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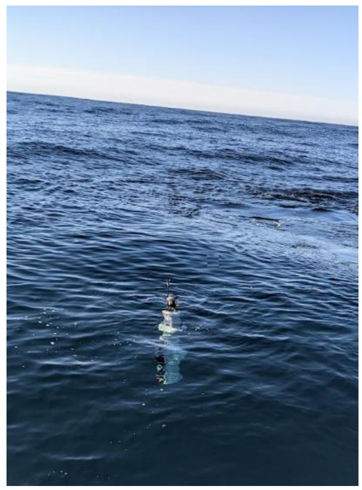
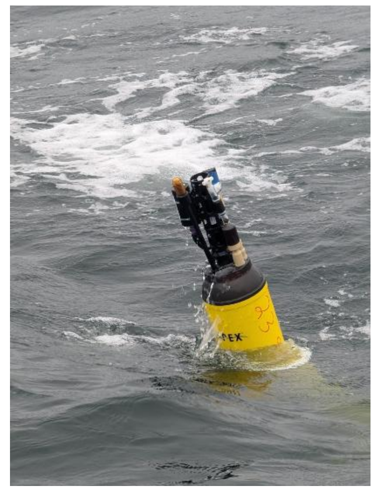
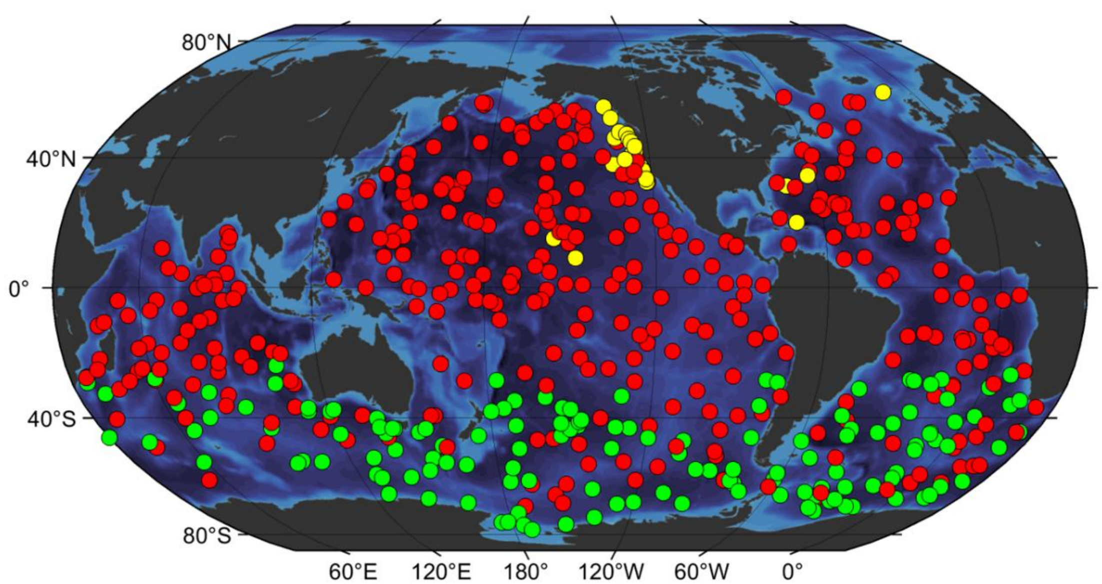
US BGC-Argo status and future: Prepared for the Ocean Studies Board Project "Future Pathways for the BGC-Argo Program"

The GO-BGC Executive Team*







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Photos: BGC-Navis, BGC-SOLO, and BGC-Apex floats at deployment.
Map: Operating GO-BGC (red), SOCCOM (green), and NOAA/NASA floats (yellow) managed by the BGC-Argo data center at MBARI on Feb. 1, 2026.

Introduction to BGC-Argo

In 2016, researchers from around the world convened at the Laboratoire d'Océanographie de Villefranche-sur-Mer in France to develop an implementation plan for "Biogeochemical Argo." Building upon NOAA's successful global Argo program, which had implemented an array of ~4000 robotic floats to profile temperature and salinity in the top 2000m of the world's ocean, the team had an ambitious plan to augment one quarter of those floats with newly available sensors to measure nitrate, oxygen, pH, backscatter, chlorophyll, and irradiance and create a global observing system of publicly-available, near real-time data for ocean biogeochemistry and ecosystems. The Biogeochemical-Argo Science and Implementation Plan (BAPG, 2016) is the result.

Proof of concept for the array had been provided by years-long deployments of nearly 700 floats with various biogeochemical sensor suites by US and international researchers, as well as the initial steps towards integration of BGC variables into the international Argo data system. On the basis of that progress, in 2014 the US National Science Foundation, with support from NOAA and NASA, funded the first large-scale deployment of 5-sensor biogeochemical (BGC) floats, as part of the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) project (Sarmiento et al., 2023). SOCCOM showed that BGC-floats could survive and reliably provide near real-time, quality controlled biogeochemical data from some of the harshest and most remote environments, including under ice, for multiple years. In 2020 the US NSF took another large step forward in establishing a BGC-Argo array by funding the Global Ocean Biogeochemistry Array (GO-BGC), an infrastructure project to build and deploy 500 BGC 5- and 6-sensor (5+ sensor) floats around the world.

The combined US and international efforts have resulted in a global array of over 800 BGC-Argo floats presently operating. Nearly 500 of these BGC-Argo floats carry 5 or more biogeochemical sensors as described in the Implementation Plan. Up to this point, the US has funded the vast majority of 5+ sensor floats through SOCCOM, NOAA-funded efforts at PMEL and AOML, and the GO-BGC array, which will be completed this year. These floats will make up the planned, US half of the planned BGC-Argo array of 1000 5+ sensor floats. The scale-up of the US contribution in the last 10 years has dramatically increased the number and distribution of biogeochemical measurements available in near real-time, creating a truly global multi-sensor observing system. It has been embraced by US researchers and the international community. Much of the expertise in float development, technological improvements, and reliability enhancement has been transferred to industry, enabling the current US manufacturing capability.

Hundreds of papers have been published that take advantage of the new high temporal and spatial resolution of BGC-float data (https://biogeochemical-argo.org/peer-review-articles.php), with researchers applying the data to "quantifying fluxes and stocks in the global ocean carbon system, evaluating changes in the size and intensity of the ocean's oxygen deficient zones, rates of ocean acidification, and understanding the transport of particulate organic matter through the ocean where it can sustain upper trophic levels." (GO-BGC External Advisory Committee Annual Report, 2025). A few examples of the major results enabled by this data include the first ever, direct measurements of basin and global ocean primary productivity (Johnson and Bif, 2021; Stoer and Fennell, 2022; Izett et al., 2024). They enable a global assessment of Annual Net Community Productivity, a metric that drives vertical carbon export, using in situ oxygen observations (Yamaguchi et al., 2024). Hundreds of float profiles in the Southern Ocean seasonal ice zone have revolutionized our understanding of ecosystem processes in a region almost inaccessible to ship-based studies (e.g., Horvat et al., 2022; Vives et al., 2024). Stoer and Fennel (2024) assess the phytoplankton biomass throughout the upper ocean and find large discrepancies between float estimates and space-based sensors, which see only the upper few 10's of meters. Profiling floats provide the vertical sampling that reveals the coupling of deep, carbon dioxide-rich waters with air-sea gas exchange at the surface (Prend et al., 2022; Chen et al., 2022; Carranza et al., 2025). The pH observations from profiling floats will become an important contribution to assessments of ocean carbon dioxide uptake as the array expands (Williams et al., 2017; Gray et al., 2017; Bushinsky et al., 2019; Liniger et al., in prep.).

Unfortunately, the incredible success of BGC-Argo is currently threatened by the lack of a sustained funding source for both the US and international programs. Here we review the current status of the main US projects, lessons learned, research findings, and impacts of technological change to support efforts to find a path forward to sustaining the global array.

The US contribution to BGC-Argo

The US BGC-Argo projects operate within the BGC-Argo element of the OneArgo program (Owens et al., 2022; Thierry et al., 2025). There are three main US projects, GO-BGC, SOCCOM, and NOAA projects. The US contribution is planned to be about 50% of the 5+ sensor array with the remaining 50% from other nations (BAPG, 2016). However, the nearly 500 US floats are the great majority (84%; Figure 1A) of the currently active 5+ sensor array. The large fraction results because the US has spun up its contribution much faster than other nations.

The largest of the recent US efforts has been GO-BGC. The mission of GO-BGC is:

> *To build a persistent, robotic observing system that extends from the surface into deep waters with open data, and which enables scientists and educators to analyze, understand, and communicate the processes that control ocean health and the flow of carbon at climate relevant time scales.*

This mission is achieved by deploying 500 robotic profiling floats equipped with chemical (oxygen, nitrate, and pH) and bio-optical (chlorophyll fluorescence, optical backscatter, and downwelling irradiance) sensors that deliver freely available, high quality data in real-time. These floats would contribute half of the 1000 float array called for in the BGC-Argo Science and Implementation Plan (BAPG, 2016), with the remainder coming from other nations. The GO-BGC proposal argued that this data would enable the science community to address questions such as:

- What is the ocean's role in regulating the carbon cycle?
- What are the natural and anthropogenic drivers of open ocean deoxygenation, and how can the two drivers be distinguished?
- What are the consequences of ocean acidification and the impact of decreasing pH on ocean biogeochemistry?
- How do physical changes in mixing and circulation affect nutrient availability and ocean productivity?

Note that scientific research was explicitly not supported by the Mid-Scale Research Infrastructure program that funded GO-BGC. The function of GO-BGC is to build a facility that collects and distributes science-quality ocean data to the community at the global scale. The GO-BGC metrics for achievement therefore reflect work done by the ocean science community using the BGC-Argo datasets. The GO-BGC contribution enables the global reach of BGC-Argo (Figure 1), which has not been achieved by any other US or international BGC-Argo programs. Broader Impacts from GO-BGC, beyond providing a global dataset, have included workshops for scientific users, enhancing education and training through the provision of data, and building a pipeline of students and educators that are familiar with the capabilities of the system.

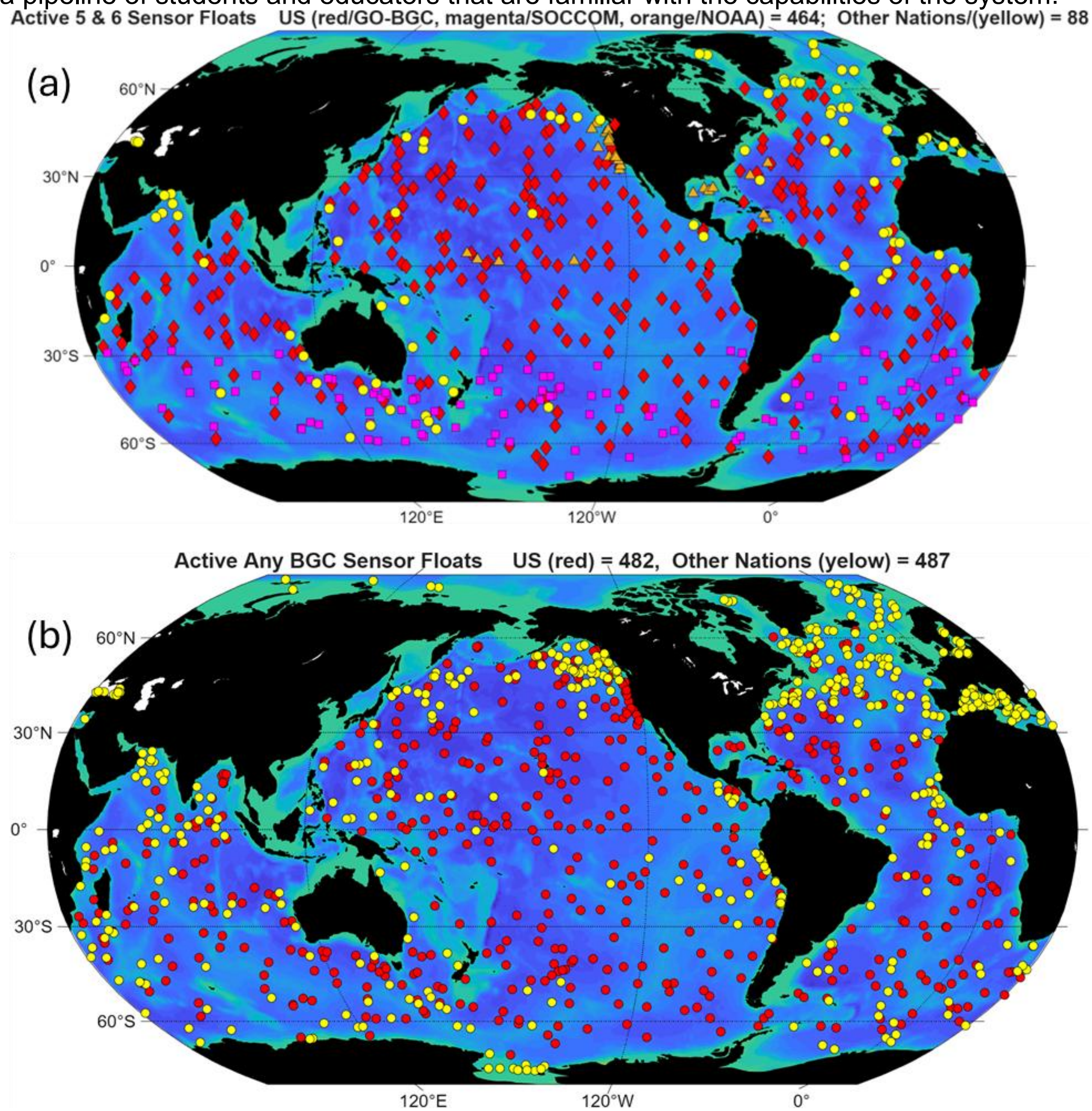


Figure 1. (a) Active (reporting data in the last 120 days) 5+ BGC sensor floats on 8 January 2026. GO-BGC - red diamonds; SOCCOM - magenta squares; NOAA funded (primarily PMEL and AOML) - orange triangles; International - yellow circles. (b) Active floats with any BGC sensor. Red circles are US and yellow circles are international. The number of US floats has a minor increase from (a) to (b) as nearly all carry the recommended 5 or 6 sensors. The international float number increases 5.5x from (a) to (b). Most of the additional floats in the bottom panel carry only oxygen sensors.

