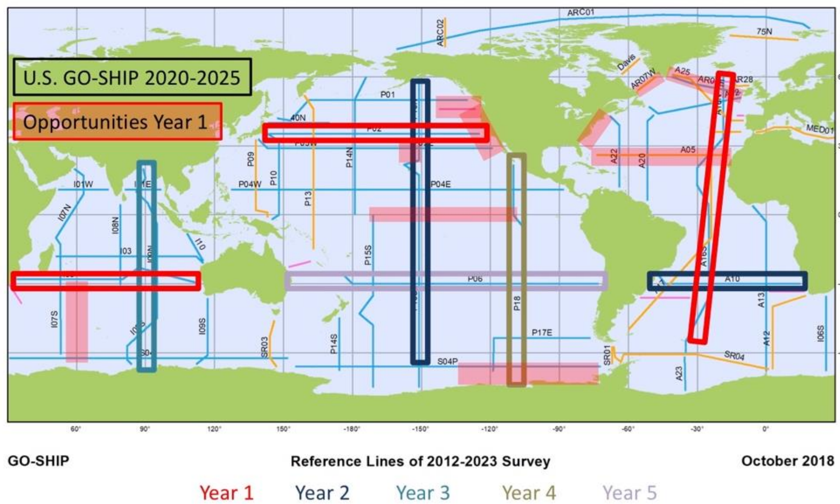


Figure 15. International GO-SHIP decadally-repeated hydrographic sections, with highlights identifying all proposed Yr 1 to Yr 5 (2020-2025) U.S. GO-SHIP deployment cruises, covering about 1/3 of proposed BGC float deployments with highest quality BGC shipboard measurements. High quality regional research cruises of opportunity will support most of the remainder while proposed ship time for Kaharoa will cover regions where research cruises are rare. Shaded reds show potential Year 1 deployments other than US GO-SHIP.

C6. Sensor Validation. We will strive to deploy as many floats as possible in conjunction with ship-based validation measurements, in order to support continuing improvements in data processing and sensor performance, as well as to quantify the accuracy of the float data. As described above, sensor validation in the SOCCOM program has included comparisons of float sensor data with samples collected and analyzed by standard, shipboard methods at the time floats were launched, and comparisons to the high-quality, historical shipboard GLODAPv2 database as floats passed near these stations. Of the 159 SOCCOM floats deployed thus far, 40% of the floats were deployed on 10 international and US GO-SHIP cruises, 50% were deployed on 14 other cruises that provided most BGC observations with SOCCOM staff augmenting the shipboard observations, and 10% were deployed on a cruise where all BGC observations were provided by SOCCOM. These efforts yielded the sensor comparisons with standard methods (Figure 7). We believe that the SOCCOM project demonstrates that the operations have matured to a level where validation is not necessary for 100% of the floats, although we propose to retain a higher level of shipboard sampling in the SOCCOM region because of the sparseness of historical measurements. However, it should be possible to deploy at least 50% of the global floats from research vessels making BGC observations, which would extend the float sensor validation to different ocean basins and float models. We will continue to perform comparisons with GLODAPv2 observations for all floats, as described in Figure 8 of Section B2. These comparisons will provide verification of performance for sensors that do not receive an initial validation.

C7. Data System. To confirm platform and sensor operation and to commission each float, a complete data handling system is required. We will receive 6 profiles from each float (2 months of data) to validate their operation. After that point, the float will be considered to be commissioned and operation of the floats and complete data processing will be supported as described in Section D1. The same data system and data release protocols are used in both the commissioning and operational phases. The data system developed for the SOCCOM program is scalable and it will be used for this project. This system has three major modes of access. Raw and processed data for each float are written to the Argo Global Data Assembly Centers (GDACs), where data access is targeted at experienced users and operational forecasting centers. Complete snapshots of the entire database from this program will be written to a permanent digital archive maintained by the Research Data Curation Program at the UCSD library with a DOI (digital object identifier) at quarterly intervals. These snapshots include derived parameters such as pCO_2 and Dissolved Inorganic Carbon estimated from float pH observations that are not available via the Argo GDACs. The most recent snapshot from the SOCCOM program is available with the DOI 10.6075/J0GH9G8R. A third system, termed SOCCOMViz, is available through the SOCCOM website (SOCCOM, 2019). It is a user-friendly system that allows the user to plot parameters and delivers ASCII data files. An analogous website and data visualization system will also be utilized for this project. All of the float data collected will be publicly available in real-time. This includes automated quality control processes that create science quality observations. The data system is described further in the Data Management Plan. Costs to sustain the data system are included in the proposed operations budget. Note that additional data access methods using ERDDAP web-based data access protocols (DAP) have been provided through independent efforts by the community. All computer code and algorithms will be publicly available through a Github website as described in the Data Management Plan.

