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On the Future of Argo: *A Global, Full-Depth, Multi-Disciplinary Array*

Dean Roemmich[1*†], Matthew H. Alford[1†], Hervé Claustre[2†], Kenneth Johnson[3†], Brian King[4†], James Moum[5†], Peter Oke[6†], W. Brechner Owens[7†], Sylvie Pouliquen[8†], Sarah Purkey[1†], Megan Scanderberg[1†], Toshio Suga[9†], Susan Wijffels[7†], Nathalie Zilberman[1†], Dorothee Bakker[10], Molly Baringer[11], Mathieu Belbeoch[12], Henry C. Bittig[2], Emmanuel Boss[13], Paulo Calil[14], Fiona Carse[15], Thierry Carval[8], Fei Chai[16], Diarmuid Ó. Conchubhair[17], Fabrizio d'Ortenzio[2], Giorgio Dall'Olmo[18], Damien Desbruyeres[8], Katja Fennel[19], Ilker Fer[20], Raffaele Ferrari[21], Gael Forget[21], Howard Freeland[22], Tetsuichi Fujiki[23], Marion Gehlen[24], Blair Greenan[25], Robert Hallberg[26], Toshiyuki Hibiya[27], Shigeki Hosoda[23], Steven Jayne[7], Markus Jochum[28], Gregory C. Johnson[29], KiRyong Kang[30], Nicolas Kolodziejczyk[31], Arne Körtzinger[32], Pierre-Yves Le Traon[33], Yueng-Djern Lenn[34], Guillaume Maze[8], Kjell Arne Mork[35], Tamaryn Morris[36], Takeyoshi Nagai[37], Jonathan Nash[5], Alberto Naveira Garabato[4], Are Olsen[20], Rama Rao Pattabhi[38], Satya Prakash[38], Stephen Riser[39], Catherine Schmechtig[40], Claudia Schmid[11], Emily Shroyer[5], Andreas Sterl[41], Philip Sutton[42], Lynne Talley[1], Toste Tanhua[32], Virginie Thierry[8], Sandy Thomalla[43], John Toole[7], Ariel Troisi[44], Thomas W. Trull[6], Jon Turton[15], Pedro Joaquin Velez-Belchi[45], Waldemar Walczowski[46], Haili Wang[47], Rik Wanninkhof[11], Amy F. Waterhouse[1], Stephanie Waterman[48], Andrew Watson[49], Cara Wilson[50], Annie P. S. Wong[39], Jianping Xu[16] and Ichiro Yasuda[51]