GO-BGC is built on the framework of the NSF supported SOCCOM project, which established the first basin-scale array of multi-sensor BGC-Argo floats (Sarmiento et al., 2023). SOCCOM, funded as a research science program by NSF’s Office of Polar Programs, has deployed more than 320 floats with BGC sensors since 2014 with some 130 currently active. This project demonstrated the capability to deploy a large array of multi-sensor BGC-Argo floats, fully process and quality control the data in real-time (Maurer et al., 2021), and support transformational scientific analysis at the basin scale. The third renewal proposal for SOCCOM was written on the premise that most US floats would be provided by GO-BGC and, thus, the current SOCCOM project supports only 24 total floats over three years from 2025 through 2027.

The SOCCOM project, in turn, was built upon the backbone of the Core-Argo array of temperature and salinity floats enabled by decades-long NOAA support. While focused on Core-Argo, NOAA has also supported BGC-Argo projects centered at PMEL and AOML that have a primary focus on deployments near US coasts, as well as assistance with SOCCOM floats. Without this long-term support for sustained observing, fostered by NOAA, the BGC-Argo projects would not have been possible.

We note that the US BGC-Argo mission and data products closely align with US research and development priorities, as outlined in the "Fiscal Year (FY) 2027 Administration Research and Development Budget Priorities and Cross-Cutting Actions" document of the Office of Management and Budget and the Office of Science Technology and Policy (OMB, 2025) (here OMB2025). OMB2025 prioritizes 'Polar Regions Research' and 'Ocean Exploration and Observation'. The SOCCOM and GO-BGC projects have a particular focus on the Southern Ocean and exploration through acquisition of a global dataset of unparalleled resolution. Moving BGC-Argo into the Arctic is a near-term goal. OMB2025 calls for observations in connection with deep-sea mining, which is discussed in the "Who are Existing or Emerging Partners" section. One of the notable accomplishments of BGC-Argo is producing an open access, global dataset of ocean measurements, consistent with the OMB2025 call for increasing "*capacity to effectively and efficiently manage large volumes of ocean observation and research data*." The BGC-Argo dataset is enabling a transformation in Artificial Intelligence studies that meets the OMB2025 goal of "the creation and publication of structured scientific datasets for AI model training." This comprehensive dataset meets the goal of "Applied AI priorities…for the acceleration of scientific discovery". Both GO-BGC and SOCCOM have an emphasis on training that meets the OMB2025 goal "to educate and train the future workforce with the skills in science, technology, engineering, and mathematics (STEM) required to compete in the global marketplace and support American businesses."

The mission and data products of US BGC-Argo also reinforce the goals of the NSF "FY 2026-2030 Strategic Plan" (NSF, 2026). The global data set "accelerates discovery and innovation" by providing a transformative, 4D view of the global ocean chemistry and biology. The international structure of Argo will "build partnerships that achieve shared goals, tap into complementary expertise, leverage resources and create pathways for motivating research questions and pursuing real-world solutions." The open nature of the data meets essential criteria for "Gold Standard Science" that enables transparent, rigorous, and impactful research.The global sensor array is a model for "innovation through the development of critical and emerging technologies".

The US National Academies of Science report "Forecasting the Ocean: The 2025-2035 Decade of Ocean Science" notes the need to "establish a new paradigm for forecasting ocean processes at scales relevant to human well-being" (NAS, 2025). It is difficult to envision how this would happen without the reliable, in situ stream of data provided by BGC-Argo that is described below. The NAS report poses the urgent research question, "How will the ocean's ability to absorb heat and carbon change?" The OneArgo program and the BGC-Argo mission are key systems that provide real-time data to address this urgent question.

The report poses a second urgent question, "How will marine ecosystems respond to changes in the Earth system?" and then "research directions that support this question include determining the effects of warming, acidification, and de-oxygenation on the dynamics and productivity of ocean biota, and codeveloping tools for rapid measurements and assessments of ocean biological and functional diversity.” BGC-Argo is largely the only observing system that provides the capabilities for real-time observations of these processes at the global scale.

The global measurements made by BGC-Argo are key to the NAS report theme of “Forecasting the Ocean”. They enable science to directly address topics such as improving “ability to forecast extreme events”. Thus, the US BGC-Argo program is key to meeting national science objectives.

US Project Status

Progress towards meeting the US goal of 500 multi-sensor floats has been driven primarily by the GO-BGC project in the last 5 years. GO-BGC has deployed 359 floats as of 10 January 2026 and 315 floats are now operating. We define operational floats as ones communicating within the past 120 days. This metric includes floats that have only intermittent communications, but which do provide useful data for scientific analyses. SOCCOM supports ~130 (the uncertainty relates to floats under seasonal ice) operational floats. There are an additional 26 multi-sensor floats from NOAA labs or supported by NOAA project funds.

The US should reach its 500 float objective in 2026. There are 464 floats equipped with 5+ sensors now active and 150 new GO-BGC and SOCCOM floats will be deployed by 31 October 2026. The annual loss rate for US floats has been ~7%/year due to random failures, not including battery exhaustion. This has been consistent with our proposal plan. There will be an expected loss of perhaps 33 floats to random events (0.07 x 464) and ~40 floats lost due to battery exhaustion (a smaller number than expected because it is a young array) in the next year. That should yield about 541 operational floats late in the year. Deployed floats span the globe and US BGC-Argo projects have created a truly global array (Figure 1). All data from the floats are available in near real-time (24 hours) with automated quality control (Maurer et al., 2021). The entire dataset is then subjected to human supervised quality control twice per year to review the automated adjustments.

While the US profiling float array will reach the 500 float target in 2026, it will begin to decay shortly after that as floats exhaust their batteries and are not replaced. International partners in BGC-Argo have deployed a large number of floats (Figure 1B), but these are primarily equipped only with oxygen sensors. While providing valuable information, only a few of the international floats contribute directly to the 1000 multi-sensor float objective (Figure 1A). Further, most international floats are clustered in a few regional arrays (eastern N. Pacific, sub-polar N. Atlantic, Mediterranean Sea; Figure 1) and do not have a global extent. Sustaining the US effort is key to achieving the global, 1000 float array envisioned in the BGC-Argo Science and Implementation Plan (BAPG, 2016). A renewal proposal to NSF (GO-BGC-2) for 3 years and 110 floats/year was submitted in October 2024. That proposal remains under consideration. However, the budget situation at NSF is unclear and we are not confident that our renewal will be approved. NOAA also considered a plan to fund the entire US component of OneArgo, but flat funding prevented inclusion of BGC-Argo at a significant level.Thus, an alternative funding source is likely to be required to sustain the US effort.

In the following, we review the accomplishments and progress towards our project goals as well as various possible pathways forward for US BGC-Argo.

What scientific progress has the BGC Argo program enabled over the past decade?

We focus here on the basin to global scale questions identified in the SOCCOM and GO-BGC proposals. Major science questions that were called out in these proposals are listed in the following sections with a summary of the work that has been done to address these topics. As noted above, much of this work is done by scientists not directly associated with GO-BGC and it highlights the open nature of BGC-Argo data.

The Implementation Plan called for multi-sensor floats because the collocation of sensor data provides an unparalleled synergism when all the variables are interpreted simultaneously. A nice example of this is the work by Huang et al. (2023), elucidating the processes controlling Southern Ocean carbon cycling. Much of the work discussed below benefits from this multi-sensor synergism.

The ocean's role in regulating the carbon cycle

Air-sea carbon flux. An early focus in the SOCCOM project was on estimating air-sea flux of CO_2 using pCO_2 estimated from profiling float pH (Williams et al., 2017; Gray et al., 2017; Bushinsky et al., 2019). This work has the potential to contribute valuable pCO_2 estimates in the chronically undersampled surface ocean (<3% of 1x1° grid cells and months are sampled each year). However, the results have been criticized in a variety of reports due to an apparent overestimation of the pCO_2 value. A thorough review (Johnson et al., in progress) suggests this error in pCO_2 results from two biases: a small (~0.005) systematic error in pH values and a larger bias in the reported dissociation constant of CO_2 ($pK_{1adj} = pK_{1measured} – 0.01$) needed to calculate pCO_2. If the two adjustments are made, there is excellent consistency between profiling float estimates of pCO_2 and a variety of machine learning products (Figure 2) as well as with direct SOCAT products.

Despite the possibility of a systematic offset in float pCO_2 values, the float data contribute broadly to air-sea carbon flux analyses. Bushinsky et al. (2019) highlight the effects of spatial undersampling on estimates of air-sea CO_2 flux by merging float and ship data into a single product. Carranza et al. (2024) use the profiling float data, coupled with atmospheric reanalysis data, to demonstrate the strong effect of Southern Ocean storms on air-sea gas exchange. Storms accounted for 55% of Southern Ocean CO_2 flux, which is undersampled in shipboard observations as most ships avoid storms when possible. Carranza et al. also show that the effect of storms is weaker by nearly 2x in the CESM earth system model.

Interior ocean carbon assessment is arguably the primary contribution that BGC-Argo floats make for the ocean carbon balance, just as Argo temperature and salinity contribute almost all information about interior ocean heat and freshwater content and their changes. The vertically resolved data from float profiles can be used to construct the mass balances of inorganic carbon and alkalinity that drive the air sea flux (Prend et al., 2022; Chen et al., 2022). These results show the importance of having vertically resolved data to understand the role of coupling between the deep ocean and surface waters on air-sea flux. Sauvé et al. (2023) used the distribution of Dissolved Inorganic Carbon (DIC) determined from pH measurements by profiling float sensors to compute a complete, mixed layer carbon budget in the Southern Ocean (Figure 3). This result was enabled by the broad distribution of SOCCOM profiling floats around Antarctica and the full seasonal and vertical coverage of the dataset. Such capability enables a transformational understanding of ocean carbon cycling.

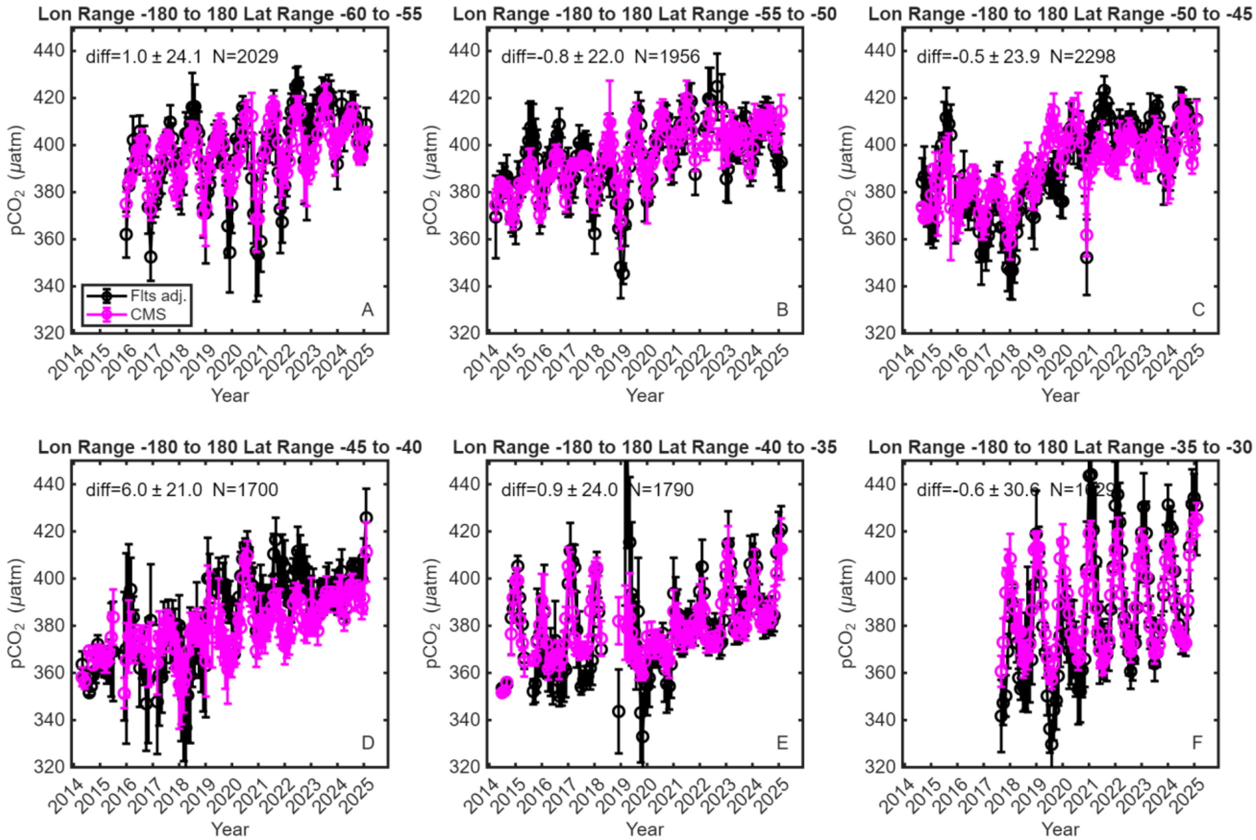


Figure 2. Monthly mean pCO_2 from floats, after adjusting pH and pK_1, and from the Copernicus Marine Services (CMS) near real-time pCO_2 product that is based on the machine learning method (trained on SOCAT data) developed by Chau et al. (2024) in 6 zonal bands that span 5° latitude bins. The CMS values are from the same 1° x 1° and month grid cell as each float profile. Mean difference (float - CMS), standard deviation of difference, and total number of observations are shown for each plot. From Johnson et al. (in prep.).

