Responses to Reviewer #1

Manuscript # bg-2021-123 "Biological production in two contrasted regions of the Mediterranean Sea during the oligotrophic period: An estimate based on the diel cycle of optical properties measured by BGC-Argo profiling floats", by M. Barbieux, J. Uitz, A. Mignot, C. Roesler, H. Claustre, B. Gentili, V. Taillandier, F. D'Ortenzio, H. Loisel, A. Poteau, E. Leymarie, C. Penkerc'h, C. Schmechtig, and A. Bricaud.

We appreciate the constructive comments and suggestions from the Reviewer. Here we present our detailed responses to the Reviewer's comments as well as the changes we propose to make to the manuscript in order to address these comments. The Reviewer's comments are in black, our responses follow each comment in blue. The line numbers refer to the revised version of the manuscript.

GENERAL COMMENTS

This study is an original contribution to the field of bio-optical oceanography. Though the approach used in this study is not new, the ms provide a detailed analysis of a unique dataset that includes high-resolution vertical measurements of biogeochemical properties acquired in two ecoregions of the Mediterranean Sea, during summer oligotrophy.

The application of the cp-based approach to estimate particles production from such data provides new findings, that significantly improve our understanding of particles dynamics in oligotrophic areas. The ms successfully addresses the challenge of filling typical observation gaps in a traditionally under-sampled ocean.

The introduction clearly introduces the general context and specific objectives of the present study.

The M&M is detailed, sound and robust. The structure of the M&M is sometimes a bit confusing, and there this some overlap between sections 2.3 – 2.5 and section 2.6. I have two major methodological comments (see below comment #2), and would suggest to display more examples cp and bbp measurements (see below comment #1).

The Results and Discussion, which are merged in a single section, are nicely structured and generally well supported.

The conclusion is too long, and there is some degree of redundancy with the discussion. Synthetizing the conclusion to the main results and "take-home messages" would improve the article.

We thank the Reviewer for his/her positive comments on our study. We address his/her questions about the methodology and structure of the manuscript point by point below.

SPECIFIC COMMENTS

1) As the whole study is built on cp and bbp measurements, it is necessary to show the data (an appendix could be used for that purpose). A schematic representation of the cp diel variability (Figure 2) is useful to explain the method, and the example provided in Fig. 5 (Ionian Sea) is interesting, but this is not sufficient.

The full c_p and b_{bp} dataset used for quantifying the diel variability in the optical properties and the derived POC production is shown for both the surface and SCM layers of the Ligurian and Ionian Seas in Fig. 4. In order to accommodate the Reviewer's comment, and following an approach similar to Gernez et al. (2011) and Kheireddine and Antoine (2014), we propose to add as appendix two figures shown at the end of this document and modify the text accordingly: "*Diel cycles, characterized by a daytime increase and a nighttime decrease, are observed in both c_p and b_{bp} time series in all three layers of the water column, as illustrated for the SCM layer of the Ionian Sea in Fig. 5 (examples of the diel cycles of c_p and b_{bp} for both the Ligurian and Ionian Seas are provided in Appendix A)" (Sect. 3.2.1 l. 567–569).*

2) Here, I raise two methodological comments concerning section 2.3. "Characterization of the diel cycle of the bio-optical properties".

First comment: in the literature, the diel variability is generally defined as the change in cp between sunrise and sunset (Siegel et al., 1989; Cullen et al., 1992, etc.). Such daytime increase in cp has been previously associated to particle growth and production.

In the present study, the diel variability is computed as the relative variation between two sunrises (in the Ionian Sea, eq. 3) or two noons (in the Ligurian Sea).

We thank the Reviewer for this important remark that allowed us to identify an error in the manuscript, not in the method but in its presentation. The description and the representation (Fig. 2) of the sampling scheme of the Ligurian float is actually erroneous. The time reference used for computing diurnal changes in c_p and b_{bp}, further converted into production, is actually identical for both the Ligurian (fLig) and Ionian (fIon) floats, i.e. sunrise to sunset.

In the revised version of the manuscript, we will correct Fig. 2 (see new version below) and modify the accompanying text as follows: "*The fLig float cycle commences with the first profile at sunrise (t_{sr}), a second at solar noon (t_n), a third profile at sunset the same day (t_{ss}), and a fourth profile at* *sunrise the next day (t_{sr+1}). The fLig float then acquires a profile at solar noon 4 days later (t_{n+4}), and then restarts 3 days later the acquisition of 4 profiles in 24 hours from sunrise (t_{sr+7}).*" (Sect. 2.2 l. 295–299).

We will also correct Sect. 3.2.1: "*We also consider the relative daily variation $\tilde{\Delta} c_p$ and $\tilde{\Delta} b_{bp}$ (expressed as % change) for each float and each day of observation, from sunrise to sunrise … with $c_p(t_{sr})$ and $b_{bp}(t_{sr})$ being the values of c_p and b_{bp} at sunrise and $c_p(t_{sr+1})$ and $b_{bp}(t_{sr+1})$ the values at sunrise the next day*" (l. 319–324).

Did the authors also characterize the sunrise-to-sunset variability?