[1] Scripps Institution of Oceanography, La Jolla, CA, United States, [2] French National Center for Scientific Research, Villefranche Oceanographic Laboratory, Sorbonne Université, Villefranche-sur-Mer, France, [3] Monterey Bay Aquarium Research Institute, Moss Landing, CA, United States, [4] National Oceanography Centre, Southampton, United Kingdom, [5] College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR, United States, [6] Commonwealth Scientific and Industrial Research Organisation, Hobart, TAS, Australia, [7] Woods Hole Oceanographic Institution, Woods Hole, MA, United States, [8] Institut Français de Recherche pour l'Exploitation de la Mer, Brest, France, [9] Department of Geophysics, Graduate School of Science, Tohoku University, Sendai, Japan, [10] School of Environmental Sciences, Centre for Ocean and Atmospheric Sciences, University of East Anglia, Norwich, United Kingdom, [11] Atlantic Oceanographic and Meteorological Laboratory, National Oceanic and Atmospheric Administration, Miami, FL, United States, [12] JCOMMOPS, Brest, France, [13] School of Marine Sciences, The University of Maine, Orono, ME, United States, [14] Institute of Coastal Research, Helmholtz-Zentrum Geesthacht, Geesthacht, Germany, [15] UK Met Office, Exeter, United Kingdom, [16] State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography, Ministry of Natural Resources, Hangzhou, China, [17] Irish Marine Institute, Galway, Ireland, [18] Plymouth Marine Laboratory, Plymouth, United Kingdom, [19] Department of Oceanography, Dalhousie University, Halifax, NS, Canada, [20] Physical Oceanography, Geophysical Institute, University of Bergen, Bergen, Norway, [21] Massachusetts Institute of Technology, Cambridge, MA, United States, [22] Fisheries and Oceans Canada, Sidney, BC, Canada, [23] Japan Agency for Marine-Earth Science and Technology, Yokosuka, Japan, [24] Laboratoire des Sciences du Climat et de l'Environnement/Institut Pierre Simon Laplace, Gif-sur-Yvette, France, [25] Bedford Institute of Oceanography and Fisheries and Oceans Canada, Dartmouth, NS, Canada, [26] National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory, Princeton, NJ, United States, [27] Graduate School of Science, Department of Earth and Planetary Science, The University of Tokyo, Tokyo, Japan, [28] Neils Bohr Institute, Copenhagen, Denmark, [29] National Oceanic and Atmospheric Administration/Pacific Marine Environmental Laboratory, Seattle, WA, United States, [30] Korea Meteorological Administration, Seoul, South Korea, [31] CNRS-IRD-Ifremer, LOPS Laboratory, University of Brest, Brest, France, [32] Helmholtz-Zentrum für Ozeanforschung Kiel, Kiel, Germany, [33] Mercator-Ocean, Brest, France, [34] School of Ocean Sciences, Bangor University, Bangor, United Kingdom, [35] Institute of Marine Research, Bergen, Norway, [36] Marine Research Unit, South African Weather Service, Cape Town, South Africa, [37] Graduate School of Marine Science and Technology, Ocean Sciences, Tokyo University of Marine Science and Technology, Tokyo, Japan, [38] Indian National Centre for Ocean Information Services, Hyderabad, India, [39] School of Oceanography, College of the Environment, University of Washington, Seattle, WA, United States, [40] French National Center for Scientific Research, OSU Ecce Terra, Sorbonne Université, Paris, France, [41] Koninklijk Nederlands Meteorologisch Instituut, De Bilt, Netherlands, [42] National Institute of Water and Atmospheric Research, Auckland, New Zealand, [43] Southern Ocean Carbon & Climate Observatory, Cape Town, South Africa, [44] Servício de Hidrografia Naval, Buenos Aires, Argentina, [45] Instituto Espanol de Oceanografia, Canary Islands, Spain, [46] Institute of Oceanology Polish Academy of Sciences, Sopot, Poland, [47] State Key Laboratory of Marine Environmental Science, Xiamen University, Xiamen, China, [48] Department of Earth,

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***Correspondence:**
Dean Roemmich
droemmich@ucsd.edu

†Lead authors

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Ocean and Atmospheric Sciences, The University of British Columbia, Vancouver, BC, Canada, [49] Earth System Science Group, College of Life and Environmental Science, University of Exeter, Exeter, United Kingdom, [50] National Oceanic and Atmospheric Administration – National Marine Fisheries Service, Pacific Grove, CA, United States, [51] Atmosphere and Ocean Research Institute, The University of Tokyo, Tokyo, Japan

The Argo Program has been implemented and sustained for almost two decades, as a global array of about 4000 profiling floats. Argo provides continuous observations of ocean temperature and salinity versus pressure, from the sea surface to 2000 dbar. The successful installation of the Argo array and its innovative data management system arose opportunistically from the combination of great scientific need and technological innovation. Through the data system, Argo provides fundamental physical observations with broad societally-valuable applications, built on the cost-efficient and robust technologies of autonomous profiling floats. Following recent advances in platform and sensor technologies, even greater opportunity exists now than 20 years ago to (i) improve Argo's global coverage and value beyond the original design, (ii) extend Argo to span the full ocean depth, (iii) add biogeochemical sensors for improved understanding of oceanic cycles of carbon, nutrients, and ecosystems, and (iv) consider experimental sensors that might be included in the future, for example to document the spatial and temporal patterns of ocean mixing. For Core Argo and each of these enhancements, the past, present, and future progression along a path from experimental deployments to regional pilot arrays to global implementation is described. The objective is to create a fully global, top-to-bottom, dynamically complete, and multidisciplinary Argo Program that will integrate seamlessly with satellite and with other *in situ* elements of the Global Ocean Observing System (Legler et al., 2015). The integrated system will deliver operational reanalysis and forecasting capability, and assessment of the state and variability of the climate system with respect to physical, biogeochemical, and ecosystems parameters. It will enable basic research of unprecedented breadth and magnitude, and a wealth of ocean-education and outreach opportunities.

