TECHNICAL NOTE

OneArgo: A New Paradigm for Observing the Global Ocean

AUTHORS

W. Brechner Owens
Woods Hole
Oceanographic Institution

Nathalie Zilberman
Scripps Institution of Oceanography

Ken S. Johnson
Monterey Bay Aquarium
Research Institute

Hervé Claustre
Sorbonne Université and CNRS,
Laboratoire d'Océanographie
de Villefranche

Megan Scanderbeg
Scripps Institution of Oceanography

Susan Wijffels
Woods Hole
Oceanographic Institution

Toshio Suga
Graduate School of Science,
Tohoku University

ABSTRACT

OneArgo is a major expansion of the Argo program, which has provided two decades of transformative physical data for the upper 2 km of the global ocean. The present Argo array will be expanded in three ways: (1) Global Core: the existing upper ocean measurements will be extended to high latitudes and marginal seas and with enhanced coverage in the tropics and western boundaries of the major ocean basins; (2) Deep: deep ocean measurements will be obtained for the 50% of the global oceans that are below 2,000-m depth; and (3) Biogeochemical: dissolved oxygen, pH, nitrate, chlorophyll, optical backscatter, and irradiance data will be collected to investigate biogeochemical variability of the upper ocean and the processes by which these cycles respond to a changing climate. The technology and infrastructure necessary for this expansion is now being developed through large-scale regional pilots to further refine the floats and sensors and to demonstrate the utility of these measurements. Further innovation is expected to improve the performance of the floats and sensors and to develop the analyses necessary to provide research-quality data. A fully global OneArgo should be operational within 5–10 years.

Keywords: Argo floats, Argo sensors, OneArgo, climate change, biogeochemical measurements

Introduction

When it was originally conceived in 1998, the goal of the Argo program was to provide profiles of temperature and salinity over the upper 2 km of the ice-free global ocean at a nominal spacing of 300 km on a 10-day interval to match the observations of ocean sea level obtained from Jason satellite altimeters (Argo Steering Team, 1998). The Argo program is now a major component of both the Global Ocean Observing System and the Global Climate Observing System. Roemmich et al. (2019) proposed at OceanObs '19 to expand the original Argo Program to OneArgo. OneArgo will (a) improve Argo's global coverage and value beyond the original design; (b) extend Argo to span the full ocean depth; (c) add biogeochemical (BGC) sensors for improved understanding of oceanic cycles of carbon and nutrients, and ecosystems; and (d) consider experimental sensors that might be included in the future. Progress toward full implementation of OneArgo has begun but will take 5–10 years to complete and necessitate a tripling of funding.

The Argo program established a revolutionary new framework and infrastructure for collecting, managing, and freely sharing in situ oceanographic measurements on a global scale for use in operational, climate assessment, and research communities (Johnson et al., 2022). Intergovernmental Oceanographic Commission (IOC) resolution XX-6 set up a process to notify Coastal States to protect their rights when Argo floats drifted into their territorial waters. Another resolution, IOC Resolution IOC/EC-LI, was adopted in 2018 to extend these regulations to BGC Argo floats and their six BGC parameters. OneArgo will build on Argo to provide data expanded geographically, both horizontally and vertically, with new multidisciplinary parameters while maintaining the rights of coastal states.

In collaboration with commercial vendors, OneArgo will develop and improve upon the existing Argo float design by expanding their lifetimes to maintain the global array, incorporating higher accuracy conductivity/temperature/depth (CTD) sensors to sample the deep ocean (4,000–6,000 m for Deep Argo), and adding new BGC and optical sensors to collect BGC data. The data system has already been developed to assemble and disseminate the expanded data files, and procedures to quality control and calibrate the new sensors are being refined and evaluated. The goal of OneArgo is to integrate the Deep and BGC floats seamlessly, avoiding degrading the spatial and temporal coverage that the present Core array delivers for real-time, seasonal, and climate analyses. While the work to implement OneArgo is well underway, there is still a large resourcing challenge to meet and many developments that must be completed before it will provide the global data set needed for the expanded scientific objectives proposed under the auspices of the UN Ocean Decade.