We used the indicators of Gernez et al. (2011) and Kheireddine & Antoine (2014) to characterize the relative daily variations (sunrise to sunrise the next day) of the c_p and b_{bp} coefficients. Following the Reviewer's question, we will characterize the amplitude of the c_p and b_{bp} diurnal variations (sunrise to sunset). For this purpose, we will modify Sect. 2.3 as follows:

"… we use the metrics defined by Gernez et al. (2011) and Kheireddine & Antoine (2014). First, we compute the amplitude of the diurnal variation of the c_p and b_{bp} coefficients as:

$$\Delta c_p = c_p(t_{ss}) - c_p(t_{sr}) \quad (3a)$$

$$\Delta b_{bp} = b_{bp}(t_{ss}) - b_{bp}(t_{sr}) \quad (3b)$$

with $c_p(t_{sr})$ and $b_{bp}(t_{sr})$ the values of c_p and b_{bp} at sunrise and $c_p(t_{ss})$ and $b_{bp}(t_{ss})$ the values at sunset the same day" (Sect. 2.3 l. 311–317).

We will also add to Sect. 3.2.1 the following text: "*Considering the time series of the Ligurian and Ionian Seas, as well as the surface and SCM layers, the c_p and b_{bp} coefficients show mean diurnal amplitudes, Δc_p and Δb_{bp}, spanning between 0.001 m^{-1} and 0.02 m^{-1} and 7 x 10^{-6} m^{-1} and 9 x 10^{-5} m^{-1}, respectively. These results are consistent with Gernez et al. (2011), who observed Δc_p values ranging within 0.01 m^{-1} and 0.07 m^{-1} in the surface layer of the Ligurian Sea (BOUSSOLE mooring) during the summer to fall oligotrophic period. Relative to the mean c_p and b_{bp} values, the mean Δc_p and Δb_{bp} correspond to diurnal variations of 9–20% and 5–10%, respectively.*" (l. 569–576).

Second comment: the time reference used to characterize the daily changes in cp are not the same in the Ionian Sea (reference = sunrise) and in the Ligurian Sea (reference = noon). This introduces a bias in the comparison between the results from both study sites, and should be discussed.

Would it be possible to compute the diel variability using the same time reference (e.g. sunrise) in both cases? The same two comments also apply to Section 2.6.3 “Calculation of the production rate”.

As indicated in our response to the Reviewer’s previous comment, the sampling scheme of the fLig float was incorrectly described in the manuscript. Both the fLig and fIon measurements enable to characterize daily variations in c_p and b_{bp} from sunrise (t_{sr}) to sunrise the next day (t_{sr+1}). Hence no bias is introduced in our estimates.

In eqs. 9-12, the authors explain how a daily and depth-integrated production of particles, P can be inferred from diel changes in cp. Is the variable "P" a proxy of the net community production (NCP) as defined in Claustre et al 2008? Or is it something different? It would be useful to add this precision in subsection 2.6.3. It is not clear whether the production has been inferred using the day-to-day or the daytime (sunrise to sunset) change in the cp-derived POC.

How was the gross community production (GCP) estimated?

We apologize for any lack of clarity in Sect. 2.6.3. The variable P designates gross community production, resulting from particle growth over 24h, i.e., from sunrise (t_{sr}) to sunrise the next day (t_{sr+1}), and within the layer of the water column comprised between depths z1 and z2:

"$$P = \int_{t_{sr}}^{t_{sr+1}} \int_{z2}^{z1} \mu\,(z,t)\; b(z,t)\; dz\; dt, \qquad (9)$$“

In practice, it is calculated as the depth-integrated net variation of POC over 24h plus POC losses:

"$$P = B_{t_{sr+1}} - B_{t_{sr}} + l \int_{t_{sr}}^{t_{sr+1}} B(t)\; dt. \qquad (11)$$“

We will attempt to clarify this point in the revised version of the manuscript through the following modifications:

“*The daily (24-hour) depth-integrated gross production of POC, P (in units of gC* m^{-2} d^{-1}*)*” (l. 439).

“*where the gross production P is calculated as the sum of the net daily changes in POC biomass plus POC losses, assuming a constant rate (l) during daytime and nighttime*” (l. 447–448).

Here also, the time reference differs between the Ligurian and Ionian Sea (L343-345). How is it expected to influence the results? Would it be possible to standardize the method?

As indicated above, the daily variations in c_p and b_{bp} are characterized from sunrise (t_{sr}) to sunrise the next day (t_{sr+1}) for both the fLig and fIon floats.

3) As the instruments deployed at BOUSSOLE provide high-frequency measurements, it would be very interesting to compare the surface cp time-series acquired by the fLig float with the BOUSSOLE data (accounting the lag of 2 days identified in L371-380). Such a comparison would be useful to assess if some information is missed by the lower (but still high) temporal resolution of the BGC Argo float, as well as to assess the spatial representativity of BOUSSOLE point-based measurements.

We recognize that comparison of high frequency observations from the BOUSSOLE mooring with those acquired by the BGC-Argo float, covering a larger spatial scale, would be of interest. However, we believe that this would require a specific study that is beyond the scope of the present work that focuses on a comparison of two contrasted oligotrophic systems with a zoom on the subsurface layer.