Keywords: Argo, floats, global, ocean, warming, circulation, temperature, salinity

INTRODUCTION

The Argo Program is a major component of both the Global Ocean Observing System (GOOS) and the Global Climate Observing System (GCOS), providing near-real time data for ocean and atmospheric services and high quality data for climate research. The Argo Program began its implementation in 1999 and has provided global coverage of the upper 2000 m of the oceans since 2006. By November 2018, Argo had provided 2,000,000 profiles since the program began, and a comparable number of velocity drift estimates at 1000 m depth. Although originally designed to provide temperature and salinity profiles in the upper 2 km of the ice-free oceans, the array has been expanded into seasonal ice zones using floats equipped with ice avoidance algorithms. Argo profiling floats also are sampling in many marginal seas. In addition, ongoing regional pilot programs have demonstrated that Argo floats can now (1) measure biogeochemical parameters to address oceanic uptake of carbon, acidification and deoxygenation (Biogeochemical, BGC, Argo) and (2) make measurements throughout the water column to 6000 m depth (Deep Argo). Notification through the Argo Information Center (AIC), following Intergovernmental Oceanographic Commission (IOC) guidelines to protect the rights of Coastal States, has enabled global coverage. Presently the number of functioning Argo floats remains steady, with total float count around 4000. This has been possible, despite relatively flat funding, through a collaboration of international partners and significant technological innovation. The Argo Data System provides real-time data within 24 h of collection through the Global Telecommunications System (GTS) and via the internet for use at global prediction centers. The Argo Data Management Team (ADMT) also oversees delayed-mode quality control of the data and the availability of Argo data at the Argo Global Data Assembly Centers.

To meet future needs, Argo should (1) support continuing innovation in float technology, (2) enhance coverage in critical regions such as the equatorial band, where higher temporal resolution is needed and the western boundary regions where mesoscale 'noise' is high, (3) implement Deep Argo and Biogeochemical Argo in the global array, (4) assess the technical readiness and scientific value of experimental measurements for possible future inclusion in Argo, for example those used to estimate small scale mixing, and (5) collaborate with our end-user community to improve the use of Argo data in prediction systems and services. This review lays out the motivation, development, and present status of the Argo Program, and addresses the five issues mentioned above. It is important to note that Core Argo has reached and maintained full implementation through innovation and broad community support. Only a small fraction of the funding needed to support the ambitious community requests for an expanded Argo Program can be identified at present. It is important for Argo to meet its future challenges as a single integrated program. The present elements of Argo – Core, Deep, and BGC – and of its data management system are not separable, and any other future enhancements will similarly be considered as contributions to the unified effort.

MOTIVATION, DEVELOPMENT, TECHNOLOGY

Core Argo

During the 1990s, the World Ocean Circulation Experiment brought increased understanding of important oceanic roles in climate variability and change (Siedler et al., 2001). The need to observe the global subsurface ocean, together with a fit-for-purpose revolutionary autonomous technology (Davis et al., 2001), led to a multinational proposal for a global subsurface ocean observing system (Argo Steering Team, 1998). The proposed 'Argo Program' would be comprised of over 3000 profiling floats, obtaining a snapshot of the physical state of the ocean from 0 to 2000 m every 10 days. All data would be freely shared in near-real time (NRT, within 24 h) to support forecasting, and with a highly quality-controlled delayed-mode (DM) version delivered within 12 months for climate research and assessments. Argo floats were deployed in regional arrays beginning in 1999 and then globally from 2004 to the present. Argo has fulfilled its promise to complement and integrate across many satellite and *in situ* elements of the GOOS and across many regional observational networks (deYoung et al., 2019; Foltz et al., 2019; Hermes et al., 2019; Lee et al., 2019; Newman et al., 2019; Palazov et al., 2019; Smith et al., 2019; Todd et al., 2019).