C8. Program Cost Estimate. The acquisition, deployment, and operation cost estimates for this array are based on experience in the US Argo program, which has deployed over 7000 Core-Argo floats, and with the SOCCOM project, which has deployed over 150 floats through its first 4 years. SOCCOM is on budget and schedule to deploy the proposed ~200 floats. The SOCCOM floats, in addition to international regional arrays, are the foundation of the present BGC-Argo observing system. The procedures used to acquire and deploy the SOCCOM floats are fundamentally similar to the processes and procedures proposed here, with the exception that three institutions (UW, SIO, WHOI) will be involved in the acquisition and deployment process, rather than one (UW).

Table 3. Annual costs. Note that the Operations budget is not a direct part of this request, but would be funded in a separate proposal (see section D1).

Phase	Yr 1	Yr 2	Yr 3	Yr 4	Yr 5	Total
Floats	$4,058,670	$6,263,313	$8,311,715	$9,526,786	$9,575,331	$37,735,815
Prep, deploy	$649,048	$880,948	$1,166,463	$1,380,143	$1,444,313	$5,520,915
Management	$824,447	$767,913	$776,967	$806,961	$814,479	$3,990,765
Broader Imp.	$205,634	$228,029	$216,729	$231,024	$206,281	$1,087,699
Ship time		$150,000	$300,000	$150,000	$300,000	$900,000
Contingency	$744,000	$538,235	$696,177	$856,804	$872,340	$3,707,556
Total	$6,481,799	$8,828,438	$11,468,051	$12,951,718	$13,212,744	$52,942,750
Operations	$1,499,742	$1,869,765	$2,281,498	$2,650,682	$2,948,837	$11,250,254

The budget is dominated (71%) by the capital cost of the BGC floats (Table 3). The cost of a BGC float, in turn, is dominated by the cost of sensors (BAPG, 2016). Current, list prices for the 6 BGC sensors called for here plus the float CTD (conductivity, temperature, depth) totals $69,500 from Sea-Bird Scientific, the primary vendor for these systems. Following negotiations with Sea-Bird, they have quoted a price of $45,245 (vendor quotes are in Supplementary Documents) for the CTD, oxygen, nitrate, pH, MCOMS chlorophyll, backscatter, and fluorescent dissolved matter (not required here, but an integral part of the MCOMS system), and 4 channel downwelling irradiance sensors. This is a 35% reduction, which would be available to all manufacturers provided that the aggregate yearly number of orders is at least 80% of the yearly numbers in Table 2. The price is intended to be fixed over the 5 year proposal period with a provision that no significant changes in component prices occur. The 35% reduction exceeded our objective criteria of a 10% price reduction for each doubling of production, assuming a 90% experience curve that is fairly typical for smaller scale production.

The price quotes that we have obtained for commercially prepared Sea-Bird Scientific Navis floats and MRV Systems S2A BGC floats (provided MRV obtains the $45,245 sensor price) are both near $75,000 per float (Supplemental Documents). The cost for a Teledyne Webb APEX float assembled at UW with oxygen, pH, nitrate, chlorophyll and optical backscattering will be around $50K. The nitrate sensor for the UW floats and a subset of the pH sensors will be built at MBARI. No radiometer is included on the APEX floats.