Interior carbon stocks. The surface pCO_2 values are used to assess ocean uptake of anthropogenic carbon. However, this calculation is sensitive to uncertainties in gas-exchange parameterizations, wind speed estimates, and they require correction for the natural, pre-industrial air-sea CO_2 flux, and any changes to it resulting from physical climate perturbations. An exciting, recent development is the demonstration by SOCCOM Postdoc Guillaume Liniger that the profiling float pH measurements can be combined with machine learning methods to quantify the change in ocean dissolved inorganic carbon stocks with monthly resolution (Figure 4; Liniger et al., in preparation).

To calculate DIC stocks, a Neural Network is trained on profiling float dissolved inorganic carbon (DIC) values, computed as in Johnson et al. (2021). Input variables to the NN include temperature, salinity, oxygen, position and date. A gridded DIC product was then created with monthly resolution from 2016 to 2024 on a 1° x 1° grid using the monthly gridded temperature and salinity from Core-Argo floats (Roemmich and Gilson, 2009) and the GOBAI-O2 gridded oxygen product at the same resolution (Sharp et al., 2023). The rate of DIC increase can then be computed at each grid point and a map created. Figure 4 shows the rate of DIC increase from 2016 to 2024 mapped at 1° x 1° resolution. Each panel was created by training the DIC NN with different numbers of randomly selected BGC-Argo floats. Large differences are seen as the number of observations used to train the NN increases, with areas that are DIC sources to the atmosphere (blue values) shifting to sinks (red values). The top panel in Figure 4 has a number of floats that exceeds the US goal of ~200 in the Southern Ocean (half the desired US and international total). It is clear that Machine Learning with smaller numbers of floats is not adequately resolving inorganic carbon changes.

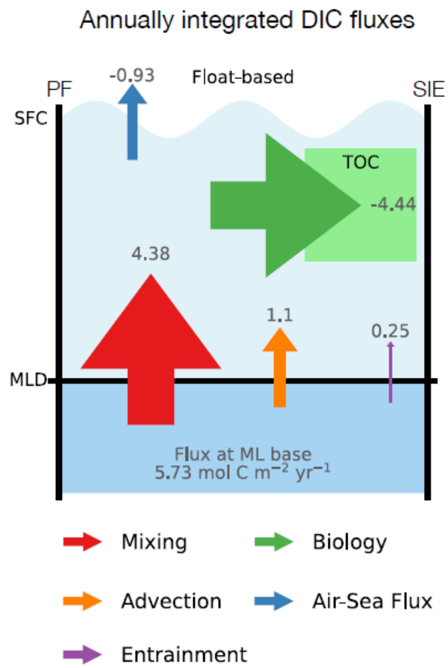
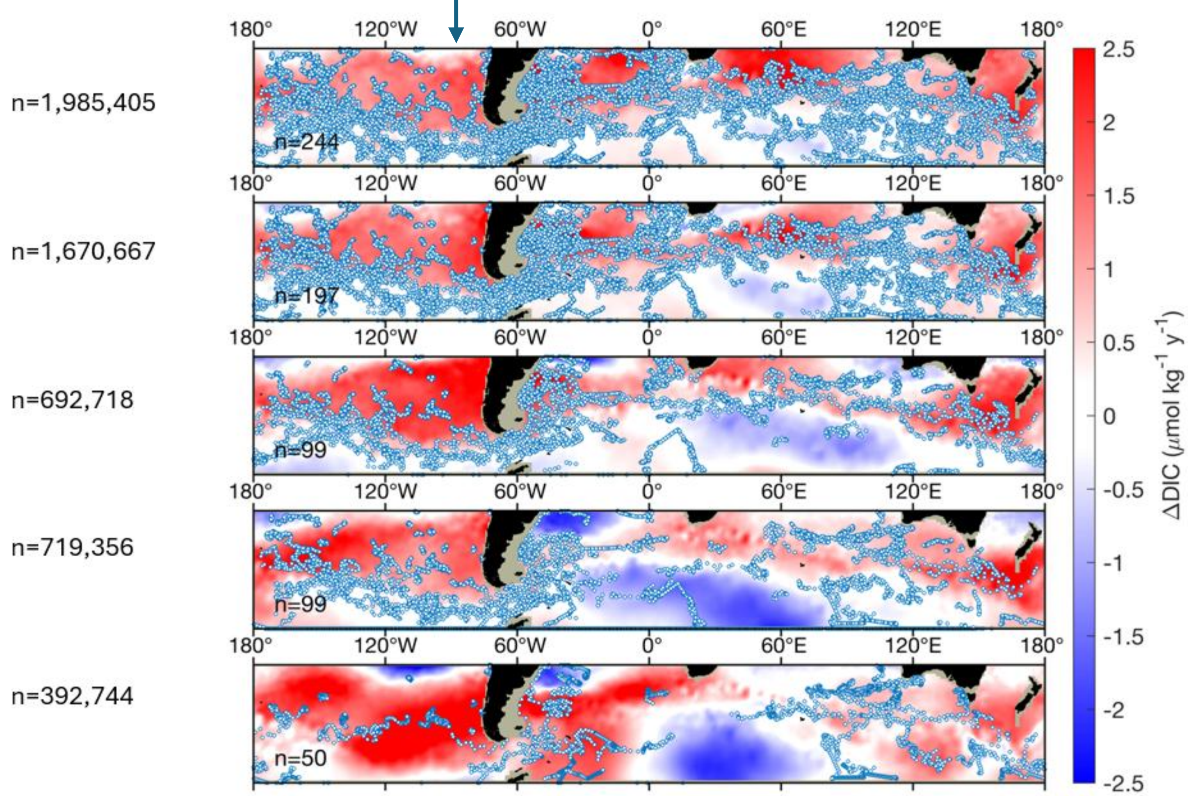


Figure 3. The zonally integrated, annual carbon budget between the Polar Front (PF) and Seasonal Ice Edge (SIE) determined using profiling float data from Sauvé (2025). Fluxes are in units of mol C m^{-2} yr^{-1}.

Figure 4. The rate of change in the mean DIC concentration from the surface to 1500 m from 2016 to 2024 at 1° x 1° resolution. Each panel differs only by the number of floats (lower left in each panel) and observations (left of each panel) used to train a Neural Network model of DIC. Dots show the position of each profile in the training data set. Complete float records were selected randomly from the complete BGC-Argo data set. From Liniger et al. (in prep.).



What are the natural and anthropogenic drivers of open ocean deoxygenation?

Dissolved oxygen data are the most abundant BGC observations with more than 300,000 vertical profiles available. This dwarfs the available shipboard measurements (Figure 5). Observations span the global ocean and extend through all seasons, unlike the shipboard data that is heavily biased to summer months. The float data have enabled a revolution in assessments of the global ocean oxygen inventory. A variety of statistical and machine learning products based on shipboard and BGC-Argo oxygen data (Sharp et al., 2023; Ito et al., 2024; Garcia et al., 2024; Gouretski et al., 2024; Du et al., 2025; Han et al., 2025; Ma et al., 2025; Wang et al., 2025) have been developed. An international project is underway to assess these products (Ito et al., 2025). These products clearly show the decreasing stock of oxygen in the ocean (Figure 6). These products will revolutionize our ability to resolve the basic ventilation pathways (Koelling et al., 2025) and identify the spatial and temporal variability of processes responsible for ocean deoxygenation. The work by Yamaguchi et al. (2024) to create a global ocean O_2 budget is an excellent example of the assessments that are now possible with a global and seasonally resolved dataset that is based, in large part, on BGC-Argo.

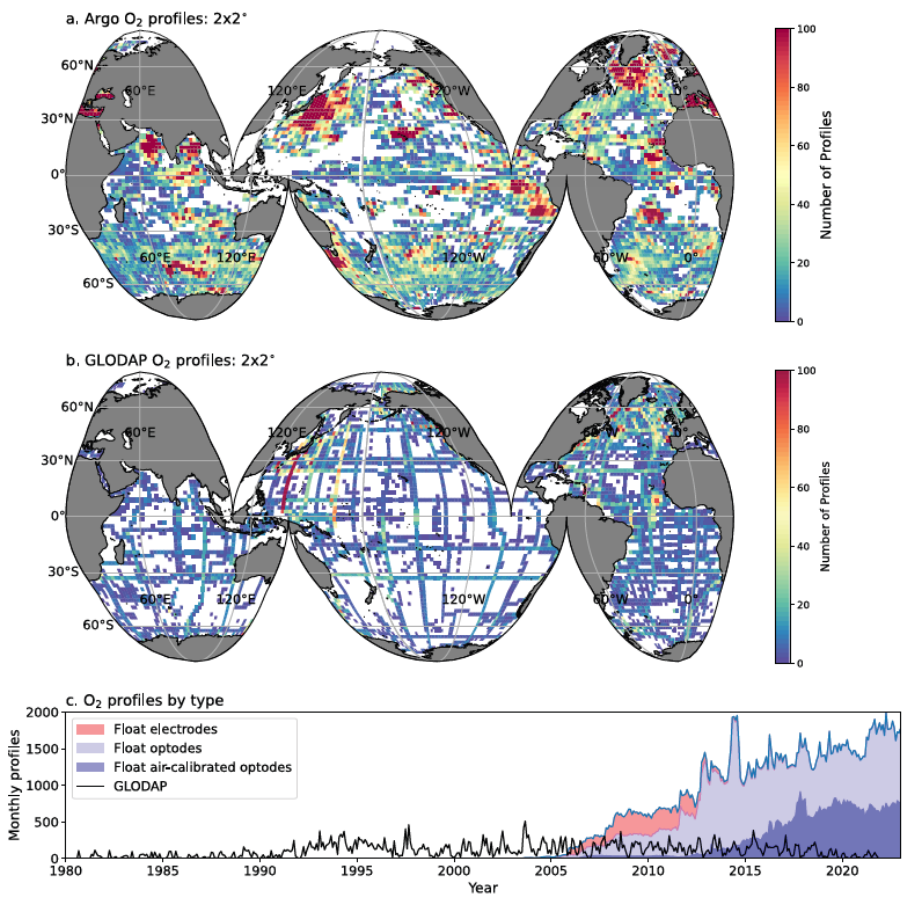


Figure 5. Observational density of oxygen profiles in space and time. (a) Number of profiling float oxygen profiles per 2° x 2° grid, (b Number of GLODAP oxygen profiles per 2° x 2° grid. (c) Number of profiles per month from floats with Clark oxygen electrodes (red), floats with optode oxygen sensors (blue-grey), floats with air-calibrated oxygen sensors (dark blue), and from GLODAP. Figure from Bushinsky et al. (2025).

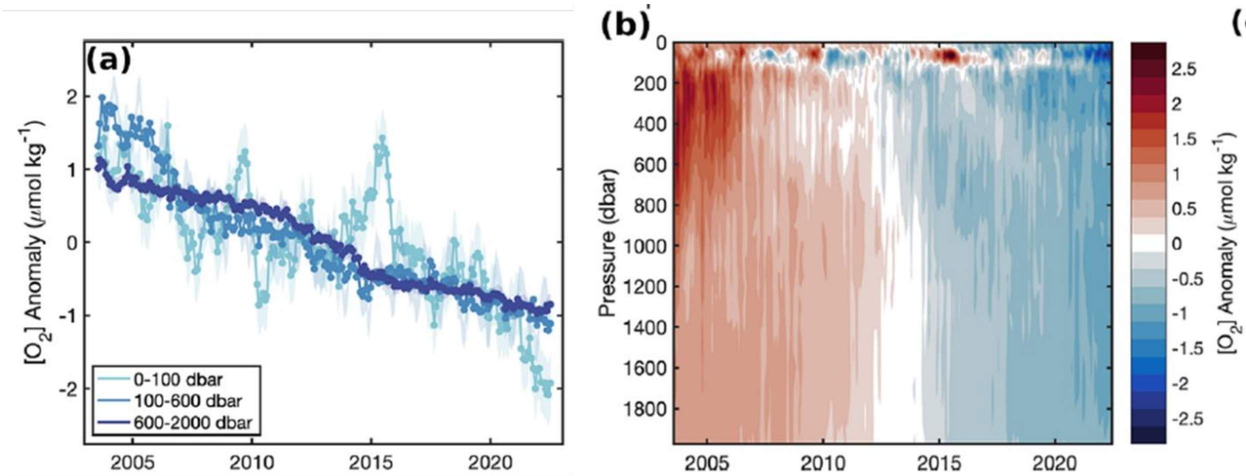


Figure 6. Oxygen inventories as an anomaly from mean value in GOBAI-O2 machine learning product (Sharp et al., 2023) showing the decrease in ocean oxygen. (a) Global mean anomaly in 3 depth bands versus year. (b) Global mean anomaly versus depth and time. Red are anomalies larger than the mean and blue are smaller than the mean. From Sharp et al. (2023).