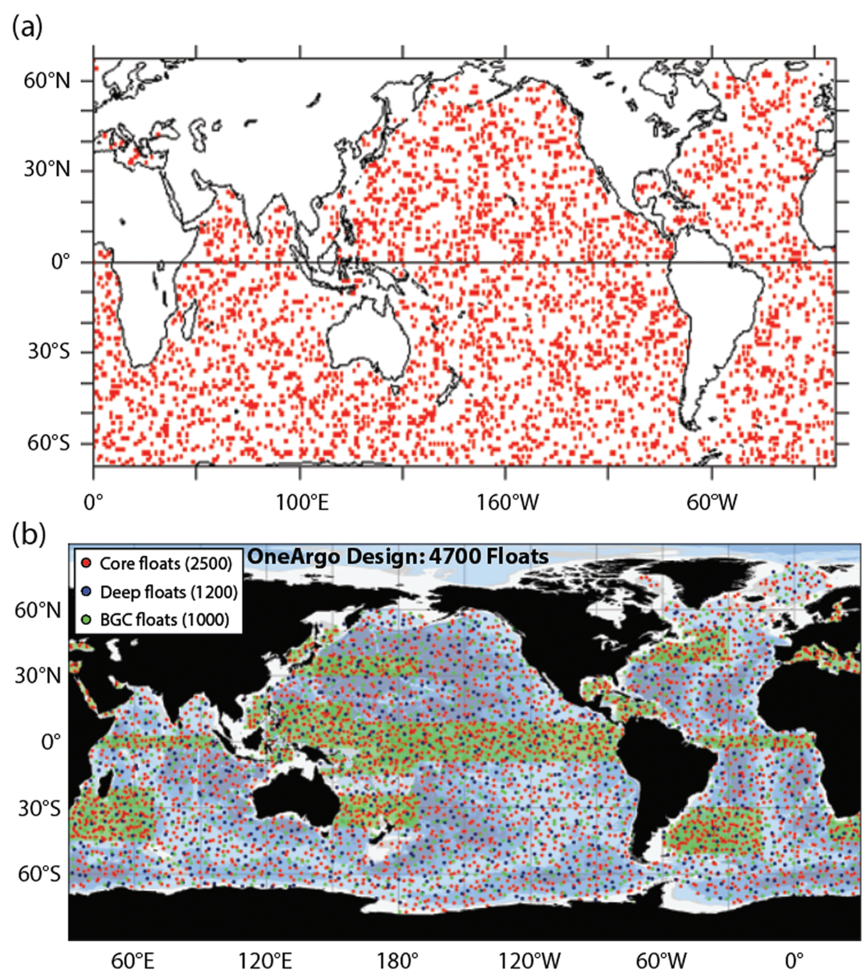
The following sections address the details for the Core, Deep, and BGC components of OneArgo. A brief summary section presents the status of OneArgo and recommendations for its implementation.

Core Argo

The World Ocean Circulation Experiment (WOCE; Siedler, Gould, & Church, 2001) and Tropical Ocean-Global Atmosphere (McPhaden et al., 1998) programs carried out from the mid-1980s to late 1990s increased our understanding of the ocean's role in seasonal to interannual climate variability and change. While the Jason-1 satellite altimetry mission provided measurements of sea surface height variability, there was a need for global subsurface measurements to illuminate the subsurface manifestation of this variability. The technical development of autonomous subsurface floats during WOCE provided the necessary capability to fulfill this need, which led to the multinational proposal for a global subsurface ocean observing system (Argo Steering Team, 1998), comprising 3,000 profiling floats, obtaining a global snapshot of the temperature and salinity of the upper 2 km of the ocean every 10 days to match the repeat cycle of the satellite altimetry mission (Figure 1a). The Argo Steering Team was established with representation from several agencies and countries and the Argo Data Management Team was set up to develop, oversee, and facilitate data management and quality control procedures. National and regional Data Assembly Centers were established to receive, decode, and quality control Argo data according to agreed-upon real-time tests and then share it with central repositories (Global Data Acquisition Centers, GDACs) and send it within 12 h onto the Global Telecommunication System data stream to support real-time ocean analyses and forecasting at operational centers. Quality controlled

