Project information	
Project full title	EuroSea: Improving and Integrating European Ocean Observing and Forecasting Systems for Sustainable use of the Oceans
Project acronym	EuroSea
Grant agreement number	862626
Project start date and duration	1 November 2019, 50 months
Project website	https://www.eurosea.eu

Deliverable information	
Deliverable number	D3.16
Deliverable title	**Euro-Argo updated strategy**
Description	Euro-Argo strategy in the context of the OneArgo new international design
Work Package number	WP3
Work Package title	Network Integration and Improvement
Lead beneficiary	Euro-Argo ERIC
Lead authors	Claire Gourcuff, Hervé Claustre, Damien Desbruyères, Virginie Thierry
Contributors	Romain Cancouet, Gianpiero Cossarini, Giorgio Dall'Olmo, Yann-Hervé De Roeck, Estérine Evrard, Kjell Arne Mork, Giulio Notarstefano, Emanuele Organelli, Anna Teruzzi, Pedro Velez
Due date	30.06.2023
Submission date	28.08.2023
Comments	The final completion of this document has been delayed by a few weeks due to the project's internal review.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 862626.

https://doi.org/10.3289/eurosea_d3.16

Table of contents

Executive summary

The Euro-Argo programme, coordinated by Euro-Argo ERIC, represents the European contribution to the Argo international programme, a major component of both the Global Ocean Observing System (GOOS) and the Global Climate Observing System (GCOS).

Originally designed to provide temperature and salinity profiles in the upper 2 km of the ice-free ocean, the Argo array has progressively been expanded into seasonal ice zones and marginal or enclosed seas. Furthermore, regional pilot programmes, where Euro-Argo partners played an important role, have allowed to develop and test Argo floats able to measure biogeochemical (BGC) parameters (BGC-Argo), and floats able to make measurements throughout the water column to 6000 m depth (Deep-Argo). The BGC-Argo and Deep-Argo Missions are now being implemented by Euro-Argo and internationally to complement the initial Core-Argo Mission. Together they form the new global, full-depth and multidisciplinary OneArgo programme.

This document provides rationale for the OneArgo network implementation strategy in Europe, focussing on the new Deep-Argo and BGC-Argo missions. Euro-Argo's long-term objective is to maintain one fourth of the international OneArgo array, which corresponds to about 1200 European active floats, including 300 Deep and 250 BGC floats. This ambitious target should be achieved by 2030.

The European contribution to BGC-Argo is driven by scientific interest in the European scientific community, while considering the needs of both the operational and satellite-based ocean colour communities, and ensuring a global implementation of the OneArgo design. The monitoring of European marginal Seas, namely the Baltic, the Black and the Mediterranean Seas, is one of Euro-Argo priorities for BGC-Argo. Maintaining a network of BGC-Argo floats in these regions will contribute to the monitoring and assessment of the marine environment status and functioning in relation to climate change as part of the European Union Green Deal. In complement, Euro-Argo aims to contribute to the implementation of BGC-Argo at global scale, in coordination with international programmes, with a specific interest in maintaining an appropriate BGC floats array in the Nordic Seas and the South West Indian.

Euro-Argo has been a key player in driving the evolution of Argo and its new missions. A new type of float able to carry additional BGC sensors, while enabling the float to fulfil its BGC-Argo mission (10 days cycles, for 4 years) has recently been developed in Europe. A number of these jumbo floats have been deployed with two additional types of sensors: (i) particle size imagers and (ii) hyperspectral radiometers, showing encouraging results. On the longer term, new developments are also planned within the GEORGE HE EU project[1] to integrate novel sensors ultimately enabling for the first time systematic autonomous, in situ seawater CO2 system characterisation, and CO2 fluxes on Argo and other ocean observing platforms.

Euro-Argo has been involved in Deep-Argo since the beginning, in particular through the deployment of a pilot array in the North Atlantic. Currently, Euro-Argo is following international recommendations for the Deep-Argo mission to both maintain the current pilot experiments and initiate new regional foci in regions of substantial seasonal-to-decadal variability, while pursuing efforts towards technological refinements (e.g. long-term stability) and a coordinated data-management strategy (e.g. quality control). Because of their predominant roles in the ventilation and long-term sequestration of climatic signals into the deep (via convective mixing and downslope cascading), the North Atlantic, the Nordic Seas and the Southern Ocean

[1] https://george-project.eu/

stand out as the most natural targets and will be European scientific priorities. Efforts will also be made to maintain an appropriate number of Deep active floats in the Mediterranean Sea, and to contribute to the global Deep-Argo network implementation in collaboration with other international programmes.

Euro-Argo teams will continue their strong involvement in the development of data quality control procedures and in the monitoring and assessment of sensors accuracy, in collaboration with manufacturers, to improve data reliability. Pilot projects are also planned for the coming years to integrate commercially available optical scattering sensors, that have been tested to 6000 m, onto Deep-Argo floats.

The distribution of dissolved oxygen (DO) concentration at global scale is driven by physical, biogeochemical and biological processes and DO data is in a key position of many biogeochemical processes. The optode DO sensor is of proven maturity and can provide very accurate measurements, after appropriate corrections have been applied. It is currently carried by a large proportion of Euro-Argo floats, including most of European Deep-Argo floats, and in the long-term, Euro-Argo plans to equip at least 3/4 of its fleet (all missions) with a DO sensor.

The implementation of the new OneArgo design, and more specifically the BGC and the Deep-Argo missions, come with new challenges for Euro-Argo, including the cost, but also the need for growing capacity both at manufacturer level and in the teams involved with operations, data management, data quality and sensor accuracy assessment and monitoring. As one piece of a multiplatform ocean observing system, Argo and Euro-Argo will also have to improve synergies with other ocean observing networks in the future, to efficiently progress in ocean knowledge and management. The European strategy for Deep-Argo and BGC-Argo presented here will be part of a wider effort initiated by Euro-Argo to define the general “Euro-Argo scientific strategy for the OneArgo array implementation”.

1. Introduction

1.1. Context: from Argo to OneArgo

The international Argo programme, initiated in 1999, is a major component of both the Global Ocean Observing System (GOOS) and the Global Climate Observing System (GCOS). Its global array of autonomous profiling floats reports ocean properties in depth in near real-time for ocean and atmospheric services. This unprecedented ocean data coverage of the upper 2000 m of the ocean, enables monitoring, understanding, and prediction of the ocean's physical processes and its role in Earth's climate (Riser et al. 2016, Wijffels et al. 2016). The Argo initial design was achieved in 2007, with 3000 active floats (Roemmich et al. 2009).

In parallel, profiling float technology has progressively been adapted to integrate biogeochemical (BGC) and optical sensors. Various pilot studies have successfully demonstrated the potential of profiling floats to explore and understand biogeochemical processes (e.g. ocean uptake of carbon dioxide, ocean acidification, deoxygenation, and variability in biological productivity) which led to the publication of several community papers (Gruber et al. 2007, 2010; Johnson et al. 2009; Claustre et al. 2010). The BGC-Argo mission was officially launched in 2016 with the publication of its Science and implementation Plan (Biogeochemical-Argo Planning Group, 2016). Run in close collaboration with the Argo program, BGC-Argo aims to operate a global array of 1,000 biogeochemical floats measuring six core variables, down to a depth of 2000 m: oxygen, nitrate, pH, chlorophyll a, suspended particles, and downwelling irradiance.

While the amount of temperature and salinity measurements in the upper 2000 m of the ocean's interior has tremendously increased since the beginning of the Argo era, the lack of deep-sea measurements has remained. Yet, full-depth ocean temperature and salinity data is essential to answer Argo's scientific and operational objectives, including the timely key issues of closure of the global heat and sea level budgets. To tackle this shortcoming, several models of Argo float able to sample the ocean below 2000 m have been developed in the last decade (e.g. Kobayashi 2013, Le Reste et al. 2016, Roemmich et al. 2019a). A global Deep-Argo design was proposed by Johnson et al. (2015), a Deep-Argo mission team was formed, and regional Deep-Argo arrays started to be implemented in the Southwest Pacific Basin, South Australian Basin, Australian Antarctic Basin, and North Atlantic Ocean, leading the way forward to implement a global Deep-Argo array.

Following the OceanObs 2019 Conference, a new design was proposed by the Argo Steering Team, driving towards spatial completeness to include polar sea-ice zones and marginal seas, increasing regional resolution in key areas like the Western Boundary currents and equatorial regions and gathering the three Argo missions (core-Argo, BGC-Argo and Deep-Argo): the OneArgo array (Roemmich et al. 2019b). In the new global, full depth, and multidisciplinary OneArgo design of 4700 active floats, BGC and Deep Argo floats contribute to the core float data stream with 10-day cycles, profiling to at least 2000 dbar and parking at 1000 dbar. The OneArgo programme now aims at the new design presented in Figure 1.