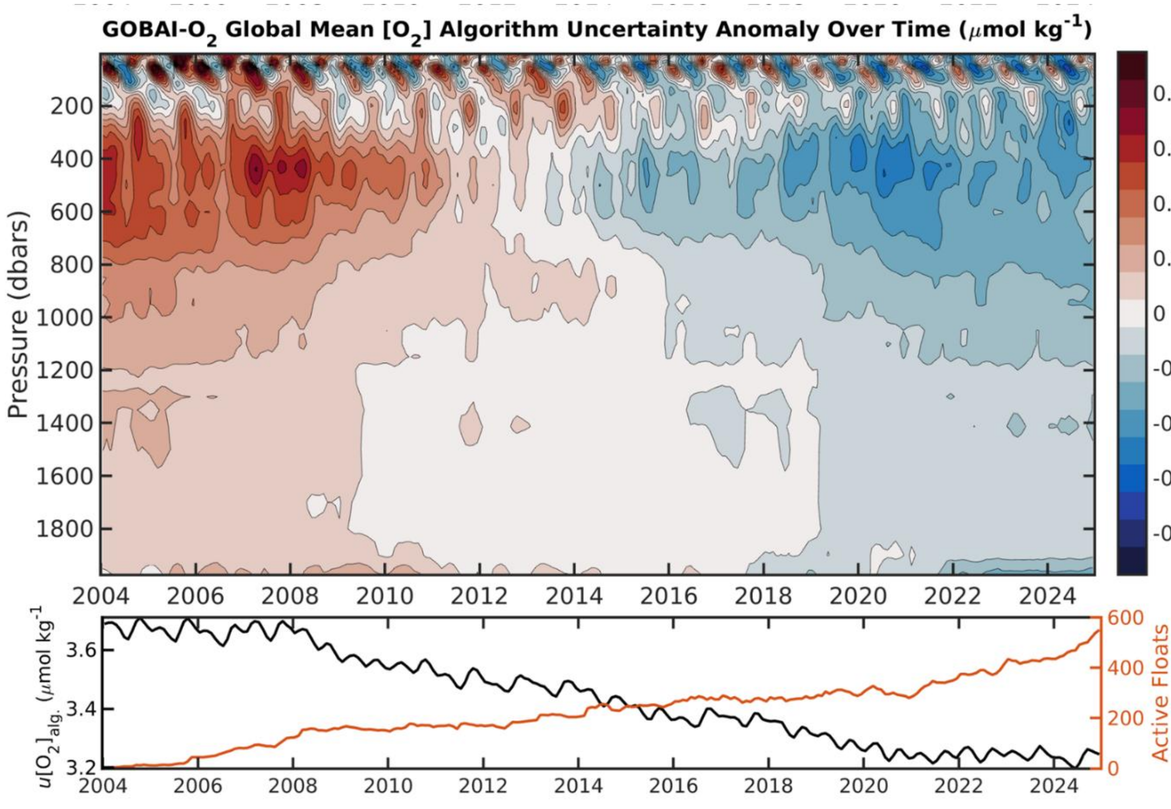


Figure 7. Estimated oxygen concentration error predicted by the GOBAI-O2 Neural Network algorithm. (A) Algorithm uncertainty versus depth and time estimated at each spatiotemporal grid cell as the root mean squared error across five CMIP model simulation experiments between model truth and algorithm predictions. (B) Mean algorithm uncertainty versus time (black line) and number of BGC-Argo floats available to train the algorithm (red).

The number of BGC-Argo floats with oxygen sensors now exceeds 850, approaching the design goal of 1000 floats with oxygen sensors. While many of these floats carry only oxygen sensors and do not contribute directly to the 1000 multi-sensor float design that enables the synergism from collocation of multiple sensors, they do contribute valuable data. The large number of floats with oxygen enables assessments of the effect of array size on mapped oxygen uncertainty. Figure 7 shows the estimated uncertainty in oxygen predicted with the GOBAI-O2 Neural Network (Sharp et al., 2023) over time as the float array grows from zero (only ship data available) to 600 floats available for assessment (the remaining floats are either used to validate the ML algorithms, have failed oxygen or salinity sensors, or the Data Assembly Center responsible for the float has not quality controlled the data). The error in oxygen concentrations mapped using machine learning methods decreases continuously as the number of floats increases. The application of machine learning methods does not appear to be a significant shortcut to reduce the desired number of profiling floats with oxygen.

What are the consequences of ocean acidification and the impact of decreasing pH on ocean biogeochemistry?

The pH sensors on profiling floats now enable the rates of pH decrease (ocean acidification) to be determined throughout the Southern Ocean, from the surface to 100's of meters depth (Mazloff et al., 2023; Figure 8). The zonal mean rates are spatially variable, which reflects the broad-scale pattern of the overturning circulation.

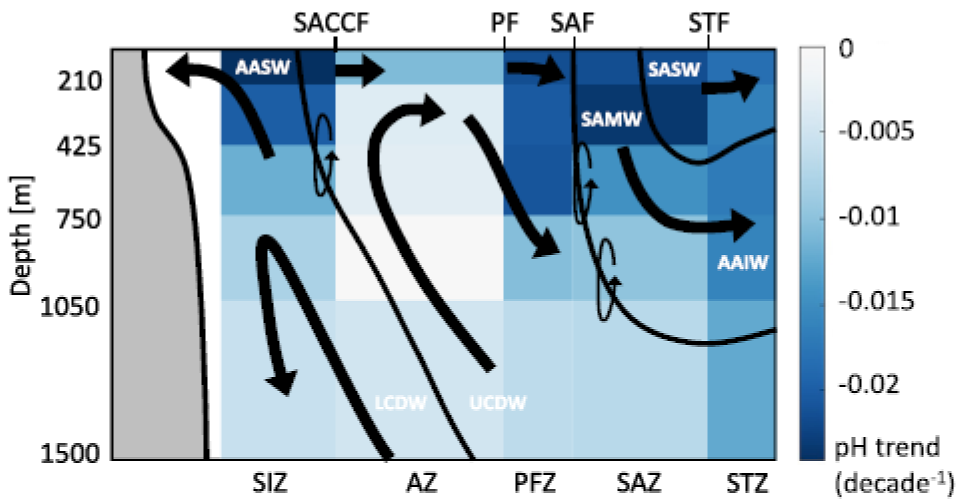


Figure 8. Zonal mean rate of change in ocean pH (pH/decade) from SOCCOM float pH Climatology and GLODAPv2 observations. Superimposed is a schematic of Southern Ocean meridional overturning circulation from Talley et al. (2011). Minimal change in regions where meridional circulation brings old, non-acidified water towards the surface. Abbreviations: Southern ACC Front (SACCF), Polar Front (PF), Subantarctic Front (SAF), and Subtropical Front (STF), Seasonal Ice Zone (SIZ), Antarctic Zone (AZ), Polar Frontal Zone (PFZ), SubAntarctic Zone (SAZ), SubTropical Zone (STZ), Antarctic Surface Water (AASW), Subantarctic Mode Water (SAMW), Antarctic Intermediate Water (AAIW), and Subantarctic Surface Water (SASW), Lower and Upper Circumpolar Deep Water (LCDW, UCDW).

The rates reported in Mazloff et al. (2023) utilized a merged product of float and shipboard observations. The float record is approaching the length needed to enable direct observation of the acidification rate using the sensor data set only with resolution at the basin scale. Figure 9 shows the acidification rate in 5° zonal mean bands using only float pH observations in the top 10 m. The record is just long enough to resolve the pH decreases with statistical significance following Sutton et al. (2022). Rates (pH/yr) are consistent with the trend (-0.0025 pH/yr) expected from the rate of atmospheric CO_2 increase over the past 10 years (+2.6 μatm/yr) with several oceanographically consistent exceptions. The rates between 40°S to 50°S exceed -0.0025 pH/yr. This may reflect an increasing rate of upwelling of low pH deep water driven by strengthening westerly winds (Morrison et al., 2015), which produces a greater rate of pH decrease than expected from atmospheric CO_2 alone. At the southern extremes (60°S to 70°S), ice covered waters decrease atmospheric exchange and dampen the pH change. Extending the record will allow direct assessment of ocean acidification rates across the Southern Ocean with greater spatial resolution.

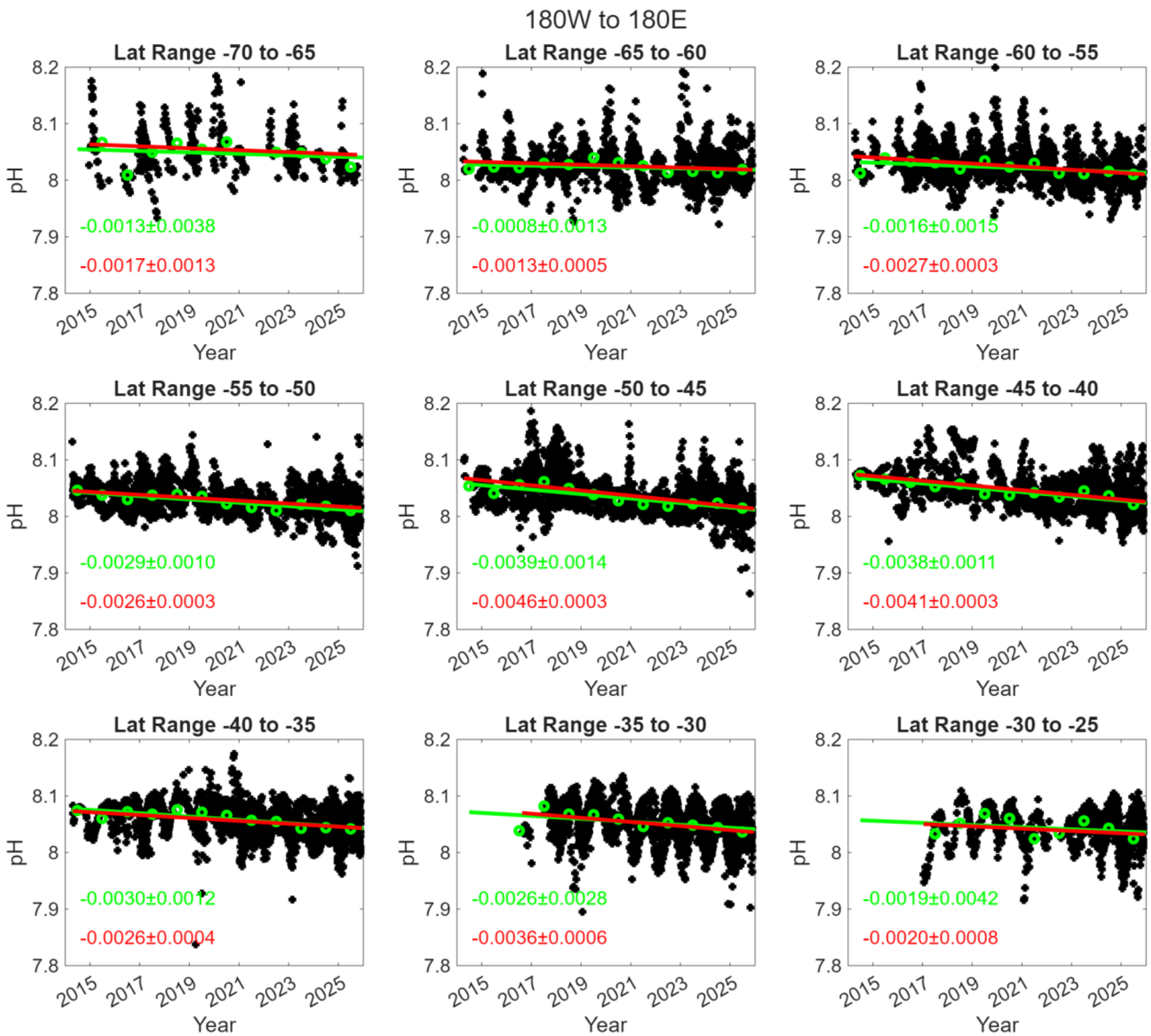


Figure 9. Zonal mean pH observations from SOCCOM and GO-BGC floats in the upper 10 m of all data from 180°W to 180°E and in 5° latitude bands from 70°S to 25°S. Each red line is a least squares fit to all data points while each green line is fitted to annual average values for years with at least 10 months of data. The slope (pH/yr) ± 1 SD of line fitted to all data (red) and the annual means (green) is shown.

The high-quality pH observations from floats enable consistent estimates of the surface ocean aragonite saturation state to be made. Aragonite undersaturation is a key threshold in ocean chemistry that may impact the thermodynamic stability of shells produced by many marine animals. Aragonite, a mineral species of $CaCO_3$ found in the shells of many marine species, will spontaneously dissolve when the saturation index (Ω-$_{Aragonite}$) falls below a value of 1. At values above 1, aragonite will tend to precipitate from seawater, although various kinetic factors inhibit this from occurring spontaneously in most of the ocean. McNeil and Matear (2008) warned of a coming tipping point in Southern Ocean biogeochemistry, “Southern Ocean wintertime aragonite undersaturation is projected to occur by the year 2030 and no later than 2038”. Due to fundamental thermodynamic equilibria, the aragonite saturation state in frigid polar waters is much lower than the mean ocean value. It hovers at a value much closer to the saturation threshold of 1 when compared to lower latitudes (Figure 10). Further, saturation values are lowest in winter due to low temperatures and trapping of respiratory carbon dioxide under seasonal sea ice. Observations of ocean chemistry, which until recently have required the presence of ships to conduct sampling, have been rare in winter (Figure 10C). The Ω-$_{Aragonite}$ projections of McNeil and Matear can now be confirmed by the year-round observations from SOCCOM and GO-BGC profiling floats operating in the Southern Ocean, including the seasonal ice zone.

In 2008, surface $\Omega_{Aragonite}$ values computed from scattered shipboard measurements made during Austral summer in the seasonal ice zone were near 1.4 to 1.8 (Figure S3 of McNeil and Matear, 2008; Figure 10C). Values less than 1.2 were rare. Now, during winter and under seasonal layers of sea ice, the Antarctic continent is almost completely encircled by an ocean with Ω-$_{Aragonite}$ < 1.2, primarily due to the increase in atmospheric CO_2 (Figure 10A). Regions with $\Omega_{Aragonite}$ < 1.1, highlighted by the yellow contour lines in Figure 10A and 10B, are emerging. McNeil and Matear (2008) forecast the emergence of regions with Ω-$_{Aragonite}$ < 1 between 2030 and 2038. Such regions are now beginning to appear in the data record (Figure 10C). Without pH measurements from profiling floats operating under sea ice, we would be blind to the development of this transition point in ocean biogeochemistry. While neural network models are efficient methods to infill between sparse measurements, they are less skillful at extrapolating shipboard measurements, whose availability often lags by years, to the present. There would be significant uncertainty when projecting sparse summer observations into the winter, under ice conditions.