FIGURE 1

(a) Original Argo Program Conceptual Array (from Argo Steering Team, 1998). (b) Conceptual OneArgo array with floats color coded for Core, Deep, and BGC-Argo. The floats are randomly distributed in regions with the intention to locate either one or two floats per 3° × 3° square (from Roemmich et al., 2022).



delayed-mode data, produced by Argo data experts following agreed-upon procedures, are available within 12 months for climate research and assessments. As of 2022, the Argo program has collected nearly 3 million profiles. Uncertainty of the Earth's Energy Imbalance estimate has decreased by a factor of 4 due to Argo (Johnson et al., 2016; Wijffels et al., 2016), and over 5,000 peer-reviewed papers using Argo data have been published.

The original array was limited spatially, excluding marginal seas and the polar oceans, and significantly undersampled in dynamically important regions, such as the tropical oceans and western boundary currents. OneArgo proposes to address these limitations (Figure 1b). A challenge for OneArgo will be to implement the array shown in Figure 1b, while maintaining the spatial and temporal density of Core Argo, which is crucial for real-time forecasts and minimizing uncertainties in climate and seasonal analyses. While it took nearly 5 years for the Argo program to develop its basic features and infrastructure, significant technological and analytical advances have continued. These improvements have enabled the Argo array to grow from the original goal of 3,000 floats to an operational array of nearly 4,000 floats today, despite level funding in many programs. The change in telemetry and positioning from Service Argos to Iridium/GPS significantly reduced the energy requirements, increased vertical resolution by over an order of magnitude and allowed measurements closer to the sea surface. This change also reduced the time on the surface to less than 1 h, which decreased sensor degradation and float displacements due to surface currents allowing floats to stay within the equatorial current system and limiting grounding near ocean boundaries. Improvements in the buoyancy systems have also increased float lifetimes. New CTDs are being evaluated that have the potential to decrease the CTD energy cost to 10% of that used at present. Methods to detect sea ice have been developed so that floats can operate in polar seas with minimal losses. In addition to float technological advancements, improved quality control procedures are being developed to efficiently identify errors in the data and adjust for any sensor drift. That is, Argo floats and data management procedures have continued to evolve and improve to maintain the Core Argo array as effectively as possible.

Deep Argo

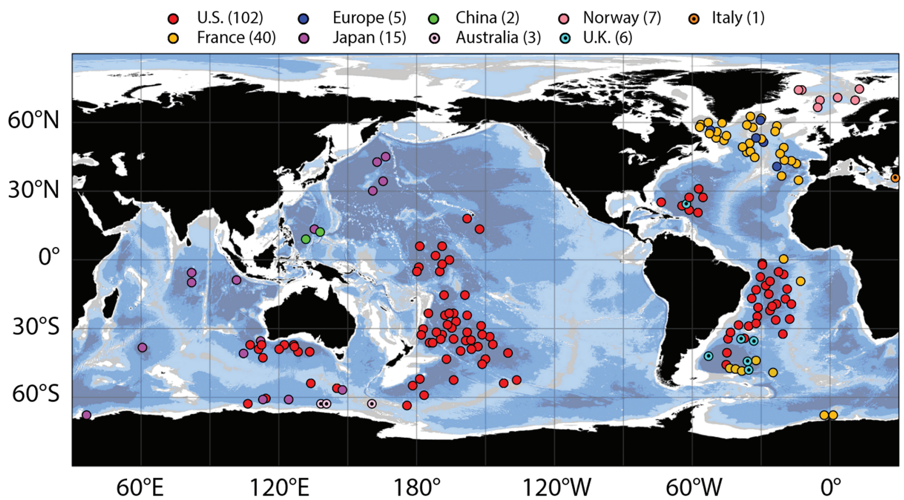
Half of the global ocean volume lies below 2,000 m. The climatic rate of ocean heat gain for this volume of 0.065 (± 0.04) W m^{-2} from 1991 to 2010 (Desbruyères et al., 2016) is about 10% of the 0.61 (± 0.09) W m^{-2} from 2005 to 2015 in the upper 1,800 dbar (Johnson et al., 2016; Wijffels et al., 2016). This estimate of heat gain in the deep ocean is based on limited, basin-wide hydrographic sections, which occur on a nominal decadal repeat cycle (Talley et al., 2016) and have uncertainties 2/3 of the observed signal compared to 1/7 for shallow, Argo-based ocean heat content estimates. Tracking deep ocean change and variability is essential for climate assessments, ocean forecasting systems, and understanding deep ecosystems. To meet these needs, low-power Deep Argo CTDs were developed with accuracies comparable to shipboard data. With a new hull, more efficient hydraulic systems and a hybrid lithium battery system, Deep Argo floats can have a lifetime comparable to those used in Core Argo. Prototype floats operating to 4,000–6,000 m were developed and successfully deployed in 2012–2014. Plans for a global 5° by 5° global array of 1,200 floats, presented at a Deep Argo Implementation Workshop in May 2015 (Zilberman & Maze, 2015) were accepted by the Argo Steering Team, and a Deep Argo Mission Team was created. In addition to reducing the uncertainties in the global estimates for the deep ocean heat-gain, the array will constrain operational and assess climate model analyses on sub-basin scales to assess and improve their performances.