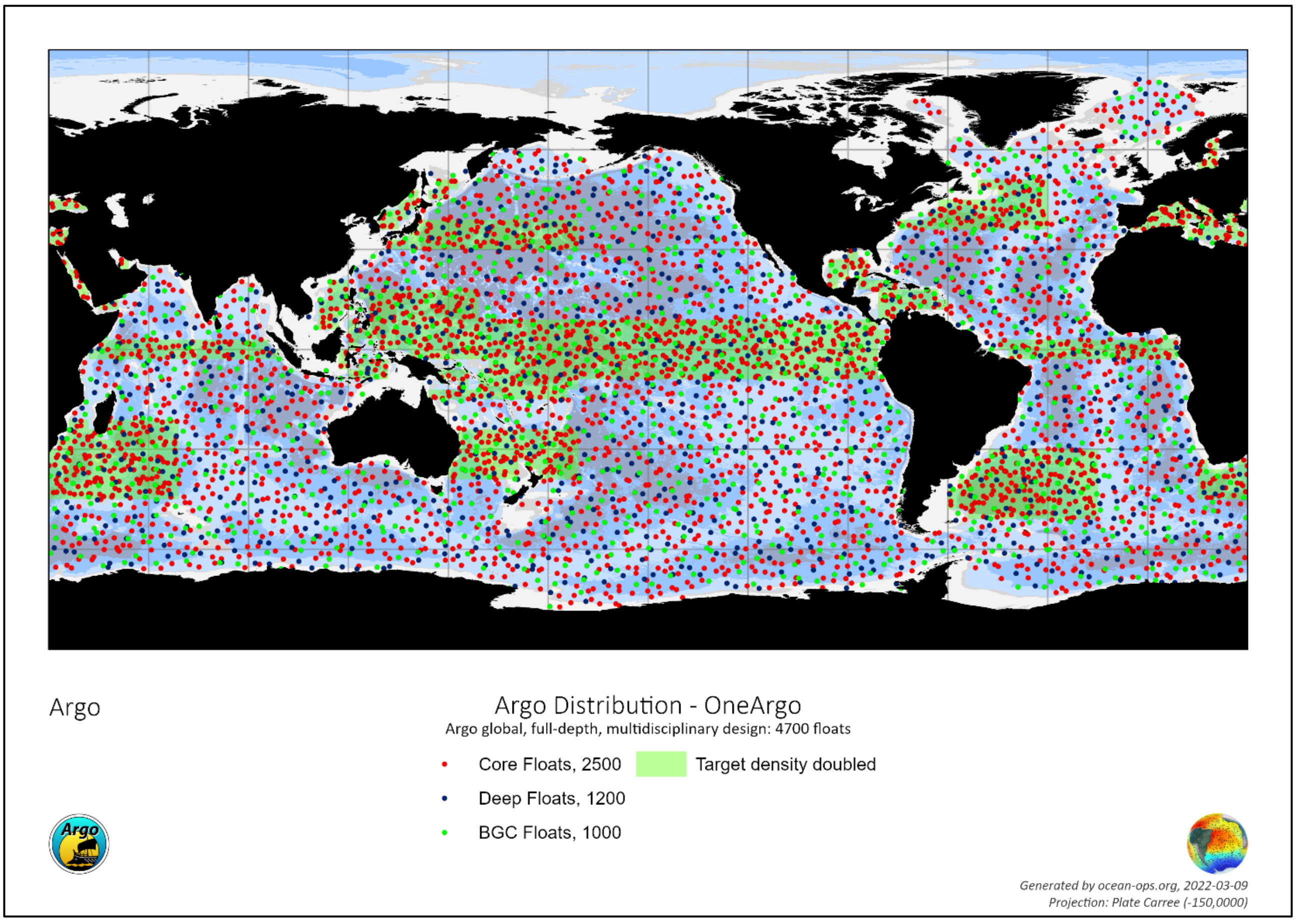

Figure 1. OneArgo design[2] - adapted from Roemmich et al. 2019b

1.2. OneArgo in Europe

The Euro-Argo programme, coordinated by Euro-Argo ERIC, represents the European contribution to the Argo international programme. The ERIC and its members aim to operate one fourth of the global Argo array, with specific emphasis on regions of explicit European interest such as the northern high latitudes and the European marginal Seas. Euro-Argo partners have played an important role in the pilot studies that led to OneArgo, and in cutting-edge technological developments needed to improve Argo platform performances and to diversify sensor availability (e.g. Le Traon et al. 2020). The implementation of OneArgo has already started at European level for several years, in all its dimensions (BGC-Argo, Deep-Argo, European marginal seas, high latitudes). OneArgo will bring along new services and scientific opportunities to advance our understanding of the role of the ocean in the Earth system and to address issues associated with climate change, and anthropogenic impact on ocean ecosystem health.

However, the Argo community, including Euro-Argo, is facing several challenges, one of the most important being the need for significant additional resources: the cost of the new design has been estimated as 3 times the current cost (4 to 5 times the cost of the initial Argo design). Technological and supply issues are other

[2] https://argo.ucsd.edu/oneargo

challenges slowing down the implementation, and efforts will have to be undertaken in all aspects of Argo (from advocacy to data management) to ensure a smooth implementation of the European contribution to OneArgo.

1.3. Objective of the document

The aim of this document is to provide rationale for the Argo network implementation strategy in Europe, with a focus on the implementation of the new international BGC-Argo and Deep-Argo missions. Euro-Argo aims at maintaining one fourth of the international Argo array, which corresponds – in the context of the current OneArgo design (Figure 1) – to maintaining about 1200 active floats, including 300 Deep and 250 BGC floats, by 2030, a very high target that is currently far from being funded. The strategy for Euro-Argo float deployments has always been and will continue to be driven by the needs of both the European scientific community and operational users (e.g. Copernicus, ECMWF, national weather forecast centres and satellite programmes). Various communities of Argo data users were invited to share their views on Argo during the BGC and Deep Argo workshop organised in September 2021 within EuroSea, which provided some insights on how the Euro-Argo contribution to OneArgo could evolve to better serve the European Argo data user community.

This document describes the main needs in Europe in terms of Deep and BGC-Argo data and the way Euro-Argo will deploy its contribution to the international effort accordingly, with regional focuses, e.g. in European marginal Seas. It is part of a wider effort to be initiated by Euro-Argo to define the general "Euro-Argo scientific strategy for the OneArgo array implementation". The aim is to release this full new scientific strategy in 2024. The targets in numbers of active floats in various regions will be used to monitor our progress in implementing the OneArgo array in Europe, and more generally, this document provides rationale for advocacy towards national & European stakeholders to raise appropriate funds for this implementation.

The following section describes the European contribution to the BGC-Argo mission, including both the contribution to the current international design implementation and innovation activities that will drive the future of Argo from a European perspective. Section 3 describes the contribution to Deep-Argo, with some perspectives on its evolution, and section 4 is dealing with the issue of dissolved oxygen, one of the more mature BGC-Argo parameters, that also stimulates interest in the physical community, including Deep-Argo.

2. European contribution to BGC-Argo

2.1. Scientific objectives

The launch of the science and implementation plan in 2016 was the official start of the international Biogeochemical-Argo (BGC-Argo) program (Biogeochemical-Argo Planning Group, 2016). Following the OceanObs'19 conference, BGC-Argo became one of the three missions of the OneArgo program (Roemmich et al. 2019b). BGC-Argo aims at operating a global network of 1 000 biogeochemical floats measuring, to a depth of 2 000 m, six essential variables: oxygen, nitrate, pH, chlorophyll a, suspended particles and downwelling irradiance.

These essential ocean variables have been selected as a trade-off between (a) the sensing technology for these measurements that had been demonstrated on a large number of floats (the technological readiness level was considered as sufficient for a global deployment) and (b) the strong interest of these variables in supporting the three main themes of the Global Ocean Observing System (GOOS): climate, marine ecosystem health and operational services.

Taking this into consideration, the BGC-Argo science plan presently targets five scientific themes: ocean carbon uptake, ocean acidification, biological carbon pump, nitrogen cycling in oxygen minimum zones (OMZ), and phytoplankton communities. Additionally, BGC-Argo aims at contributing to two ocean management topics which include living marine resources and carbon budget verification.

After nearly a decade of operation of a progressively growing fleet, BGC-Argo definitively appears as a unique program capable of monitoring biogeochemical processes on a global scale, throughout the year, in all weather conditions and under seasonal sea ice. The strengths of this observational network rely on two main aspects. Firstly, the cost-effectiveness of these robotized measurements, which reduce the cost of a vertical profile by more than an order of magnitude compared with conventional data acquisition. BGC-Argo clearly appears as a unique way to fill observational gaps and the only way to obtain a certain level of synopticity of in-depth measurements. Secondly, one of the keys to success is the community's flexibility and willingness to continually adapt to new technologies and protocols for quality control and data calibration. A sufficiently flexible data system has indeed been created to continue to adapt to these advances. Best practices have been defined for the planning, deployment, data handling and usage of BGC-Argo data (Bittig et al. 2019), contributing to the improvement of BGC-Argo performances in measuring key biogeochemical parameters. Data quality and interoperability have improved to the point where regional or basin-wide studies are becoming possible, and users other than BGC-Argo specialists are increasingly using the data.

As a consequence, BGC-Argo allows access to the exploration and understanding of processes and time scales that cannot be observed from oceanographic cruises. The science outcomes from BGC-Argo are now numerous and diverse. They indeed cover the whole spectrum of the five science topics over a variety of spatial (from mesoscale to global) and temporal (from diurnal to interannual) scales (e.g. Claustre et al. 2020, exhaustive list of scientific papers[3]).

As a summary, BGC-Argo is now an official and fully integrated component of Argo, sharing the same long-term vision of implementing a sustainable and cost-effective network through continuous improvement of technology, development of common logistics and free data delivery. The global BGC-Argo data set that is being progressively acquired begins to present strong synergies with remote sensing, modelling and shipboard observation programs. It is starting to revolutionise our understanding of ocean biogeochemistry and marine resources, laying in particular the foundations for enlightened ocean management. The main challenge for the BGC-Argo mission presently is to reach as soon as possible its sustained fleet target.

2.2. European priorities

As important players in the international BGC-Argo mission, Euro-Argo partners are ready to take up the challenge to increase their BGC float deployments in the coming decade, starting in regions of strong scientific and operational European interest. The European contribution to BGC-Argo will be driven by scientific interest in the European scientific community, while considering the needs of both the operational and satellite-based ocean colour communities, and ensuring a global implementation of the OneArgo design.

There is a strong interest of the European ocean science community for Ocean Color applications. Bio-optical sensors installed on BGC-Argo floats provide a clear link with satellite-based remote sensing of Ocean Colour.

[3] https://biogeochemical-argo.org/peer-review-articles.php

Remote sensing of Ocean Colour acquires information of biogeochemistry and marine biological resources at the ocean surface, from hundreds of metres to the global scale and temporal scales from days to decades. However, the information acquired from space is limited to max 40 m depth of the upper ocean (Organelli et al. 2017) which limits the understanding of biogeochemical processes governing the subsurface and deep ocean. Together, BGC-Argo profiling floats and remote sensing can complement their observations over multiple horizontal, vertical, and temporal scales in order to achieve a 4-Dimensional view of ocean biogeochemistry and carbon cycle (Claustre et al. 2020; Brewin et al. 2022).

Besides, BGC-Argo floats are also relevant to validate remotely sensed products at the global scale and with temporally unbiased observations (e.g., Organelli et al. 2017; Xing et al. 2020; Begouen Demeaux et al. 2022). BGC-Argo measurements of chlorophyll, optical backscattering and radiometry are assets exploiting the same products derived from space. Measurements of downwelling and upwelling radiometry are also at the base of the calibration/validation activities of satellites remote sensing reflectances (Gerbi et al. 2016; Leymarie et al. 2018; Wojtasiewicz et al. 2018). BGC-Argo can thus provide Space Agencies with the fundamental information required to maximise the quality of observations of satellite sensors across the global ocean (e.g., European Copernicus Sentinel 3 missions), while such Fiducial Reference Measurements (FRM) are currently limited only to two fixed sites (one in the Mediterranean Sea, one in the Pacific Ocean).

Both ocean colour and more recently BGC-Argo contribute significantly to reducing uncertainties in marine biogeochemical simulations through data assimilation. While ocean colour is important for constraining the surface dynamics of models (e.g., phytoplankton blooms at the surface), BGC-Argo profiles are important for simulating subsurface biogeochemical dynamics under oligotrophic and stratified conditions. For example, data assimilation applications in the operational Marine Copernicus model system for the Mediterranean Sea (Cossarini et al. 2019, Teruzzi et al. 2021, Amadio et al. submitted) show how BGC-Argo profiles help models simulate important subsurface dynamics that ultimately control primary productivity: the nutricline depth and slope, the subsurface chlorophyll maximum depth and its concentration. In addition, the dynamics of the oxygen maximum and minimum zone can be better simulated when BGC-Argo oxygen data are assimilated, provided that good quality control of the oxygen dataset is performed (Amadio et al. submitted).

There is an urgent need to increase the number of BGC-Argo sensors at global and local scales, as shown by the Observing System Simulation Experiments (OSSE) for the global ocean (Ford et al. 2021). Alternatively, neural networks techniques are promising for reconstructing profiles of nutrients concentration or carbonate system parameters from concurrent in situ measurements of temperature, salinity, hydrostatic pressure, and oxygen (DO) together with sampling latitude, longitude, and date (Sauzède et al. 2017, Fourrier et al. 2020, Pietropolli et al. 2023). Their advantages have been demonstrated in model validation (Mignot et al. 2023) and in data assimilation in regional domain models (Mediterranean Sea; Amadio et al. submitted).