TECHNICAL COMMENTS

In the title, the term "optical properties" is maybe to general, and could be more detailed (e.g. beam attenuation coefficient).

Although in Sect. 3.2.2 we disregard b_{bp}-derived production to focus only on c_p-derived production, our study also considers (and compares) b_{bp} and c_p. Thus, we believe it would not be totally correct to mention only “beam attenuation coefficient” in the title, but it would also be too long to indicate both “particulate beam attenuation and backscattering coefficients”. Unless it is a mandatory request from the Reviewer, we would prefer to keep the title as is.

The variables cp, bbp, Zeu, Zpd, etc. should be italicized throughout the ms

Ok, we will italicize the variables.

L167-175 how was the time period of the two floats selected?

The aim of the study is to compare two different oligotrophic systems. Based on previous knowledge, the Ligurian Sea is oligotrophic in summer while the Ionian Sea is permanently oligotrophic. We thus selected the oligotrophic summer period for both the fLig and fIon floats. We used the entire time series of the fIon float and restricted the time series of the fLig float so it coincides in months with that of fIon. We will modify the text in order to clarify this point: “*The Ligurian Sea float (hereafter noted fLig, WMO: 6901776), was deployed in the vicinity of the BOUSSOLE fixed mooring (7°54’E, 43°22’N) during one of the monthly cruises of the BOUSSOLE program (Antoine et al. 2008) and profiled from April 9, 2014 to March 15, 2015. For the purpose* *of this study focusing on oligotrophic systems, we selected the fLig float measurements acquired during the time period May 24 to September 13, 2014 to coincide in months with the Ionian Sea float time series.*" (Sect. 2.2 l. 199–204).

L265 typo in "Loisel et al."

Ok. We will correct "Loisel e al. 2011" to "Loisel et al. 2011".

L287-300 and Table 1. The same cp-to-POC relationship is used in the Ligurian and Ionian Sea, despite the bio-optical differences between the two basins. Two different relationships have also been reported in the literature (Oubelkheir et al 2005, Loisel et al 2011). The authors decided to apply the results from Oubelkheir et al. (2005). Why not from Loisel et al (2011)? This could be added to the discussion in L502-508.

Several bio-optical relationships, linking c_p-to-POC or b_{bp}-to-POC, were considered in our analysis. The production estimates derived from these relationships, including that of Loisel et al. (2011), are provided in Table 5.

The justification of our choice is presented in Sect. 2.5: "*In the present study, we used the relationships from Oubelkheir et al. (2005) and Loisel et al. (2011) for c_p and b_{bp}, respectively. Both relationships were established from in situ measurements collected in the Mediterranean Sea and produce c_p- or b_{bp}-derived POC values falling in the middle of the range of all the POC values resulting from the different bio-optical relationships taken from the literature (Tables 1 and 2)*" (l. 397–401).

We also note that the variability in the production estimates induced by the choice of the bio-optical relationships is discussed in Sect. 3.2.2 (*l. 647–660*): "*The empirical relationships linking the c_p (or b_{bp}) coefficient to POC are known to exhibit regional and seasonal variability … For the time period and study regions here, the c_p-based community production varies by a factor of 2, depending on the selected bio-optical relationship… Compared to the reference value obtained using the Oubelkheir et al. (2005) relationship, the c_p-based estimates are 25% lower and 37% higher using the relationships of Marra et al. (1995) and Stramski et al. (2008), respectively*."

In order to consider specifically the relationship of Loisel et al. (2011), we will add a sentence indicating that: "*using the Mediterranean relationship of Loisel et al. (2011), instead of that of Oubelkheir et al. (2005), would reduce the c_p-based estimates by 17% in both study regions (Table*

5). That said, although the absolute magnitudes vary depending upon proxy choice, the differences observed between locations is robust." (l. 661–664).

Figure1: it would be useful to display the summertime-averaged satellite-derived Chl concentration in Figure 1

We will add as background a summer climatology of ocean color-derived surface chlorophyll *a* concentration (see revised Fig. 1 below).

Figure 2: adding grey vertical bar to represent nighttime would help reading the graph

Ok. We will add grey shaded areas to indicate nighttime in the revised version of Fig. 2 (see below).

Figure 3: I suggest to add "Ligurian Sea" and "Ionian Sea" at the top of the left and right panels, respectively (and same comment for Figures 4, 6 – 10).

Ok. We will indicate "Ligurian Sea" and "Ionian Sea" at the top of Fig. 4 and Figs. 6–10.

In Figure 3, displaying the cp-to-Chl ratio would also be useful to help reading section 3.1 (in particular L389 - 408)

In order to accommodate the Reviewer's comment, we might add two panels showing the time series of the c_p/Chl ratio in the water column in the Ligurian and Ionian Seas (see Figs. 3d and 3g below) and the short following text in Sect. 3.1 (l. 516–517 and 522–524): "*In the Ligurian Sea, the SCM is intense … This induces vertical variations in the c_p-to-Chl ratio, with moderate values at surface, diminution at the level of the SCM, and maximum values below the SCM (Fig. 3d). In contrast, in the Ionian Sea, … the c_p-to-Chl ratio shows larger values in the upper part of the water column coinciding with larger values of the c_p coefficient, and minimal values at the SCM due to a pronounced increase in Chl simultaneously to a reduction of c_p (Fig. 3g).*"

Nevertheless, we would prefer not to insist on the distribution of the c_p-to-Chl ratio in Sect. 3.1 that aims to provide an overview of the biogeochemical and bio-optical characteristics, and keep it for Sect. 3.4.1 that largely presents and discusses the distribution of the bio-optical ratios. Discussing the c_p-to-Chl ratio requires some context and references, which are presented in Sect.

