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Biogeochemical Argo: The Test Case of the NAOS Mediterranean Array

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The necessity of wide, global-scale observing systems for marine biogeochemistry emerged dramatically in the last decade. A global network based on Biogeochemical (BGC) Argo floats is considered to be one of the most promising approaches for reaching this goal. As a first step, pilot studies were encouraged to test the feasibility of a global BGC-Argo array, to consolidate the methods and practices under development, and to set up the array's characteristics. A pilot study in The Mediterranean Sea—deemed a suitable candidate for a test case because it combines a relatively large diversity of oceanic BGC conditions in a reduced open-ocean basin—was consequently approved as a part of the “Novel Argo ocean Observing System” (NAOS) project, a French national initiative to promote, consolidate, and develop the Argo network. We present here a first assessment of the NAOS Mediterranean array, in view of scientific choices on observing-system strategy, on implementation and statistics on network performances, and on data-quality control.

Keywords: BGC-Argo floats, Mediterranean, bioregions, ocean color, physical biological interactions

INTRODUCTION

The global Argo network is undoubtedly one of the biggest success stories in modern oceanography (Gould et al., 2004; Riser et al., 2016). Thanks to a well-balanced mix of international coordination, single-country involvement, free data access, and technological innovation, Argo provides an *in situ* complement to ocean-observing systems from space, which has enhanced decadal reanalyses and predictions on the ocean's state (Le Traon, 2013). Following the OceanObs'09 conference (Claustre et al., 2010a,b), one major extension planned for the Argo program was the addition of new sensors to provide observations for biogeochemical (BGC) studies—a development motivated by the readily available miniaturized sensors for BGC parameters, and the fact that profiling floats equipped with fluorescence, nitrate, irradiance, or oxygen sensors were already collecting records (Körtzinger et al., 2005; Xing et al., 2011; Johnson et al., 2013). Proof-of-concept studies opened up the perspective of implementing a BGC-Argo global array (Biogeochemical-Argo Planning Group, 2016), with coordination facilities and data-management procedures following Argo's policies.

In light of global warming, it is mandatory that we meet the challenge of monitoring the ocean ecosystems. A global BGC-Argo array stands to contribute to this goal by enabling *in situ* observation of BGC dynamics from seasonal to decadal scales, hence the accurate assessment of phytoplankton contents and carbon stocks as a complement to global satellite observations. The array therefore offers to provide a crucial upgrade from previous monitoring capacities.

Indeed, in the last two decades, only satellite ocean color has provided synoptic estimates of BGC fluxes and of their variability at a global scale (Longhurst, 1998; Doney, 2006; Martinez et al., 2009a). However, satellite observations are limited to the sea surface and investigation needs to extend to the interior ocean to address key processes like carbon export and sequestration (Siegel et al., 2016). A three-dimensional image (i.e., global and from surface to bottom) of ocean biogeochemistry is desirable over a period of several years, but hardly sustainable when using conventional *in situ* means of observation (i.e., from research vessels). As an alternative, the BGC-Argo program represents a cost-effective solution that needs, however, to be assessed in terms of various metrics: (i) performances to characterize interior processes (choice of core parameters and proxy transformation to BGC variables, limits of detection, and accuracy of the autonomous sensors); (ii) array dimensioning (interoperability with the classic Argo array and satellite ocean color); (iii) inherent bias that may be inferred by the free-drifting nature of the platform (natural signals seen as a mixture of variations in both time and space, possibly aliased by BGC-Argo profiling frequency). Pilot studies are therefore necessary to accomplish these assessments.

The Mediterranean Sea stood out early on as a suitable candidate to perform a BGC-Argo pilot study. The basin is often referred to as a “miniature ocean” because most of the processes governing global ocean dynamics occur within a 15° latitudinal band (Bethoux et al., 1999) and over time scales ranging up to only some decades (Margalef, 1985). Moreover, despite its reduced extent in the mid-latitude temperate zone, the Mediterranean Sea exhibits a large diversity of BGC conditions (review papers of Siokou-Frangou et al., 2010; de Madron et al., 2011; Malanotte-Rizzoli et al., 2014). Indeed, the basin is considered an oligotrophic area because its macronutrient concentrations, primary production, and phytoplankton biomass are low or even very low (de Madron et al., 2011). However, where and when hydrodynamic and atmospheric conditions are favorable, nutrients are upwelled in the sunlit layers, leading to a rapid phytoplankton biomass and a possible increase of primary production. Recurrent spring blooms are observed in specific regions such as the northwestern basin, the south Adriatic Sea, or the western Levantine basin (Gacic et al., 2002; Marty and Chiaverini, 2002; D'Ortenzio et al., 2003). The magnitude of these blooms nevertheless remains low compared to that in “classic” bloom regions such as the North Atlantic Ocean. The resulting seasonality of a phytoplankton biomass is spatially variable from one Mediterranean sub-basin to another. In this way, when Lavigne et al. (2013), used existing Argo observations to analyze the role of mixed-layer depth dynamics in shaping phytoplankton seasonality, they demonstrated that only an *in situ* equivalent of satellite observations could provide the required amount of information to determine robust cause–effect relationships. For such analysis, a BGC-Argo network would be an optimal tool.

In this context, the French national project “Novel Argo ocean Observing System” (NAOS, Le Traon et al., 2012), devoted to consolidating the French contribution to the global Argo network and to preparing its evolution, funded a Mediterranean BGC-Argo pilot study. Since 2012, an array of profiling floats

have been deployed and subsequently sustained. Currently, about 3900 profiles of BGC parameters have been collected. A theoretical design was defined at the outset of the project on the basis of current knowledge on phytoplankton biomass spatial distribution and seasonality, in the absence of any previous BGC-Argo regional network. In the 7 years since the first deployments, the NAOS Mediterranean array has been implemented, closely following this design plan. The aim of this present study is to provide a first assessment in light of current data collection. Note that we do not assess here the capability of the network to increase our knowledge of the BGC functioning of the Mediterranean. Several papers have already demonstrated the strong potential of the BGC-Argo NAOS Mediterranean array (Lavigne et al., 2013, 2015; de Fommervault et al., 2015a,b; Kessouri et al., 2017; Mayot et al., 2017a,b; Testor et al., 2018). The purpose of this study is more operational: a theoretical design has been implemented and it is timely to assess if it fulfills the initial requirements.

Below, Section “The BGC-Argo Floats” outlines the technological enhancements of the BGC-Argo profiling floats, emphasizing their differences with respect to standard Argo floats. Section “Design of the Array” presents the design of the array and summarizes its achievements in terms of field operations. Section “Results: Assessments of the Array” is dedicated to the different points of assessment. First, metrological verification of the BGC sensors are deployed, strictly according to standard data quality control procedures. Network performances are then presented in terms of spatial and temporal distribution of the data set before assessing whether the array is well dimensioned to provide long-term observation of BGC functioning over the whole of the Mediterranean Sea. Finally, Section “Discussion” reviews the accomplishments, lessons learned, and benefits of the pilot study, with the aim of proposing a revised design for future BGC-Argo arrays.

THE BGC-ARGO FLOATS

The Mediterranean pilot study was supported by the NAOS project's contribution of 30 so-called PROVOR-CTS4 floats—autonomous, free-drifting platforms manufactured by the French company NKE. The PROVOR-CTS4 model is an extension of the PROVOR-CTS3 series which constituted a large part of the French Argo fleet deployed in the 2000s (since replaced by the ARVOR series in recent years). Technological advances underlining the PROVOR-CTS4's development were accomplished throughout the course of the remOcean ERC project and the NAOS project, bringing into partnership IFREMER, the CNRS Oceanographic Laboratory of Villefranche, and the manufacturer NKE (Leymarie et al., 2013). Here follows a brief overview of these advances.

The first evolution was to equip PROVOR-CTS4 floats with a complete set of BGC sensors. On the upper part of the float, together with the standard SBE41-CP CTD probe for temperature and salinity, a three-wavelength (380, 412, 490 nm) irradiance radiometer and a photosynthetically available radiation (PAR) sensor (Satlantic OCR-504) are installed. A WetLabs ECO triplet is also integrated to the side of the float; it includes two

fluorometers, one for chlorophyll concentration (hereafter CHL) and the other for colored dissolved organic matter, along with a backscattering meter for estimation of the particle backscattering coefficient. The float can also be equipped with a dissolved oxygen sensor (Aanderaa optode) and with a nitrate concentration sensor (Satlantic SUNA).