Based on BGC-Argo floats currently active, the BGC-Argo mission includes 16 countries, of which 10 are from Europe (counting Euro-Argo ERIC as a country). Europe altogether (Euro-Argo ERIC and its national Members) is committed to contribute to 25 % of this fleet, meaning that 250 floats should be sustainably operated (~60 floats to be deployed on a yearly basis) when the target of 1000 floats will be reached.

The monitoring of European marginal Seas, namely the Baltic, the Black and the Mediterranean Seas, is one of Euro-Argo priorities for BGC-Argo. Maintaining a network of BGC-Argo floats in these regions under anthropogenic pressure will contribute to the monitoring and assessment of the marine environment status and functioning in relation to climate change as part of the European Union Green Deal, help improve operational ecosystem models and support the development of high-quality satellite products on Ocean

Color (e.g. Grégoire et al. 2023 for the Black Sea). The subpolar gyre of the North Atlantic Ocean and the Nordic Seas, the ocean area connecting the North Atlantic with the Arctic Ocean, are of great importance for the formation and transformation of water masses and the transport of carbon to the interior of the ocean. Thus, the North Atlantic Ocean and the Nordic Seas act as a channel for atmospheric CO2 from surface to depth, a process that sustains the global ocean carbon sink (e.g., Sabine et al. 2004; Davila et al. 2022) and will be two of the regions targeted by Euro-Argo for BGC-Argo float deployments. Other regions of European scientific interest are the south-west sector of the Indian Ocean (from subequatorial waters to seasonal Ice zone) and the Southern Ocean. All the above-mentioned regions will be targeted as priorities by Euro-Argo for BGC-Argo float deployments in the years to come, the second objective being to fill the global observational gap as part of partnerships and coordination at an international level for the implementation of the global OneArgo array.

2.3. The future of BGC-Argo in Europe

The development of NKE PROVOR CTS5 with a possible Jumbo version (20 cm taller and 60% more batteries) was initiated as part of the EU ERC REFINE project[4]. This float offers the possibility to extend and diversify the BGC-Argo mission through the implementation of new sensors. In particular and beside the measurement of the six core BGC-Argo variables, it can carry and easily manage additional sensors like hyperspectral radiometers and particle size imagers.

The Underwater Vision Profiler 6 (UVP6) is a camera-based particle counter. It allows to quantify the particle size distribution between 0.1 and 2 mm. It has an embedded IA-based classification of 20 categories of zooplankton in the same size range (Picheral et al. 2022). UVP6 is an upgraded version of the UVP5 (deployed attached to CTD rosettes) and is intended to be deployed from autonomous platforms, in particular profiling floats. So far, two groups have deployed such a sensor. Two floats with UVP6 have been deployed by Norwegian colleagues in the Norwegian basin. Nineteen UVP6 floats have been deployed over the spring 2022-summer 2023 period in various open ocean areas (REFINE project). These deployments have been realised over a wide range of environmental / biogeochemical conditions from hyper-oligotrophic waters of the South Pacific Subtropical Gyre to the high latitude environments of the Labrador Sea and of the Southern Ocean (both sides of the Kerguelen plateau). The first results have begun to showcase the potential of the sensor to clearly characterise the temporal dynamic of particles contributing to the gravitational export of carbon within the mesopelagic zone. When associated with transmissometer measurements during the parking phase (so-called optical sediment trap technique) UVP measurements allow to better constrain the quantification of biological carbon pump. Additionally, the first UVP time series acquired over more than one year (Labrador Sea) suggest the sensor is able to track the seasonal migration of copepods. In parallel to the analysis of the first acquisition of these first deployments, the procedure to make data available through the Data Assembly Centres (and Global Data Assembly Centres) are being established. This constitutes a perquisite to subsequently develop the real-time quality control procedures. When the data distribution pipeline will be ready, this type of measurement and associated sensors will be ready to be evaluated by OneArgo Steering Team as a potential sensor that could deliver additional biogeochemical / ecosystem measurement to the already 6 recognized variables.

European scientists have recently upgraded the BGC-Argo sensor package with hyperspectral radiometers mounted at the top of the float to avoid platform self-shading (Organelli et al. 2021). These radiometers can

[4] https://erc-refine.eu/

fully define the quantity and the colours of the sun's radiant energy in the water at 140 bands, in the UltraViolet (UV) and VISible (VIS) light. Being able to recognize hundreds of colours puts the way forward to develop new proxies to study phytoplankton communities, particulate and dissolved carbon dynamics, and ecosystem health along the water column. For example, phytoplankton cellular traits (such as photosynthetic pigment composition and concentration) shape the quantity of light and its colour across the whole visible spectral range (400-700 nm). Similarly, coloured dissolved organic matter and detrital particles absorb, and thus reduce, the light available in the UV and blue bands. Figure 2 shows how energy and colour of light change with depth, while differences of the maximum available band at depth indicate the presence of different phytoplankton communities between the Baltic and Mediterranean seas (Organelli et al. 2021).

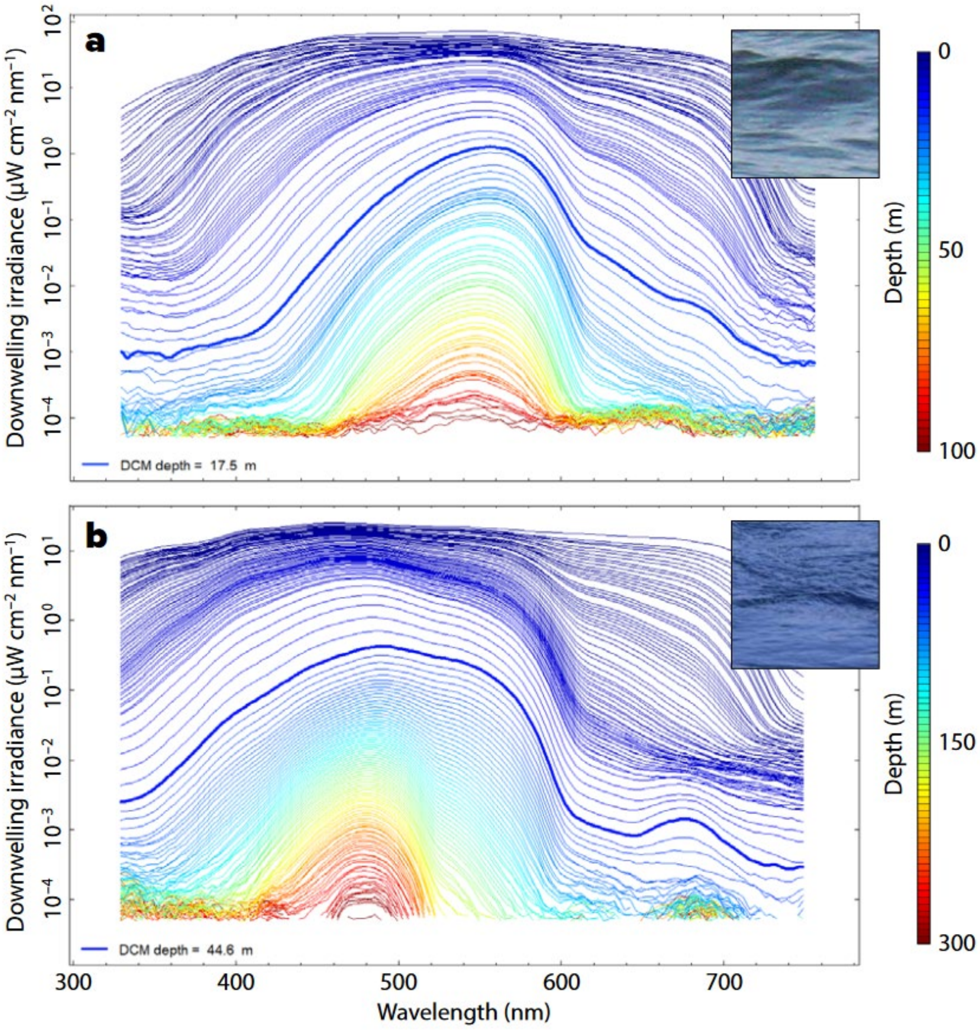

Figure 2. From Organelli et al. (2021). Hyperspectral downwelling irradiances in the Baltic Sea (a) and in the Mediterranean Sea (b).

A dozen of BGC-Argo floats equipped with hyperspectral radiometers are already operating in the global ocean (ERC REFINE project), and more are coming to better monitor and study ocean biogeochemistry and ecosystem health, as well as to improve management of living resources and ecosystem services (Organelli et al. 2021). Many of these floats also acquire information on the upwelling light, thus being a support of CAL/VAL activities for current and upcoming satellite hyperspectral Ocean Colour sensors (e.g., ASI's PRISMA, DLR's EnMAP, NASA's PACE, ESA's CHIME).

On the longer term, new developments are planned within the GEORGE HE EU project to integrate novel sensors ultimately enabling for the first time systematic autonomous, in situ seawater CO2 system characterisation, and CO2 fluxes on Argo and other ocean observing platforms.

3. European contribution to Deep-Argo

3.1. Scientific objectives

Since 2019, the so-called "Core", "BGC" and "Deep" missions of the Argo program have jointly constituted the three components of its new phase that is now global, full-depth and interdisciplinary, with enhanced coverage in tropical areas, western boundary regions and marginal seas (Roemmich et al. 2019b; Claustre et al. 2020). Of the 4600 floats necessary to reach the objectives of this new phase, 1250 floats will be able to go deeper than 2000 m. On the basis of their expected lifetime, this represents about 300 deployments of deep-reaching (4000m or 6000m) float each year.

This overarching objective is underlined by the current lack noted by the ocean-observing community. In particular, the OceanObs conference in 2019, aiming to define guidelines for ocean observation for the next decade, highlighted the chronic under-sampling of the ocean abysses (Levin et al. 2019), which has been consequently identified as one of the three scientific and technological challenges behind the evolution of Argo in the next decade (Roemmich et al. 2019b). Indeed, about half of the global ocean volume is found below 2000 m depth – that is, beyond the reach of the Core-Argo fleet – and only sparsely monitored through expensive coast-to-coast shipborne surveys spaced out by 1 or 2 years at best, but usually by 5 to 10 years (Sloyan et al. 2019). Such observational restrictions inevitably limit our understanding and prediction of deep-ocean machinery (e.g. circulation and water mass properties), and most importantly, its role in influencing current climate changes, including global and regional energy and sea-level budgets, anthropogenic carbon uptake, or deoxygenation. For instance, about 15% of the global ocean's anthropogenic warming (93% of the Earth's system heat gain) is presumably occurring in deep (2000-4000 m) and abyssal (4000-6000 m) layers (Desbruyères et al. 2017). Yet even this global-scale figure is still largely uncertain and would require systematic and homogeneous observations to be confirmed and decomposed regionally. Moreover, this need for comprehensive monitoring of climate-relevant changes in the deep ocean (e.g. temperature, salinity) must be paralleled by an increased understanding of its regional dynamics. Providing observation-based global mapping of deep and abyssal horizontal currents is particularly essential to ensure that they are adequately represented in climate models, and consequently, to produce more robust climate projections. This long-term objective, which likewise relies on systematic and homogeneous observations (Ollitrault and Colin de Verdière, 2014), can already be guided by local investigation of deep and abyssal water-mass pathways, for which the use of biogeochemical tracers such as oxygen represents the most promising approach (Racapé et al. 2019).