3.4.1 and would not be appropriate in Sect. 3.1. Hence, we rather not incorporate these modifications.

L482-485 the results also compare with the "delta POC" estimates reported in Gernez et al. (2011; see their fig. 14)

Here the Reviewer refers to the following sentence: *"The present c_p-derived values also compare favorably with … (0.8–1.5 gC m^{-2} d^{-1} in May–August; Barnes & Antoine 2014)"*, which we will modify accordingly: "*The present c_p-derived values also compare favorably with … (0.5–0.8 gC m^{-2} d^{-1} in Gernez et al. 2011; 0.8–1.5 gC m^{-2} d^{-1} in Barnes & Antoine 2014)*" (Sect. 3.2.2 l. 643–645)

L539-542 Here the authors assumed that negative values could be associated with particles transport. Please note that negative values could also occur if the losses exceed particles growth (which could occur if the community is dominated by heterotrophs).

Here we present estimates of gross community production, calculated as the sum of the net changes in POC over 24 h (from sunrise, t_{sr}, to sunrise of the next day, t_{sr+1}) plus POC losses. Therefore, negative values may arise if POC at sunset (B_{ss}) is lower than POC at sunrise the next day (B_{sr+1}), leading the loss term to be negative (Eq. 8). A negative loss term, which is biologically impossible, occurs if the 1D assumption is not satisfied. We hope that the clarification made to the methodological section will make this point clearer (see our response to the Reviewer's second comment).

L543-549 this is very interesting. It would be useful to provide the averaged cp/Chl (at the depth of the SCM) of the Ligurian Sea and Ionian Sea. Besides photo-acclimation, are there other ecophysiological hypothesis that would be consistent with this hypothesis? (e.g. composition and size distribution of the community of living particles, higher influence of nutrient stress in the Ionian Sea?).

Although, at first order, low values of the c_p/Chl (or b_{bp}/Chl) ratio are interpreted as resulting from photoacclimation, we acknowledge that several other sources of variations may be at play, as indicated in the following section (Sect. 3.4.1 l. 751–756): *"The b_{bp} / Chl and c_p / Chl ratios are both proxies for the POC / Chl ratio …, and thus an indicator of the contribution of phytoplankton to the whole organic carbon pool. The variations are also interpreted as changes in the composition of phytoplankton communities … and their acclimation to the light-nutrient regime*".

Further, we mention, in addition to photoacclimation, different factors potentially responsible for low values of the bio-optical ratios: "*may reflect photoacclimation, by which phytoplankton organisms increase their intracellular Chl, and/or an increase in the fluorescence-to-Chl ratio in relation to limited or null non-photochemical chlorophyll fluorescence quenching… the invariant low c_p / Chl and b_{bp} / Chl values are consistent with both photoacclimation of phytoplankton to low-light conditions and a diatom-dominated phytoplankton assemblage (Cetinić et al. 2015; Barbieux et al. 2018). The relatively stable ratios observed in this region suggest a relative steadiness in the composition of the phytoplankton assemblage over the considered period*." (l. 804–820).

L607-623 when discussing the range of variability of cp/Chl, please consider referring to Loisel & Morel (1998)

We thank the Reviewer for noting this oversight. We will add a reference to Loisel and Morel (1998) in the following sentences: "*The variations are also interpreted as changes in the composition of phytoplankton communities (e.g. Sathyendranath et al. 2009) and their acclimation to the light-nutrient regime (e.g. Geider et al. 1987; Loisel & Morel 1998; Geider et al. 1997; Cloern 1999)*" (Sect. 3.4.1 754–755); "*Low-light conditions typically prevailing in the SCM layer are usually associated with low values of the c_p / Chl and b_{bp} / Chl ratios (e.g. Loisel & Morel 1998; Behrenfeld & Boss 2003; Westberry et al., 2008; Barbieux et al. 2019)*" (l. 803).

We will also indicate that: "*These results are consistent with the study of Loisel & Morel (1998), reporting low values ranging within 0.1–0.2 m^2 mg Chl^{-1} at the deep chlorophyll maximum level of oligotrophic sites*" (Sect. 3.4.1. l.778 –779).

L653 "it appears to result from changes in light conditions": light and/or nutrients?

The paragraph which the Reviewer refers to indicates that both light and nutrient availability plays a role in the observed production increase: "*the observed production episode may result from physical forcing that induces an upwelling of the water mass, thereby resulting in an alleviation of the light/nutrient limitation and an adequate balance between light and nutrient availability in the SCM layer*" (Sect. 3.4.2 l. 827–829).Then, in the next sentence, we do not question the role of nutrients, but simply point to the fact that changes in the light regime may explain photosynthetic (not bacterial) growth: "*Because it appears to result from changes in light conditions, we may attribute this production event to phytoplankton (not community) growth*" (l. 833–835). We will replace "phytoplankton" by "photosynthetic" to clarify.