To enable measurements within 3 m of the ocean floor without contaminating the CTD and while keeping the float from grounding, a mechanical bottom detection (wire) system has been mounted on the bottom of 6,000-m floats and bottom detection algorithms have been implemented on 4,000-m float models. Procedures to evaluate and quality control the deep ocean data have extended those for Core Argo. The Deep Argo mission team will operate as an international consortium that reports to the Argo Steering Team (https://argo.ucsd.edu/expansion/deep-argo-mission/).

Regional pilot arrays have been deployed in the South Pacific and the North and South Atlantic (Figure 2). These arrays have resolved (a) abyssal warming in the Southwest Pacific and Brazil basins (Johnson et al., 2019, 2020), (b) seasonal variability in deep western boundary current recirculation along the Tonga Kermadec Ridge (Zilberman et al., 2020), and (c) variations in deep-ocean properties and pathways in the North Atlantic (Desbruyères et al., 2022) and Southern Ocean (Foppert et al., 2021;

FIGURE 2

Location of the 181 Deep Argo floats active in March 2022, including 4,000-m capable Deep Arvor and Deep NINJA, and 6,000-m capable Deep SOLO and Deep APEX floats, color coded by national program. The background colors indicate ocean bottom depth: < 2,000 m (white), 2,000–3,000 m (light gray), 3,000–4,000 m (light blue), 4,000–5,000 m (blue), and > 5,000 m (dark gray). Data courtesy of OceanOPS.



Thomas et al., 2020). Recently added dissolved-oxygen sensors on Deep Argo floats provide data to differentiate pathways and identify mixing of water masses (Racapé et al., 2019). Dissolved oxygen observations in the deep ocean are also crucial to study the expansion of Oxygen Minimum Zones, investigate anthropogenic carbon storage, and assess and predict associated impact on ocean health and biodiversity. Large uncertainties exist in ocean geomorphology as only 20.6% of the seafloor has been measured (Nippon Foundation, 2021). Measurements of near-bottom pressure from the Deep Argo array and the hydrostatic equation have the potential to reduce this uncertainty by providing novel measurements of ocean bathymetry. A pilot program to evaluate bathymetry estimates from Deep Argo data is underway.

Through these pilot regional arrays, tremendous advancements have been made on Deep Argo float and sensor technology. Ongoing challenges include the need to diversify Deep Argo float and sensor manufacturers and scale up production. Three new Deep Argo float models and two CTDs are being tested in the field; one additional float model is under development.