The second modification was to equip PROVOR-CTS4 floats with an Iridium RUDICS (Router-Based Unrestricted Digital Internetworking Connectivity Solutions) communication device, which provides an improved outflow of data (as required by the additional sensors) compared to Iridium Short Burst Data (SBD), and even more so compared to the standard ARGOS system. Additionally, the Iridium system allows “two-way” communication with the float: commands can be sent from land to the float, for example, to change sampling or navigation parameters during the mission; an “end-of-life” instruction can also be sent to the float, to facilitate recovery of the platform (i.e., the float emerges at the sea surface and sends its GPS position every 15 min).

The third evolution enables PROVOR-CTS4 floats to fine-tune control of their new sensors and handle the data stream. Depth intervals and resolution can be programmed for each sensor, strongly augmenting the sampling options, and additionally, these can be modified remotely, through the Iridium system. The nominal sampling rate of the sensors is 2 s, which results in approximately 0.2 m vertical resolution (assuming a nominal ascent rate of 0.1 m/s). On this basis, PROVOR-CTS4 provides functionality to set the resolution of vertical sampling of sensors by layers. For the NAOS network, we selected a surface layer (0–350 m), at the resolution of 1 m, and a deep layer (350–1000 m) at 10 m resolution. For the CTD sensors, vertical resolution is the same as for the BGC sensors. CTD sensors of the NAOS BGC-Argo network are calibrated and processed following the procedure described in Taillandier et al. (2018). For nitrate sensors, the vertical resolution is different: 5 m for the surface layer (0–250 m) and 20 m for the deep layer (250–1000 m). Limitations due to the size of data sets transmitted to land have been overcome thanks to Iridium RUDICS stream flow.

A PROVOR-CTS4 mission consists in a succession of cycles. Each cycle is composed of three phases. First, a “parking phase” during which the float drifts at a fixed depth (usually 1000 m), following ocean currents. After a fixed interval of time (which could span up to 7–10 days), the float initiates its “profiling phase”: having reached a profiling depth (generally 1000 m), it starts to ascend to the surface. During this phase, sensors are activated, and measurements are carried out along the vertical at specific resolutions. When the float reaches the surface, it transmits its profile and location to land through a satellite connection (“transmission phase”), before diving again to its parking depth and starts a new cycle.

The data set transmitted to land by Iridium communication is composed of sequentially stored raw values from every sensor at specified scan rates. The fluorometers, backscattering meter, and radiometer provide one output signal (in counts) per parameter; the oxygen sensor provides three signals (phase, dephase, temperature); the nitrate sensor provides absorption spectra composed of signals at 40 wavelengths. The raw engineering

data from each sensor are processed into environmental variables following internationally defined BGC-Argo procedures (Schmechtig et al., 2015, 2018; Johnson et al., 2018; Thierry et al., 2018). These procedures use factory calibration statements: a set of equations to obtain scaled output values from raw values established for each class of sensor, and a set of equation parameters obtained for each sensor during a pre-mission calibration bath. These procedures also perform a series of automatic quality checks that are implemented in real time (i.e., 24 h after transmission), including adjustments to reference data collections from hydrographic cruises (i.e., Olsen, 2017) in order to correct possible shifts from pre-mission factory calibration. In particular, these adjustments correct the overestimation by a factor 2 for the factory-calibrated CHL measured by WetLabs ECO triplets (Roesler et al., 2017).

DESIGN OF THE ARRAY

The Implementation Plan

The difficulty of designing a BGC-Argo network lay in the lack of prior knowledge about the vertical distribution of the main BGC variables in the ocean interior. The challenge was to elaborate an *a priori* plan that identified the critical seeded regions, defined parking and profiling depths, evaluated vertical resolution and profiling frequency, as well as the number of floats required when we only had a rough picture of the spatiotemporal variability of the main BGC parameters.

In the case of the Argo network (Roemmich et al., 2009), array design was tackled using two different approaches: modeling (Observing System Simulation Experiments, e.g., Guinehut et al., 2002) and remote sensing (statistical analysis of altimetric observations, e.g., Roemmich et al., 1998). In this way, the main characteristics of the Argo array ($3^\circ \times 3^\circ$ mesh grid, 1000 m parking depth, 10-day profiling frequency) were strongly influenced by the results from altimetry and generally corroborated by modeling analysis.

While these approaches were also referred to for the BGC-Argo Mediterranean project, key input into array design came from one other source: remote-sensing ocean-color observations. Ocean color undoubtedly represents the most important source of observations for ocean biogeochemistry (McClain, 2009). By processing the multispectral radiances at the top of atmosphere, CHL in the surface layer is obtained. Currently, ocean-color surface CHL archives are composed of more than 20 years of high spatial resolution global maps, generally at daily resolution. Furthermore, the Mediterranean Sea is one of the world's less cloudy regions and the number of available ocean-color scenes is very high. Consequently, ocean-color data are intensively used for studies of the Mediterranean (among the others Antoine et al., 1995; Volpe et al., 2012; Mayot et al., 2016) and it contributes strongly to the identification of the main characteristics of the basin's BGC functioning. In summary, while, as for the Argo network, numerical modeling-based analysis helped influence the choice of some characteristics of the Mediterranean BGC-Argo array (as will be explained in section “On the Choice of Parking Depth”), ocean-color Mediterranean observations provided an

excellent data set for identifying the array's characteristics of a BGC-Argo array. Similar to Argo, although to a minor extent, an analysis based on a numerical model also contributed to choosing some characteristics of the Mediterranean BGC-Argo array, as will be explained in Section "On the Choice of Parking Depth."

Among the different existing approaches in ocean-color data exploitation, we opted for a specific method: bioregionalization (i.e., geographical repartition on the basis of common patterns) based on the phenology of surface CHL. By using phytoplankton phenology to identify regions of similar BGC characteristics, this method offered the advantage of a compact and integrated picture of both the spatial and temporal variability of surface CHL in the Mediterranean Sea (D'Ortenzio and Ribera d'Alcalà, 2009). In this way, 10 years of weekly climatology of satellite ocean-color observations were used to classify areas having similar seasonal cycles for normalized surface CHL. Satellite surface CHL was normalized by the annual maximum of each series, in order to focus more on the shape of the temporal evolution of the relative phytoplankton biomass change rather than on the absolute CHL values. Additionally, such normalization minimized the well-known overestimation of CHL in the Mediterranean by the satellite ocean-color processing algorithm (D'Ortenzio et al., 2002; Volpe et al., 2007). The resulting bioregions were then considered statistically homogenous from the point of view of surface CHL seasonality. The underlying assumption of the approach was that different shapes of surface CHL seasonality imply different mechanisms of physical-biological interactions. In other words, two regions that have different phytoplankton seasonality are likely to be governed by different processes. Moreover, the assumed homogeneity of a bioregion provided a way to extrapolate *in situ* observations over a larger area, and to aggregate them in consistent time series for seasonal cycles. This satellite bioregionalization of the Mediterranean highlighted, and confirmed, most of the well-known characteristics of the basin (see Figure 1).

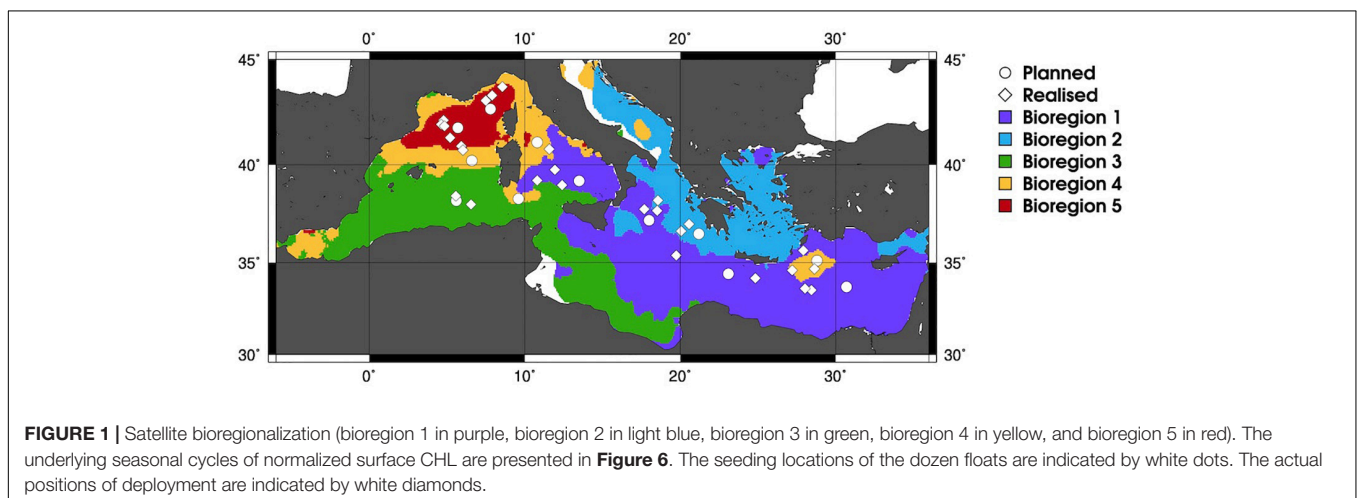
After the phenological bioregionalization of D'Ortenzio and Ribera d'Alcalà (2009) was established as an appropriate framework to drive the NAOS design, a working group

composed of an international consortium of scientists with an interest in Mediterranean BGC characteristics proposed and discussed different options (D'Ortenzio et al., 2012). The main point that piloted the discussion was that the final network should be able to generate time series of surface observations comparable to the time series characterizing the bioregions proposed by D'Ortenzio and Ribera d'Alcalà (2009). That the time series of surface CHL by BGC-Argo floats are in accordance with surface CHL, as obtained by satellite (both calculated over the bioregions), is then the metric that was used here to verify *a posteriori* the performances of the NAOS network.