The international Argo community launched, in the early 2010s, Deep-Argo regional pilot experiments in the subpolar North Atlantic, southwestern Pacific and Atlantic, and Southern Oceans (Zilberman et al. 2020) that constituted the first phase of a Deep-Argo program that aims at extending about a third of the present 4000-

float array towards the seafloor. Having jointly demonstrated the technological readiness of the Deep-Argo floats, these experiments will now progressively transition over the coming decade towards a global implementation of the Deep-Argo Program: 1200 floats at a 5° x 5° horizontal resolution (Johnson et al. 2015; Roemmich et al. 2019b). OSSEs performed by four European ocean forecasting centres have shown the potential of such a Deep-Argo array in the reduction of salinity and temperature biases in the deep ocean basins in all four systems (Gasparin et al. 2020). International recommendations have been made to both maintain the current pilot experiments and initiate new regional foci in regions of substantial seasonal-to-decadal variability, while pursuing efforts towards technological refinements (e.g. long-term stability) and a coordinated data-management strategy (e.g. quality control). The European contribution to these international recommendations is described in the following section.

3.2. European deployment strategy

The long-term target for the European (Nations plus European Union) contribution to the Deep-Argo array is to maintain 300 Deep-Argo active floats, which is 25% of the international target. Assuming a 4-year lifetime for the floats, this would represent 75 floats to be deployed each year. Deployment strategies will aim to fulfil two key goals of the implementation phase: to establish and maintain a near-global homogeneous fleet while investigating key areas and scientific questions. Because of their predominant roles in the ventilation and long-term sequestration of climatic signals into the deep (via convective mixing and downslope cascading), the North Atlantic, the Nordic Seas and the Southern Ocean stand out as the most natural targets and will be European scientific priorities. They have, for instance, largely dominated the global pattern of deep and abyssal linear temperature changes in recent decades (Desbruyères et al. 2016). The Nordic Seas is a key region of water mass transformation in the northern loop of the global thermohaline circulation (e.g., Swift 1984). Atlantic Water is here transformed, through intense cooling, into a water mass that is dense enough to feed the lower North Atlantic Deep Water (Aagaard et al. 1985). The Mediterranean Sea is another key area of European interest. The Mediterranean Sea plays an important role in the world ocean, more particularly in the Atlantic Ocean circulation. Despite its limited surface, it is characterised by complex ocean dynamics, with several regions of dense water mass formation (Malanotte-Rizzoli et al. 2014).

First, deployments within the abyssal (>4000 m depth) subtropical North Atlantic (25°N-45°N) will provide a timely extension of the Deep-Argo network currently maintained within the deep (<4000 m depth) subpolar North Atlantic (45°N-65°N) with Deep-Argo 4000 m floats (Le Traon et al. 2020). This extension will specifically allow climate-relevant budgets (heat, freshwater, oxygen, sea level) to be built through comprehensive ocean monitoring between the international RAPID[5] and OSNAP[6] mooring lines, which continuously measure the strength of subtropical and subarctic oceanic currents (Srokosz and Bryden, 2015; Lozier et al. 2019). Based on the global straw plan for Deep-Argo implementation (5°x5°), it will be a priority for Euro-Argo to ensure that the Deep-Argo arrays in the Nordic Seas, and in the subpolar and subtropical North Atlantic, are maintained. The number of Deep-Argo floats to be deployed by Euro-Argo will be defined each year in collaboration with other international programmes. In addition, a precise number of floats to sample these areas will be refined throughout dedicated project tasks involving the analysis of existing core and deep Argo profiles and repeated hydrography sections.

[5] https://www.rapid.ac.uk
[6] https://www.o-snap.org

Second, deployments within the Southern Ocean and along the northward pathways of Antarctic Bottom Water – the deepest and most voluminous water mass of the global ocean (Johnson, 2008) – will allow tracking of a strong anthropogenic and abyssal warming signal that supposedly prevails in this region (Purkey and Johnson, 2010). Euro-Argo plans to maintain part of the Deep-Argo floats active in the Southern Ocean, more specifically in its Atlantic and Indian sectors where Europe-led cruises frequently take place.

There is a great potential for the Deep-Argo extension in the Mediterranean Sea. There are several sub-basin areas with a depth between 2000 and 5000 metres that should be explored by the Argo platforms (Algerian, Ligurian, Tyrrhenian, Ionian, Cretan and Levantine sub-basins). Deployment of Deep-Argo floats in selected areas can contribute to the understanding and study of the deep waters, their properties and circulation. The formation areas of dense waters are located in nine regions in the Rhodes Gyre area, in the Aegean Sea, in the Adriatic Sea, in the Tyrrhenian Sea and in the Gulf of Lion, as defined in Pinardi et al. 2023. The abyssal circulation is characterised by two primarily meridional deep cells, separated by the Sicily Channel, in the Western Mediterranean and the Eastern Mediterranean (Pinardi et al. 2019; Pinardi et al. 2023). The maintenance of 6 to 7 platforms in the deeper regions of the Mediterranean Sea should be a reasonable target to obtain a homogeneous spatio-temporal coverage of the deep water masses. Although robust statistics on the death rate are still not available for this kind of platform in the Mediterranean Sea, we can estimate that about 2-3 deployments per year should be done in order to reach this goal. Good cooperation between countries involved in the MedArgo program is needed to deploy Deep-Argo floats in the different sub-basins. The few successful Deep-Argo floats deployed in the Mediterranean Sea since 2016 were configured with a cycle time of 5 days and a deep park pressure (3500-3800 dbar) to try to keep the floats in the deepest area for a longer time and to reduce risks that floats approach coastlines. Full-depth profiles were acquired at each cycle and three different vertical resolutions were adopted: 2 dbar for the 0-100 m layer, 10 dbar for the 100-700 layer and 25 dbar below 700 m. Floats with such a configuration can perform about 150 cycles and can live approximately two years. Going back to the standard 10 days cycle could limit further the displacement between consecutive profiles.

In addition, Euro-Argo will start to contribute to the global Deep Argo array implementation through deployments in under-sampled areas via dedicated scientific projects and deployments of opportunity. This additional effort will be distributed across the Euro-Argo members following their specific interests as well as the recommendations from the international steering team, in the aim of contributing to one fourth of the OneArgo array.

Importantly, the aforementioned European objectives will be built upon a cost-effective strategy, striking a balance between the Deep-Argo floats with 6000 dbar capability (Deep-6k floats) in relatively deeper areas (e.g. subtropical North Atlantic and Southern Ocean) and the twice-cheaper Deep-Argo floats with 4000 dbar capability (Deep-4k floats) in shallower areas (e.g. subpolar North Atlantic and Nordic Seas). Finally, both the scientific experiments (North Atlantic, Southern Ocean and Mediterranean Sea) and the global array will greatly benefit from the oxygen data acquired by the Deep-4k and Deep-6k floats. As mentioned above, homogeneous and systematic DO measurements indeed permit efficient tracking of convectively-formed water masses (because of their recent contact with the atmosphere) and illuminate our understanding of deep and abyssal ventilation in those regions (e.g. deep-water formation rates, deep-water pathways; Racapé et al. 2019), as well as informing on (human-driven) deep-ocean deoxygenation.

However, in spite of the need to establish a strong contribution to Deep Argo, there are still many technological challenges, the most important of them being to ensure the accuracy of the conductivity sensors (to measure salinity) in the deep Argo floats. Recently, in the framework of the Euro-Argo RISE project[7] (Euro-Argo RISE H2020 deliverable 3.3 'Deep float experiment final evaluation and recommendations'[8]), a focused study has concluded that despite the progress done so far by the CTD (Conductivity, Temperature Depth) sensor manufacturers, namely SBS and RBR, as well as by the Argo community in increasing the accuracy and stability of the CTD sensors, it is still necessary to carry out a reference CTD profile at the deployment site. Without this CTD profile, neither the SBE nor RBR sensors would achieve the needed accuracy. As a result, today Deep-Argo floats can only be deployed from Research Vessels and their data rely on GO-SHIP measurements. Despite the recent advances of the conductivity sensors, there is still a need to investigate the long-term behaviour of the conductivity sensors. The European community has been active in defining Delayed Mode Quality Control procedures for Deep Argo data since the beginning of the Deep Argo mission, and will continue to investigate sensors behaviour in collaboration with manufacturers, in order to achieve the required accuracy (±0.002 PSS-78 for salinity, ±0.001°C for temperature, and ±3 dbar for pressure, Roemmich et al. 2019b). Efforts should be continued to collect appropriate reference high quality data required for such Deep Argo data quality assessment.

3.3. Biogeochemical observations from Deep floats

Dissolved oxygen (DO) is the parameter that stands as a first-choice candidate for initiating deep and abyssal biogeochemical observations. Indeed, a systematic and homogeneous monitoring of DO below 2000 m depth will not only enable the tracking of primary pathways of deep and abyssal water masses, but also significantly improve our understanding of current ocean deoxygenation trends (Schmidtko et al. 2017; Bopp et al. 2013) and their consequences on biogeochemical cycles and ecological habitats. Therefore, in addition to building the physical description and comprehension of links between deep-oxygen changes and water-mass ventilation, oxygen inventories of the full water column are of primary interest to better constrain biogeochemical cycles and to better understand dissolved-oxygen sources and sinks. See further details in Section 4.

Optical scattering is a proxy for particle concentration in seawater (Stramski et al. 2004), and holds promise as a potential addition to Deep-Argo floats. Deep scattering measurements are needed to improve our understanding of the fate of sinking particles produced at the surface (Volk and Hoffert, 1985) and their role in burying organic carbon in sediments, to quantify sediment resuspension and transport near the ocean bottom (Brewer et al. 1976; Biscaye and Eittreim, 1977), and to measure transport and redistribution of trace metals (Lam and Bishop, 2008; Estapa et al. 2015). A network of Deep-Argo floats equipped with optical scattering sensors would allow the investigation of the spatio-temporal variability of such processes.

Another application of deep-ocean scattering data is to assess the environmental impacts of deep-sea mining by establishing a baseline for the amount of suspended particles below 2000 m and inferring variations from this baseline due to mining operations.

Deep-rated optical scattering sensors are commercially available and have been tested to 6000 m (e.g. Gardner et al. 2018). The high sensitivity of optical scattering to minerals and large particles (Briggs et al. 2020) implies that no increase in sensor sensitivity nor accuracy is needed to quantitatively resolve the deep-ocean signal. Their integration into Deep-Argo floats has yet to be realised. Pilot projects are planned for the coming years.

[7] https://www.euro-argo.eu/EU-Projects/Euro-Argo-RISE-2019-2022
[8] https://www.euro-argo.eu/content/download/165130/file/D3.3_v1.0_under_EC_review.pdf

4. Dissolved oxygen

4.1. Scientific objectives

The distribution of dissolved oxygen (DO) concentration at global scale is driven by physical, biogeochemical and biological processes and has been used to gain insights on those processes since the early age of oceanography (Wüst, 1936), using ship-based data and Argo data (e.g. Riser and Johnson, 2008; Piron et al. 2016; Ulses et al. 2021).