BGC Argo

BGC-Argo extends Core Argo to include a full suite of BGC sensors: dissolved oxygen, nitrate, pH (proton concentration), chlorophyll fluorescence, light scattering by particles (particle abundance), and downwelling irradiance (solar light penetration). These enhanced profiling floats have enabled year-round measurements on ocean-basin-scales of BGC cycles that are rarely observed by conventional, ship-based sampling. These processes include global primary productivity (Johnson & Bif, 2021), carbon export (Briggs et al., 2020; Dall'Olmo et al., 2016), air-sea gas exchange (Bushinsky et al., 2017; Gray et al., 2018), plankton distributions (Cornec et al., 2021), and phytoplankton production events (Ardyna et al., 2019) and phenology (Yang et al., 2020). Ocean color satellites observe some of these processes at high resolution, but only near the sea surface and in cloud- and ice-free areas. The observations of complete seasonal cycling of chemistry and biology in the upper 2 km of the ocean are essential to understanding ocean BGC variability and the processes that govern how these cycles respond in a changing climate.

Profiling floats with one or more of these BGC sensors have been deployed throughout the global ocean over the past 20 years, and over 300 peer-reviewed publications have used BGC sensor data from BGC-Argo floats (bibliography is maintained at https://biogeochemical-argo.org). Research utilizing BGC-Argo data has revolutionized our understanding of oceanic chemical and biological cycling (summaries available in Chai et al., 2020; Claustre et al., 2020; Johnson, 2017). The success of BGC-Argo measurements and scientific advancements achieved stimulated extensive community planning efforts for a global BGC-Argo array. Following an international meeting in 2016, a plan for BGC-Argo, "The Scientific rationale, design and Implementation Plan for a Biogeochemical-Argo float array" (Biogeochemical-Argo Planning Group, 2016) was completed. The goal for BGC-Argo is to deploy and then sustain an array of 1,000 floats equipped with the full suite of BGC sensors. These floats must also contribute to Core Argo and will meet the Argo program protocols, including real-time, public data access.

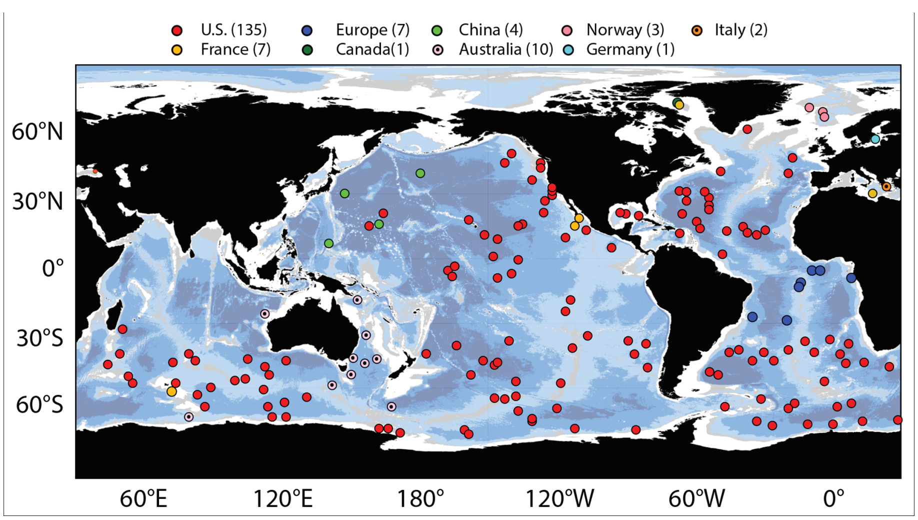
The array size requirement was determined from a variety of studies, including observing system simulation experiments, correlation length scales for BGC variables, and the subsampling of high-resolution satellite observations. These BGC-Argo floats with the full suite of sensors will be deployed with a relatively even spacing throughout the global ocean in waters deeper than 2 km. The BGC-Argo mission team will operate as an international consortium that reports to the Argo Steering Team (http://www.biogeochemical-argo.org; https://argo.ucsd.edu/expansion/biogeochemical-argo-mission/).