By selecting ocean-color satellite data (organized by bioregions) to drive and verify the design of the BGC-Argo network in the Mediterranean, we implicitly give more emphasis to surface processes (related more to primary production and phytoplankton dynamics) than to depth processes (concerned more with secondary production, export of carbon and oxygen, and nitrate variability). This in fact is only partially true because bioregions, or BGC provinces, are considered to homogeneously characterize the overall BGC functioning of a given zone (see Longhurst, 1998). In addition, viable alternatives are as of yet unavailable. Existing three-dimensional climatologies of oxygen and nitrates are based on very little data (see Ayata et al., 2018 for an up-to-date survey of available *in situ* profiles in the Mediterranean Sea), and their representativeness in large parts of the basin is questionable. Meanwhile, basin-scale models, despite regular improvements, are still far from perfect (Lazzari et al., 2012), and, furthermore, are largely validated and tuned with ocean-color satellite data. However, the question of the pertinence of this bioregions-driven BGC-Argo design for parameters other than CHL should be considered and will be discussed further.

Characteristics of the Array

Three characteristics determine a BGC-Argo network: the number of floats, the parking depth, and the profiling frequency. The three characteristics were defined using different approaches, as explained below.



On the Optimal Number of Missions to Be Sustained

The bioregionalization of D'Ortenzio and Ribera d'Alcalà (2009) distinguishes six bioregions (see **Figure 1**): one mostly localized in coastal regions (not considered here), two in the areas where recurrent ("bioregion 5," red area in **Figure 1**) or episodic ("bioregion 4," yellow area) phytoplankton blooms are observed; three having similar shapes in their seasonal CHL cycles, and covering the rest of the basin ("bioregion 1," "bioregion 2," "bioregion 3"; dark blue, light blue, and green areas, respectively).

Following the recommendations of the dedicated scientific team (D'Ortenzio et al., 2012), two floats were designated to permanently observe each bioregion. The only exception was bioregion 4, composed of five geographically separated zones, with different behaviors in the eastern and in the western Mediterranean sub-basins. To account for this geographical dispersion, it was decided that two floats would be assigned to bioregion 4's eastern Mediterranean zones, and two other floats to its western Mediterranean zones.

The theoretical deployment locations are shown in **Figure 1** (white dots).

On the Choice of Parking Depth

In the Mediterranean Sea, the Argo program is coordinated by a dedicated international action (Poulain et al., 2007), which has adapted the global Argo sampling strategy (and in particular the parking depth) to the specificities of the basin. Note that while NAOS is a distinct research project, MedArgo is the regional declination of the international Argo program, its role mainly being to coordinate Argo deployments and quality control in the Mediterranean for temperature and salinity. Although prior to NAOS, very few BGC-Argo floats were deployed in the Mediterranean, the MedArgo experience was considered important for the selection of a parking depth (the PI of MedArgo participated in the discussions). MedArgo selected a parking depth of 350 m with the aim of tracking the pathways of a particular water mass, the Levantine Intermediate Water that occupies this level in most of the Mediterranean Sea. This parking depth was also initially considered for the Mediterranean BGC-Argo network, largely to benefit from nearly 10 years of existing trajectories and to keep the data set for temperature and salinity (D'Ortenzio et al., 2012) homogeneous.

However, the NAOS BGC-Argo array implementation plan would require a parking depth that would enable float residence times among bioregions at the scale of 1 year or more. To test the different designs, a numerical Lagrangian experiment (based on Lagrangian dispersion of numerical particles) was conducted. In this way, the fate of profiling floats was simulated on the basis of 16 scenarios for different locations and seasons of deployment, according to the following numerical experimentation. Horizontal currents were provided by a 4-year simulation of the NEMO-MED12 ocean-circulation model (Lebeaupin Brossier et al., 2012), with the following specifications: a horizontal grid resolution of 1/12 degree over the Mediterranean Sea, a temporal resolution of 1 week between January 1998 and December 2001, 50 vertical z-levels (35 in the first 1000 m). Numerical particles were seeded at each grid point of four z-levels (150, 380, 640, 1060 m), thus simulating

different parking depths for the BGC-Argo network, on the first day of every month in the first 3 years. Using the computational approach of Martinez et al. (2009b), 6814–9775 numerical trajectories (given the depth of z-level) were computed over 365 days of integration, representing 144 realizations (12 months times four z-levels times 3 years) and 1,190,844 trajectories in 1 year. Following the method of Pizzigalli et al. (2007), these realizations were analyzed following 16 scenarios by regrouping the data sets by seasons (four season times four z-levels).

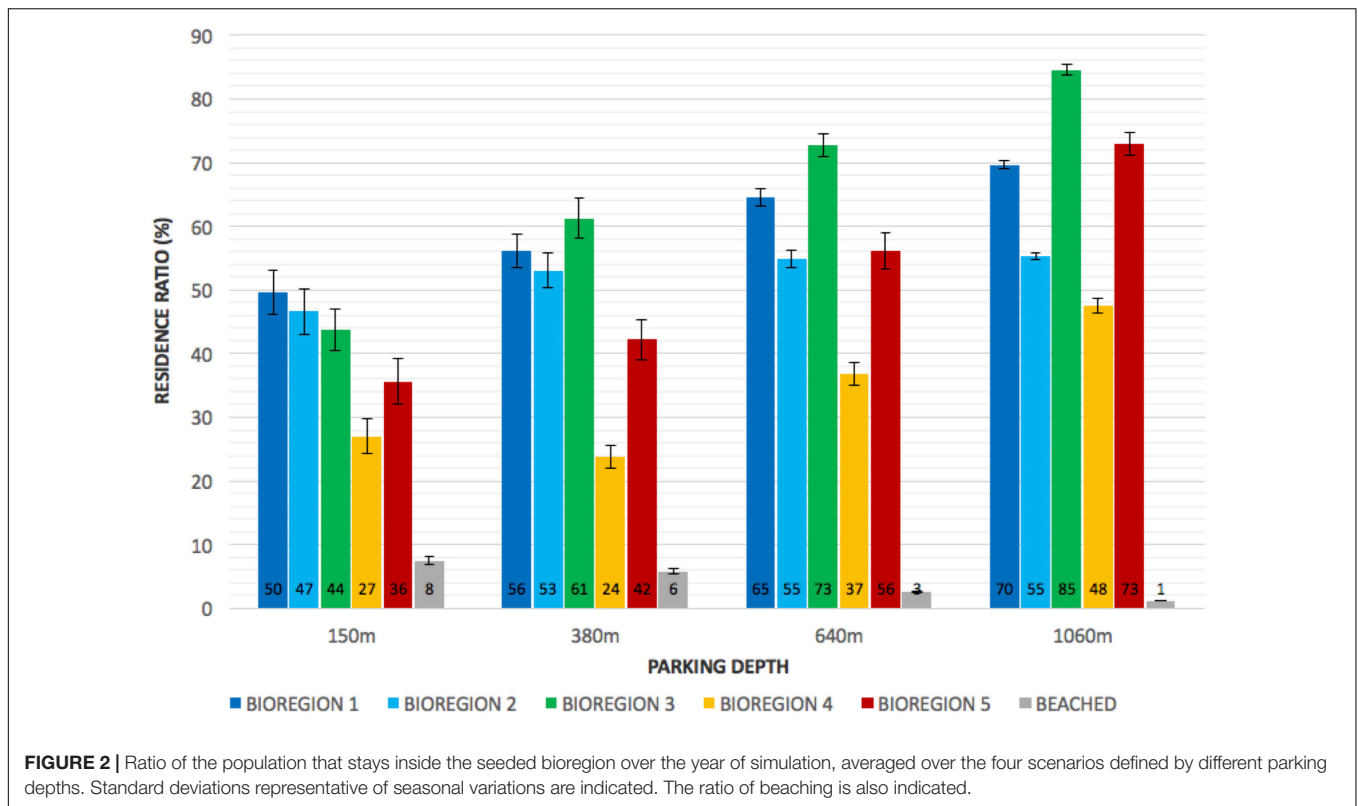
The result of this sensitivity study is presented in terms of residence ratio, which is the number of particles that stayed inside the bioregion after one year, out of the initial number of particles seeded in the bioregion (**Figure 2**). Overall, a float deployed in a specific bioregion has a likelihood of between 24 and 85% of staying in the same bioregion. This figure goes up to 70, 55, 85, 48, and 73% in bioregions 1, 2, 3, 4, and 5, respectively, for a parking depth of 1060 m. It also appears that the ratio of the population that beached within a year decreases with deeper parking levels. Therefore, the parking depth of the NAOS BGC-Argo array was set to 1000 m in the light of these simulations, in order to increase the residence times in all the bioregions and to reduce the probability of beaching.