L679-689 as acknowledged by the authors, these are very hypothetical statements that are not supported by the present study. I therefore suggest to remove the quantitative results of such crude estimations from the conclusion (i.e. remove or re-write L745-747).

In order to make the conclusion more synthetic, as recommended by the Reviewer, we will keep only the essential results and the elements of recommendations or perspectives. This will allow us to shorten the conclusion by about a third.

REVISED FIGURE 1

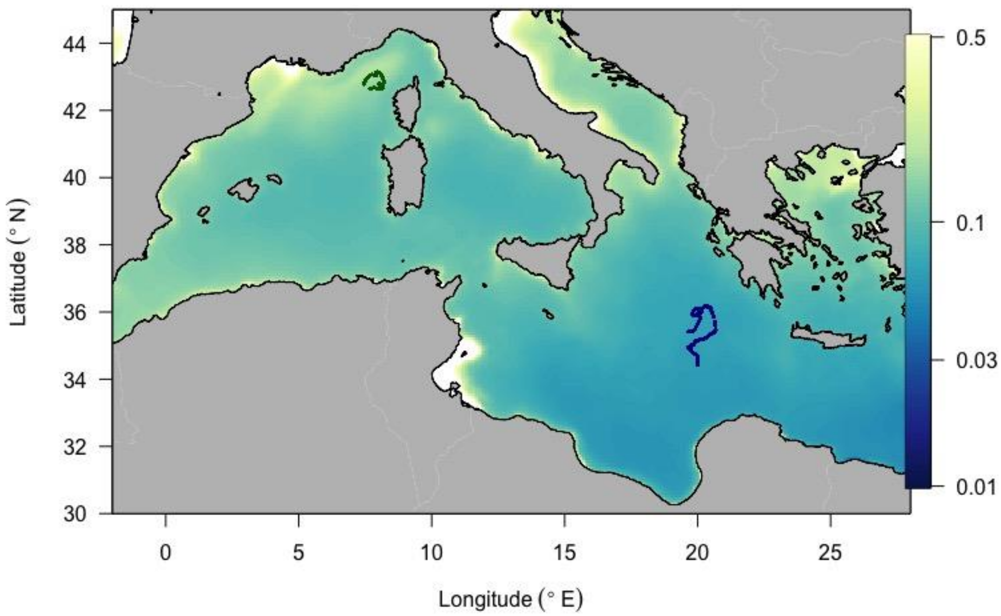

Figure 1: Trajectories of the two BGC-Argo profiling floats fLig (WMO6901776) and fIon (WMO6902828) deployed respectively in the Ligurian Sea (green) and the Ionian Sea (blue), superimposed onto a 9-km resolution summer climatology of surface chlorophyll *a* concentration (Chl; in mg m^{-3}) derived from MODIS Aqua ocean color measurements.