A number of key elements that contributed to Argo's success over the past 20 years are evident. The underpinning profiling float technology is simple, robust, and cost-effective. A strong international consensus on the high value of Argo, by agencies and the science community, contributed to Argo's rapid roll-out. Once Argo was in place, a broad base of applications (see section "Core Argo" under the section "End User Engagement") including basic research, assessment of the state of the Earth's climate, tertiary and secondary education, and ocean modeling for reanalysis and operational prediction, drew strong community support. Effective partnerships developed between Argo teams and commercial suppliers, to exploit and improve float and sensor technologies. The IOC provided necessary protocols to facilitate the operation of Argo floats in national waters (Intergovernmental Oceanographic Commission [IOC], 1999), while the AIC[1] supplied the mechanisms for tracking and reporting to coastal states (Pinardi et al., 2019).

Technology advances have continued throughout Argo's 20-year history. New generation profiling floats are smaller, lighter, and more energy efficient. A profoundly important transition from unidirectional to faster bidirectional communication (Iridium) improves vertical resolution and shortens surface times from 12 h to 20 min, greatly reducing bio-fouling, array divergence due to surface drift, grounding, and other hazards. Ice-avoidance measures in float controllers (Klatt et al., 2007) have extended the range of Argo through the seasonal ice zones (Wong and Riser, 2011). Improved CTD sensors, as well as procedures for delayed-mode quality control (Owens and Wong, 2009) have increased the accuracy and consistency of the Argo dataset. Float lifetimes have increased, to 4–5 years for most Argo National Programs, reducing the cost per profile while extending reseeding intervals. All of these improvements are propagated across the Argo national programs through communication of Best Practices (Pearlman et al., 2019).

Argo's systematic and regular observation of the global subsurface ocean has transformed ocean observing. Northern hemisphere, near-coastal, and seasonal sampling biases of earlier eras are removed. The global Argo array has been sustained and improved for more than a decade, providing data for over 3000 research publications and becoming a mainstay of global ocean data assimilation, modeling, and prediction applications. The notable convergence, in the Argo era, of diverse estimates of historical global ocean heat content changes (e.g., Johnson et al., 2016) has increased the confidence that can be placed on the reliability of national and international assessments of climate change. International partners in Argo merge their efforts to produce a seamless global array, providing standardized observations, and delivering near real-time and research quality data with public access. Argo has led the way among ocean observing networks with regard to international cooperation, operations planning, Data Availability, and metadata quality.

BGC-Argo

The Biogeochemical (BGC)-Argo program began with the deployment of optical (Bishop et al., 2002; Mitchell, 2003; Boss et al., 2008) and oxygen (Körtzinger et al., 2004; Riser and Johnson, 2008) sensors on profiling floats between 2000 and 2003. The success of these efforts was highlighted at the Autonomous Platforms and Sensors meeting (Rudnick and Perry, 2003), which was the founding meeting for this community. It was followed by the development of a global vision for biogeochemical data acquisition through the inclusion of oxygen sensors on Argo platforms (Gruber et al., 2007), and the launch the same year of a working group of the International Ocean-Color Coordinating Group, "Bio-optical sensors on Argo floats" (IOCCG, 2011). In the meantime, both the oxygen and optical communities were promoting their vision for developing a global network of profiling floats carrying oxygen and optical sensors as part of the OceanObs09 conference (Claustre et al., 2010;

[1] http://argo.jcommops.org/

Gruber et al., 2010), following a meeting in Johnson et al. (2009) that addressed the development of a global observing system using both gliders and profiling floats.

In 2016, a meeting was held in Villefranche-sur-mer to develop an implementation plan for BGC-Argo. The subsequent report (Biogeochemical-Argo Planning Group, 2016) was the starting point of the BGC-Argo program. Observing system simulation experiments (OSSEs) performed for this meeting suggested that a 1000-float array would significantly constrain the processes that control global oxygen and carbon distributions, including air-sea fluxes and exports from the surface (Kamenkovich et al., 2017). Assuming a mean BGC float lifetime of 4 years, sustaining a 1000-float array requires 250 floats per year with an estimated annual cost near US$25-M. Each of the floats would carry sensors for six core ocean variables measured with targeted accuracies[2]: chlorophyll fluorescence (Chla), particle backscatter, oxygen, nitrate, pH, and irradiance. The 1000-float array would provide observational data to transform ability to quantify: (i) air-sea carbon fluxes, (ii) ocean deoxygenation, oxygen minimum zones and related denitrification fluxes, (iii) ocean acidification, (iv) the biological carbon pump, and (v) phytoplankton communities. The observing system would improve management of living marine resources and carbon budget verification, both key societal goals. In 2017, a BGC-Argo Scientific Steering Committee was formed (under the Argo Steering Team), to guide the development of the network and the implementation of the program objectives, and to continue developing a vision for the future. In 2018, during the Executive Council of IOC, unanimous support from Member States was given to the proposal to incorporate the six biogeochemical measurements in the Argo array. Additionally the Executive Council approved a framework for the future addition of new parameters to Argo.