Biological carbon pump

BGC-Argo floats provide the essential observations needed to understand the multifaceted processes that transport organic carbon from the surface into the mesopelagic at the global scale (Boyd et al., 2019). Stoer and Fennell (2024) used BGC-Argo observations to determine the stock of particulate organic carbon and seasonal cycles that drive the biological carbon pump. Much the stock lies at depths where satellites cannot observe. As they noted, “Our study demonstrates that profiling robots enable more reliable monitoring of Earth’s phytoplankton, which is urgently needed to understand the impact of climate change.” Sauzède et al. (2017) merged float optical backscatter and chlorophyll with equivalent satellite remote sensing products detected near the surface in a machine learning framework to create a three dimensional, depth resolved climatology. Fox et al. (2024) expanded on this work to create a global merged product of BGC-Argo and satellite measurements of optical backscatter and inferred POC to 1000 m. This allowed them to assess spatial and temporal variability in the gravitational carbon pump. Oetjens et al. (2025) develop an improved, mechanistic model for vertical carbon transport across the Southern Ocean using BGC-Argo data. De Greef et al. (in review) use the global BGC-Argo dataset to constrain the significance of the carbon eddy subduction pump. They find it can be regionally important, but at the global scale it accounts for less than 5% of the carbon exported by gravitational sinking.

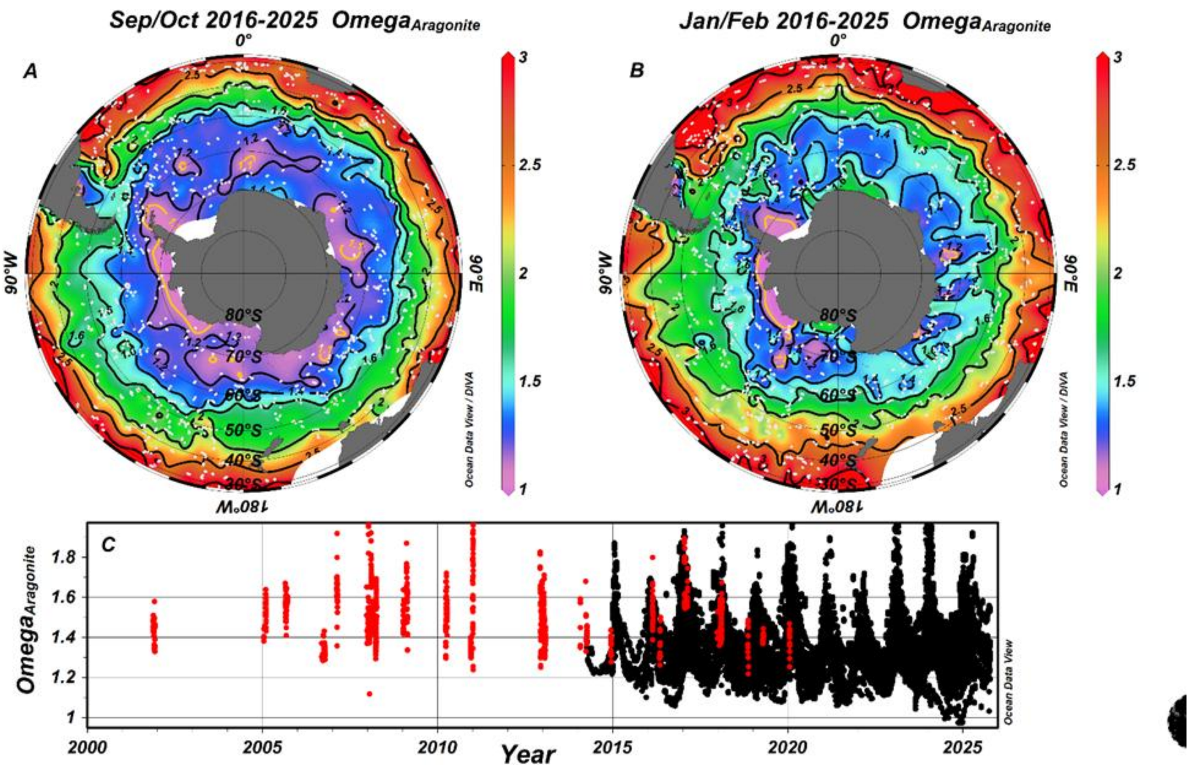


Figure 10. Aragonite saturation state of surface waters in the Southern Ocean at in situ temperature and pressure. Surface values of $\Omega_{\text{-Aragonite}}$ computed from pH values observed by SOCCOM and GO-BGC (Global Ocean Biogeochemistry Array) profiling floats and total alkalinity estimated by empirical algorithms fitted to shipboard measurements (Carter et al., 2021) in Austral winter (A) and Austral summer (B) are shown. White dots show locations of vertical profiles collected from January, 2016 to October, 2025. Data collected in the upper 55 m, to be consistent with McNeil and Matear (2008) are averaged for each profile. (C) A time series of $\Omega_{\text{-Aragonite}}$ values in the upper 55 m at latitudes from 58°S to 80°S. Values derived from profiling floats (black dots) and shipboard observations in the GLODAPv2.2024 dataset (red dots) are shown.

How do physical changes affect nutrient availability and ocean productivity?

Global ocean primary productivity estimates have only been available from remote sensing observations of ocean color or optical backscatter that are coupled to biophysical models that compute productivity (e.g. Behrenfeld and Falkowski, 1997) or from scattered shipboard observations (Huang et al., 2021). The biophysical models have been calibrated with sparse, in situ measurements from ^{14}C incubations. Profiling floats now provide the capability to directly measure gross oxygen primary productivity at the global scale (Johnson and Bif, 2001; Stoer and Fennel, 2022; Izett et al., 2024). The float productivity values are based on direct, in situ measurements of oxygen (Figure 11) or optical backscatter. Profiling float measurements of GOP can extend through the water column to the base of the euphotic zone. While BGC-Argo measurements of productivity made with this method will lack high spatial resolution, they provide an important ground truth for estimates derived from satellite observations.

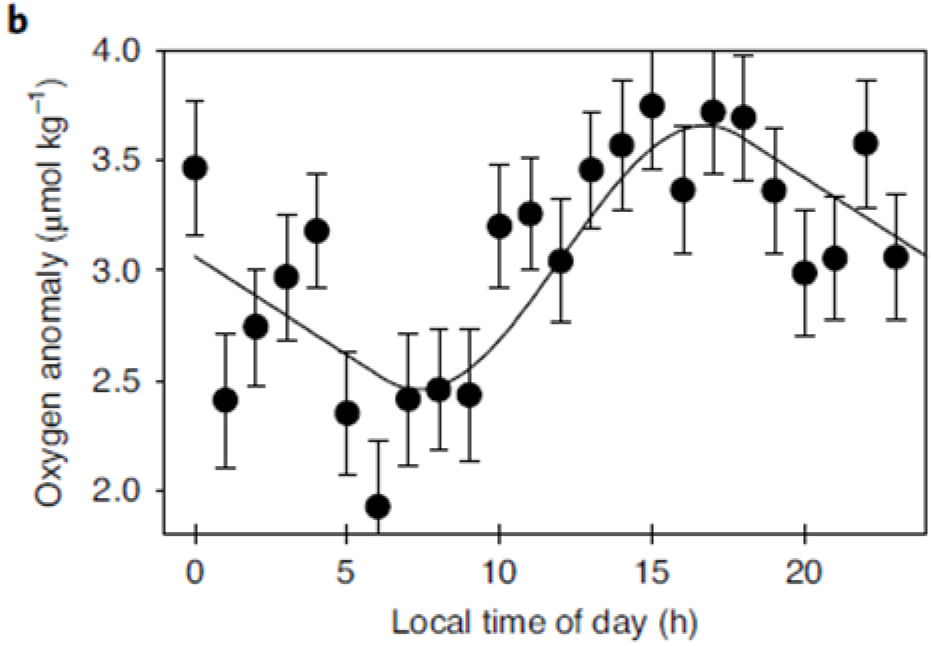


Figure 11. The diel cycle of oxygen anomaly (oxygen concentration minus concentration at atmospheric equilibrium) versus local time of day for all profiles from 2010 to 2020 in the Northern Hemisphere (60°N to 10°N). The diel cycle is created by phytoplankton photosynthesis and respiration. Error bars are one standard error. From Johnson and Bif (2021).

The profiling float measurements detect gross productivity of the primary producer community. Profiling float measurements can also yield measurements of productivity and respiration integrated across the ecosystem to constrain annual net community production (ANCP). Quantification of ANCP is particularly relevant to carbon studies as it constrains the net flux of organic carbon from the euphotic zone into the ocean interior, where it may be stored for long periods of time. Yamaguchi et al. (2024) used the merged ship and float oxygen dataset to assess the physical and biological fluxes of oxygen across the global ocean. Figure 12 shows the zonal mean fluxes with ANCP shown as the green numbers. Their global net oxygen production of 889 Tmol year^{-1} equates to an ANCP of 7.36 ± 2.12 Pg C year^{-1}. As defined in their study, this is the carbon transported below the deepest mixed layer in each location and sequestered from the atmosphere for many decades to centuries.

Liniger et al. (2025) used profiling floats with nitrate sensors in the Southern Ocean to train Neural Networks that enabled the prediction of nitrate concentration with 1°x1° spatial resolution and monthly resolution from 2004 to the present. The product was used to calculate the annual uptake of nitrate at each gridpoint, which makes it possible to infer the annual biological production of organic carbon, or Annual Net Community Production (ANCP), at each 1°x1° gridpoint since 2004 (Figure 13). The results show that ANCP averaged over the Southern Ocean has been increasing, likely due to warming temperatures. Weis et al. (2024) merged ANCP values computed by a similar method with model-based assessments of dust deposition to show that iron derived from dust supports one third of Southern Ocean productivity. Further, by carrying multiple collocated chemical and bio-optical sensors, BGC floats are making it possible to differentiate the types of carbon being produced by phytoplankton (Huang et al., 2023). This in turn is enabling more reliable estimates of in situ carbon export and export efficiency (Huang and Fassbender 2024), which are key metrics of ecosystem functionality.

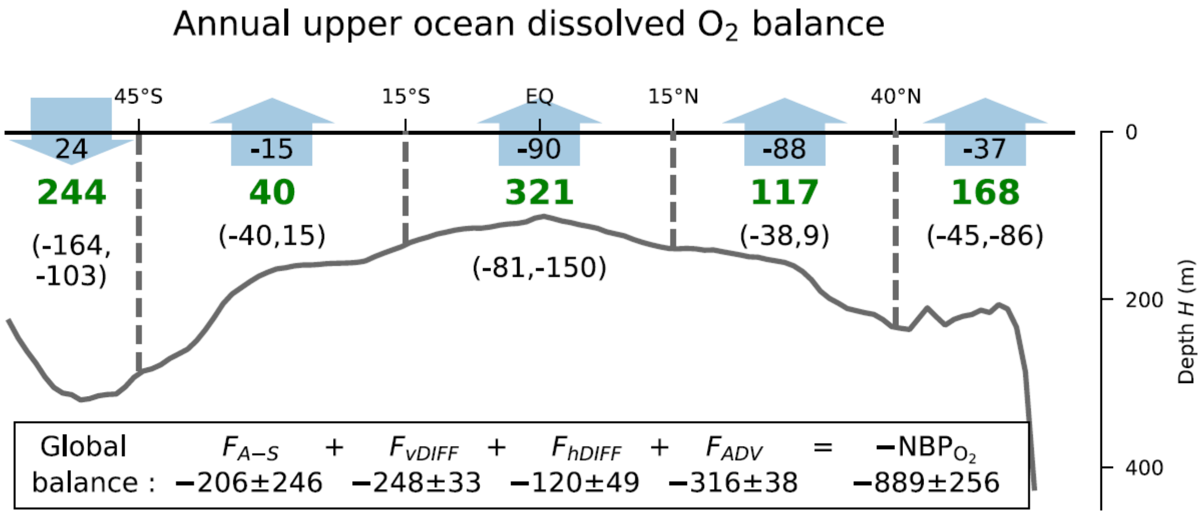


Figure 12. Zonal mean physical and biological fluxes determined by Yamaguchi et al. (2024). All units are Tmol O_2 year^{-1}.

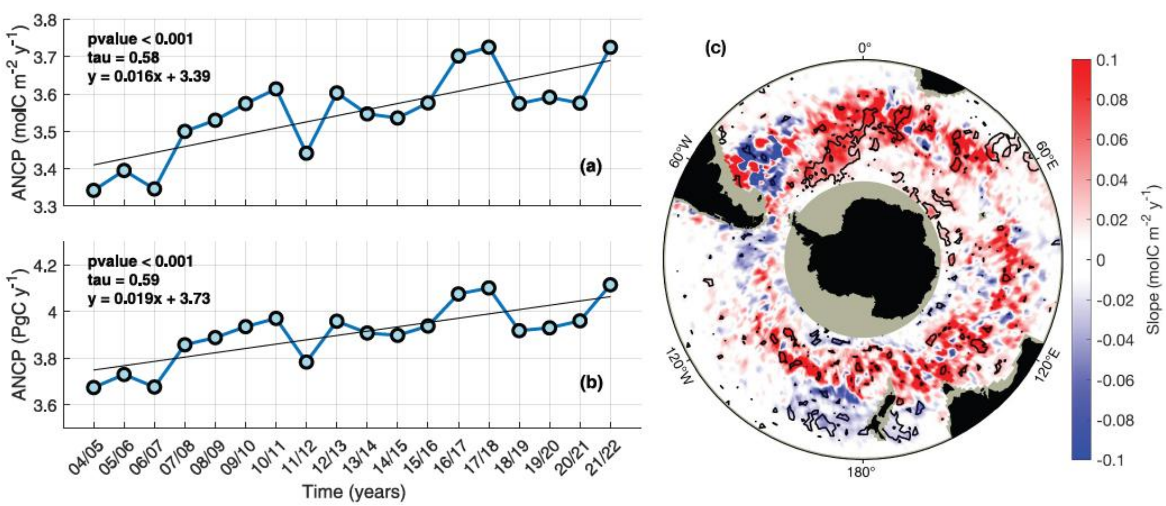


Figure 13. Annual Net Community Productivity (ANCP) in the Southern Ocean determined from annual cycles of nitrate concentration converted to carbon units (Liniger et al., 2025). a) ANCP as mean rate per unit area versus year, b) total ANCP over the entire region, c) ANCP rate of change (mol C m^{-2} y^{-1} y^{-1}) at each 1° x 1° grid point.