The ocean is the largest ecosystem on the planet, and the ability of organisms to survive with depleted levels of dissolved oxygen is extremely limited. Oceanic regions with low-oxygen concentration called Quasi-permanent oxygen minimum zones (OMZs) have been expanding over the past 50 years and will continue to grow in response to rising ocean temperature (Busecke et al. 2021; Keeling et al. 2010). Earth model simulations predict oxygen decline from the surface to abyssal depth in the 21st century that is tied to GHG emissions (Kwiatkowski et al., 2020). The expansion of these inhospitable areas directly impacts marine ecosystems and ecosystem services with a decrease in biological diversity, physiological adaptation of species, and ultimately depletion of fish stocks (Garçon et al. 2019). The ability of marine biogeochemical models to simulate the response and feedback of marine ecosystems to climate change is contingent upon the availability and accuracy of observational constraints (Séférian et al. 2020). Due to the scarcity of oxygen observations, the physical and biogeochemical processes controlling the size and distribution of these low-oxygen habitats remain poorly understood (Levin et al. 2018).

A global DO array would be required to address climate change issues, to investigate key related physical processes, such as deep convection, ocean ventilation and circulation (Keeling et al. 2010, Piron et al, 2016) and to monitor current changes in DO concentration. The global coverage is key to capture spatial and temporal variability, since the observed loss in the global oceanic oxygen content (greater than 2 % since 1960) (Schmidtko et al, 2017) shows large variations in different ocean basins and at different depths. A full-scale global Argo-DO array is also extremely valuable to expand the scope of BGC-Argo, since DO data is in a key position of many biogeochemical processes. It can also be used to interpolate, e.g., through neural network techniques (Sauzède et al. 2017), nutrient concentrations (nitrate, phosphate and silicate) and carbonate system parameters (total alkalinity, dissolved inorganic carbon, pH and partial pressure of CDO), and ultimately estimate anthropogenic carbon (Cant) storage and export (Asselot et al. 2023, in revision).

There is thus a strong need in the scientific community to set up and maintain a long-term observing system that will produce a homogeneous and validated DO dataset. Therefore, discussions have started to expand the Argo mission with oxygen sensors to a larger subset of the Argo floats.

4.2. Where we are now

The case for measuring dissolved oxygen in Argo was made already in the white-paper report by Gruber et al. (2010), and the Biogeochemical-Argo program provided the required coordination framework for the deployment, acquisition, or use of these observations. To date, there are over 540 active Argo floats carrying oxygen sensors (half of them deployed by Euro-Argo) in the global ocean, which corresponds to about 14% of the active floats.

Extensive R&D activities helped to understand the behaviour of optical oxygen sensors (Bittig et al. 2014; Bittig and Körtzinger, 2015) and to define quality control procedures when those sensors are implemented on mobile platforms such as Argo floats (Takeshita et al. 2013, Thierry et al. 2021, Bittig et al. 2018). The best accuracy reached in the field by Argo DO sensors is 1-2 µmol kg-1 and requires a careful correction of the data to take into account sensor drift (Bittig et al. 2018, 2019), time response (Bittig et al. 2014; Gordon et al. 2020) and pressure dependent response of the sensor (Bittig et al. 2018, Racapé et al. 2019).

Oxygen data from Argo floats are now sent to the Global Telecommunications System through which most of operational users get their data in Real Time, and it is one of the variables that is routinely assimilated in the Mediterranean system of the Copernicus Marine Service (Amadio et al. submitted).

4.3. European deployment strategy

As a long-term goal, Euro-Argo will advocate that at least half of the OneArgo floats will be equipped with oxygen sensors, considering that DO sensors will be mounted on all BGC floats and most of the Deep floats. The optode DO sensor is of proven maturity and can provide very accurate measurements (1% of the signal), owing to in-air measurements done during the float lifetime (Bittig et al. 2018) in the upper 2000 m of the ocean. Oxygen sensors on Deep floats are also very valuable (see section 3.3), although the accuracy needed to resolve deoxygenation trends has not been reached yet (Grégoire et al. 2021).

Most of the research and progress with respect to DO sensor characterization and development of processing and quality control procedures for Argo-DO took place in Europe. With this expertise, Euro-Argo is primed to pioneer the equipment of most of the Euro-Argo fleet with DO sensors. This step could lead to a major advance in biogeochemical monitoring of the marine ecosystem and operational services in the European Seas. Some further, specific needs regarding DO data are for instance to (i) monitor the inflow of DO-rich waters and oxygen depletion in the Baltic Sea, (ii) analyse productivity and ecosystem response to climate change in the Nordic Seas, (iii) monitor deep-convection at high-latitudes and especially in the subpolar gyre of the North-Atlantic. Most of Deep-Argo floats deployed by Euro-Argo will also be equipped with oxygen sensors, for the reasons presented in section 3.3. The profound scientific interest by European and international scientists and operational data users supports the goal to increase the share of DO-equipped Argo floats beyond the BGC-Argo target of 25 % of all floats, and to equip at least 3/4 of the Euro-Argo fleet (all missions) with a DO sensor in the long-term. This will require to equip more than half of the European core-Argo floats with a DO sensor.

In particular, and as a pilot study, Euro-Argo plans to add DO to all Argo floats to be deployed in the Mediterranean Sea in the future. This is both to derive other biogeochemical variables through “smart” extrapolations (e.g., Sauzède et al. 2017) as well as to better track water masses and deep-convection events. This experiment in a marginal sea will provide data to assess advantages and disadvantages of adding DO to half of the European core-Argo fleet.

The international Argo programme is also currently working on a strategy for the deployment of “core-DO” floats. Discussions should take place with other observing networks and communities to help Argo assess the needs in terms of Argo oxygen data. The potential of oxygen data has been demonstrated but further studies are needed, including OSSEs, to better assess the needs and see how these needs could be articulated within a refined OneArgo design. Euro-Argo will obviously take into account the results of these discussions to further refine its strategy for oxygen data.

5. Network implementation and associated cost

5.1. Euro-Argo targets for Deep and BGC-Argo floats

Table 1: Number of active floats to be maintain by Euro-Argo - long term targets

	# of active BGC floats	# of active Deep floats
Mediterranean Sea	7	6
Black Sea	3	0
Baltic Sea	2	0
Arctic (>60°N)	-	3
Rest of the world ocean	238	271
TOTAL	**250**	**300**

5.2. Implementation cost

As mentioned previously, the OneArgo design is ambitious. Its implementation will require strong efforts and additional resources. An assessment of the resources needed for Euro-Argo to achieve 25% of the OneArgo design, including the contribution to BGC-Argo and Deep-Argo is presented in Table 2. The share of Deep-4k and Deep-6k floats has been set to 50/50, and the BGC floats to be deployed were all considered as 6-variables floats. The costs presented are yearly costs based on a constant rough estimate of retail price for each type of float, which is obviously unrealistic. The table shows the yearly cost of the initial core-Argo design (blue), the current Euro-Argo expenses (green) and the cost of the Euro-Argo contribution to the complete OneArgo implementation (orange). Costs include float procurement and operation (i.e. testing, shipping, satellite communications) on one hand, and personal costs on the other hand (i.e. personal cost for data processing, operations, etc.).

In total, the estimated cost of Euro-Argo contribution to OneArgo is 25M€ per year: among the 15.4M€ needed for float procurement and operation (i.e. excluding personal costs), 7.8M€ are for BGC-Argo and 4.7M€ for Deep-Argo.

To achieve its target of maintaining 25% of the OneArgo design in the next decade, Euro-Argo will have to find an additional 10M€ per year.

Table 2: Cost assessment of the Euro-Argo contribution to the OneArgo array implementation and comparison with the initial core-Argo array.

	2023 Retail price	2023 Operation cost/year	Lifetime (years)		Core Argo only international active floats (DESIGN)	EU share to deploy/year	Annual cost EURO-ARGO	EURO-ARGO mean annual float deployment 2019-2022	Mean annual cost EURO-ARGO	OneArgo international active floats (DESIGN)	EU share to deploy/year	Annual cost EURO-ARGO
Core	20 000 €	600 €	5		4000	200	4 600 000 €	139	2 780 000 €	2500	125	2 875 000 €
Deep -4000m	40 000 €	800 €	4					20,25	810 000 €	600	37,5	1 620 000 €
Deep -6000m	80 000 €	800 €	4							600	37,5	3 120 000 €
BGC 1-5 variables	80 000 €	1 075 €	4					40,5	3 240 000 €			
BGC 6 variables	120 000 €	1 075 €	4					7,75	930 000 €	1000	62,5	7 768 750 €
				Floats	4000	200	4 600 000 €	207,5	7 760 000 €	4700	262,5	15 383 750 €
				Personal costs			2 360 000 €		7 500 000 €			10 000 000 €
				TOTAL costs			**6 960 000 €**		**15 260 000 €**			**25 383 750 €**

6. OneArgo as a contribution to a multiplatform ocean observing system

An integrated ocean observing system is the crux of a holistic scientific understanding of the Earth system. Each of the GOOS components has its own specificities and all observing platforms are complementary to each other. By nature, Argo sensors are autonomous and post-calibration is not possible. Quality Control thus mainly depends on colocalised reference measurements usually acquired at deployment, or possibly checked against satellite data later on for gross offsets or drifts. Although core-Argo data are distributed in RT after basic automatic Quality Control tests for operational applications, the data are sometimes affected by sensor drift. At a later stage, data are thus carefully examined and, if required, corrected by experts, comparing the measurements with ship-based data. This Delayed Mode Quality Control is a prerequisite for the data to be used for ocean science applications, for all EOVs. The Argo programme thus strongly relies on high accuracy CTD casts and reference samples such as calibrated CTD-O_2 cast; bottle NO_3, etc. (Bittig et al. 2019) collected from ships (GO-SHIP), and this is more particularly true for BGC-Argo and Deep-Argo, whose sensor technology is less mature than for core-Argo floats. For instance, recommendations have been provided within the EuroSea project for the quality control of pH measurements from Argo floats, using a multi-platform approach (Deliverable 7.2[9]).

The Framework for Ocean Observing (Lindstrom et al. 2012) sets the basis for international integration and coordination of interdisciplinary ocean observations. In that context, the synergy of Argo with other ocean observing networks has been considered both at international and European levels, through many collaborative activities recently carried out in projects (e.g. H2020 EU projects AtlantOS, EuroSea, Euro-Argo RISE) and coordination frameworks (e.g. Ocean Coordination Group in GOOS, European Ocean Observing System - EOOS - and Regional Ocean Observing Systems - ROOSes - in Europe).

Networks coordination is needed for a better Ocean integration (Tanhua et al. 2019, Révelard et al. 2022). An efficient coordination at all levels of the ocean observations value chain leads for instance to increased cost effectiveness of the global observing system and better data uptake by users thanks to improved interoperability. Collaboration has proven its worth in the technological (e.g. through EOOS technology Forums organised in 2020 and 2022) and data quality domains (e.g. in the H2020 AtlantOS, EuroSea and ENVRI-FAIR H2020 projects). One example is the involvement of Argo data experts in the development of Ocean Gliders Best Practices and Standard Operation Procedures, within the EuroSea project. More generally, the subject of enhanced collaboration between various ocean observing networks has been discussed during the Marine Research Infrastructures' workshop organised as a side event of the 9th EuroGOOS Conference in May 2021 (Euro-Argo RISE project), the Deep and BGC-Argo workshop in September 2021[10] (EuroSea project) and at the UN Ocean Decade Forum co-organised by Argo international as part of Monaco Ocean Week, in March 2022.