The first BGC-Argo deployments consisted of a few floats at a time. These have evolved to regional scale projects such as remOcean (North Atlantic sub-polar Gyre, 20 floats) and NAOS (Mediterranean Sea, 30 floats), and to basin-scale projects such as SOCCOM (Southern Ocean Carbon and Climate Observations and Modeling) with more than 100 floats deployed thus far, toward a target of 200. These pilots have showcased the potential of community-shared efforts to support better understanding of major biogeochemical processes at the global scale and to explore new research topics. The profiling float data sets have been vetted by research groups via publications approaching several 100 in total. BGC-Argo observations are open and free through the Argo data system both in NRT and DM.

These projects are transforming our understanding of variability in the ocean over time scales difficult to achieve with ship-based observations. A few of these achievements include characterization of ocean nitrate supply (Johnson et al., 2010; D'Ortenzio et al., 2014); observation of bloom dynamics beneath the surface (Boss and Behrenfeld, 2010; Mignot et al., 2018); novel carbon export mechanisms through a mixed-layer pump (Dall'Olmo and Mork, 2014; Dall'Olmo et al., 2016) or eddy subduction (Llort et al., 2018); oxygen minimum zone processes (Whitmire et al., 2009; Prakash et al., 2012; Stanev et al., 2018); ocean net community production over complete annual cycles throughout the ocean (Riser and Johnson, 2008; Bushinsky and Emerson, 2015; Hennon et al., 2016; Plant et al., 2016); ocean ventilation (Körtzinger et al., 2004; Wolf et al., 2018); air-sea exchanges of O_2 (Bushinsky et al., 2017) and CO_2 (Williams et al., 2017; Bittig et al., 2018; Gray et al., 2018); and mesoscale/sub-mesoscale processes (Sukigara et al., 2011; Kouketsu et al., 2016). In a major advance, the data are now being assimilated into biogeochemical models to enable greater understanding and improved predictions (Verdy and Mazloff, 2017).

The development of BGC-Argo floats has been based on the standard Argo Pressure/Temperature/Salinity (P/T/S) platforms, integrating new sensors when their readiness level appeared compatible with long-term, operational use. Today, the community is operating three main BGC-Argo platforms (**Figure 1**): PROVOR, Navis, and APEX floats. While each of these platforms is capable of carrying the six core sensors outlined in the BGC-Argo implementation plan, due to present hardware limitations and the objectives of funded research programs, few have yet been deployed with all six. Deployments of floats carrying the six core variables are highly desirable as well as harmonizing of mission parameters with those of Core Argo.

Deep Argo

Deep Argo is motivated by the substantial oceanographic variability found in the 50% of ocean volume that lies below the 2000-dbar profiling target for conventional Argo floats. Development of floats and CTDs capable of accurate measurements to 6000 dbar makes global full-depth Argo implementation feasible, including sampling of bottom-intensified ocean variability.