Currently, 450 profiling floats with BGC sensors deployed by 16 nations are operating throughout the world ocean. While the number of BGC floats is approaching half of the target level of 1,000 floats, many of these floats carry only one or two BGC sensors, generally oxygen. Relatively few (170) have the complete six sensor suite or a nearly complete five sensor suite (Figure 3). As a result, the synergistic capability of the array that results from operating multiple sensors on one platform is less than 20% of the target. However, there is now significant funding available to increase the size of the five or six sensor float array. In the United States, the National Science Foundation–funded Global Ocean Biogeochemistry Array (GO-BGC; https://go-bgc.org) will deploy 500 BGC floats with five or six sensors on each. GO-BGC should achieve its target of 56 floats deployed in its first year by mid-2022. In addition, the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM; https://soccom.princeton.edu/) project has entered a second funding cycle in 2020 and will deploy 200 BGC floats with five or six sensors in the Southern Ocean. Together, GO-BGC and SOCCOM should establish more than half of the BGC-Argo proposed array. The Euro-Argo consortium aims to operate 25% of the global array and commitments from international partners will make a significant contribution to the rest of the planned array. With the current programs and commitments, it is very likely that the array will reach its target size by the end of this decade.

Although the BGC-Argo array is maturing, significant challenges remain, particularly the availability of floats with five or more BGC sensors. There are a limited number of commercial vendors and current vendors have had difficulty scaling up all the needed systems. As a result, the time to receive floats with the needed sensors is quite long and sensor costs have not scaled down with increasing volume and production experience. Despite these challenges, the extent of the BGC-Argo array is expanding, and transformational science has been achieved.

FIGURE 3

Location of the 170 BGC-Argo floats with five or six sensors active in March 2022, color coded by national program. The total number of BGC-Argo floats was 455. The background colors indicate ocean bottom depth: < 2,000 m (white), 2,000–3,000 m (light gray), 3,000–4,000 m (light blue), 4,000–5,000 m (blue), and > 5,000 m (dark gray). Data courtesy of OceanOPS.



Conclusions

While the original Argo program fundamentally changed our ability to describe the seasonal to interannual variability and rate of ocean change of the upper 2 km of the global ocean, OneArgo will extend this revolutionary set of global observations to higher latitudes and marginal seas with enhanced resolution in specific regions including the tropics and western boundaries currents, provide data over the full water column, and collect BGC data to describe essential biological and geochemical variability and its response to a changing climate. The requisite technology and data management infrastructure has been developed but requires sustained funding support and continued improvements to meet OneArgo objectives. Pilot studies have demonstrated the ability to operate OneArgo's missions, and full global implementation is now underway. As was the case for the original Argo Program, realizing the new global OneArgo array will take several years, but it is now within reach. Fully implemented, OneArgo will drive a second revolution in ocean sciences and advances in climate prediction and projections.

Future challenges include continuing to (a) develop and innovate the technology for the new floats and sensors, (b) fully develop the quality control and data management system, (c) operationally integrate the three OneArgo missions (Core, Deep, and BGC) into a cohesive array, and (d) work with the UN Decade Programs to optimize the utility of OneArgo data for the expanded oceanographic community.

Corresponding Author:

W. Brechner Owens
Woods Hole
Oceanographic Institution
Woods Hole, Massachusetts 02543
Email: bowens@whoi.edu

References

Ardyna, M., Lacour, L., Sergi, S., d'Ovidio, F., Sallée, J.B., Rembauville, M., … Claustre, H. 2019. Hydrothermal vents trigger massive phytoplankton blooms in the Southern Ocean. Nat Commun. 10:2451. https://doi.org/10.1038/s41467-019-09973-6.

Argo Steering Team. 1998. On the Design and Implementation of Argo—An Initial Plan for the Global Array of Profiling Floats. International CLIVAR Project Office. 32 pp.

Biogeochemical-Argo Planning Group. 2016. The scientific rationale, design and implementation plan for a Biogeochemical-Argo float array. https://doi.org/10.13155/46601.

Briggs, N., Dall'Olmo, G., & Claustre, H. 2020. Major role of particle fragmentation in regulating biological sequestration of CO2 by the oceans. Science. 367(6479):791–3. https://doi.org/10.1126/science.aay1790.