The number of floats needed to compute primary productivity directly from diel cycles of oxygen (or other BGC parameters), rather than estimating it from models fitted to extremely sparse observations (see Figure 1 of Johnson and Bif, 2021), is large. Izett et al. (2024) concluded, “our results indicate that the projected array of 1000 BGC-Argo floats (Roemmich et al., 2021; Biogeochemical-Argo Planning Group., 2016) should be sufficient to obtain annual, or better, GPP snapshots at most latitude Bands.” S. Traylor (in prep.) extended this work by applying diel oxygen productivity calculations on the ocean biomes identified by Fay and McKinley (2017) to assess the limits of the method. Figure 14A shows the biome map. As an example, Biome 4 in the central Pacific (~0-50ºN) would have 110 floats in an evenly distributed 1000 float global array. It currently has 63 floats with oxygen. Figure 14B shows the change in the fractional error (1 SD/Mean) of the annual GOP determined from diel oxygen cycles versus the number of floats used in the analysis (more floats were included by using more years of data). As shown in the figure, the error levels out when about 80 floats are available and reaches a minimum near 100 floats, which is similar to the desired number. This work reaffirms the assessment of Izett et al. (2024) and the target of 1000 floats reached in the BGC-Argo Science and Implementation Plan (BAPG, 2016). Additional floats that carry only oxygen sensors will augment the capability to observe GOP.

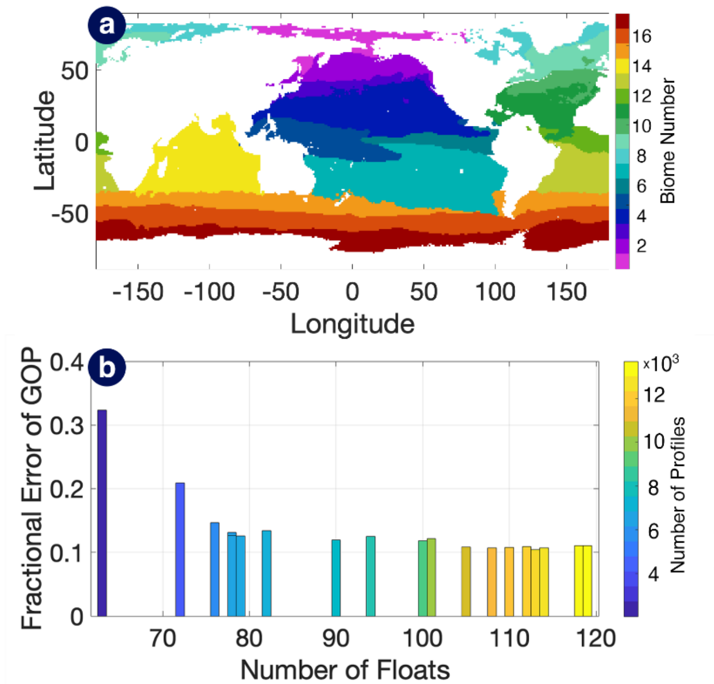


Figure 14. (a) Ocean biomes defined by Fay and McKinley (2017). (b) Fractional error (1 SD/mean) of Gross Oxygen Productivity determined in Central Pacific biome 5 versus the number of profiling floats available to calculate GOP using the method shown in Figure 11.

Are the original science questions still relevant, and what new questions should guide the future program?

We continue to explore new capabilities provided by the sensor data. A good example is utilization of the ISUS and SUNA nitrate sensors to quantify other chemicals that have distinct ultraviolet absorption spectra. This capability was initially demonstrated by detecting hydrogen sulfide in the Black Sea (Stanev et al., 2018). In the past year, we have demonstrated the capability to quantify nitrite (Bif and Johnson, 2025). Nitrite is a key intermediate in the redox cycling of nitrate in oxygen deficient zones (ODZ). Floats with UV nitrate sensors now provide the unique capability to observe the temporal variability of nitrite in these regions. A manuscript describing the multi-year variability of nitrite in the Eastern Tropical North Pacific (Bif et al., in review) has passed through a first round of review at Nature Communications with enthusiastic support from each of 3 reviewers: “I think the community working on ODZ biogeochemistry and biogeochemical-Argo data has needed a study like this for some time.” (reviewer 1); “This is a highly impactful study that provides novel insights into the role of nitrogen turnover processes on the carbon chemistry." (reviewer 2); "It is interesting from an ocean technology perspective but, most importantly, in providing new insights into key biogeochemical processes in a pivotal region of the ocean." (reviewer 3). The capability to detect nitrite will have applications beyond ODZs. For example, there is extremely interesting nitrite variability in the equatorial Pacific that is likely tied to iron limitation of nitrate reduction.

The relationship between chlorophyll fluorescence measured by profiling floats and chlorophyll measured by extraction methods in the laboratory (Roesler et al., 2017) or by remote sensing of ocean color (Long et al., 2024) varies geographically. Extremely large ratios of chlorophyll determined by fluorescence to chlorophyll determined by extraction or by ocean color are found in the Southern Ocean. Extensive laboratory work indicates that these large ratios are an indication of iron limitation (Schallenberg et al., 2022; Ryan-Keogh et al., 2023). This work opens a pathway for the global BGC-Argo array to assess variability in ocean iron limitation. When float sensor data is merged with models of aerosol iron deposition (Weis et al., 2024) it becomes possible to develop quantitative assessments of the role of trace elements in regulating ocean productivity.

We continue to improve sensor performance to enable new science opportunities. As new and modified sensors are developed, we test their performance in the system prior to adoption, which is an important contribution to commercial capabilities. For example, we played a seminal role in motivating the development and then validation of the new Sea-Bird SBS-83 oxygen sensor. Unlike past Argo oxygen sensors, which were either slow in response, but capable of air calibration, or faster responding but not capable of air calibration, the SBS-83 is both fast and can be calibrated in the air on each profile. We have tested the sensors carefully. This includes deployment of floats with three different models of oxygen sensor, including the SBS-83. They are now being incrementally introduced into our array with 111 now deployed. The adoption of this new technology is a key step to eliminating a second order bias in oxygen data due to slow oxygen sensor response. Having both types of sensors operating is also key to validating numerical filters that can be used to improve the data from the slower responding generation of sensors. This work will enable improved estimates of ocean deoxygenation. A funding gap in BGC-Argo may result in the loss of much of this expertise and a decrease in industrial capability.

Broader Impacts and Workforce Development

Student and postdoctoral fellow training has been an integral part of US BGC Argo since SOCCOM started in 2014. Students and postdocs from partner institutions have participated in research cruises, deployed floats, and worked with float data. They have also actively participated in workshops helping to introduce others to the data resources available online. SIO has completed a "Makerspace" laboratory with research grade electrical and mechanical prototyping equipment, enabling very tight coupling between education, technology development, and research. Graduate courses have been held every year since 2023 introducing students to BGC Argo sensors and technology and enabling students to build and test their own sensors and instruments.

Built on the SOCCOM "chemistry school" success, GO-BGC has also been holding data user workshops every other year of the program (2022, 2024, and 2026) increasing the potential users of BGC Argo data to a much wider audience. In alternate years (2023 and 2025), teacher professional development workshops have been held at UW designed to introduce K-16 educators to the BGC Argo effort and facilitate the development of student curricula focused on profiling float data. These workshops were based on the successful EARTH (Education And Research: Testing Hypotheses – www.mbari.org/EARTH) workshops that have been running for 20 years at locations around the United States. 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 the lesson plans and curriculum based on local and national standards, these are then posted online and are often presented at regional and national meetings by the educators (NSTA, NMEA, ASLO).

We have also continued the highly successful “Adopt-a-Float” program initiated through the SOCCOM project. Ninety floats have been adopted by schools and other groups from all 50 states (including Guam and Puerto Rico) as well as 16 other countries. All float adopters (and anyone else who might be interested) can access the data coming back from their float (or any float) via the Adopt-a-FloatViz system and are sent a monthly newsletter (which can also be accessed online).

GO-BGC has also been working with the internationally successful MATE (Marine Advanced Technology and Education) ROV Competition since 2021. The MATE ROV Competition challenges students in grades 4-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 competition emphasizes and inspires a mindset of entrepreneurship and innovation. MATE creates 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;
- 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; and
- Disseminate these products as well as information about the project via the MATE ROV Competition website (www.materovcompetition.org) and presentations at education and industry conferences (e.g., NSTA, Underwater Intervention, Oceans) as well as during MATE competition events.
- And for the last two years MATE has also been coordinating and running a community college focused workshop at UW providing students an opportunity to work with profiling floats, float data, sensors, and spend a day at sea deploying what they have worked on during the week long workshop.

Operational and Technical Challenges

What will be needed to sustain BGC Argo in the long term?

The goal of the BGC-Argo Science and Implementation Plan (BAPG, 2016) is to sustain a 1000 float array with each float equipped with 6 BGC sensors (oxygen, nitrate, pH, chlorophyll, optical backscatter, downwelling irradiance). The plan assumed that the US would sustain half of that array (500 floats), as in Core-Argo. The US program is now nearing the 500 float target and the US floats are a great majority (84%) of the active multi-sensor float array (Figure 1A). They enable the global span of the dataset. Creating and operating the array of nearly 500 US BGC floats gives us a good background to estimate costs to sustain the US contribution to BGC-Argo and an understanding of adjustments that could be made. As shown below, the cost of operating the US BGC-Argo array has decreased significantly over the past 10 years relative to projections in the BGC-Argo Science and Implementation Plan.

The GO-BGC proposal was based on the assumption that our BGC multi-sensor floats would have a 4 year mean lifetime resulting from random failures and battery exhaustion. The project was therefore budgeted on the assumption that 125 floats/year would be needed to sustain a 500 float array. Improvements in the Apex float controller in 2019, as well as improvements in the ISUS nitrate sensor power budget, have extended the maximum float lifetimes to nearly 7 years for Apex floats. Figure 15 shows a 6 year data record for one of the first Apex floats with improved electronics. This float has sufficient remaining energy to operate for nearly one more year. Although maximum lifetimes are now close to 7 years, mean lifetimes will be near 5 years (Figure 16) due to various failure mechanisms. As a result, the replacement rate for floats in the GO-BGC-2 (renewal) proposal submitted to NSF was set at 110 floats per year.

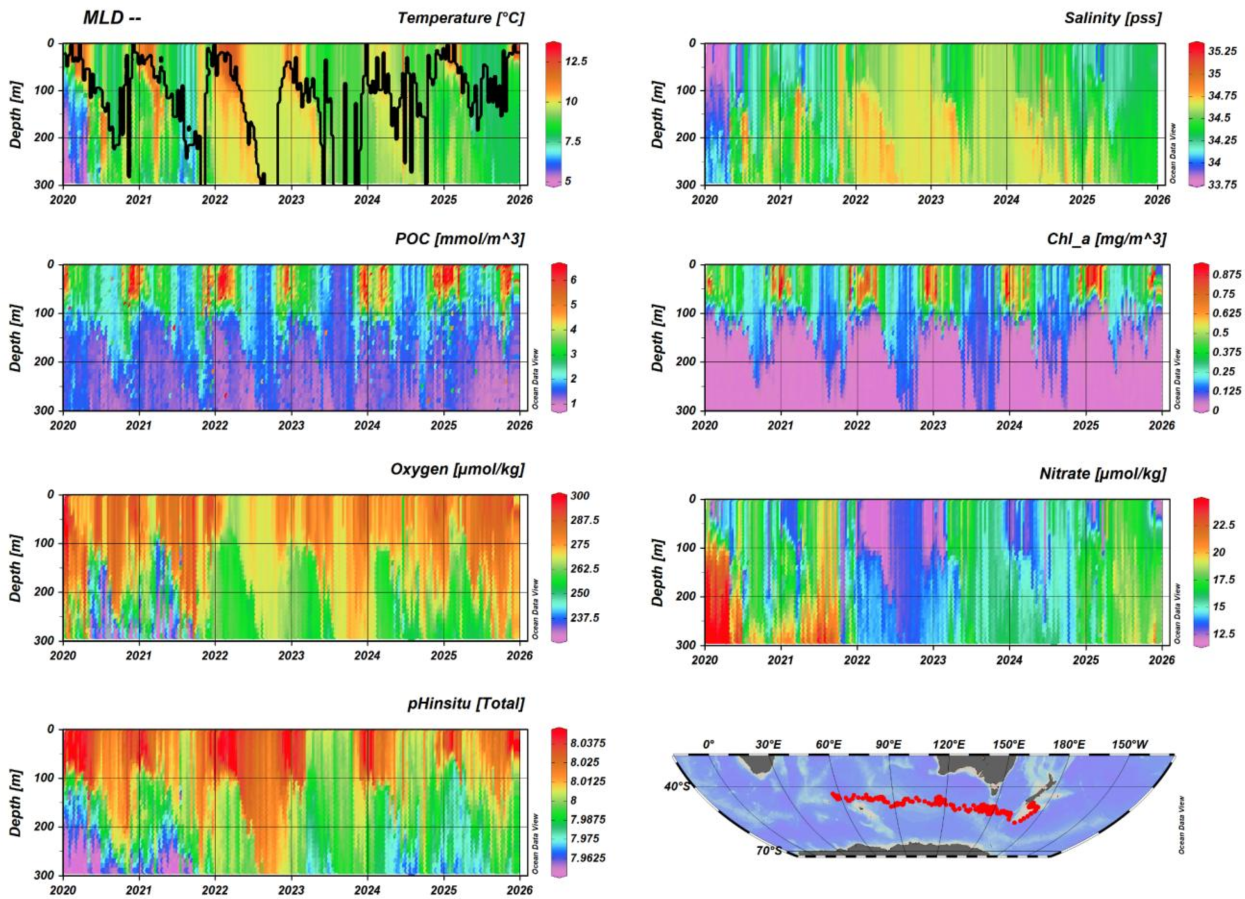


Figure 15. A six year data record in the upper 300 m for UW Apex float 5906209. Temperature, salinity, Particulate Organic Carbon (POC - a linear transformation of optical backscatter), Chlorophyll, Oxygen, Nitrate and pH at in situ conditions are shown. The Mixed Layer Depth (MLD) is shown as a black line on the temperature plot.