REVISED FIGURE 2

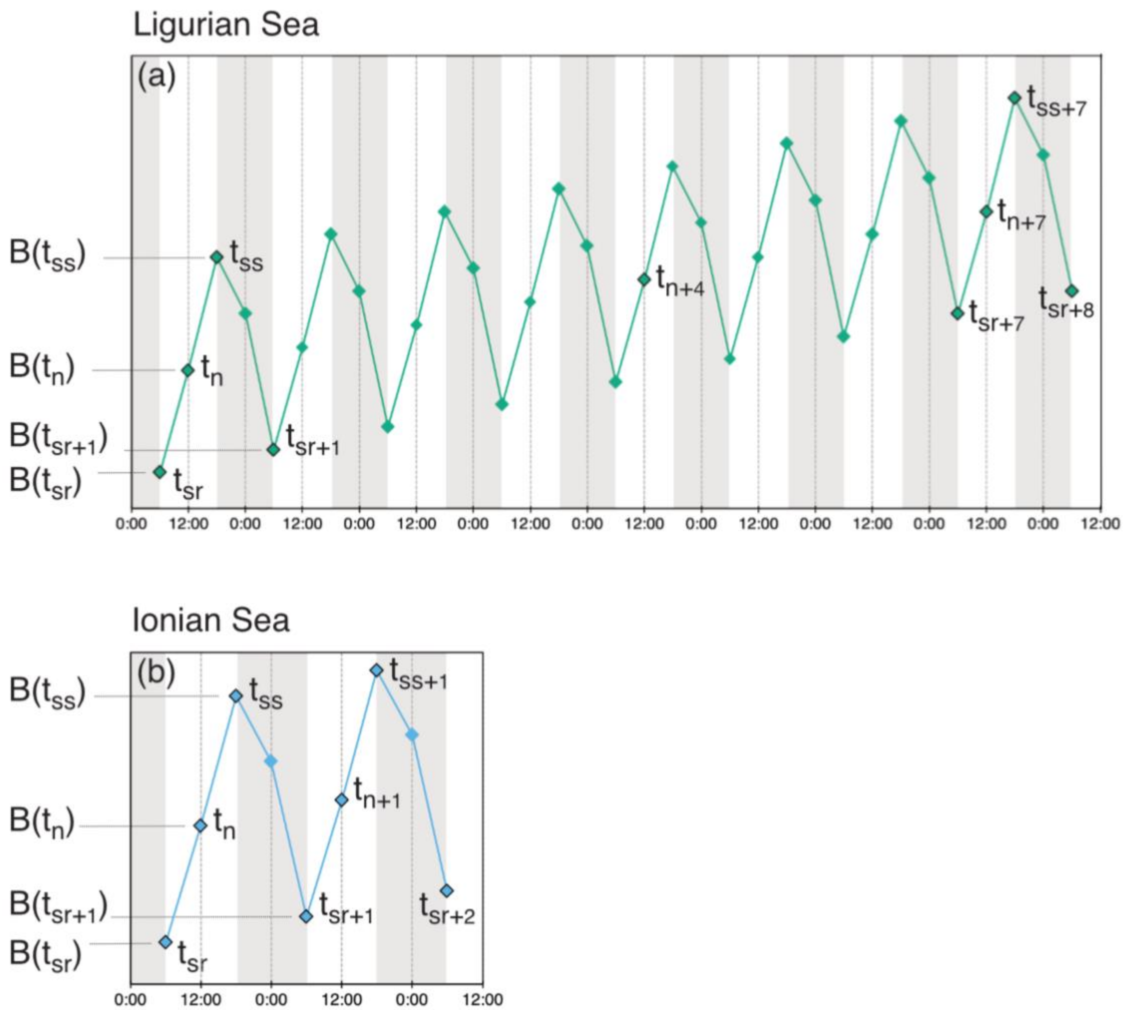

Figure 2: Schematic representation of the diel variations of the depth-integrated bio-optical properties converted to POC biomass (B) and the sampling strategies employed in the (a) Ligurian Sea and (b) Ionian Sea. The diamond-shaped symbols indicate schematically the float profile times, labeled with time stamps associated with sunrise (sr), noon (n), sunset (ss) and midnight (m), with the corresponding POC biomass estimated within the considered layer (e.g., $B(t_{sr})$, etc.). The numeric subscripts (+1, +2, +4, +7 or +8) indicate the number of days since the first profile of the summertime time series.