While price quotes are firm, we have included a ~10% contingency budget ($3,307,000) on the capital acquisitions each year as a precaution against identified risks (Section C9). The primary risk to the program is the lack of a warranty on profiling floats and sensors from the manufacturer. A one-year warranty has typically escalated float prices by much more than 10%, to cover worst case failure rates and typically only covers the first year. Our experience has been that with careful float testing and preparation in our labs, loss rates will be on the order of 5% in the first year, indicating that the warranty is not effective. However, there have been rare failures that span large numbers of floats, the best example being a rapid failure of pressure sensors that affected as many as 30% of Core-Argo floats in 2009. The failure mechanism resulted from a minor change in the pressure sensor manufacturing process. If such an event were to occur, we would request permission to use the contingency funds to replace floats after the situation was rectified by the manufacturer. In addition, we have included a modest contingency fund ($400,000) to cover any unanticipated engineering requirements that may arise if problems are identified with any of the floats or sensors. This based on amounts now budgeted for engineering in the SIO and UW NOPP proposals. The combined contingency budget is 7% of the total program budget. Although 7% contingency is relatively low for a major facility project, we believe that it is appropriate given the maturity of the project.

In addition to the capital equipment costs, there are significant labor costs required to test floats on receipt from manufacturers, prepare them for shipping, test them after being loaded onto ships, and manage the satellite communications network for each float provider. Float preparation and testing amounts to 10% These labor costs for float preparation and testing have proven essential for the high success rates of US Argo profiling floats shown in Figure 10. When amortized over the life of floats, the extra preparation effort results in significant cost savings.

Significant costs have been included to support program management. This includes the Program Manager Hotinski at 75% time, System Engineer Massion at 25% time, Assistant System Engineer Walz at 25% time, and 25% time for Administrative Assistant Salisbury. In addition, each Co-PI and Senior Personnel will contribute significant efforts to program management. PI Johnson will dedicate 50% effort. There is only modest data center support requested in this program, in order to ensure the preliminary data from each float is validated. The bulk of the data center effort will be included in the operational budget, which is discussed below. Program management amounts to 8% of the total budget.

A strong Broader Impacts component has been included with scientist training workshops to ensure the community understands and accesses the data that will be produced when the floats become operational. Educator workshops, designed to incorporate the output data of the array in educational programs, are also included. The Broader Impacts effort maintains an Adopt-A-Float program that enables K-12 classes to name a float and participate in course work based on the real-time data produced by floats. Finally, we will collaborate with the well-known MATE (Marine Advanced Technology Education) program to incorporate profiling float technology in their annual ROV (Remotely Operated Vehicle) competitions. Broader Impacts efforts use 2% of the budget.

A modest budget has been included to support key BGC measurements on deployment cruises, if they will not otherwise be made. Such measurements include chlorophyll concentration by HPLC and particulate organic carbon, which are not part of the GO-SHIP protocol (fortunately there are ongoing discussions to include these observations in the GO-SHIP measurement suite), and pH/total alkalinity measurements for Southern Ocean deployments where there is little historical data, continuing the SOCCOM shipboard sampling protocols. Finally, we have included a modest ($900k) budget for ship time using a dedicated vessel to access regions that may not be accessible with externally funded research cruises of opportunity. Such regions are illustrated by the white spaces on Figure 4A. The US Core-Argo program uses the New Zealand research vessel Kaharoa for this purpose (Roemmich et al., 2010). These efforts total 2% of the budget.

C9. Risk Management and Up-scoping/De-scoping Options. As noted above, several elements of the program design are organized to mitigate potential risks. Examples, discussed further in the PEP, include:

- Acquisition of floats and sensors without a warranty. There is risk due to a large-scale loss of floats due to a common fault. Multiple float suppliers and a phased deployment plan with vigilant monitoring minimize this risk. Contingency funds to replace floats is the final risk management step.
- Dependence on a sole source. Use of multiple float suppliers partially mitigates this risk. Sea-Bird Scientific is the sole, experienced commercial source for most of the sensors. We mitigate this by maintaining sensor production capability for nitrate and pH at MBARI. Core-Argo is piloting other CTD models.
- Utilization of newer, but less tested platform types. This risk is mitigated by a gradual introduction of new float types (Navis and SOLO-II) into the array. Contingency funds are included to support a modest amount of engineering to resolve any late emerging faults in the newer BGC float designs.
- Dependence on externally funded research cruises for deployments. This is mitigated through the use of international research cruises, our deep association with multiple international sea-going research programs, and coordination with core-Argo which uses many different types of cruises for deployments.
- Delays in float production. Completion of the project by deployment of all 500 floats is tightly constrained by the current float production schedule (Table 2) and there is a significant possibility that the some of the last set of floats produced in Year 5 will not be ready for deployment until after the 5 year project expires. If this occurs, a no-cost extension would be utilized to deploy the last set of floats.