110 floats/year is a replacement rate that now exceeds the number needed to sustain an array of 500 US BGC-Argo floats, assuming no significant technical issues arise. However, BGC sensor failures occur independently of float survival rates. Annual sensor survival rates range from 99.5% survival/year for CTD’s to 93% survival/year for pH. The cumulative probability that

all 6 BGC sensors survive is about 86% per year. The 110 floats/year rate would sustain an array of about 425 floats with all 6 sensors operating. In addition, ~100 floats would be operating with 1 or more BGC sensors not functional. These floats would make important contributions to the scientific dataset, albeit not with the same functionality as a float with all sensors operating.

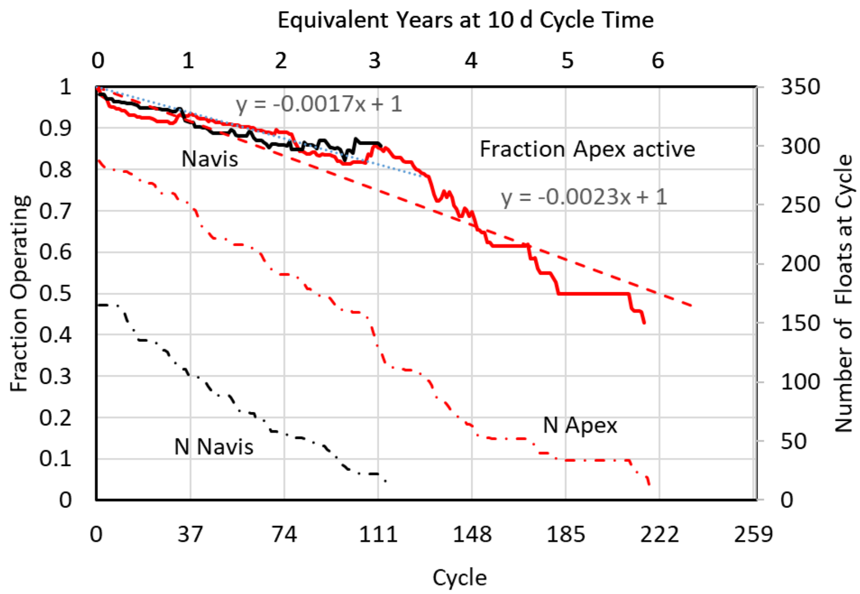


Figure 16. Fraction of 5+ sensor UW Apex floats equipped with the APF 11 float controller (solid red line) and UW and WHOI Navis floats (solid black line) versus cycle number (bottom axis) and equivalent years at a 10 day cycle time (top axis). The dash-dot lines are the total number of each float type available (operating plus dead) to calculate the operating statistics at each cycle number. The fraction operating calculation is cut off when there are fewer than 20 total floats available.

How could costs be reduced and what trade-offs should be considered?

The costs to sustain a program are driven by the float and sensor costs needed each year to replace failing floats. Total annual project cost is, to a large extent, a multiplier of the number of floats. Lifetime costs for SOCCOM and GO-BGC floats (capital, communications, deployments, initial data setup and subsequent data processing, program management, education/outreach) are near $150,000. The GO-BGC-2 proposal was submitted to NSF for 330 total floats acquired over 3 years. It was budgeted at $43,864,866 for the capital, deployment, and management costs. A separate operational proposal for communication costs and to process and distribute data after floats were deployed would have been required. These costs are near $2,000,000 per year ($6,000,000 total for 3 years) based on the current GO-BGC operations. Total program cost would have then been near $49,864,866 over three years or $151,000 per each float deployed. Note that these amounts do not include any costs to do scientific analysis with array data, other than minimal assessments of array function. A metric for successful operation is uptake and analysis of the data by independent researchers.

The current lifetime cost for a 5 or 6 sensor BGC-Argo float is remarkably similar to the projected lifetime cost of these floats in the BGC-Argo Science and Implementation Plan (BAPG, 2016) after adjusting for inflation during the 10 years since the plan was written. The lifetime cost of a 5 or 6 sensor float in 2016 was projected to be $107,600 (Table 5 of the BAPG, 2016). The US mean inflation rate for the past 10 years is 3.2%, which adjusts the 2016 cost estimate to $147,400. This is within 2% of the cost used in the GO-BGC-2 proposal and is explainable because the Implementation Plan did not include the costs of Broader Impacts efforts required by NSF. The consistency of the cost estimates in 2016 and 2026 reflects the care with which the Implementation Plan was written. Further, floats produced in 2026 will operate considerably longer than floats produced in 2016. The 1 year extension in lifetime amounts to a ~20% reduction in the inflation corrected cost per profile. We do note, however, that international partners have struggled to produce floats at the same cost as the US program. This probably reflects some naivety by the Plan authors regarding multi-national costs, tariffs, agent fees, and volume production.

The cost per float should remain relatively constant if the number of floats is decreased until a point where industry economies of scale force them to increase their per unit (float or sensor) charges. We estimate that would occur when float acquisitions dropped to about half of current rates, based on discussions with suppliers. Thus, a US program that acquired only ~50 floats per year, and sustained an array near 250 floats, would operate on a budget near $8,300,000 per year (~$25,000,000 total over 3 years). If the program operated at this level, there would likely not be enough work to justify having 3 major BGC float producing institutions (UW, WHOI, SIO). It is also likely that at least one BGC float supplier would leave the market.

Reducing the array size will come at a cost to the scientific capabilities of the system. As shown in Figure 7, the machine learning mapping error for oxygen depends on the number of floats. Figure 4 shows large and oceanographically inconsistent trends in the rate of DIC concentration change that occur as the number of floats used to train Neural Networks decreases. As another example, Figure 14 shows that the error in measuring primary productivity increases rapidly as the number of floats decreases. There is no other method that directly measures ocean productivity. A decrease in float numbers would directly affect our ability to measure ocean productivity change. Fewer floats would reduce our ability to detect spatial variability in ocean acidification rates (Figure 9). The only effective way to reduce the number of floats without reducing science capability is to extend float lifetimes, as has been done with the Apex float. However, also note that as float lifetimes extend and annual numbers of float purchases are decreased, manufacturers may find that production economies of scale are reversed and they may increase per float prices to sustain their profit margins.

Much of value from the BGC-Argo array comes from having a global ocean view. It is the consensus of the GO-BGC Executive Team that if funding required a reduction in array size, up to 50% of the target, priority should still be given to maintaining a global distribution, rather than regional arrays. Only if array size were less than 50% of the Implementation Plan target should the focus shift to maintaining regional arrays.

The float capital costs are largely driven by the expense of the sensors. Capital costs for a float range from about $85,000 for an Apex float assembled at UW with nitrate and pH sensors supplied by MBARI to about $110,000 for a commercial float. The per profile costs will be similar as the latest generation of commercial float will likely have a longer projected lifetime than an Apex once the reliability of these new platforms are increased. The nitrate and pH sensors are the most expensive sensors. Proven units are available commercially only from Sea-Bird Scientific. These sensors were developed at MBARI (Johnson et al., 2013; Johnson et al., 2016). To avoid a sole-source supply risk, MBARI has continued to manufacture a significant number of these units at a cost that is about 60% of the commercial price. The unit price of a commercial SUNA nitrate sensor for the GO-BGC-2 proposal was near $24,000 (recent price reductions may lower this), while the complete, 6 sensor package (including CTD) was about $55,000 for a large purchase with no warranty. While that cost seems high, it is not particularly higher than the cost of the SBS-61 CTD used on Deep-Argo floats.

Program costs could be reduced by about 13% by eliminating both the ISUS and SUNA nitrate sensors, which are the most expensive of the BGC sensors. The relatively small change reflects recent, large reductions in the nitrate sensor price at Sea-Bird. However, eliminating nitrate would create a significant reduction in capabilities. Sensing nitrate and nitrite is key to our understanding of oxygen deficient zone nitrogen cycling. That capability was independently highlighted by the reviewers of the Bif et al. (in review) paper that reexamines nitrogen cycling using the new capability to detect nitrite, as noted above. Nitrate also provides a key metric for productivity changes at high latitudes (Plant et al., 2016; Liniger et al., 2025). Observing nitrate is also key to our understanding of carbon cycling in the low nutrient, central gyres (Johnson et al., 2010; Fawcett et al., 2018; Curry et al., 2026). Direct observations of nitrate with sensors on floats and gliders demonstrates that the large Annual Net Community Production in these oligotrophic regions is supported by non-Redfieldian carbon production, which only becomes apparent when sensors for multiple chemical species are operated.

Note that the sensor and float costs in GO-BGC and GO-BGC-2 are significantly lower than prices offered to other programs because we had committed to a large purchase over multiple years, which enabled much more efficient commercial planning and production. One of the key lessons from GO-BGC was that a funding mechanism where large, multi-year orders could be assured for industry will lead to significantly lower prices. SBS informed us that this enabled them to institute multi-year planning for these orders, which was the major factor in this price decrease. Thus, building a sustained and predictable acquisition schedule is a key to affordability.

The original GO-BGC proposal and the pending NSF renewal both included modest support for ship time ($900,000 and $600,000). The ship funds have been used to support multiple charter cruises on the New Zealand Research Vessels Kaharoa and Kaharoa II, which can carry large numbers of floats and deploy them quickly. These ships have deployed over 50 floats for GO-BGC in regions of the Southern Hemisphere that are difficult to reach with traditional research cruises and ships of opportunity. While ship funds could be eliminated from the budget, doing so would slow deployments and likely result in a less than optimum float distribution in the Southern Hemisphere.

Could AI/ML compensate for reduced investment in BGC Argo floats?

Does machine learning allow us to deploy fewer BGC floats? Perhaps this question could be rephrased as, “Does the combination of temperature and salinity have sufficient predictive power for each biogeochemical parameter such that ML can detect the correlations using sparse biogeochemical data and then use the denser Core-Argo array to create accurate grids of biogeochemical values?” The answer is likely that Machine Learning can improve our ability to produce more accurate maps, but it will not substantially reduce the number of floats needed to train ML methods particularly as changing ocean processes can influence the stoichiometric relationships between foundational elements (e.g., C, N, O). For example, through temperature dependent respiratory quotients (C:O) or changes to the fractions of particulate vs. dissolved organic matter produced and respired (each with a unique C:N) the elemental ratios involved in biogeochemical processes will shift.

Figure 4 shows a substantial increase in the uncertainty of Southern Ocean DIC predictions from a Neural Network trained on temperature, salinity, oxygen, position and time when the size of the training data set is halved. It is apparent that the Neural Network trained on a small number of floats does not have sufficient skill to make predictions consistent with the Neural Network trained with a float array at the desired density for US floats. It is an open question whether the desired array size is sufficient, although the distributions do appear to be converging at the largest densities.

Figure 7 shows that the uncertainty of oxygen predicted by ML methods is reduced as the number of floats in the training dataset increases. This figure may indicate a plateau is reached at around 600 floats in the training data set. Jon Sharp (personal communication) believes the plateau is a real feature, but also includes some 'edge effects', where the algorithm becomes less effective near the end of the time series as fewer training data points are available. Given the need for a validation data set and possible shortfalls in international contributions, the target of 500 US floats is reasonable.

In addition, Neural Networks developed to predict biogeochemical variables in the shipboard GLODAPv2 dataset have large uncertainty when only temperature, salinity, and position are used as variables (Carter et al., 2021). Predictive skill increases if oxygen is added as a training variable, but the best results are obtained when a suite of biogeochemical variables are used to train the Neural Network that predicts other variables. This implies that the correlations found by training only on temperature and salinity or temperature, salinity, and oxygen do not capture all of the needed information to predict other biogeochemical variables. The Machine Learning methods will likely only predict scenarios they've been trained on, so truly anomalous conditions resulting from say a massive MHW could result in wildly incorrect predictions. Hence the need for a robust training dataset. The Neural Networks are impressive in their skill, but still lack the accuracy of measurements.

Much of the skill in predictions based on temperature, salinity and oxygen derives from the relationship between biogeochemical variables created by a near uniform composition of living and dead marine organic matter. This nearly uniform composition is known as the Redfield Ratio. Redfieldian behavior applies to much of the biogeochemical cycling in the ocean, but often the most interesting results are observed in the anomalies to Redfield behavior (Johnson, 2010; Deutsch et al., 2012; Johnson et al., 2022). Observing such anomalies is one of the primary motivations to have multiple sensors that have some connectivity between their observations, but not complete connectivity, that is created by the Redfield Ratio. It is an open question whether a Neural Network would capture non-Redfield behavior. This is not possible to test using a model dataset, as nearly all BGC behavior in models is built around Redfield behavior.