Bushinsky, S.M., Gray, A.R., Johnson, K.S., & Sarmiento, J.L. 2017. Oxygen in the Southern Ocean from Argo floats: determination of processes driving air-sea fluxes. J Geophys Res-Oceans. 122(11):8661–82. https://doi.org/10.1002/2017JC012923.

Chai, F., Johnson, K.S., Claustre, H., Xing, X., Wang, Y., Boss, E., … Sutton, A. 2020. Monitoring ocean biogeochemistry with autonomous platforms. Nat Rev Earth & Environ. 1:315–26. https://doi.org/10.1038/s43017-020-0053-y.

Claustre, H., Johnson, K.S., & Takeshita, Y. 2020. Observing the global ocean with Biogeochemical-Argo. Annu Rev Mar Sci. 12:23–48. https://doi.org/10.1146/annurev-marine-010419-010956.

Cornec, M., Claustre, H., Mignot, A., Guidi, L., Lacour, L., Poteau, A., … Schmechtig, C. 2021. Deep Chlorophyll Maxima in the global ocean: occurrences, drivers and characteristics. Global Biogeochem Cy. 35(4): e2020GB006759. https://doi.org/10.1029/2020GB006759.

Dall'Olmo, G., Dingle, J., Polimene, L., Brewin, R.J.W., & Claustre, H. 2016. Substantial energy input to the mesopelagic ecosystem from the seasonal mixed-layer pump. Nat Geosci. 9:820–3. https://doi.org/10.1038/ngeo2818.

Desbruyères, D.G., Bravo, E.P., Thierry, V., Mercier, H., Lherminier, P., & Cabanes, C. 2022. Repeat hydrography and Deep Argo reveal a warming-to-cooling reversal of overflow-derived water masses in the Irminger Sea during 2002 2021. Geophys Res Lett. In Review.

Desbruyères, D.G., Purkey, S.G., McDonagh, E.L., Johnson, G.C., & King, B.A. 2016. Deep and abyssal ocean warming from 35 years of repeat hydrography. Geophys Res Lett. 43(19):10,356–65. https://doi.org/10.1002/2016GL070413.

Foppert, A., Rintoul, S.R., Purkey, S.G., Zilberman, N., Kobayashi, T., Sallée, J.B., … Wallace, L.O. 2021. Deep Argo reveals bottom water properties and pathways in the Australian-Antarctic Basin. J Geophys Res-Oceans. 126(12):e2021JC017935. https://doi.org/10.1029/2021JC017935.

Gray, A.R., Johnson, K.S., Bushinsky, S.M., Riser, S.C., Russell, J.L., Talley, L.D., … Sarmiento, J.L. 2018. Autonomous biogeochemical floats detect significant carbon dioxide outgassing in the high-latitude Southern Ocean. Geophys Res Lett. 45(17):9049–57. https://doi.org/0.1029/2018GL078013.

Johnson, K.S., & Bif, M.B. 2021. Constraint on net primary productivity of the global ocean by Argo oxygen measurements. Nat Geosci. 14(10):769–74. https://doi.org/10.1038/s41561-021-00807-z.

Johnson, G.C., Cadot, C., Lyman, J.M., McTaggart, K.E., & Steffen, E.L. 2020. Antarctic bottom water warming in the Brazil Basin: 1990s through 2020, from WOCE to Deep Argo. Geophy Res Lett. 47: e2020GL089191. https://doi.org/10.1029/2020GL089191.

Johnson, G.C., Hosoda, S., Jayne, S.R., Oke, P.R., Riser, S.C., Roemmich, D., … Xu, J. 2022. Argo–two decades: Global oceanography, revolutionized. Annu Rev Mar Sci. 14(1):379–403. https://doi.org/10.1002/2016GL070413.

Johnson, G.C., Lyman, J.M., & Loeb, N.G. 2016. Improving estimates of Earth's energy imbalance. Nat Clim Change. 6:639–40. https://doi.org/10.1038/nclimate3043.