If constraints such as budget reduction require a de-scoping of the project, this can be accomplished by reducing the number of floats with modest impact on our project goals. As noted above through OSSE studies, the errors in estimates of global processes grow as the array size is reduced. At some point a large reduction in array size has a negative feedback. The large price reduction that has been negotiated on commercial float sensors (~35% of current list prices) is based on acquisition of at least 400 units (80% of the projected 500 floats). Up-scoping would likely involve utilization of unspent contingency funds. If this occurs, the funds would be used to acquire additional floats and sensors.

C10. Project Execution Plan. The project execution plan (PEP) is the governing document that establishes the means to execute, monitor, and control implementation of the array. It ensures that participants, funders, and the community are aware and knowledgeable of project objectives and how they will be accomplished. The detailed PEP, including a preliminary Work Breakdown Structure and Integrated Master Schedule, is included as a Supplementary Document.

C11. Long-term operations. The science and operations of the array described here are based on the creation of the 500-float array over a 5-year period, followed by another 5-year period as floats operate until their batteries are exhausted. Observing decadal scale and longer changes will require deployments beyond the 5-year period of this proposal at rates near 125/yr. However, the 500 floats to be acquired in this program will establish the foundation for the global array and enable a transformational view of chemical and biological processes through observation of repeated seasonal cycles across the globe. Floats deployed in the Southern Ocean will extend the systematic observations of this region, obtained through the SOCCOM project, to more than 10 years and begin to enable decadal-scale observations in this climate sensitive region.

Detection of climate-driven changes in the ocean biogeochemical processes observed by this array in the remaining regions of the ocean will require continued future deployments. Such deployments are beyond the scope of this proposal, but we believe they would represent a reasonable follow-on, as the success of this project is demonstrated through the science that will utilize the data, as well as global government and environmental policy that requires quality data and observations. The science payoff from the investment in this project, which is focused on seasonal and interannual variability, does not depend on continued funding. This project will establish the baseline functioning of the carbon, oxygen, and nitrogen cycles in a relatively unperturbed ocean; a major scientific accomplishment. The payoff from this transformational observing system would likely be greatly expanded if the system were sustained into decadal scale observing. While a funding mechanism for such a continuation is not clear at this time, a successful global assessment of the present ocean will greatly strengthen the arguments for its continuation as a vital oceanographic and earth system community data stream.

D. Operations and Utilization Plan

D1. Operational Budget Estimate. The operational phase of the array begins once the first float returns 6 profiles. Therefore, an operational budget is needed soon after float acquisition and these costs will increase each year as more floats enter the water, reaching a maximum at Year 5. Total annual operating costs for years 1 to 5 are shown in Table 3. The operational costs will then continue for an additional 5 years after the last float is deployed, decreasing each year as floats exhaust their power. The operational budget will, therefore, span 10 years. The operational budget over this period is based on the experience in sustaining Core-Argo floats and BGC floats at UW, SIO, WHOI, and MBARI. These operational costs include Iridium satellite fees to transmit data back from floats; supporting data centers to process raw BGC data and Core-Argo data and to perform data quality control; Argo data system support; and maintaining a project website to provide real-time information on array status, float tracking, and data. Furthermore, the status of the array such as age distribution of floats, sensor performance, and priorities for float deployments must be routinely assessed during the operational period and this information relayed to the Float Production Team and the Float Deployment Team. Finally, modest funding is included for travel and meetings with the US Ocean Carbon and Biogeochemistry (OCB) Program subcommittee on BGC-Argo, Argo Steering Team, and Argo Data Management Team. The annual operational costs are detailed in the Supplementary Documentation. Our presumption, confirmed by discussions with NSF Ocean Science program managers, is that the operational budget would be supported by NSF if this proposal is funded.

Finally, we note that these costs do not include any funds for research using these data. We expect that NSF would receive significant research proposal pressure from the scientific community to exploit the data stream from a global array of profiling BGC floats. In particular, no budget to assimilate the data into operational models is included. Oceanographic state estimates, such as the ECCO system that assimilates a vast set of physical observations into a dynamically consistent ocean circulation framework (Fukumori et al., 2018), have become an essential tool for analysis of physical oceanographic processes. The BGC observation system envisioned here will create the potential for a parallel effort in ocean biogeochemistry. This effort has begun in SOCCOM with the Biogeochemical-Southern Ocean State Estimate (Verdy and Mazloff, 2017).