In terms of network implementation and ocean observing system design, although the OneArgo design does not take into account other platforms in its global definition, the design implementation at regional level will require strong coordination to be efficient and to properly answer user needs (e.g. operational services such as the Copernicus Marine Service). The MOOSE[11] Network is an example of multiplatform approach -

[9] https://www.euro-argo.eu/EU-Projects/EuroSea-2019-2023/Deliverables
[10] https://www.euro-argo.eu/News-Meetings/Meetings/Others/BGC-Deep-Argo-Workshop
[11] https://www.moose-network.fr/

including Argo - used at regional level to observe the spatio-temporal variability of processes interacting between the coastal-open ocean and the ocean-atmosphere components in the Mediterranean Sea (Figure 3). The Euro-Argo strategy for ocean monitoring in the European marginal seas will address this complementarity with other networks.

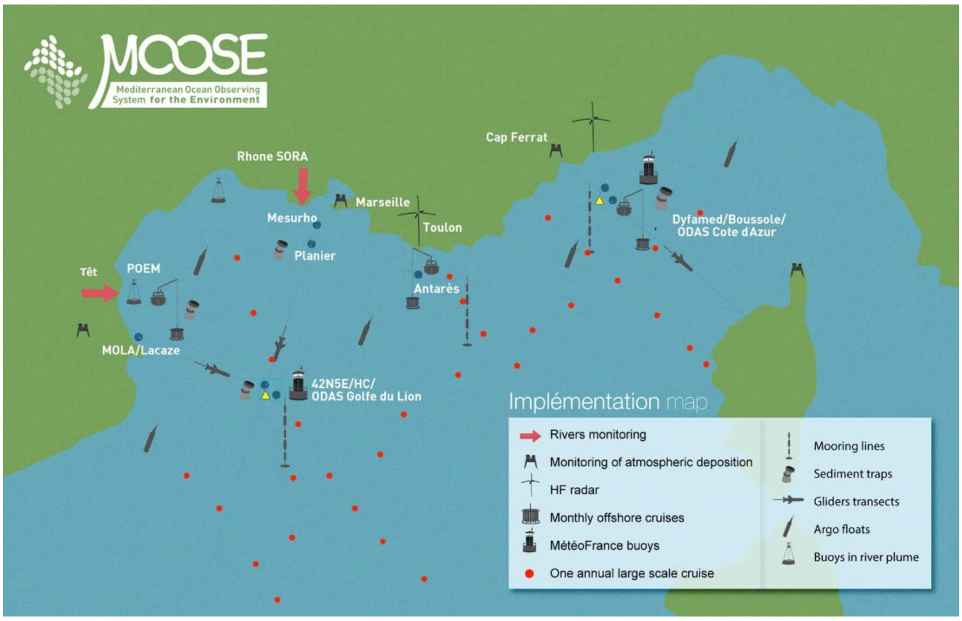

Figure 3. MOOSE observing system ©MIO

The coming years will be critical in progressing on ocean integration and multiplatform approaches. Some of the propositions identified for progressing towards relevant and coherent resolution for the observation of the EOVs will be undertaken within the upcoming AMRIT Horizon Europe project (2024-2026) that involves several key ocean observation networks (Gliders, GO-SHIP, EMSO, Argo). The EOOS has just launched its strategy and roadmap for implementation for 2023-2027, and the UN Decade of the Ocean is still running until 2030, providing opportunities for collaboration between networks. Euro-Argo will participate and take advantage of the outcomes of these initiatives and will revisit its strategy for OneArgo implementation according to these outcomes.

7. Conclusion and perspectives

OneArgo will bring along new services and scientific opportunities to advance our understanding of the role of the ocean in the earth system and to address issues associated with climate change, including its impact on ocean ecosystem health. The new design, and more specifically the BGC and the Deep-Argo missions, come with new challenges for Euro-Argo.

Among the future challenges in the implementation of both BGC-Argo and Deep-Argo in Europe, the cost is one of the most pressing. According to the rough estimates made within this study, Euro-Argo will have to find an additional 10M€ per year to be able to implement one fourth of the full OneArgo design, which will require strong advocacy efforts. While procuring and deploying the required Core, Deep and BGC floats and associated sensors, Euro-Argo will also have to ensure the data flows towards Argo data users are evolving accordingly. The development of data quality and assessment procedures and monitoring for all the parameters will also be critical. For instance, the challenges that represent the implementation of the Deep Argo strategy in Europe requires to ensure that the measurement meets the needed accuracy, and therefore it is necessary to establish a monitoring program capable of calibrating deep sensors, if needed. Euro-Argo will have to consider the need for growing capacity both at manufacturer level and in the teams involved with operations, data management, data quality and sensor accuracy assessment and monitoring.

The European strategy for Deep and BGC Argo presented here is part of a wider effort initiated by Euro-Argo to define the general "Euro-Argo scientific strategy for the OneArgo array implementation". The aim is to release this full new scientific strategy in 2024. Such a strategy will have to be revisited regularly, to consider recommendations from the Euro-Argo Scientific and Technical Advisory Group, and possible evolutions of the OneArgo design and associated international recommendations in the coming years. As one piece of a multiplatform ocean observing system, Argo and Euro-Argo will also have to improve synergies with other ocean observing networks in the future, to efficiently progress in ocean knowledge and management. Euro-Argo will also have to consider the evolution of its various user community needs, including operational users. The progress made in the various pilot studies mentioned here, that will drive the evolution of Argo in Europe, will also have to be reflected in the strategy for Euro-Argo network implementation in the future.

References

Aagaard, K., J.H. Swift, and E.C. Carmack (1985). Thermohaline circulation in the Arctic Mediterranean seas. *Journal of Geophysical Research*, 90(C3), 4833– 4846. https://doi.org/10.1029/JC090iC03p04833.

Amadio et al., submitted. Combining Neural Networks and Data Assimilation to enhance the spatial impact of Argo floats in the Copernicus Mediterranean biogeochemical model. *Submitted to Ocean Science.*

Asselot, R., L. I. Carracedo, V. Thierry, H. Mercier, R. Bajon and F.F. Pérez (2023). Argo-O2 data combined with neural networks floats reveal the anthropogenic carbon pathways towards the deep North Atlantic, *submitted to Nature Communications. In revision.*

Begouen Demeaux, C. and E. Boss (2022). Validation of Remote-Sensing Algorithms for Diffuse Attenuation of Downward Irradiance Using BGC-Argo Floats. *Remote Sens.* 14, 4500. https://doi.org/10.3390/rs14184500.

Biscaye, P.E. and S.L. Eittreim (1977). Suspended particulate loads and transport in the nepheloid layer of the abyssal Atlantic Ocean - *Mar. Geol.,* 23, pp. 155-172.

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

Bittig, H., B. Fiedler, R. Scholz, G. Krahmann, and A. Körtzinger (2014). Time response of oxygen optodes on profiling platforms and its dependence on flow speed and temperature. *Limnol. Oceanogr. Methods*. 12, 617–636. doi: 10.4319/lom.2014.12.617.

Bittig, H. C., and A. Körtzinger (2015). Tackling oxygen optode drift: near-surface and in-air oxygen optode measurements on a float provide an accurate in situ reference. *J. Atmos. Oceanic Technol.,* 32, 1536–1543. doi:0.1175/JTECH-D-14-00162.1.

Bittig, H. C., A. Körtzinger, C. Neill, E. van Ooijen, J.N. Plant, J. Hahn, et al. (2018). Oxygen optode sensors: principle, characterization, calibration, and application in the ocean. *Front. Mar. Sci.* 4:429. doi: 10.3389/fmars.2017.00429.

Bittig, H., T. Maurer, J. Plant, C. Schmechtig, A. Wong, H. Claustre, et al. (2019). A BGC-Argo guide: planning, deployment, data handling and usage. *Front. Mar. Sci.* 6:502, doi: 10.3389/fmars.2019.00502.

Bopp, L., L. Resplandy, J.C. Orr, S. C. Doney, J.P. Dunne, M. Gehlen, P. Halloran, C. Heinze, T. Ilyina, R. Séférian, J. Tjiputra and M. Vichi (2013). Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models, *Biogeosciences,* 10, 6225–6245, https://doi.org/10.5194/bg-10-6225-2013.

Brewer, P. G., D.W. Spencer, P.E. Biscaye and A. Hanley (1976). The distribution of particulate matter in the Atlantic Ocean - *Earth and Planetary Science Letters*.

Brewin, R. J. W., G. Dall'Olmo, J.A. Gittings, X. Sun, P.K. Lange, D.E. Raitsos, H.A. Bouman, I. Hoteit, J. Aiken and S.A. Sathyendranath (2022). Conceptual Approach to Partitioning a Vertical Profile of Phytoplankton Biomass Into Contributions From Two Communities. *Journal of Geophysical Research-Oceans* http://dx.doi.org/10.1029/2021JC018195.

Briggs N., G. Dall'Olmo and H. Claustre (2020). Major role of particle fragmentation in regulating biological sequestration of CO2 by the oceans. *Science.* 2020 Feb 14;367(6479):791-793. doi: 10.1126/science.aay1790. PMID: 32054763.

Busecke, J. J. M., L. Resplandy, S.J. Ditkovsky and J.G. John (2021). Diverging fates of the Pacific Ocean oxygen minimum zone and its core in a warming world. *AGU Advances*. 3, e2021AV000470. https://doi.org/10.1029/2021AV000470 (2021)

Claustre, H., D. Antoine, L. Boehme, E. Boss, F. D'Ortenzio, O. Fanton D'Andon, C. Guinet, N. Gruber, N.O. Handegard, M. Hood, K. Johnson, A. Körtzinger, R. Lampitt, P.Y. LeTraon, C. Lequéré, M. Lewis, M.-J. Perry, T. Platt, D. Roemmich, S. Sathyendranath, P. Testor, U. Send and J. Yoder (2010). Guidelines towards an integrated ocean observation system for ecosystems and biogeochemical cycles. In: *Proceedings of the "OceanObs'09: Sustained Ocean Observations and Information for Society" Conference*, Venice, Italy, 21-25 September 2009 http://dx.doi.org/10.5270/OceanObs09.pp.14.

Claustre, H., K.S. Johnson and Y. Takeshita (2020). Observing the Global Ocean with Biogeochemical-Argo. Annual Review of Marine Science http://dx.doi.org/10.1146/annurev-marine-010419-010956.

Cossarini, G., L. Mariotti, L. Feudale, A. Mignot, S. Salon, V. Taillandier, A. Teruzzi and F. D'Ortenzio (2019). Towards operational 3D-Var assimilation of chlorophyll Biogeochemical-Argo float data into a biogeochemical model of the Mediterranean Sea. *Ocean Modelling,* 133, 112–128. https://doi.org/10.1016/j.ocemod.2018.11.005.

Davila, X., G. Gebbie, A. Brakstad, S. K. Lauvset, E.L. McDonagh, J. Schwinger and A. Olsen (2022). How is the ocean anthropogenic carbon reservoir filled? *Global Biogeochemical Cycles*, 36(5), e2021GB007055.

Desbruyères, D. G., S.G. Purkey, E.L. McDonagh, G.C. Johnson and B.A. King (2016). Deep and abyssal ocean warming from 35 years of repeat hydrography, *Geophys. Res. Lett*., 43, 310–356, https://doi.org/10.1002/2016GL070413.