On the Profiling Frequency

The MedArgo program operates with a cycling period of 5 days. However, it was proposed for the NAOS BGC-Argo array that during specific periods of the year (e.g., phytoplankton bloom), the sampling frequency should be increased to 2 days, for better characterization of rapid variations in phytoplankton biomass, like the onset and termination of spring blooms. On the other hand, it was decided that the cycling period should be decreased to 10 days during summer (i.e., oligotrophic period) when abrupt events in terms of phytoplankton dynamics are not expected. Using this strategy and assuming oligotrophic and blooming periods of 60 days (as typical of the Mediterranean Sea), we obtained a total of 85 cycles/year (i.e., six cycles for the oligotrophic period plus 30 for the blooming period plus 49 cycles for the rest of the year). The float manufacturer indicated a nominal lifetime of 250 cycles for a PROVOR-CTS4 BGC-Argo (Leymarie et al., 2013), resulting in an expected lifetime of approximately 3 years for the NAOS BGC-Argo floats (i.e., 250/85).

Mission Summary After 7 Years of Operations

With 30 PROVOR-CTS4 floats funded by the NAOS project, the implementation plan envisaged two waves of deployment, each consisting of 15 floats. The standard mission was parameterized for a cycling period of 5 days, a parking depth of 1000 m, and a profiling depth of 1000 m. A relatively large part of the fleet was equipped with nitrate and oxygen sensors. At the beginning of the program, since the performance of these sensors (mainly in very low concentrations areas, as typical of the Mediterranean) was still not defined, and also given the high cost of the instruments, only six floats with oxygen and nitrate sensors were deployed in the first wave. However, the analysis of nutrients and oxygen data from the first wave, mostly undertaken by de Fommervault et al.



(2015b), demonstrated the performance of these sensors even in the case of long deployments. Consequently, most of the floats in the second wave were equipped with nitrate and oxygen sensors.

Field operations were conducted in two different formats. The first wave of deployment was carried out between 2012 and 2013 thanks to opportunities raised by oceanographic cruises: the French cruises DEWEX, MOOSE-GE, and SOMBA-GE, the Italian cruises VENUS and ADREX, and the Spanish cruise MEDSEA. The second wave of deployment was completed *via* a dedicated oceanographic cruise, BIOARGOMED, in May 2015 (Taillandier et al., 2018). In terms of ancillary data and preparation, the dedicated cruise achieved considerable improvements regarding the efficiency of organization, preparation of the floats, and the homogeneity of collected samples of reference.

Statistics on the deployments are reported in Table 1, distinguishing between active (at November 2019), recovered, and lost floats. Note that of the 27 floats deployed, 14 were recovered, and five refurbished and redeployed during the second wave, giving a total of 32 deployments. A few floats, recovered in poor condition, were then retired. The others were cleaned, their batteries changed, and their sensors subjected to simple tests to verify the appropriateness of an eventual re-deployment. Most of the recoveries were associated with a CTD cast with nutrient, CHL, and oxygen samples, providing reference data to verify the calibration of the sensors (see section “Metrological Verification of the Sensors” and Taillandier et al., 2018). Only sensors that passed this simple test and

that performed well in comparison with concurrent CTD and sample data (see section “Metrological Verification of the Sensors”), were retained for eventual re-deployment (five floats were redeployed out of 14 recovered) without more in-depth calibration. It should be noted that floats equipped with oxygen and nitrate sensors represent two-thirds of the fleet. Very few sensors failed during the 7 years of operation. Most of the failures were observed in oxygen sensors: three sensors failed after deployment, and two showed considerable bias after five and 90 profiles, respectively. Two CHL sensors displayed significant bias after a relatively long period following deployment (i.e., 94 and 220), although in one case, the bias disappeared after 11 cycles. No failure was detected for the nitrate sensors.

RESULTS: ASSESSMENTS OF THE ARRAY

Metrological Verification of the Sensors

The quality of the data sets produced by BGC sensors depends on the ability of BGC-Argo procedures to correct inaccurate initial calibrations and subsequent drifts that occur during a mission. The Mediterranean pilot study contributed to developing and evaluating the data-quality check methods, presently implemented in the BGC-Argo Real-Time and Delayed Mode procedures (Schmechtig et al., 2015, 2018; Johnson et al., 2018; Thierry et al., 2018). Compared to the existing BGC-Argo experiments, however, the NAOS Mediterranean

TABLE 1 | The NAOS Mediterranean array in terms of the achieved number of profiles and days.

WMO	Date deployment	Date end	Number of profiles	Number of days	Comments on sensors	Sensor config.
Active floats						
6901776	28/05/2016	25/06/2018	123	758	Bias on O2 sensor from cycles 90	AO
6902826	23/05/2017	26/06/2018	63	399		A
6901657	24/06/2018	30/06/2018	7	6		AO
6901764	23/05/2015	29/06/2018	194	1133		AON
6901766	23/05/2015	24/06/2018	212	1128	O2 sensor stops at cycle 5	AON
6901772	20/06/2018	30/06/2018	30	10		AON
6901773	22/05/2015	30/06/2018	207	1135		AON
6901774	25/06/2018	30/06/2018	6	5		AO
6901775	18/06/2018	30/06/2018	12	12		AO
Average			95	510		
Lost floats						
6902733	27/05/2016	19/01/2018	95	602		AON
6901510	26/05/2013	26/05/2015	178	730	O2 sensor failed at deployment	AON
6902700	06/11/2015	16/01/2016	42	71	O2 sensor failed at deployment	AON
6901512	09/04/2013	04/05/2014	145	390		AON
6901528	16/05/2013	25/05/2015	186	739		AON
6901511	18/02/2013	22/06/2015	278	854		A
6901483	23/07/2013	27/03/2014	59	247		AON
6901490	16/06/2013	07/07/2013	9	21		AON
6901529	26/05/2013	10/02/2015	137	625		A
6901600	22/08/2014	20/12/2015	102	485	Bias at depth for CHL from cycle 94	A
6901769	31/05/2015	02/01/2018	179	947		AON
Average			128	519		
Recovered floats						
6901032	25/11/2012	24/01/2013	21	60		AON
6901513	09/05/2013	27/05/2015	261	748	CHL profiles biased from cycles 220 to 231	A
6902732	16/06/2013	30/05/2015	179	713		A
6901496	16/07/2013	13/03/2014	55	240		AO
6901776	15/03/2014	09/04/2015	88	390	Bias on O2 sensor from cycles 90	AO
6901605	11/02/2014	16/07/2014	51	155		A
6901655	02/08/2014	21/05/2015	81	292		A
6901765	23/05/2015	11/06/2018	191	1115		AON
6901767	31/05/2015	23/06/2018	207	1119		AON
6901768	16/05/2015	20/06/2018	214	1131		AON
6901770	21/05/2015	14/06/2018	192	1120		AON
6901771	27/05/2015	23/05/2017	155	727		AON
Average			140	650		

Dates of deployment and of end-of-mission (i.e., last transmitted profile or date of recovery) are also indicated. Averages are also given for the number of profiles and days, respectively, for active, lost, and recovered floats. Comments on sensor failure are also provided. The last column indicates the sensor configuration for each float: N = nitrate, O = oxygen, and A = CHL.

array benefited from three important and specific add-ons. First, the recovery of a significant proportion of the floats, systematically accompanied by water and CTD sampling, offered a means to evaluate the long-term performance of the sensors. Second, the quasi-systematic acquisition of validation data at the deployment (and often at the recovery) provided evaluation and characterization of the calibration and observational errors of the BGC sensors (Taillandier et al., 2018; Mignot et al., 2019). Reference data were acquired using standard high-quality methods: High-performance liquid chromatography (HPLC) for chlorophyll concentration; Winkler titration for oxygen concentration; colorimetry for nitrate concentration