REVISED FIGURE 3

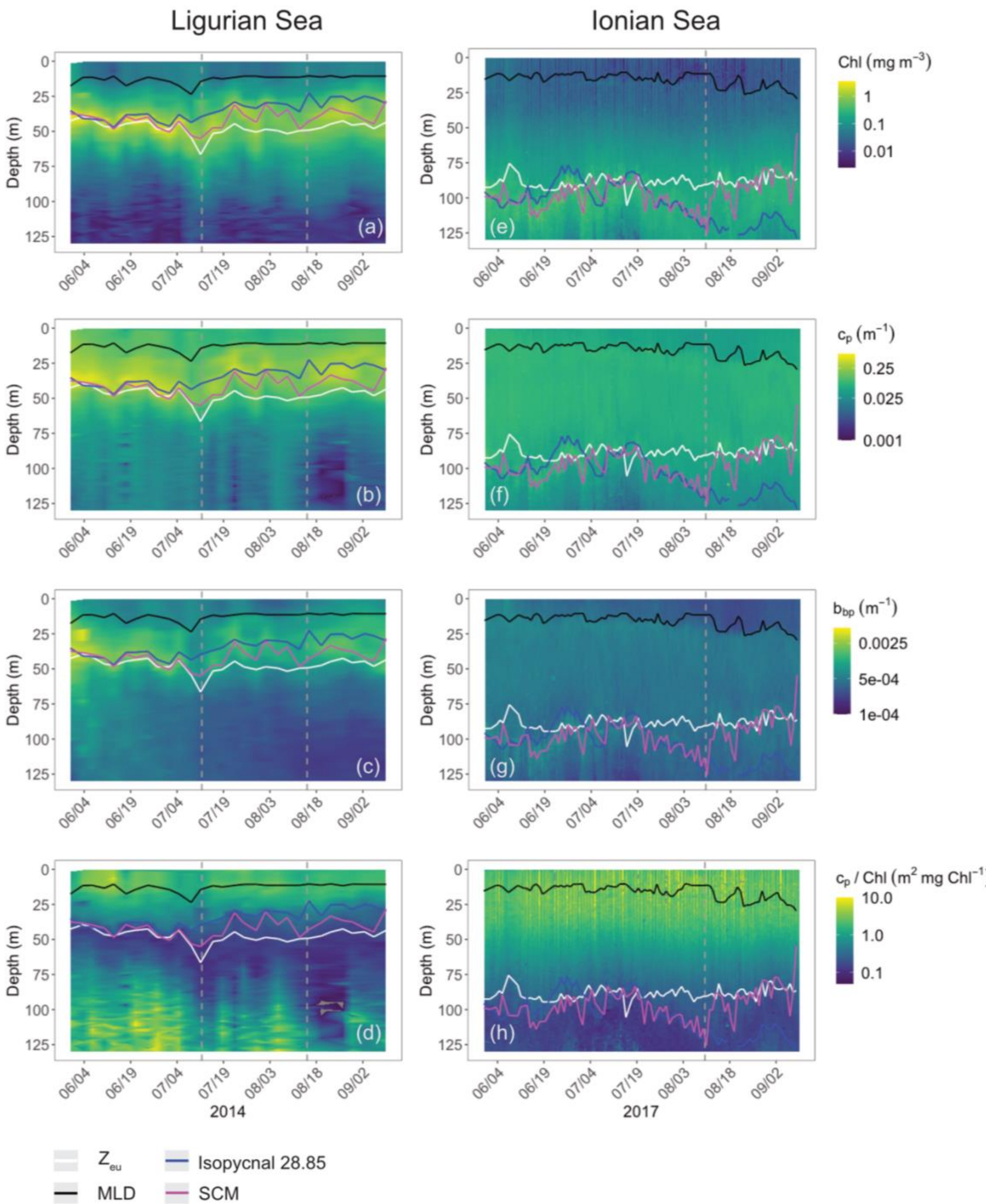

Figure 3: Time series of Chl (a and e), c_p (b and f), b_{bp} (d and g), and c_p/Chl (d and h), in the Ligurian Sea (left) and the Ionian Sea (right). The Mixed Layer Depth (MLD; black line), the isopycnal 28.85, expressed as σ_t (blue line), the euphotic depth (Z_{eu}; white line) and the depth of the SCM (magenta line) are superimposed onto the bio-optical timeseries. The dashed lines indicate the dates at which the c_p and the b_{bp} values in the SCM layer reach a minimum.