D2. Program Oversight. Community oversight of this program would be provided through the OCB Subcommittee on BGC-Argo, as well as the Argo Steering Team. PI Johnson is currently co-chair of the OCB subcommittee and will step down from that role when the committee assumes an oversight role for this project. We also note that several members of that subcommittee are PIs or Senior Personnel on this proposal. We will work with NSF to resolve any possible or identified conflicts. A budget to support an annual meeting of this OCB Oversight Committee, in conjunction with the annual meeting for program personnel, has been included.

D3. Utilization and Evaluation Plan. The data produced by this project will be made publicly available, typically within 24 hours, following policies established by the Argo program and adopted by the SOCCOM project. We expect the data produced by a global BGC-Argo array to be widely utilized, based on the Argo and SOCCOM experience. Over 3600 publications have utilized Core-Argo data (temperature and salinity). More than 80% of these papers were written by scientists with no formal affiliation to the various national Argo steering teams (M. Scanderbeg, pers. comm.). To date, some 200 peer-reviewed publications using BGC-Argo data are available in a bibliography that is maintained on the BGC-Argo website (Biogeochemical-Argo, 2019). These publications focus primarily on the observations from one or a few floats, reflecting the small arrays that have been built for specific science projects. As noted in Section B1, the availability of a comprehensive data set spanning the Southern Ocean has enabled the community to begin producing basin-scale assessments of biogeochemical processes.

SOCCOM data are also being utilized by scientists with no affiliation to the SOCCOM program (e.g., Dall'Olmo et al., 2016; Poteau et al., 2017; Llort et al., 2018; Fay et al., 2018; Stukel and Ducklow, 2017; Ardyna et al., 2019). This illustrates the quality and accessibility of the data sets. The availability of BGC data has been an important resource for early career scientists by providing a quality-controlled product that enables them to produce scholarly works. Omand and Mahadevan (2013), Fay et al. (2018), and Bif and Hansell (2019) are a few examples of papers produced by graduate students and postdocs in programs with no direct connection to BGC-Argo laboratories.

To facilitate the usage of the data, we will conduct workshops to train community members in data access, processing, and the underlying technology. In addition, we will hold periodic town hall meetings at national and international conferences such as the AGU Fall Meeting and the Ocean Sciences Meeting.

Evaluation of the program will occur through three mechanisms. Each year, an internal evaluation by the project personnel on the Data Team and Float Production Team will assess float and sensor reliability and data quality. Such a process has been at the core of the SOCCOM program, where assessments such as those summarized in Figures 7 to 12 are routinely discussed. If technical issues are apparent, a plan will be implemented to address the issue. Contingency funding is included to support engineering if significant problems arise. The second set of evaluations will occur through an annual assessment of the utilization of the program data by the community in research publications. As in SOCCOM and the Argo program, we will track publications using the data generated by the program. Citable DOIs will be provided to facilitate this along with a recommended statement for acknowledgments.

Finally, the program will have an annual meeting that will serve as a mechanism to report to program managers, the oversight committee, and BGC-Argo colleagues. The program oversight committee will be asked to provide an annual review to the Executive Team and the community for this meeting.

E. Lifecycle Cost Estimation Summary. A detailed lifecycle cost estimate is provided in the Supplementary Documentation. Lifecycle costs are dominated by the MSRI project budget to acquire and deploy 500 floats (Table 4). The operational budget (Section D1) will extend over a 10-year period. We present annual costs for the first 5 years in Table 3 with details in the Supplemental documents. The second 5 years is presumed to operate at a similar level. There has been an extensive prefunding effort over the past 11 years to bring BGC-Argo to fruition. This includes the NSF-funded SOCCOM project, which serves as a prototype at the scale of an ocean basin for a complete global system ($22,381,000). Prior to the SOCCOM effort, several NSF projects funded float deployments at time series stations to validate operation (NSF 0824990 and NSF 0825348, $1,528,705 total) and two NOPP projects funded development of the float nitrate (N00014-09-1-0052, $1,484,217) and pH sensors (N00014-10-1-0206, $1,781,922). NOPP funded projects are beginning at SIO and MRV Systems to adopt the SOLO float to carry BGC sensors ($1,149,212) and at UW to work with Sea-Bird Scientific to refine operation of the Navis float ($1,157,311). The Biogeochemical Argo Science and Implementation Plan (BAPG, 2016) was prepared as a grass-roots effort with no formal budget. This program has also benefited from additional work on sensors, data quality, and management issues completed outside of the US and shared via the Argo Data Management Team. There is no divestment cost after floats have completed their mission. Floats are lost at 2000 m depth when the batteries expire.