(Taillandier et al., 2018; Mignot et al., 2019). Collocations were made with shipboard measurements (analyzed from seawater bottle samples) at the time of the float deployment or recovery as the reference profile (an approach referred to below as “Argo-like”). This was the case most of the time: the float profiles and reference profiles were not acquired at strictly the same locations or times. Third, in particular during the second wave of deployments which was carried out by a dedicated oceanographic cruise, some reference and float profiles were collected in strict space and time collocation as the floats were pre-deployed (or post-deployed in the case of recovery) attached to the CTD-Carousel (mentioned here as “dual-CTD,”

for details see Taillandier et al., 2018). Metrological verification at deployment and at recovery was performed for more than two-thirds of the fleet. Comparisons between *in situ* and float data at the deployments were reported in Mignot et al. (2019). Here, we simply reproduce their main results, summarized in **Table 2** (under the section “deployment”), which show healthy agreement between the float and *in situ* data. This agreement is confirmed by the comparisons at recovery, with the slopes for the three parameters deviating only slightly from the values obtained at the deployments. For the offset, differences are, however, obtained for the three parameters, in particular in the case of the “Argo-like” comparison. In the case of oxygen and CHL, “dual-CTD” comparison performances are ameliorated, indicating the relevance of performing accurate co-localizations. In the case of CHL sensors, a thick biofilm was found at the two recoveries, and an additional evaluation on “dual-CTD” was performed (**Table 2**, “after cleaning” line), significantly improving the statistics on the offset. Overall, the performances of the sensors remain stable in relation to the statistics at the deployment, at least for the slope. For the offset, the results are inhomogeneous. CHL offset appears stable, although the occurrence of biofilm could generate a degradation of sensor performances on long-term missions. For the nitrate, an important trend in the offset is observed, indicating a general degradation of sensor performances. For oxygen, offsets remain comparable to the values at deployment, but only in the case of accurate co-localization between float and CTD (the case of “dual-CTD”).

Given the reduced sample size due to the scarcity of collocations, measurement uncertainties should be examined individually, float by float, rather than globally, for the whole set in which case errors are minimized. Another limitation is the range of oxygen, nitrate, and chlorophyll concentrations that are narrower in the Mediterranean than in the global ocean. Due to such oligotrophic conditions, part of the measurements could not be accurately detected by the sensors. This assessment of uncertainties nevertheless agrees with the one presented by Johnson et al. (2017) that used a

larger set of collected data on a larger range of values for *in situ* conditions.

Dispersion of the Array in the Satellite Bioregionalization

The satellite bioregionalization of the Mediterranean Sea proposed by D'Ortenzio and Ribera d'Alcalà (2009) distinguishes five bioregions, all seeded by floats in 2012 and 2015. The dispersion of the array among these bio-provinces, shown in **Figure 3**, is now evaluated in terms of residence times.

In general, the basin was mostly seeded in its northern parts, with partial dispersion in the southern regions. Although all the bioregions were sampled, the final number of profiles carried out per bioregion is variable from one bioregion to another, depending on the surface area of the bioregion and on the local circulation. Some areas were not explored at all, for example, the easternmost and the southern central zones. However, as these zones nonetheless fall within bioregions where profiles were collected, and assuming the homogeneity of the bioregions, these gaps are not considered critical. From a spatial point of view, the performances of the array in terms of coverage were assessed by calculating the surface areas sampled by floats. A mesh grid and bathymetric contours of resolution 1/8 degrees were used (**Table 3**). Note that the five bioregions do not cover the same surface area and they may be fragmented. Bioregion 1 covers 40% of the entire Mediterranean Sea whereas bioregion 5 covers only 5%. There are also bioregions split into separate sites, especially bioregion 4 (**Figure 1**), for which we calculated statistics by grouping results obtained in each site classified within the one bioregion. It should be noted that a significant portion of Mediterranean bioregions cannot be sampled with a parking depth of 1000 m because of bathymetry shallower than 1000 m. In other words, the shallow regions of the Mediterranean Sea, which represent 42% of the sea surface area, cannot be sampled by the NAOS array. Under this caveat, the NAOS array covered 20% of the deep Mediterranean area, with coverages ranging from 14% in the largest bioregion (bioregion 1) up to 48% in the smallest (bioregion 5). To further explore the time scales of dispersion, the elapsed times inside the bioregions of deployment were computed and averaged over the 32 missions. Statistics on the bioregions in which the floats drifted after they left their bioregion of deployment were also computed. **Figure 4** shows that in all bioregions, the first half of the mission time was spent in the bioregion of deployment. Dispersion of the array is therefore low, in particular in the first year, regardless of the bioregion. Overall, Lagrangian assessment demonstrates that the average dispersion of the array is on the same spatial scale as satellite bioregionalization and on a time scale of 1 year.

However, each bioregion was sampled differently across the length of the whole time frame (**Figure 5**, left panel). After the first 6 months of operation, the average number of profiles per month reached at least 40 for the whole Mediterranean. The peak in May 2015 was due to the renewal of the first wave of deployments, during which the cycling period was high (1 day). The following year benefited from more profiles, with missions from the two waves overlapping. The temporal

TABLE 2 | Accuracy of autonomous biogeochemical sensors from a set of metrological verifications performed at deployment and recovery.

	Deployment			Recovery					
	Slope	Offset	#	Argo-like			Dual-CTD		
				Slope	Offset	#	Slope	Offset	#
Oxygen (mmol · kg ⁻¹)	0.99	2.90	1	0.905	4.012	1	1.00	1.385	
Nitrate (mmol · kg ⁻¹)	1.04	0.46	2	0.91	-1.32	1	0.93	-2.295	
Chlorophyll (mg · m ⁻³) (after cleaning)	1.08	-0.06	6	1.05	-0.04	2	1.02	0.004	
						2	1.01	0.00	

Slope and offset are indicated by their means. These statistics depend on the range of values, the number of occurrences, and the type of operation (dual-CTD in strict collocation with reference data or Argo-like). The values at deployment are reproduced from Mignot et al. (2019).

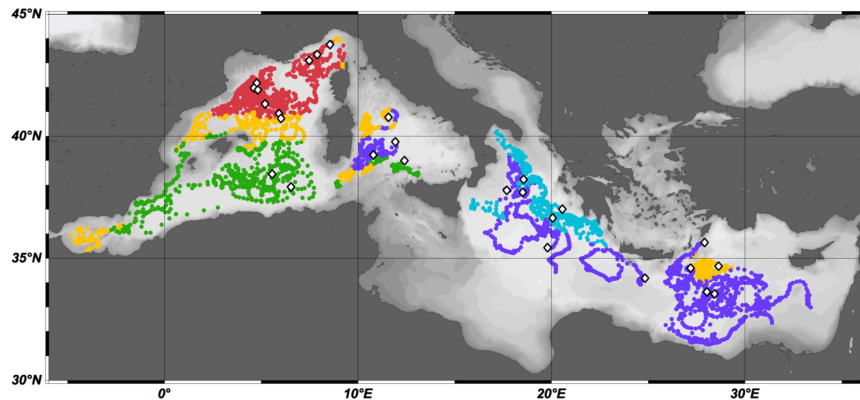


FIGURE 3 | Distribution of the profiles collected by the NAOS array since 2012. The underlying satellite bioregionalization is indicated by color (bioregion 1 in purple, bioregion 2 in light blue, bioregion 3 in green, bioregion 4 in yellow, and bioregion 5 in red). The seeding locations are indicated by diamonds.

TABLE 3 | Area and proportion of the whole Mediterranean covered by the satellite bioregionalization.

	BIOREGION 1	BIOREGION 2	BIOREGION 3	BIOREGION 4	BIOREGION 5	Whole Med
Area (10^3 km ²)	1013	407	609	267	119	2510
Ratio of the whole Med	40%	16%	24%	11%	5%	100%
Ratio deeper than 1000m	78%	31%	49%	52%	91%	58%
Ratio sampled by floats	15%	29%	17%	31%	48%	21%

Ratios of accessible areas with respect to whole areas, and ratios of areas sampled by the array with respect to accessible areas, are indicated.

distribution obtained was encouraging. Bioregion 1 was sampled every month, with 5–20 profiles per month during the first wave and at least 20 profiles per month during the second wave of deployment. For bioregion 2, there is only one gap of 2 months during the first wave and one of 3 months during the second wave: the number of profiles ranges from 5 to 20 profiles per month. Bioregion 3 was sampled every month except in April 2016, and the sampling was more intense during the first wave than during the second. Bioregion 4 was sampled continuously starting from July 2014, whereas the sampling effort in bioregion 5 decreased after July 2016.

Finally, the temporal distribution of BGC-Argo profiles was optimized to provide a robust estimation of monthly averages per bioregion (Figure 5, right panel). Over one climatological

year, the total number of profiles per month ranged from 300 in October to 500 in May, with a relatively constant repartition between bioregions. In agreement with Table 3, the largest bioregion, bioregion 1, was also the most populated (90 profiles per month), whereas bioregion 2 was the least populated (about 30 profiles per month).