Desbruyères, D., E. L. McDonagh, B. A. King and V. Thierry (2017). Global and Full-Depth Ocean Temperature Trends during the Early Twenty-First Century from Argo and Repeat Hydrography. *J. Climate*, 30, 1985–1997, https://doi.org/10.1175/JCLI-D-16-0396.1.

Estapa, M. L., J. A. Breier and C. R. German (2015). Particle dynamics in the rising plume at Piccard Hydrothermal Field, Mid-Cayman Rise, *Geochem. Geophys. Geosyst*., 16, 2762–2774, doi:10.1002/2015GC005831.

Ford, D. (2021). Assimilating synthetic Biogeochemical-Argo and ocean colour observations into a global ocean model to inform observing system design. *Biogeosciences,* 18(2), 509–534. https://doi.org/10.5194/bg-18-509-2021.

Fourrier, M., L. Coppola, H. Claustre, F. D'Ortenzio, R. Sauzède and J.-P. Gattuso (2020). A Regional Neural Network Approach to Estimate Water-Column Nutrient Concentrations and Carbonate System Variables in the Mediterranean Sea: CANYON-MED. *Frontiers in Marine Science,* 7. https://doi.org/10.3389/fmars.2020.00620.

Garçon, V., J. Karstensen, A. Palacz, M. Telszewski, T. Aparco Lara, D. Breitburg, F. Chavez, P. Coelho, M. Cornejo-D'Ottone, C. Santos, B. Fiedler, N.D. Gallo, M. Grégoire, D. Gutierrez, M. Hernandez-Ayon, K. Isensee, T. Koslow, L. Levin, F. Marsac, H. Maske, B.C. Mbaye, I. Montes, W. Naqvi J. Pearlman, E. Pinto,

G. Pitcher, O. Pizarro, K. Rose, D. Shenoy, A. Van der Plas, M.R. Vito and K. Weng (2019) Multidisciplinary Observing in the World Ocean's Oxygen Minimum Zone Regions: From Climate to Fish — The VOICE Initiative. *Front. Mar. Sci.* 6:722. doi: 10.3389/fmars.2019.00722.

Gardner, W., A. Mishonov and M. Richardson (2018). Decadal comparisons of particulate matter in repeat transects in the Atlantic, Pacific, and Indian Ocean basins*. Geophys. Res. Lett.* 2018, 45, 277–286.

Gasparin, F., M. Hamon, E. Rémy, and P.-Y. Le Traon (2020). How Deep Argo Will Improve the Deep Ocean in an Ocean Reanalysis. *Journal of Climate,* 33(1), 77–94. https://doi.org/10.1175/jcli-d-19-0208.1.

Gerbi, G. P., et al. (2016). Validation of Ocean Color Remote Sensing Reflectance Using Autonomous Floats. *J. Atmos. Oceanic Technol.,* 33, 2331–2352, https://doi.org/10.1175/JTECH-D-16-0067.1.

Gordon, C., K. Fennel, C. Richards, L. K. Shay and J.K. Brewster (2020). Can ocean community production and respiration be determined by measuring high-frequency oxygen profiles from autonomous floats?, *Biogeosciences*, 17, 4119–4134, https://doi.org/10.5194/bg-17-4119-2020.

Grégoire et al. (2021). A global ocean oxygen database and atlas for assessing and predicting deoxygenation and ocean health in the open and coastal ocean. *Front. Mar. Sci.* 8, 724913 https://doi.org/10.3389/fmars.2021.724913.

Grégoire M., A. Alvera-Azcárate, L. Buga, A. Capet, S. Constantin, F. D'ortenzio, D. Doxaran, Y. Faugeras, A. Garcia-Espriu, M. Golumbeanu, C. Gonzalez-Haro, V. Gonzalez-Gambau, J.-P. Kasprzyk, E. Ivanov, E. Mason, R. Mateescu, C. Meulders, E. Olmedo, L. Pons, M.-I. Pujol, G. Sarbu, A. Turiel, L. Vandenbulcke and M.-H. Rio (2023). Monitoring Black Sea environmental changes from space: New products for altimetry, ocean colour and salinity. Potentialities and requirements for a dedicated in-situ observing system*. Front. Mar. Sci.* 9:998970. doi: 10.3389/fmars.2022.998970.

Gruber, N., S. Doney, S. Emerson, D. Gilbert, T. Kobayashi, A. Körtzinger, et al. (2007). The Argo-Oxygen Program: A White Paper to Promote the Addition of Oxygen Sensors to the International Argo Float Program.

Gruber, N. et al. Adding Oxygen to Argo: Developing a Global In Situ Observatory for Ocean Deoxygenation and Biogeochemistry (2010)*. In: Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society*, Vol. 2, Venice, Italy, 21-25 September 2009, (eds Hall, J., Harrison, D.E. & Stammer, D.). Paris, France, European Sace Agency, 12pp (ESA Publication WPP-306), http://dx.doi.org/10.5270/OceanObs09.cwp.39.

Johnson, K.S., W.M. Berelson, E.S. Boss, Z. Chase, H. Claustre, S.R. Emerson, N. Gruber, A. Körtzinger, M.J. Perry and S.C. Riser (2009). Observing biogeochemical cycles at global scales with profiling floats and gliders: Prospects for a global array. *Oceanography* 22(3):216–225, https://doi.org/10.5670/oceanog.2009.81.

Johnson, G. C. (2008). Quantifying Antarctic Bottom Water and North Atlantic Deep Water volumes, *J. Geophys. Res.-Oceans*, 113, C05027, https://doi.org/10.1029/2007JC004477.

Johnson, G. C., J. M. Lyman and S. G. Purkey (2015). Informing Deep Argo Array Design Using Argo and Full-Depth Hydrographic Section Data. *Journal of Atmospheric and Oceanic Technology*, 32(11), 2187–2198. https://doi.org/10.1175/jtech-d-15-0139.1.

Keeling, R., A. Körtzinger and N. Gruber (2010). Ocean deoxygenation in a warming world. *Annu. Rev. Mar. Sci. 2*, 199–229. doi: 10.1146/annurev.marine.010908.163855

Kobayashi, T. (2013). Deep NINJA collects profiles down to 4,000 meters, *Sea Technol*., 54(2), 41-44, doi: https://www.sea-technology.com/features/2013/0213/deep_ninja.php.

Kwiatkowski, L., O. Torres, L. Bopp, O. Aumont, M. Chamberlain, J. Christian, et al. (2020). Twenty-first century ocean warming, acidification, deoxygenation, and upper ocean nutrient decline from CMIP6 model projections. *Biogeosciences,* 17(13), 3439–3470. https://doi.org/10.5194/bg-17-3439-2020.

Lam, P. J. and J.K.B. Bishop (2008). The continental margin is a key source of iron to the HNLC North Pacific Ocean. *Geophysical Research Letters 35*.

Lindstrom, E., J. Gunn, A. Fischer, A. McCurdy, L. Glover, K. Alverson, et al. (2012). A Framework for Ocean Observing. By the Task Team for an Integrated Framework for Sustained Ocean Observing. Paris: UNESCO. doi: 10.5270/OceanObs09-FOO.

Le Reste, S., V. Dutreuil, X. André, V. Thierry, C. Renaut, P.-Y. Le Traon and G. Maze (2016). ”Deep-Arvor”: A New Profiling Float to Extend the Argo Observations Down to 4000-m Depth. *Journal of Atmospheric and Oceanic Technology*, 33(5), 1039–1055. https://doi.org/10.1175/JTECH-D-15-0214.1.

Le Traon, P.-Y., F. D'Ortenzio, M. Babin, E. Leymarie, C. Marec, S. Pouliquen, V. Thierry, C. Cabanes, H. Claustre, D. Desbruyères, L. Lacour, J.-L. Lagunas, G. Maze, H. Mercier, C. Penkerc'h, N. Poffa, A. Poteau, L. Prieur, V. Racapé, et al. (2020). Preparing the New Phase of Argo: Scientific Achievements of the NAOS Project. *Frontiers in Marine Science*, 7(838). https://doi.org/10.3389/fmars.2020.577408.

Levin, L. A. (2018). Manifestation, Drivers, and Emergence of Open Ocean Deoxygenation, *Annu. Rev. Mar. Sci.* 10(1), 229-260, https://doi.org/10.1146/annurev-marine-121916-063359.

Levin, L. A., B. J. Bett, A.R. Gates, P. Heimbach, B.M. Howe, F. Janssen, A. McCurdy, H.A. Ruhl, P. Snelgrove, K.I. Stocks, D. Bailey, S. Baumann-Pickering, C. Beaverson, M.C. Benfield, D.J. Booth, M. Carreiro-Silva, A. Colaço, M.C. Eblé, A.M. Fowler et al. (2019). Global Observing Needs in the Deep Ocean. *Frontiers in Marine Science*, 6(241). https://doi.org/10.3389/fmars.2019.00241.

Leymarie, E., C. Penkerc'h, V. Vellucci, C. Lerebourg, D. Antoine, E. Boss, M. Lewis, F. D'Ortenzio and H. Claustre (2018). ProVal: A new autonomous profiling float for high quality radiometric measurements. *Front. Mar. Sci*., 27 November 2018 Sec. Ocean Observation Volume 5 | https://doi.org/10.3389/fmars.2018.00437.

Lozier, M. S. et al. (2019). A sea change in our view of overturning in the subpolar North Atlantic. *Science* 363, 516-521. DOI:10.1126/science.aau6592.

Malanotte-Rizzoli, P., V. Artale, G. L. Borzelli-Eusebi, S. Brenner, A. Crise, M. Gacic, N. Kress, S. Marullo, M. Ribera d'Alcalà, S. Sofianos, T. Tanhua, A. Theocharis, M. Alvarez, Y. Ashkenazy, A. Bergamasco, V. Cardin, S. Carniel, G. Civitarese, F. D'Ortenzio, J. Font, E. Garcia-Ladona, J. M. Garcia-Lafuente, A. Gogou, M. Gregoire, D. Hainbucher, H. Kontoyannis, V. Kovacevic, E. Kraskapoulou, G. Kroskos, A. Incarbona, M. G. Mazzocchi, M. Orlic, E. Ozsoy, A. Pascual, P.-M. Poulain, W. Roether, A. Rubino, K. Schroeder, J. Siokou-Frangou, E. Souvermezoglou, M. Sprovieri, J. Tintoré and G. Triantafyllou (2014) Physical forcing and physical/biochemical variability of the Mediterranean Sea: a review of unresolved issues and directions for future research, *Ocean Sci.*, 10, 281–322, https://doi.org/10.5194/os-10-281-2014.

Mignot, A., H. Claustre, G. Cossarini, F. D'Ortenzio, E. Gutknecht, J. Lamouroux, P. Lazzari, C. Perruche, S. Salon, R. Sauzède, V. Taillandier and A. Teruzzi (2023). Using machine learning and Biogeochemical-Argo (BGC-Argo) floats to assess biogeochemical models and optimize observing system design. *Biogeosciences* http://dx.doi.org/10.5194/bg-20-1405-2023.

Ollitrault, M. and A. Colin De Verdière (2014). The Ocean General Circulation near 1000-m Depth. *Journal Of Physical Oceanography* , 44(1), 384-409. Publisher's official version : https://doi.org/10.1175/JPO-D-13-030.1.