Antarctic Bottom Water, which fills much of the ocean below 2000 dbar (Johnson, 2008), has been warming and freshening during the past few decades, with these changes contributing to steric sea level rise (Purkey and Johnson, 2013). The rate of ocean heat-gain below 2000 dbar, of 0.065 ($\pm$ 0.04) W m^{-2} from 1991 to 2010 (Desbruyères et al., 2016) is about 10% of the 0.61 ($\pm$ 0.09) W m^{-2} from 2005 to 2015 in the upper 1800 dbar (Johnson et al., 2016). Deep ocean (>2000 dbar) heat content changes have been estimated over decadal intervals using a sparse network of repeat hydrographic sections that are sampled at quasi-decadal intervals (Talley et al., 2016), hence only decadal estimates are possible, and uncertainties due to the sparsity of observations are about 2/3 the size of the signal. In contrast, Core Argo data enables decadal estimation of ocean heat uptake shallower than 2000 dbar with uncertainties only about 1/7 the size of the signal. In addition, monthly global analyses of Core Argo data (Roemmich and Gilson, 2009[3]) have provided a basis for investigation of seasonal-to-interannual variability (e.g., Johnson and Birnbaum, 2017). Deep Argo will similarly reduce the uncertainties in decadal deep ocean heat uptake estimates, while providing data for a broad range of scientific investigations of deep variability (Johnson et al., 2015).