This analysis of real dispersions (temporal and spatial) illustrates that the mission characteristics, as *a priori* defined (section Characteristics of the array), ensured a comprehensive coverage of the basin and a homogenous sampling of all bioregions. This first *a posteriori* verification of the theoretical design cannot, however, be considered completely exhaustive. The various extensions of bioregions and their different BGC behaviors (as characterized by the time series of surface CHL used to generate the bioregionalization) require more detailed assessment, not only restricted to purely dispersion or residence-time considerations, but also considering the BGC specificity of each bioregion.

Reconstruction of Climatological Cycles and Comparison With Satellite Observations

The five bioregions of the Mediterranean basin were obtained by grouping ocean-color pixels demonstrating similar (from a statistical point of view) seasonal cycles of normalized surface CHL. Then, for each bioregion, independently of their respective spatial extensions, a mean seasonal cycle of normalized surface CHL was derived from satellite observations. The resulting time series were considered as specifically

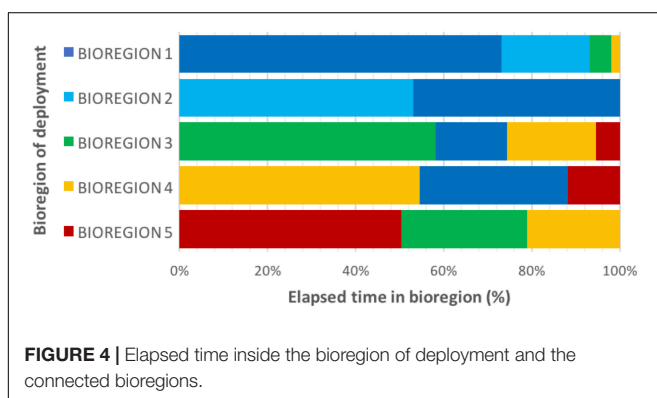
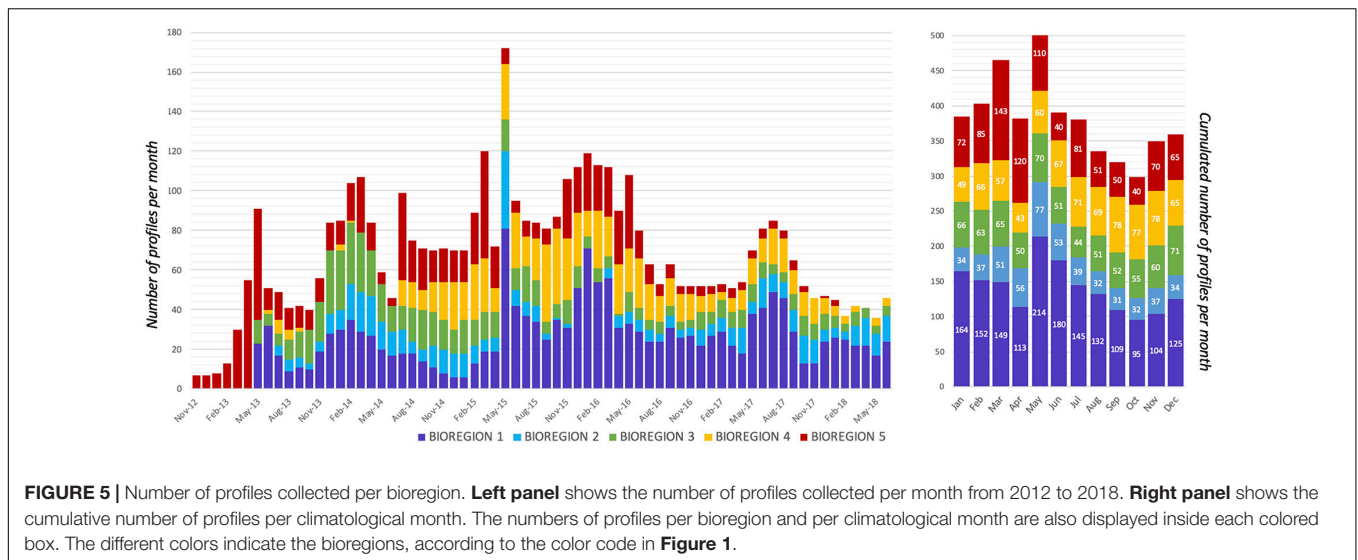


FIGURE 4 | Elapsed time inside the bioregion of deployment and the connected bioregions.



characteristic of each area, namely, because they clearly convey the key features of the surface phytoplankton phenology: bloom commencement and termination dates as well as periods of strong oligotrophy or enhancement. Comparison of these cycles with the corresponding BGC-Argo-derived seasonal cycles is used here as a metric to assess the performance of the NAOS network and to verify the pertinence of the initial design. The underlying assumption is that if the array proves able to reproduce the satellite seasonal cycles, then the resulting observing system based on BGC-Argo should be considered suitable for informing on the BGC behaviors of the basin. Consequently, the description of phenological characteristics detailed by D'Ortenzio and Ribera d'Alcalà (2009) from satellite observations is used below to point out and quantify similarities with the BGC-Argo-derived cycles.

On the basis of the per monthly distributions recorded, “climatological” cycles obtained from BGC-Argo floats were calculated for each bioregion. Following D'Ortenzio and Ribera d'Alcalà (2009), the cycles were further normalized although the procedure used here was slightly modified to account for the different nature of the BGC-Argo series. Indeed, while satellite series are calculated from the one database displaying high homogeneity, the BGC-Argo-derived series are calculated by merging profiles from various individual missions. Additionally, BGC-Argo series are generated with profiles obtained on different timestamps, with different coverage depending on the year. Simple normalization by the maxima (as in D'Ortenzio and Ribera d'Alcalà, 2009) is liable to introduce an important bias to the final series (for example, in case of maximum values derived from data sampled only by a single float or during a particular event). To minimize these effects, normalization, here, was based on the range of variability between the value of absolute maxima and minima of each series (i.e., maximum value is fixed to 1 and minimum value to 0, with other values transformed accordingly):

$$CHL_{norm} = \frac{(CHL - CHL_{min})}{(CHL_{max} - CHL_{min})}$$

For the sake of consistency, the same transformation was applied to the satellite series (**Figure 6**). The values used to normalize the time series are shown in **Table 4**.

As a first quantitative assessment, a Pearson's chi-squared test was applied to each bioregion to evaluate for similarity between the climatological cycles of the NAOS array and of the satellite ocean color (**Table 4**). The Pearson's chi-squared test (defined by Pearson (1900) and implemented here with the R function “cor”) provides an estimation of correlation between two time series. It provides a% value, which indicates the degree of similarity between two time series (100% means that a perfect linear relationship exists between the two data sets). Overall, we obtained high values when applying the test, the largest differences appearing for bioregions 4 and 5. The CHL values normalizing the time series were different for satellite and BGC-Argo data. Generally, satellite values were higher than the BGC estimates. An exhaustive explanation of these differences would require a specific matchup analysis, performed by spatiotemporally co-locating BGC-Argo estimations with satellite observations, as generally performed in ocean color cal/val analysis (i.e., Werdell and Bailey, 2005). Direct comparison of BGC-Argo data with concurrent *in situ* HPLC estimations (shown in section “Metrological Verification of the Sensors”) indicates that BGC-Argo CHL estimations are relatively accurate in the Mediterranean Sea. We thus suppose that the differences between satellite and BGC-Argo estimates could be partially ascribed to the well-known overestimation of the standard ocean-color Nasa algorithm of the Mediterranean waters (Volpe et al., 2007), or to the different characteristics of databases used to generate the time series (i.e., different years, different resolution, different data density). We introduced normalization of the time series specifically to minimize such incoherence and to focalize evaluation of the BGC-Argo network more on the temporal shape of the time series than on absolute values.