Johnson, G.C., Purkey, S.G., Zilberman, N.V., & Roemmich, D. 2019. Deep Argo quantifies bottom water warming rates in the Southwest Pacific Basin. Geophys Res Lett. 46:2662–9. https://doi.org/10.1029/2018GL081685.

Johnson, K.S. 2017. Developing chemical sensors to observe the health of the global ocean. In: IEEE Transducers 2017, 19th International Conference on Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS), pp. 10–5. https://doi.org/10.1109/TRANSDUCERS.2017.7993975.

McPhaden, M.J., Busalacchi, A.J., Cheney, R., Donguy, J.R., Gage, K.S., Halpern, D., … Mitchum, G.T. 1998. The Tropical Ocean-Global Atmosphere (TOGA) observing system:

A decade of progress. J Geophys Res. 103(C7): 14169–240. https://doi.org/10.1029/97jc02906.

Nippon Foundation. 2021. Mapping the floor of the ocean. Newsletter of the Nippon Foundation-GEBCO SeaBed 2030 Project. https://seabed2030.org/mapping-progress.

Racapé, V., Thierry, V., Mercier, H., & Cabanes, C. 2019. ISOW spreading and mixing as revealed by Deep-Argo floats launched in the Charlie-Gibbs Fracture Zone. J Geophys Res: Oceans. 1246:787–6808. https://doi.org/10.1029/2019JC015040.

Roemmich, D., Alford, M., Claustre, H., Johnson, K., King, B., Moum, J., … Yasuda, I. 2019. On the future of Argo: A global, full-depth, multi-disciplinary array. Front Mar Sci. 6:439. https://doi.org/10.3389/fmars.2019.00439.

Roemmich, D., Talley, L., Zilberman, N., Osborne, E., Johnson, K.S., Barbero, L., … Wijffels, S. 2022. The technological, scientific, and sociological revolution of global subsurface ocean observing. Frontiers in Ocean Observing: Documenting Ecosystems, Understanding Environmental Changes, Forecasting Hazards, Supplement to Oceanography. 34:2–8. https://doi.org/10.5670/oceanog.2021.supplement.02.

Siedler, G., Gould, J., & Church, J. 2001. Ocean Circulation and Climate, Observing and Modelling the Global Ocean, 1st Edition. Academic Press. 736 pp. (International Geophysics Series 77).

Talley, L.D., Feely, R.A., Sloyan, B.M., Wanninkhof, R., Baringer, M.O., Bullister, J. L., … Zhang, J.Z. 2016. Changes in ocean heat, carbon content, and ventilation: A review of the first decade of GO-SHIP global repeat hydrography. Annu Rev Mar Sci. 8:185–215. https://doi.org/10.1146/annurev-marine-052915-100829.

Thomas, G., Purkey, S.G., Roemmich, D., Foppert, A., & Rintoul, S.R. 2020. Spatial variability of Antarctic bottom water in the Australian Antarctic Basin from 2018–2020 captured by Deep Argo. Geophys Res Lett. 47(23):e2020GL089467. https://doi.org/10.1029/2020GL089467.

Wijffels, S., Roemmich, D., Monselesan, D., Church, J., & Gilson, J. 2016. Ocean temperatures chronicle the ongoing warming of Earth. Nat Clim Change. 6:116–8. https://doi.org/10.1038/nclimate2924.

Yang, B., Boss, E.S., Haëntjens, N., Long, M.C., Behrenfeld, M.J., Eveleth, R., & Doney, S.C. 2020. Phytoplankton phenology in the North Atlantic: Insights from profiling float measurements. Front Mar Sci. 7:139. https://doi.org/10.3389/fmars.2020.00139.

Zilberman, N., & Maze, G. 2015. Report on the Deep Argo Implementation Workshop. http://www.argo.ucsd.edu/DAIW1report.pdf.

Zilberman, N.V., Roemmich, D.H., & Gilson, J. 2020. Deep-ocean circulation in the Southwest Pacific Ocean interior: Estimates of the mean flow and variability using Deep Argo data. Geophys Res Lett. 47(13):e2020GL088342. https://doi.org/10.1029/2020GL088342.