[2]http://biogeochemical-argo.org/measured-variables-general-context.php

[3]http://sio-argo.ucsd.edu/RG_Climatology.html

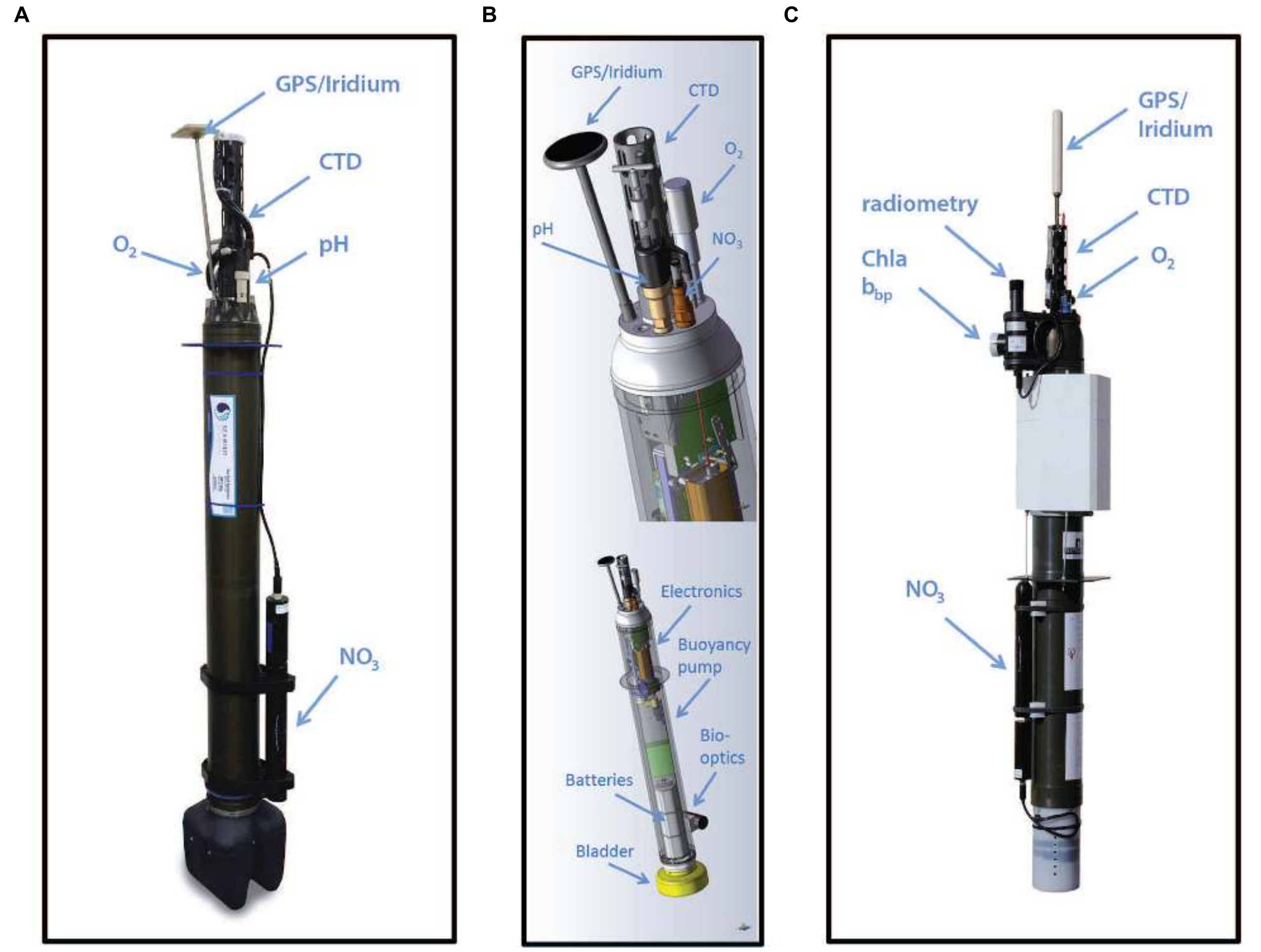

FIGURE 1 | The three main models of BGC-Argo floats presently in use include **(A)** Navis, **(B)** APEX, and **(C)** PROVOR.

The fact that abyssal trends and diffusivities both seem to be insufficiently constrained in ocean state estimates is further evidence that deep Argo is needed (Wunsch and Heimbach, 2014; Forget et al., 2015).

North Atlantic Deep Water is also changing, with the meridional overturning circulation decreasing measurably between 2004–2008 and 2008–2012 (Smeed et al., 2018). Deep ocean circulation variations have primarily been observed using transoceanic moored arrays, which are costly to maintain, and hence regionally limited (Lozier et al., 2017; Meinen et al., 2017; Smeed et al., 2018). Repeat hydrographic section data are also used for this purpose despite their sparse temporal sampling (Bryden et al., 2005; Kouketsu et al., 2011). Deep Argo would provide velocity and density information, complementing both the moored arrays and repeat hydrography, as well as facilitating decadal climate predictions and constraining full-depth ocean data assimilation (Robson et al., 2012; Yeager et al., 2012; Carrassi et al., 2016).

The value and technical feasibility of a Deep Argo Program were recognized at OceanObs'09 (Roemmich et al., 2010). Successful deployments of prototype deep floats and CTDs in 2012–2014 led to a Deep Argo Implementation Workshop in May 2015 (Zilberman and Maze, 2015), where a plan for Deep Argo's progression to a global 5° × 5° array was endorsed. Regional pilot arrays have been established in the South Pacific, South Indian, and North Atlantic oceans, further demonstrating the feasibility of a global Deep Argo array.

Argo Data Management

The Argo data system was designed in 2001 at the 1st Argo Data Management meeting in Brest, France and its main components remain in place and function well (**Figure 2**). The national Data Assembly Centres (DACs) receive data via satellite transmission, decode it, and apply quality control according to a set of agreed NRT tests. Erroneous data are corrected if possible, flagged accordingly and then sent to two Global Data Assembly Centres (GDACs) and the GTS. The GDACs collect the data from the 11 DACs, synchronize their databases daily and serve the data on FTP sites. The AIC monitors the status of the Argo Program, including data distribution, and meta data that incorporate float location, model, transmission system, owner, etc. In addition, the AIC gathers feedback on data quality from