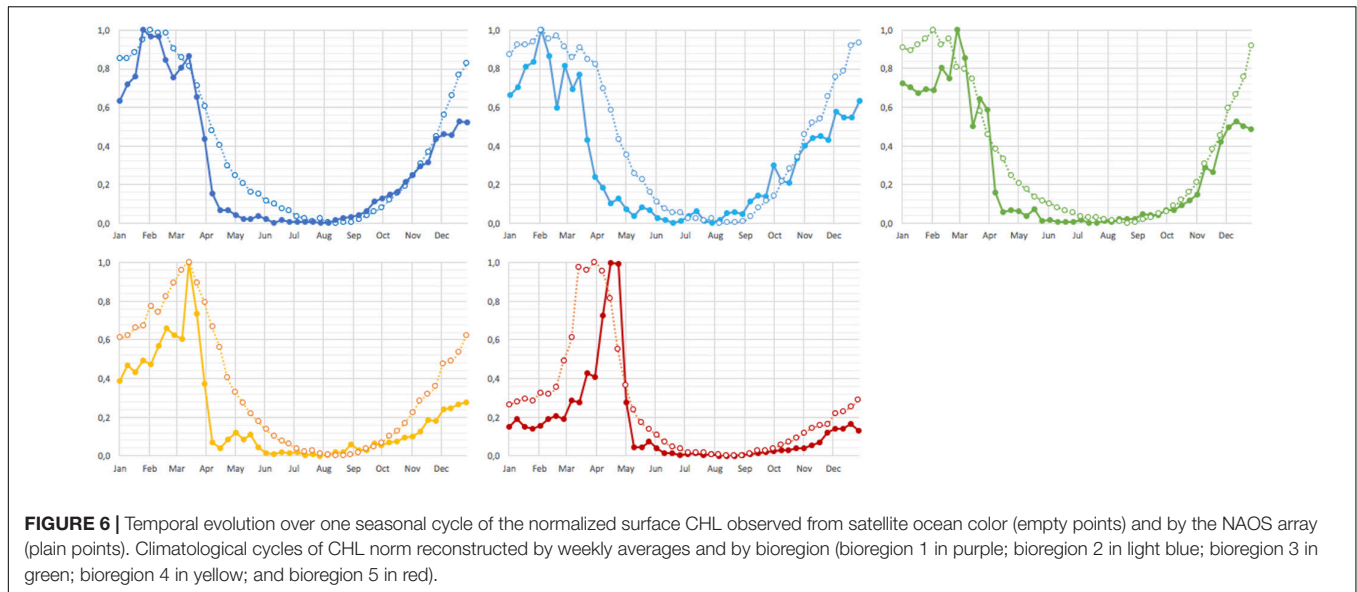


FIGURE 6 | Temporal evolution over one seasonal cycle of the normalized surface CHL observed from satellite ocean color (empty points) and by the NAOS array (plain points). Climatological cycles of CHL norm reconstructed by weekly averages and by bioregion (bioregion 1 in purple; bioregion 2 in light blue; bioregion 3 in green; bioregion 4 in yellow; and bioregion 5 in red).

TABLE 4 | Test of similarity between the climatological seasonal cycles of normalized surface CHL reconstructed from the NAOS array and satellite ocean color. The values used to normalize the time series are also shown.

	BIOREGION 1	BIOREGION 2	BIOREGION 3	BIOREGION 4	BIOREGION 5
Test of similarity	95.9%	92.9%	95.6%	89.4%	84.9%
Chl_Min_BGC (mg/m ³)	0.011	0.010	0.018	0.024	0.039
Chl_Min_Sat (mg/m ³)	0.075	0.158	0.090	0.141	0.158
Chl_Max_BGC (mg/m ³)	0.202	0.207	0.584	0.516	1.761
Chl_Max_Sat (mg/m ³)	0.238	0.327	0.398	0.565	1.065

Despite differences in the absolute values applied for normalization, comparison of the satellite and BGC-Argo time series shows that the general characteristics of the phenological series, as already identified by D'Ortenzio and Ribera d'Alcalà (i.e., two main typologies of series, bloom and no bloom, plus an intermediate one which combines the two characteristics) are well captured by the BGC-Argo series. Overall, the shapes of the time series are similar for the two databases, although some differences can be observed. For bioregions 1-2-3 (no bloom), the periods of enhancement (November, December, January, February) and those with very low values (June, July, August) coincide in the two databases. The BGC-Argo series show a delay in winter enhancement of approximately 1 month compared to the satellite series. In addition, still for bioregions 1-2-3, the winter enhancement appears relatively flat in the BGC-Argo series whereas the annual maxima are more pronounced in the satellite time series. For bioregion 4 (intermediate), the absolute maxima of the BGC-Argo series are more pronounced than those obtained from satellite measurements. The two series exhibit a maximum at the same periods (mid-March) and their periods of increase/decrease are coincident. Bioregion 5, also, gives rise to similar characteristics in the two databases, showing for both a short and intense enhancement in spring and low values for the rest of the year. The dates of the peaks, however, are different in the two series (March for satellite, April for BGC-Argo).

In conclusion, the assessment of the BGC-Argo network using satellite phenology as a comparison metric is largely but not entirely satisfactory. The BGC-Argo data are able to reconstruct most of the general characteristics of the Mediterranean phenology as inferred from satellite ocean color. Overall, the shapes of the seasonal cycles are similar in both databases. Some significant differences exist, however, in particular the 1-month delay for spring decreases in bioregions 1, 2, and 3 and the disparity in dates for the annual maximum in bioregion 5. Different shapes were also obtained for the November–December increases, which appear faster in the satellite than in the BGC-Argo series, regardless of the bioregion.

DISCUSSION

We attempted to evaluate the performance of the NAOS BGC-Argo network in view of three different criteria: the reliability of the sensors; the dispersion of records in a bioregion framework; the adequacy of the BGC-Argo profiles in relation to satellite ocean color via reconstruction of surface CHL seasonal cycles. The first criterion was analyzed in a strict metrological context by exploiting ancillary data collected at deployments and recoveries. The last two criteria were analyzed under the assumption of bioregionalization as the main driver of the implementation

plan, and these will be discussed in the next section from this point of view.

Float Recoveries and Sensor Calibration

With more than 3900 profiles realized and 27 floats out of the 30 available deployed (making a total of 32 deployments), the NAOS BGC-Argo Mediterranean array accomplished its primary goal, which was to demonstrate the feasibility of a BGC-Argo network over a 7-year period. The theoretical goal to maintain an operational network for a period of at least 3 years was reached, although the average number of days and profiles was lower than expected. The recoveries, however, biased the statistics since it is practically impossible to evaluate how much more time a recovered float could remain operational if it was not recovered. In addition, evaluations of residual energy are hard to evaluate because the float consumes a large amount of energy during the recovery procedure (i.e., surfacing, transmitting at high frequency), thus biasing any estimation. On the other hand, recoveries provided an excellent opportunity to lower the cost of the network, to evaluate sensor and float performances, and to maintain the network without additional acquisition of floats. Thanks to the proximity of Mediterranean coastlines and to rapid access by research vessels, the NAOS array benefited from a high ratio of float recoveries (about 45% of the end-of-missions), that allowed platforms to be refurbished and redeployed. Consequently, only 55% of the initial stock of floats was definitively lost. Finally, three floats from the initial stock have not yet been deployed. All these factors strongly increased the economical sustainability of the initial investment.

Float recoveries in the NAOS array are important for another reason: post-mission verification of the quality of the sensors. Metrological verification of the sensors is a restrictive but necessary exercise. An important lesson learned from the setup of the NAOS array is that the acquisition of ancillary data at deployment is mandatory: while this was severely lacking in some missions from the first wave, great attention and efforts were dedicated to the collection of reference profiles during the second wave. The first quantitative results on sensor uncertainty characterization, drawn up by Mignot et al. (2019) for the NAOS array, are in agreement with results reported by Johnson et al. (2017) from another BGC-Argo pilot study in the Southern Ocean, the SOCCOM array. Current data quality-control procedures are very useful for reducing systematic errors and improving the accuracy of oxygen, nitrate and chlorophyll concentration data sets. However, these procedures might still be still too crude as they mainly apply misfit analysis from climatological states. There is a need to develop complementary checkpoints and to provide larger metrological verification match-ups from *in situ* records. For example, the slope correction for oxygen data could be evaluated from air-oxygen measurements (Johnson et al., 2017), provided that optodes are top-mounted on a mast, which was not the case with the floats considered in this study. Similarly, the slope correction for chlorophyll data could be calculated using irradiance observations, as proposed by Xing et al. (2011).

Distribution of the BGC-Argo Profiles in a Satellite Bioregionalization Framework

The initial array design was based heavily on satellite ocean-color products, the only observational database providing a complete and long-term view of Mediterranean BGC dynamics. Following the Argo example, the implementation plan (i.e., deployment sites, the mission strategy, and the array size) was dimensioned by considering the synthetic view provided by satellite bioregionalization. The array sustained a dozen active BGC-Argo floats and it was assessed as efficient considering the objective to ensure homogenous sampling of each bioregion for at least two seasonal cycles.