Organelli, E., M. Barbieux, H. Claustre, C. Schmechtig, A. Poteau, A. Bricaud, E. Boss, N. Briggs, G. Dall'Olmo, F. D'Ortenzio, E. Leymarie, A. Mangin, G. Obolensky, C. Penkerc'h, L. Prieur, C. Roesler, R. Serra, J. Uitz and X. Xing (2017). Two databases derived from BGC-Argo float measurements for marine biogeochemical and bio-optical applications. *Earth System Science Data* http://dx.doi.org/10.5194/essd-9-861-2017.

Organelli, E., H. Claustre, A. Bricaud, M. Barbieux, J. Uitz, F. D'Ortenzio and G. Dall'Olmo (2017). Bio-optical anomalies in the world's oceans: An investigation on the diffuse attenuation coefficients for downward irradiance derived from Biogeochemical Argo float measurements. *Journal of Geophysical Research-Oceans* http://dx.doi.org/10.1002/2016jc012629.

Organelli, E., E. Leymarie, O. Zielinski, J. Uitz, F. D’Ortenzio and H. Claustre (2021). Hyperspectral radiometry on Biogeochemical-Argo floats: A bright perspective for phytoplankton diversity. Frontiers in Ocean Observing: Documenting Ecosystems, Understanding Environmental Changes, Forecasting Hazards. E.S. Kappel, S.K. Juniper, S. Seeyave, E. Smith, and M. Visbeck, Eds, *A Supplement to Oceanography*, 34(4). https://doi.org/10.5670/oceanog.2021.supplement.02-33.

Picheral, M., C. Catalano, D. Brousseau, H. Claustre, L. Coppola et al (2022). The Underwater Vision Profiler 6: an imaging sensor of particle size spectra and plankton, for autonomous and cabled platforms. *Limnol. Oceanogr. Methods* 20:115–29.

Pietropolli, G., L. Manzoni and G. Cossarini (2023). Multivariate Relationship in Big Data Collection of Ocean Observing System. *Appl. Sci*. 2023, 13, 5634. https://doi.org/10.3390/app13095634.

Pinardi, N., P. Cessi, F. Borile, C.L. Wolfe (2019). The Mediterranean Sea overturning circulation. *J. Phys. Oceanogr*. 49 (7), 1699e1721.

Pinardi N., C. Estournel, P. Cessi, R. Escudier and V. Lyubartsev (2023), Chapter 7 - Dense and deep water formation processes and Mediterranean overturning circulation, Editor(s): Katrin Schroeder, Jacopo Chiggiato, Oceanography of the Mediterranean Sea, Elsevier, Pages 209-261, ISBN 780128236925, https://doi.org/10.1016/B978-0-12-823692-5.00009-1.

Purkey, S. G., and G. C. Johnson (2010). Warming of Global Abyssal and Deep Southern Ocean Waters between the 1990s and 2000s: Contributions to Global Heat and Sea Level Rise Budgets. *J. Climate,* 23, 6336–6351, https://doi.org/10.1175/2010JCLI3682.1.

Piron, A., V. Thierry, H. Mercier and G. Caniaux (2016). Observation of basin-scale deep convection in the Irminger Sea with Argo floats in the 2011-2012 winter. *Deep-Sea Res. Part I*, 109, 76-90, doi: 10.1016/j.dsr.2015.12.012.

Racapé, V., V. Thierry, H. Mercier and C. Cabanes (2019). ISOW Spreading and Mixing as Revealed by Deep-Argo Floats Launched in the Charlie-Gibbs Fracture Zone. *Journal of Geophysical Research: Oceans*, 124(10), 6787–6808. https://doi.org/10.1029/2019JC015040.

Révelard, A., J. Tintoré, J. Verron, P. Bahurel, J. A. Barth, M. Belbéoch, J. Benveniste, et al. (2022). Ocean Integration: The Needs and Challenges of Effective Coordination Within the Ocean Observing System. *Front. Mar. Sci.* 8:737671. doi: 10.3389/fmars.2021.737671

Roemmich, D., G.C. Johnson, S. Riser, R. Davis, J. Gilson, W.B. Owens, S.L. Garzoli, C. Schmid and M. Ignaszewski (2009). The Argo Program: Observing the global ocean with profiling floats. *Oceanography* 22(2):34–43, https://doi.org/10.5670/oceanog.2009.36.

Roemmich, D., J. Sherman, R. Davis, K. Grindley, M. McClune, C. Parker, D. Black, N. Zilberman, S. Purkey, P. Sutton and J. Gilson (2019). Deep SOLO: A Full-Depth Profiling Float for the Argo Program. *Journal of Atmospheric and Oceanic Technology* 36(10) pp. 1967-1981. Doi:10.1175/JTECH-D-19-0066.1.

Roemmich, D., M. H. Alford, H. Claustre, K. Johnson, B. King, J. Moum, et al. (2019). On the future of Argo: a global, full-depth, multi-disciplinary array. *Front. Mar. Sci.* 6:439. doi: 10.3389/fmars.2019.00439

Riser, S. and K. Johnson (2008). Net production of oxygen in the subtropical ocean. *Nature* 451, 323–325 https://doi.org/10.1038/nature06441.

Riser, S., H. Freeland, D. Roemmich, et al (2016). Fifteen years of ocean observations with the global Argo array. *Nature Clim Change* 6, 145–153 https://doi.org/10.1038/nclimate2872.

Sabine, C. L. et al (2004). The Oceanic Sink for Anthropogenic CO2. *Science* 305,367-371. DOI:10.1126/science.1097403.

Sauzède, R., H.C. Bittig, H. Claustre, O. Pasqueron de Fommervault, J.-P. Gattuso, L. Legendre and K.S. Johnson (2017). Estimates of Water-Column Nutrient Concentrations and Carbonate System Parameters in the Global Ocean: A Novel Approach Based on Neural Networks. *Front. Mar. Sci.* 4:128. doi: 10.3389/fmars.2017.00128.

Schmidtko, S., L. Stramma and M. Visbeck (2017). Decline in global oceanic oxygen content during the past five decades. *Nature* 542, 335–339. doi: 10.1038/nature21399.

Séférian, R., S. Berthet, A. Yool, et al. (2020). Tracking Improvement in Simulated Marine Biogeochemistry Between CMIP5 and CMIP6. *Curr. Clim. Change Rep*. 6, 95-119. https://doi.org/10.1007/s40641-020-00160-0.

Sloyan, B. M., R. Wanninkhof, M. Kramp, G.C. Johnson, L.D. Talley, T. Tanhua, E. McDonagh, C. Cusack, E. O'Rourke, E. McGovern, K. Katsumata, S. Diggs, J. Hummon, M. Ishii, K. Azetsu-Scott, E. Boss, I. Ansorge, F.F. Perez, H. Mercier, et al. (2019). The Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP): A Platform for Integrated Multidisciplinary Ocean Science. *Frontiers in Marine Science*, 6(445). https://doi.org/10.3389/fmars.2019.00445.

Stramski, D., E. Boss, D. Bogucki, K.J. Voss (2004). The role of seawater constituents in light backscattering in the ocean. *Prog. Oceanogr.* 61(1), 27–56.

Srokosz, M. A. and H.L. Bryden (2015). Observing the Atlantic Meridional Overturning Circulation yields a decade of inevitable surprises. *Science* 348,1255575. DOI:10.1126/science.1255575.

Swift, J. H. (1984). A recent TS shift in the deep water of the northern North Atlantic, *Clim. Processes Clim. Sens. Geophys. Monogr*., 29, 39– 47. https://doi.org/10.1029/GM029p0039.

Takeshita, Y., T.R. Martz, K.S. Johnson, J.N. Plant, D. Gilbert, S.C. Riser, C. Neill, B. Tilbrook (2013). A climatology-based quality control procedure for profiling float oxygen data. *J. Geophys. Res.: Oceans*, 118 (10), pp. 5640-5650, 10.1002/jgrc.20399.

Teruzzi, A., G. Bolzon, L. Feudale and G. Cossarini (2021). Deep chlorophyll maximum and nutricline in the Mediterranean Sea: emerging properties from a multi-platform assimilated biogeochemical model experiment. *Biogeosciences*, 18(23), 6147–6166. https://doi.org/10.5194/bg-18-6147-2021.

Thierry, V., H. Bittig and the Argo-BGC Team (2021). Argo quality control manual for dissolved oxygen concentration. https://doi.org/10.13155/46542.

Tanhua, T., A. McCurdy, A. Fischer, W. Appeltans, N. Bax, K. Currie, B. DeYoung, D. Dunn, E. Heslop, L.K. Glover, J. Gunn, K. Hill, M. Ishii, D. Legler, E. Lindstrom, P. Miloslavich, T. Moltmann, G. Nolan, A. Palacz, S. Simmons, B. Sloyan, L.M. Smith, N. Smith, M. Telszewski, M. Visbeck and J. Wilkin (2019). What We Have Learned From the Framework for Ocean Observing: Evolution of the Global Ocean Observing System. *Front. Mar. Sci.* 6:471. doi: 10.3389/fmars.2019.00471.

Ulses, C., C. Estournel, M. Fourrier, L. Coppola, F. Kessouri, D. Lefèvre and P. Marsaleix (2021). Oxygen budget of the north-western Mediterranean deep-convection region. *Biogeosciences* 18, 937-960, DOI: https://doi.org/10.5194/bg-18-937-2021.

Volk, T., and M.I. Hoffert (1985). Ocean carbon pumps: analysis of relative strengths and efficiencies in ocean-driven atmospheric CO2 changes. In E. T. Sundquist, & W. S. Broecker (Eds.), *The carbon cycle and atmospheric CO2 : natural variations Archean to present. Chapman conference papers, 1984* (pp. 99-110). American Geophysical Union; Geophysical Monograph 32.

Wijffels, S., D. Roemmich, D. Monselesan, et al (2016). Ocean temperatures chronicle the ongoing warming of Earth. *Nature Clim Change* 6, 116–118 https://doi.org/10.1038/nclimate2924.

Wojtasiewicz, B., N.J. Hardman-Mountford, D. Antoine, F. Dufois, D. Slawinski and T.W. Trull (2018). Use of bio-optical profiling float data in validation of ocean colour satellite products in a remote ocean region. *Remote Sensing of Environment* http://dx.doi.org/10.1016/j.rse.2018.02.057.

Wüst, G. (1936). Schichtung und Zirkulation des Atlantischen Ozeans, Wiss. Ergebn. Deutsch. Atlant. Exped Forsch. Schiff "Meteor" 1925_27 6 (1936); (Engl. transl.) The Stratosphere of the Atlantic Ocean (ed. Emery, W.) (Amerind, New Delhi, 1978).

Xing, X., E. Boss, J. Zhang and F. Chai (2020). Evaluation of Ocean Color Remote Sensing Algorithms for Diffuse Attenuation Coefficients and Optical Depths with Data Collected on BGC-Argo Floats. *Remote Sensing* 12, no. 15: 2367. https://doi.org/10.3390/rs12152367.

Zilberman, N.V., D.H. Roemmich and J. Gilson (2020). Deep-Ocean Circulation in the Southwest Pacific Ocean Interior: Estimates of the Mean Flow and Variability Using Deep Argo Data. *Geophysical Research Letters,* 47(13), e2020GL088342. https://doi.org/10.1029/2020GL088342.