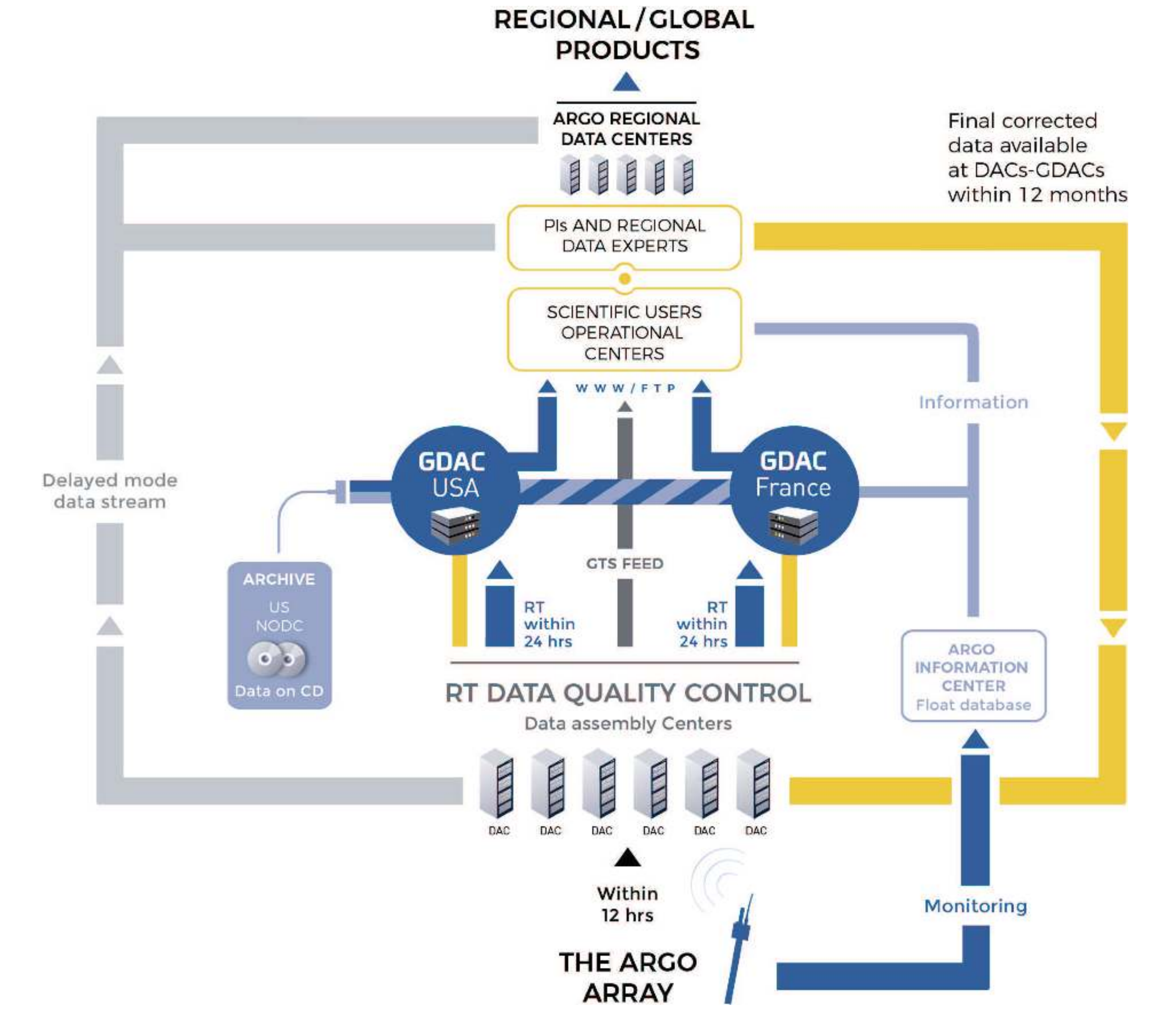

FIGURE 2 | Pathways of Argo near-real time and delayed-mode data and meta data are illustrated, originating from the Argo array and being distributed to users via the GDACs. (Copyright: Euro-Argo ERIC, printed with permission).

users and relays it to float owners and DACs. Argo's delayed-mode data system for P/T/S variables relies on Argo data experts examining the data and reflagging where necessary, using a standard method (Owens and Wong, 2009) to estimate salinity drift, in addition to applying salinity thermal lag adjustments and pressure adjustments.

To improve the quality of P/T/S variables between NRT and DM versions, a few tests have been developed to run on a regular basis (e.g., monthly, quarterly, etc.) on the GDAC data holdings. One of these is an objective analysis run monthly by Coriolis, where profiles that are inconsistent with neighbors are identified for further examination. Another is a quarterly comparison with satellite altimetry performed by CLS/France. When suspect profiles are identified, float owners and DACs are notified to make changes to data QC flags as needed.

The Argo Regional Centers (ARCs) perform a variety of tasks including coordinating float deployments, consistency checks on delayed mode quality control, finding additional reference data for delayed mode work, adopting floats for delayed mode quality control, and producing Argo data products.

While the complete data management chain (**Figure 2**) has been developed for the core mission (P/T/S, 0–2000 dbar), the extensions to Deep Argo and BGC Argo are under development to form an integrated Argo Data Management System.

ArgoMix

Here a new enhancement is suggested for possible future inclusion in Argo, consisting of direct shear and scalar microstructure (turbulence) measurements for both the upper and deep ocean. The rationale is provided by recent scientific