This *a posteriori* confirmation of the implementation plan has a twofold consequence. First, although surface (i.e., satellite bioregions) and deep (i.e., the 1000 m parking depth of floats) dynamics may be disconnected, our results legitimate the definition of the characteristics of a BGC-Argo array on the basis of satellite bioregions. Our results indicate also that, in the specific case of the Mediterranean, using bioregions to drive the array characteristics can ensure a good coverage of the basin for a relatively long time period, even in the case of bioregions with different surface areas. Second, the underlying assumption of the bioregion's pertinence (i.e., that they mimic physical-biological processes even at depth) is confirmed by the relatively stable residence time of the floats in their bioregion of deployment. In this way, although bioregions are determined by only surface CHL phenological dynamics, our results indicate that the NAOS array could be very informative about other parameters. A number of works have confirmed this last point, in particular for nitrate and oxygen observations (Coppola et al., 2017; Mayot et al., 2017a,b).

This assessment solidly reflects the results of a recent synthesis of Mediterranean biogeography by Ayata et al. (2018), who pointed out a natural demarcation in regions when considering criteria for bioregionalization other than phenological traits, on the basis of dynamical or chemical characteristics, even if consensual regions or boundaries do not clearly emerge. They stressed the fact that bioregionalization could be used to optimize the sampling strategy of future BGC and ecological studies by targeting different regions within the Mediterranean Sea, since they could be used as indicators of the spatial extent of the region that is effectively monitored. Cycling parameterization with deep parking should be retained to allow for dispersion time scales of 1 year among bioregions.

Adequacy of BGC-Argo Profiles in Time Series Reconstruction

From a climatological perspective, the array collected sufficient data to reconstruct the normalized CHL seasonal cycles as derived from satellite ocean-color images. The phenology of surface CHL reconstructed from BGC-Argo for the five bioregions is similar, although not exactly identical, to the satellite estimations. Several reasons could explain this discrepancy.

The climatological approach used here is undoubtedly inappropriate for regions subject to interannual variability. Mayot et al. (2016), when recalculating the satellite bioregions

on a yearly basis rather than using values averaged over a period of 10 years, demonstrated that bioregion 1 is characterized by strong interannual variability. In particular, the date of the annual maximum could vary within a range of 3–5 weeks. The maxima in April obtained for bioregion 1 in the BGC-Argo-derived time series could then be explained by a specific event sampled by the network. The occurrence of a strong bloom in bioregion 1 during the year 2012–2013 (Mayot et al., 2016), which was sampled by at least two floats from the NAOS network (Mayot et al., 2017a), could explain the difference between satellite and BGC-Argo CHL time series. It is expected that the effect of interannual variability will be progressively smoothed over by the increasing number of BGC-Argo profiles in the future. Ideally, with a sufficient number of profiles, a comparison between the two types of time series could be performed on an annual basis (by using the method of Mayot et al., 2016).

In the comparison between the two-time series, it is important to highlight that satellite CHL estimation is far from perfect. Algorithmic imperfections (particularly important in the Mediterranean waters, Volpe et al., 2007) and intrinsic physiological effects in phytoplankton cells (Bellacicco et al., 2016) could affect the remote sensing of CHL. The normalization applied on the time series is likely to attenuate these effects, although discrepancies between satellite and BGC-Argo series could also be explained by erroneous remote-sensing values. The differences observed in all the bioregions in November and December could result from an over-estimation of satellite CHL values. Finally, mesoscale surface processes may have different impacts on the time series as generated by the two observing systems. BGC-Argo is certainly more sensitive than satellite series to such effects because of the pseudo-Lagrangian nature of observations. Mesoscale dynamics are known to locally modify the BGC behavior of a given region. These effects are generally smoothed over when averages are calculated from satellite data, but they cannot be easily corrected in the case of BGC-Argo.

Despite the discrepancies outlined above, a similar mean shape (i.e., phenology) for the surface CHL seasonal cycles in the five Mediterranean bioregions is obtained from the BGC-Argo and the remote-sensing data. This is further confirmation that the implementation plan was relevant, at least as far as the CHL parameter and surface layer are concerned.

For the other parameters and at depth, verification of the implementation plan at basin scale is precluded by the lack of observations for large parts of the Mediterranean. However, some studies have used the observations of the NAOS BGC-Argo network to infer the sub-surface and deep BGC dynamics of the basin. In this way, Mayot et al. (2017a) used bioregions and BGC-Argo data to reconstruct the physical–biological dynamics of the spectacular bloom observed in bioregion 5 in 2013. Sub-surface and deep variability were analyzed, exploiting the vertical dimension sampled by the NAOS BGC-Argo network. Similarly, using NAOS BGC-Argo data, de Fommervault et al. (2015b) showed the complex interplay between the nitracline and the depth of chlorophyll maximum over four Mediterranean bioregions, confirming the role of surface mixed-layer variability in shaping the CHL distribution in the sub-surface layers and its evolution over a seasonal cycle. They also compared

the climatological dynamic of nitrate at 1000 m depth with observations obtained from the NAOS BGC-Argo network, showing a close equivalence of the two data sets. Finally, Lavigne et al. (2015) analyzed the climatological distribution of the deep chlorophyll maximum (as obtained by historical data sets), and compared it with equivalent, high spatiotemporal resolution estimations of this feature obtained from the NAOS BGC-Argo array. Although a basin-scale pan-Mediterranean analysis was not possible here, these studies partially confirmed that the implementation plan of the NAOS BGC-Argo network is appropriate for inferring sub-surface and depth dynamics for CHL, oxygen, and nitrates parameters.

CONCLUSION

After more than 7 years of operations in the Mediterranean Sea, the NAOS array completed one of the first pilot studies for the future global BGC-Argo network. Here, we provide a detailed assessment of its performance in terms of sensor reliability and float lifetime, Lagrangian dispersion, and phenological analysis, which we review with regards to the objectives of the implementation plan.

Overall, 32 deployments were performed throughout the Mediterranean (by deploying 27 floats out of the 30 available, and recovering 14 floats), within five distinct bioregions using satellite bioregionalization as a basis for spatial distribution. Thanks to the selected strategy (deep parking at 1000 m and a cycle duration of 5–7 days subject to evolution according to the season), the dispersion of the array remained inside the bioregions within the time scale of a year. More than 65% of the deployed floats reached 250 days of operation, showing performances close to those of the entire BGC-Argo network (source: jcommops.org). This percentage is likely to be a low estimate, because the statistics were biased by the recovery of floats, forcing the end to a mission despite their capacity to remain operational. Most of the sensors operated without any significant failures. Sensor failures were observed for only seven deployments (out of 32), and these principally concerned oxygen sensors. CHL and nitrate sensors exhibited no failures or only very minor problems. Overall, the BGC sensors performed well. Although they were deployed in (ultra-) oligotrophic conditions (thus, with a reduced range of variability and close to the sensors' accuracy limits), they showed performances similar to those obtained by the Austral SOCCOM array (Johnson et al., 2017), where the ranges of variability were larger.

Formulated on the basis of satellite-derived bioregionalization developed from CHL phenology, the implementation plan was further evaluated by comparing remote-sensing-derived phenologies with those obtained by the BGC-Argo network. The comparison shows first that the two observing systems are capable of similarly assessing surface CHL phenology over large areas of the basin. Despite some differences (which could be ascribed to the interannual variability of Mediterranean CHL phenology or to the well-known uncertainty of satellite CHL estimates), we demonstrate that the use of satellite ocean color (and in particular, of bioregionalization based on

phenology) provides an efficient framework to drive a BGC-Argo array design at basin scale. It is important to recall here that the main objective of the present analysis is to verify that the implementation plan (as defined in 2012) is effective under the metric of surface CHL seasonal cycle reconstruction. The growing number of research papers based on the NAOS array in recent years (among others de Fommervault et al., 2015b; Houpert et al., 2015; Lavigne et al., 2015; Mayot et al., 2016, 2017a,b; Bosse et al., 2017; Kessouri et al., 2018; Terzić et al., 2018; Testor et al., 2018; Barbieux et al., 2019; Cossarini et al., 2019) further confirms the effectiveness of the implementation plan. Meanwhile, other assessment methods have emerged, like the use of Observing Simulation System Experiments (OSSE), given the recent advances in the assimilation scheme for BGC-Argo data in the Mediterranean Sea (Cossarini et al., 2019). These also represent an alternative means for assessing the NAOS BGC-Argo array design by using different evaluation metrics.

In conclusion, the bioregionalization approach, as developed in the Mediterranean Sea, can be considered a possible option in the global BGC-Argo implementation plan (Biogeochemical-Argo Planning Group, 2016). The present study provides several elements which confirm, *a posteriori*, the potential of such an approach.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

AUTHOR CONTRIBUTIONS

FD'O and VT contributed to all the sections of the manuscript, to the experiment setup, and to the data analysis. EL, AP, and CP worked on the float technological development and fleet logistics. All authors contributed to manuscript revision and read and approved the submitted version.

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Conflict of Interest: AM was employed by the company Mercator Océan International.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer SR declared a past co-authorship with one of the authors HC to the handling Editor.

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