Table 4. Lifecycle cost

Phase	Total cost
Planning & development	$29,482,367
MSRI proposal	$52,942,750
Operations Yr 1 - 5	$11,250,254
Operations Yr 6 - 10	$12,000,000
Divestment	0

F. Broader Impacts. The proposed array will make global BGC data of unprecedented resolution freely available in real-time for the first time, reducing barriers to entry to oceanographic research for early career scientists and researchers at smaller colleges and universities, who may not have the resources or coastal location to build a large ocean research program. The data will also be available to policymakers, resource managers, and other stakeholders. This open data policy has resulted in wide use of float data for operational weather and climate forecasts. The nascent but rapidly growing network of BGC prediction systems, coordinated under OceanViewGODAE (GODAE, 2019) will be early and rapid users of these data. The resulting gridded products and services are an additional pathway to impact for the proposed data stream in the realm of water quality, marine resource and ecosystem management. Utilization of Argo data in marine resource management is an emerging field (Fennel et al., 2019).

In addition, there are three focused components to the proposed Broader Impacts for this program (see below). These components will be aimed at increasing diversity at all levels in oceanographic research.

F1. Outreach to the oceanographic research community. To expand the base of float data users, we will host workshops for the scientific user community in years one, three, and five. These workshops will be designed to introduce the broader science community to the data resource that will be produced and the underlying infrastructure. They will build on earlier efforts, which have included a SOCCOM profiling float "Chemistry School" at MBARI and a BGC Profiling Float Workshop at UW in July 2018, which was organized through the US Ocean Carbon and Biogeochemistry program. The workshops will accommodate ~30 in-person participants, for whom travel funds are included. We will work with our advisory US BAS subcommittee (Figure 14) to develop a diversity-conscious selection process for these participants, with an emphasis on early career participants. In addition, we will broadcast workshop sessions to allow for unlimited remote participation and use recordings to create "virtual workshops" that will be available on the project website. We will also continue the "associate investigator" model used in SOCCOM in which unfunded outside collaborators with complementary research are invited to remotely participate in webinars and our annual meeting

F2. Education and Training. Graduate student training will be key to entraining early career researchers into mid-scale infrastructure development and management. PhD student training will focus on BGC observing system and sensor design and validation. Graduate students and postdocs from partner institutions will participate in research cruises to deploy floats, matched to their level of previous experience. They will also participate in workshops designed to introduce them to the data resource, described above. In addition, we will support a "Makerspace" laboratory at SIO described in the Facilities section. This is a state-of-the-art facility with research grade electrical and mechanical prototyping equipment, enabling very tight coupling between education, technology development, and research. It will be leveraged with our other outreach efforts.

Each of our institutions has programs in place aimed at promoting diversity and the recruitment and retention of members of historically underrepresented groups at all levels (undergrad, grad, postdoc, and faculty) into oceanography and climate science, and we will work with these programs in our recruitment efforts.

F3. Building the pipeline – entraining students and educators. To increase the diversity of the workforce for oceanographic infrastructure, we will work with younger students and educators at a variety of levels.

Table 5. 2018 MATE competition demographics post competition surveys (n=4,470).

Gender	Female	28%
	Male	72%
Ethnicity	White	49%
	Asian	13%
	Hispanic	8%
	African Amer.	4%
	Amer. Indian	>1%
	Pacific Islander	>1%
	Multiple	2%
	Other	5%
	No Response	5%
Live in High Poverty Area*	Yes	39%
	No	61%

*Zipcode with greater than national average of families with children living in poverty

First, we are partnering with the MATE ROV Competition, which challenges students in grades 4 through University undergraduate from across the US and around the world to engineer ROVs to complete a set of mission tasks based on real-world, workplace scenarios. The diversity of students involved is tremendous (Table 4). The competition emphasizes and inspires a mindset of entrepreneurship and innovation. MATE will create competition scenarios and design mission tasks that incorporate profiling float-related research and technology.