APPENDIX A

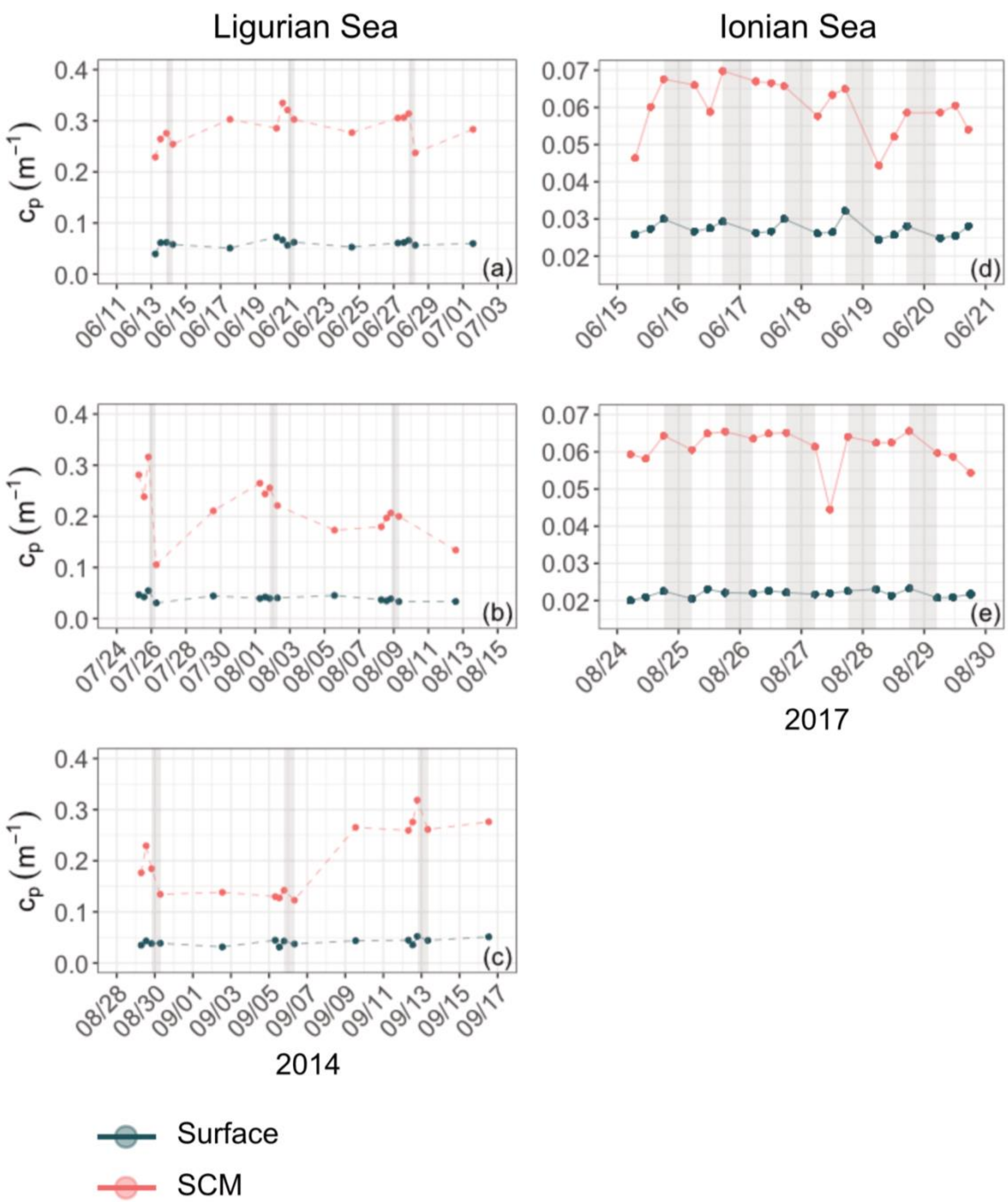

Fig. A1. Example of time series of the c_p coefficient in the surface (red) and SCM (dark green) layers, chosen within the time periods indicated by the dashed lines in Figs 3-4, from May 24 to July 14, 2014 (a), July 14 to August 16, 2014 (b), and August 16 to September 13, 2014 for the Ligurian Sea (left), and from May 28 to August 11, 2017 (d) and August 11 to September 11, 2017 (e) for the Ionian Sea (right).

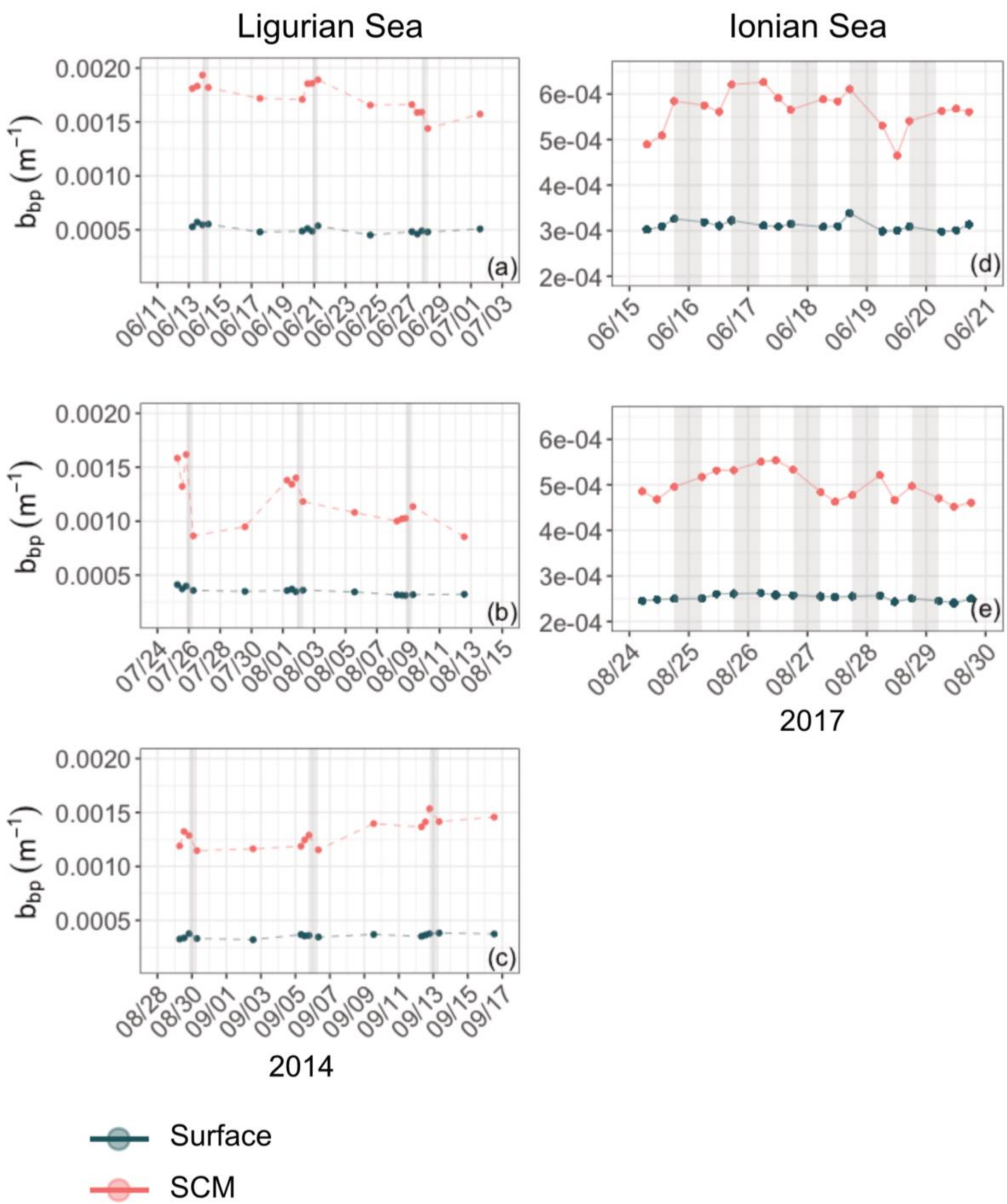

Fig. A2. Example of time series of the b_{bp} coefficient in the surface (red) and SCM (dark green) layers, chosen within the time periods indicated by the dashed lines in Figs 3-4, from May 24 to July 14, 2014 (a), July 14 to August 16, 2014 (b), and August 16 to September 13, 2014 for the Ligurian Sea (left), and from May 28 to August 11, 2017 (d) and August 11 to September 11, 2017 (e) for the Ionian Sea (right).