One can conclude from these observations that Machine Learning methods, at least as presently implemented, do not compensate for reduced array sizes.

Could emerging technologies compensate for reduced investment in BGC Argo floats?

New technologies and technical capabilities will undoubtedly have impacts on BGC-Argo operations. Emerging technologies, such as Iridium communications or lithium batteries, have greatly enhanced Argo operations that initially began with very slow System Argos communications and alkaline batteries. These technologies have extended float lifetimes, increased reliability, enhanced capabilities, and mitigated the effects of fixed budgets against inflating costs. As noted above, the increased lifetime of US BGC-Argo floats has reduced per profile costs about 20% when compared to projections of the 2016 Implementation Plan. The incorporation of biogeochemical sensors is another example of technology adoption that has enhanced the Argo mission. As new capabilities are proven, they will most likely be adopted by the Argo system.

However, it is essential that new capabilities be carefully tested and vetted before they are widely adopted. Reliable operation of the profiling float and sensor array and the associated data pipeline and quality control methods over years is an exceptionally difficult challenge and the success of Argo reflects careful adaptation of new technology to ensure it is fit for the purpose. As a result, new technologies enter into widespread use in the Argo system only when they are well vetted through deployments of multiple systems that show reliable operation over at least several years. These new technologies should demonstrate acceptable behavior over the full Argo mission envelope, which includes operation from polar regions through the tropics. This careful timeline with extensive testing of new technology is necessary to prevent widespread system failures.

Pathways to Sustainability

What are the opportunities for and challenges to transforming BGC Argo into a long-term facility?

Sustaining the array will require continuing deployments to replace aging floats. About 20% of the US array must be replaced each year. This replacement fraction will likely be larger for groups with less skill in preparing floats. If the GO-BGC-2 proposal is not renewed by NSF, then US float deployments will fall to near zero in 2027. If no new floats are acquired and deployed, then the 500-float array will begin to decline as floats exhaust their batteries. The array size will decrease at the ~20% per year rate. Even more concerning is that float engineers and technical staff will leave the field, and float manufacturers will lose their market and may cease production of these technologies. A recovery from the loss of expertise would take many years. Thus, there is a crucial need to sustain and expand capability. At this point in time, the array of 5+ sensor floats is dominated by the US contribution (Figure 1A). International partners need to increase their deployments just to enable the additional 500 floats called for in the BGC-Argo Science and Implementation Plan (BAPG, 2016). Additional increases in international contributions to replace the US effort are certainly not guaranteed and a significant decline in floats appears likely. If that occurs, the array that is now global in extent will probably become a set of small regional arrays similar to the current distribution of international floats (Figure 1). This greatly reduces the utility of the array.

The GO-BGC-2 proposal is currently submitted to NSF Ocean Science programs. In the long-term, a key to sustaining GO-BGC through NSF or other funding agencies would be to move the funding from science programs into a facilities budget. Operation of large and costly facilities directly within a science budget is challenging. The NSF has approached this challenge by moving the direct facility costs out of science budgets and incorporating them in a separate budget line. As a result, ship costs are not a direct budget item in NSF Ocean Science proposals. The agency recognized that including ship costs directly in research budgets would tend to make them non-competitive. Further, these projects generally require a sustained funding mechanism, which differs from most science proposals.

Finally, we note that the cost of BGC-Argo is mitigated by existing US Argo infrastructure, personnel, sea-going networks, data system, and expertise. Without that leverage, these projects would likely cost quite a bit more. Sustaining Core-Argo is thus a key to controlling BGC-Argo costs.

Who are existing or emerging key players or partners?

There are several areas where GO-BGC and BGC-Argo, in general, may form new partnerships. The Global Greenhouse Gas Watch (G3W) of WMO (https://wmo.int/activities/global-greenhouse-gas-watch-g3w) is a multi-national project with a goal to track the flow of greenhouse gases through the atmosphere in real-time with monthly resolution (https://g3w.wmo.int). Key to that objective is a quantitative assessment of the CO_2 flux into the ocean in with real-time, monthly resolution. BGC-Argo has the potential to contribute to this goal by providing monthly estimates of surface ocean pCO_2 (Figure 2) and interior ocean carbon storage (Figure 4).

Operational weather forecasting is increasingly based on coupled atmosphere ocean models such as the NOAA Global Forecast System, which operates as a coupled atmosphere, ocean, land, and ice system. Many operational centers are now including biogeochemical parameters in their ocean components (https://oceanpredict.org/observations-use/#section-argo-profiling-floats) as both validation tools and, in a few cases, for assimilation on a research basis. Incorporation of an assimilated biogeochemistry component is driven by studies that indicate improved model performance when properties such as chlorophyll or oxygen are included (e.g., Karagiorgos et al., 2025). BGC-Argo is the primary tool that provides the real-time, in situ biogeochemical data needed for these improved systems.

There is an increasing awareness that limiting earth surface temperature increases will require the removal of carbon dioxide from the atmosphere. The ocean is one of the planet's largest carbon reservoirs and Marine Carbon Dioxide Removal may be an essential component in any carbon dioxide removal effort. To be effective in lowering atmospheric carbon dioxide, such projects would have to operate at a global scale. BGC-Argo will be an important tool in verifying the effectiveness of such efforts and understanding potential side effects (Boyd et al., 2023).

There is increasing momentum towards active development of deep-sea mining. The International Seabed Authority has granted nearly 20 exploration licenses. Preliminary experiments associated with exploratory activity indicate that the midwater mining plumes may have large, deleterious effects on the midwater community (Dowd et al., 2025). BGC-Argo floats may play a role in observing long-term impacts of the discharge plumes, which fall within the 2 km sampling range of floats (Figure 17). Beyond direct observation of plume particles with optical backscatter sensors, floats can detect rates of midwater metabolic processes using oxygen sensors (Martz et al., 2008; Su et al., 2022).

BGC-Argo data may play an important role in managing pelagic fisheries, as viable habitat is highly constrained by species-specific temperature and oxygen constraints (e.g., Deutsch et al., 2024). Lehodey et al. (2015) have shown that the distribution of oxygen plays an important role in fishery models used to predict albacore tuna distributions. Projected decreases in oxygen have a large effect on size of the tuna stock. The gridded oxygen products under development at PMEL (Sharp et a., 2023) could become a key component in the management and optimal utilization of such fisheries.

In all of these cases, BGC-Argo is not yet an established contributor. It will require a dedicated effort to demonstrate the system capabilities and build links to the established observing systems. Some of these efforts are now underway and we expect they will come into fruition in the near future.

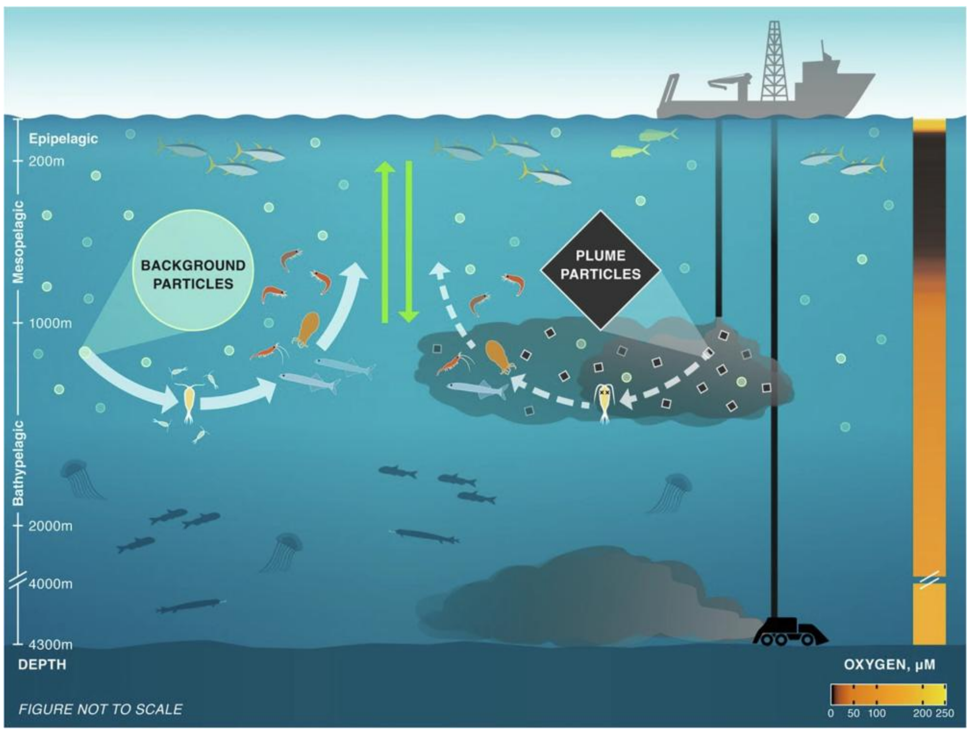


Figure 17. schematic of ocean seafloor mining showing the depth ranges at which manganese nodule mining and plume discharge will occur. The plume discharge overlaps with the 2000 m profiling range of BGC-Argo floats. From Dowd et al. (2025).

What are the opportunities to increase scientific value through expanded user base and applications (e.g., development of sensors resilient to biofouling in the surface waters)?

Real-time data and real-time analysis of the data is required for ocean and carbon management - whether understanding global carbon cycle, operational weather forecasting, quantifying marine carbon removal at the global scale, or more efficient management of global fisheries.

The availability of real-time satellite remote sensing products such as temperature, ocean color, or altimetry have demonstrated the value of delivering data with no lag time. The challenge for BGC-Argo is to emulate this. Significant work is being done at NOAA PMEL to bring Machine Learning, gridded products into low-latency production (monthly releases of weekly fields). Such products would likely be adopted widely.

What steps are most critical for the program's future?

1) Continuation of US BGC-Argo

Short-term funding
Federal agencies and academic institutions have invested substantial funding and tremendous effort into scaling up the US half of the Argo program to produce and support over 100 GO-BGC floats per year. With the end of the MSRI-2 award, which accounts for the majority of the US contribution, this robust program will come to an abrupt halt this year, with no significant US deployments planned for 2027.

Currently 96% of the GO-BGC floats have been received and there are only a handful of BGC-floats on order for all US programs going forward. This small volume of orders is not sufficient for commercial float manufacturers to maintain the highly skilled teams they have invested in for float production, nor to sustain R&D, production, and support teams at the academic partners. To prevent this disruption on both sides, funding on the order of $5 million for capital float orders and $3 million to keep key personnel employed is needed within the next 6 months. This would support the GO-BGC array at near half-strength for an additional year and sustain industrial efforts.

Intermediate and long-term funding
Moving forward, the US government should provide long-term funding for the array. As noted above, BGC-Argo meshes closely with US Federal Research priorities as outlined in OMB2025, the NSF Strategic Plan, and the NAS Report “Forecasting the Ocean”. The number of critical ocean chemical and biological observations made from ships has plummeted to historic lows (e.g. Figure 5). There is no realistic scenario where the volume of shipboard observations will be restored, if for no other reason than the ship time cost would far exceed the cost of operating an autonomous array. BGC-Argo is the only proven system that can make the required measurements at seasonal time scales and into the ocean interior. If we are to create the data needed to answer the urgent questions posed in “Forecasting the Ocean”, then BGC-Argo must be sustained.

Given US BGC-Argo’s alignment with these research priorities, it should ultimately be supported as a US research infrastructure facility with sustained, long-term Federal funding. In the interim, a 3-year renewal proposal for $44 million has been submitted to NSF and reviewed, providing a bridge to a longer-term multi-agency solution. If Federal funds are unavailable in the next few years, a rescue by private foundations that provides short-term support will be necessary.

2) Growth of International BGC-Argo

BGC-Argo is inherently an international program, driven by the need to share costs, coordinate on deployments, leverage scientific expertise in data quality control, and collaborate for operation in EEZs. Sustaining international participation is critical for the program’s future. However, implementation of the international (non-US) component of 500, 5+ sensor floats has been much slower than in the US. Multiple factors are responsible for this. Floats cost considerably more in many countries due to tariffs and agent fees, as well as small volume and intermittent purchases. Further, these smaller nations often purchase a warranty on the few floats they buy to insure against embarrassing losses of a complete year class of floats. However, the warranties add significantly to the float cost as manufacturers must protect themselves against large scale losses, as occurred in Core-Argo due to wide-spread failures in pressure sensors and in salinity sensors (Wong et al., 2020). Larger programs can be self-insuring and forego any warranty costs. In addition to high hardware costs for smaller national programs, the complexity of processing BGC-Argo data often overwhelms smaller Data Assembly Centers. This is apparent in the large amount of international, real-time BGC-Argo data that does not receive any quality control.

The solution to these problems must lie in greater international collaboration. This is exemplified by the Argo Oxygen Audit developed by the data center at MBARI to increase the amount of quality controlled oxygen data. It is the Argo policy that only the national center responsible for a given float may quality control and adjust, if necessary, that floats data and place the result back in the Argo data system. The audit does the equivalent work but only passes on a best estimate of data quality and necessary corrections to the responsible data center. The audit has reduced the amount of unprocessed oxygen data from about 70% of the total in 2019 to about 10% today. The oxygen audit should be extended to all parameters. An optical back-scatter audit is underway at LOV. While similar efforts are harder to do with float hardware, headway is being made. The community is actively sponsoring training workshops focused on enabling national programs to identify float faults before deployment and reduce infant mortality.

Improvements and extensions of these efforts to increase float survival and data quality are possible and can be done at a fraction of the cost of acquiring additional floats. However, most national programs are operating with limited budgets and have few resources to sustain such efforts. Continued interaction and education of float manufacturers by experienced Argo technicians is also a key to improving the products. This extends to both float hardware and software. Finally, because small volume orders will likely remain expensive, regional consortia of international programs could be developed to provide the kind of large orders float manufacturers need to commit to lower prices.

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