- Create competition scenarios and design mission tasks that align with and incorporate BGC-Argo-related research and technology. This will involve interfacing with BGC-Argo scientists and engineers to translate their work into scenario and task descriptions to ensure accuracy and fidelity to the project. This is MATE's standard practice for developing scenarios and tasks. Over the years they have worked with scientists and engineers at MBARI, the University of Washington, the Port of Long Beach, and, recently, the Eastman Company;
- Develop curriculum materials (including videos, PowerPoint presentations, and tutorials) and other resources (e.g. sensor kits) that complement the mission tasks and support student learning gains in BGC-Argo-related science and technology;

- Disseminate these products as well as information about the project via the MATE ROV Competition website (MATE, 2019) and presentations at education and industry conferences (e.g., NSTA, Underwater Intervention, Oceans) as well as during MATE competition events.

University MATE participants will be excellent candidates for graduate and technical positions in the BGC-Argo project, and we will prioritize their applications in our recruitment and hiring processes.

To help educators at all levels engage with BGC float data, MBARI will host a professional development workshop at the University of Washington. These workshops will be based on the successful EARTH (Education And Research: Testing Hypotheses) workshops that have been conducted for 15 years at locations around the United States (EARTH, 2019). This workshop will be held in years 2 and 4 and will focus solely on the BGC-Argo project. EARTH brings diverse educators from around the US (variety of grade levels and subject matters) to learn about the latest research and how to access data. The educators develop lesson plans and curricula while at the workshop based on local and national standards. The educational products are then posted online and often presented at regional and national meetings by the educators (NSTA, NMEA, ASLO). Educators will also be encouraged to participate in the MATE program.

Finally, we will continue the successful “Adopt-a-Float” program during the SOCCOM project. Ninety floats have been adopted by 58 schools in 26 states and three countries over the last three years. All float adopters can access the data coming back from their float (or any float) via the Adopt-a-FloatViz system. Each of the floats deployed in this program will be paired with a classroom, and teachers will be encouraged to participate in workshops and the MATE program.

G. Environmental Impacts. Environmental impacts of the Argo program have been reviewed by the NOAA NEPA Coordinator (Memorandum dated 8 June 2000). The Argo program received a Categorical Exemption because it was determined not to have significant impact on the quality of the environment. This decision, as it is now nearly 20 years old, is currently being updated by NOAA. We do not expect any significant changes. In addition, the SOCCOM program is required to obtain authorization under the US Antarctic Conservation Act, which implements the Protocol on Environmental Protection to the Antarctic Treaty, for each set of floats released south of 60° South. All SOCCOM floats are in compliance with the US Antarctic Program Master Waste Permit as determined by the NSF Office of Polar Programs Environmental Policy Manager. Copies have been uploaded in the Supplementary Documents.

H. Coordination with other Federal Agencies. NOAA is the primary agency supporting the Core-Argo program in the US and will continue to do so. The floats proposed here will provide compatible physical data, and deployment of the US BGC-Argo floats proposed here will be closely coordinated with the NOAA funded program. All proposed data sets will be streamed into the Argo GDAC, which is funded by NOAA. NOAA has also initiated deployments of modest numbers of BGC floats and we will harmonize with those efforts. NASA has also funded research programs that have purchased a modest number of profiling BGC floats and we will coordinate with their plans as well.

I. International Coordination. This proposal is intended to support half of a global BGC-Argo array, with the remainder coming from international partners, as is the case for Core-Argo and as outlined in the BGC-Argo Science and Implementation Plan (BAPG, 2016). This paradigm is generally operating well today. Of the 359 deployed floats with various BGC sensors (primarily O_2),178 are from the US. There are developing international programs that might eventually match the US expansion proposed here, with the EuroArgo effort being the furthest along. However, this project would solidify the US leadership in ocean observing, if it is funded, and an equivalent level of international participation is expected. For example, planning efforts are currently underway for an EU/Canadian North Atlantic system (Fennel et al., 2017). Australia has recently published their future plans (IMOS, 2019). If for some reason growing international participation does not materialize, the large and novel global BGC data set over multiple years from the US array proposed here would nevertheless have a transformational impact on our understanding of global biogeochemistry and ecosystems.

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