

# Three decades of marine bioregions evolution through analysis of phytoplankton phenology

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## Abstract

Ocean biogeochemistry is undergoing significant modification in response to climate change. To better track these evolutions, we present a novel ocean monitoring indicator that follows the temporal evolution of marine bioregions of similar phytoplankton phenologies. Chlorophyll-a concentration observations from remotely sensed ocean color describe seven distinct marine bioregions characterized by their unique patterns of phytoplankton biomass seasonality. The sizes and locations of these bioregions are monitored from 1998 to 2024 using a multi-sensor merged L4 ocean color product. While the bioregions’ extents appear to follow interannual and decadal climate variability, their long term evolution suggests a poleward extension of less seasonal phytoplankton phenology, which is generally characteristic of the tropical and subtropical bands. This innovative approach allows the systematic monitoring of how phytoplankton adapt their seasonal cycle in response to changes in environmental conditions, hence giving valuable insights into the evolution of marine ecosystems over the past three decades and helping advance our understanding of global ocean biological responses to environmental change.

## 1 Introduction

Phytoplankton, the main primary producers in the ocean, sustain marine food webs (Fenchel, 1988; Kjørboe, 1993) and play a central role in regulating oceanic carbon fluxes (Falkowski *et al.*, 1994). Environmental conditions shape phytoplankton growth and losses through “bottom-up” (e.g., light and nutrients availability) and “top-down” (e.g., grazing) processes. Over the past three decades, satellite ocean color measurements make it possible to estimate phytoplankton biomass (Behrenfeld *et al.*, 2005) proxied by chlorophyll-a concentration (Huot *et al.*, 2007). This, in turn, has enabled the study of phytoplankton phenology (i.e. the temporal succession of main biological events) (Longhurst, 2007; Racault *et al.*, 2012; Sapiano *et al.*, 2012, Boyce *et al.*, 2017). Climate influences the distribution of

31 environmental factors that, in turn, regulate the spatiotemporal dynamics of phytoplankton biomass  
32 (Falkowski and Oliver, 2007). Distinct seasonal patterns emerge along latitudinal gradients, from the  
33 equator to the poles (Longhurst, 1995). At high latitudes, primary production is mainly light limited,  
34 whereas in tropical and subtropical regions, phytoplankton production is essentially nutrient limited  
35 (Boyce *et al.*, 2017). Like the marine environment itself, phytoplankton biomass responds to both annual  
36 and decadal climate variability (Li *et al.*, 2024).

37 Climate change is altering oceanic ecosystems (ref from OSR #10 chapter 1), with complex impacts on  
38 phytoplankton growth. For instance, rising sea temperatures might directly affect metabolism (O'Connor  
39 *et al.*, 2009) but also environmental conditions through enhanced water column stratification  
40 (Yamaguchi and Suga, 2019), which in turn might further limit growth by hindering upward transport of  
41 nutrients to the sunlit layers (Sarmiento *et al.*, 2004; Fernández-González *et al.*, 2022). As for terrestrial  
42 plants (Cleland *et al.*, 2007; Inouye, 2022), marine phytoplankton are expected to respond to these  
43 environmental changes by adjusting their seasonal cycles (Winder and Sommer, 2012). Most of the  
44 documentation effort focused on variations in the onset, duration, and intensity of bloom events (e.g.,  
45 Sommer and Lengfellner, 2008; Martinez *et al.*, 2011; Henson *et al.*, 2018; Salgado-Hernanz, 2019). These  
46 changes may cause phenological mismatches hence disrupting energy transfer to higher trophic levels  
47 (Visser and Both *et al.*, 2005, Asch *et al.*, 2019) and have broader implications for the global carbon cycle  
48 (Fisher *et al.*, 2025). Consequently, establishing robust indicators monitoring interannual to decadal  
49 changes in phytoplankton phenology is critical to better address the evolution of the marine ecosystem  
50 with climate change.

51 With the large amount of remotely sensed ocean color observations, numerical clustering methods  
52 emerged as key tools to identify regions with similar seasonal dynamics of phytoplankton (hereafter  
53 referred to as bioregions) (International Ocean Color Coordinating Group, IOCCG, 2009). Several studies  
54 (e.g. D'Ortenzio and Ribera d'Alcalà, 2009; Lacour *et al.*, 2015; Ardyna *et al.*, 2017; Boyer *et al.*, 2017;  
55 Kheireddine *et al.*, 2021; Baudena *et al.*, 2025) have applied such methods to partition oceanic domains  
56 into bioregions characterized by similar seasonal patterns of chlorophyll-a concentration, which are  
57 often used as a basis for inferring provinces of similar biogeochemical functioning. Similarly to how  
58 Mayot *et al.* (2016) extended D'Ortenzio and Ribera d'Alcalà (2009) climatological partitioning of the  
59 Mediterranean Sea, this study presents an ocean monitoring approach built on Baudena *et al.* (2025)  
60 climatological bioregionalization of the global ocean. This method tracks variations in the extension of  
61 the bioregions in respect of time to reveal the trends in geographical changes of phytoplankton  
62 phenology. The main idea behind our approach is that tracking these variations may serve as a relevant  
63 proxy for assessing changes of phytoplankton dynamics, which, in turn, could inform on main variations  
64 of environmental factors of the marine ecosystem.

65 We introduce here a proof of concept for such an approach using the supervised clustering method  
66 introduced in Baudena *et al.*, 2025. Annual partition of the global ocean (56°S–56°N) from 1998 to 2024 is

67 obtained by classifying annual time series of remotely sensed chlorophyll-a concentration (Copernicus-  
68 GlobColor) into bioregions. After presenting the mean climatological state of the bioregions, we  
69 investigate their change in surface area over the last three decades. Then, building on D’Ortenzio *et al.*  
70 (2012) and adapting methods from Higgins *et al.* (2016), originally applied to terrestrial biomes, we  
71 compare the geographical extension of the bioregions between two decadal periods at the greatest extent  
72 of our dataset, (1998-2007 and 2015-2024) to identify the main trends in the reorganization of  
73 phytoplankton phenology. Finally, possible correlation with environmental changes and method  
74 limitations are evoked in the discussion section.

75 **2 Material and methods**

76 **2.1 Data**

77 Chlorophyll-a concentrations data were retrieved from the merged multi-sensor ocean color product ref.  
78 no. 1 (see Table 1). This product offers cloud free remotely sensed surface chlorophyll-a concentration at  
79 a 4 km spatial resolution and daily intervals. Using such a L4 product (an optimally interpolated, merged  
80 satellite dataset), as compared to L3 (merged product) in Baudena *et al.*, (2025), compensates for the lack  
81 of observation inherent to satellite ocean color (Stock *et al.*, 2020) and ensures a maximal spatialization  
82 of the bioregions at an annual temporal resolution.

| Product ref. no. | Product Id & type                                                | Data access                                       | Documentation                                                                                                                                   |
|------------------|------------------------------------------------------------------|---------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------|
| 1                | OCEANCOLOUR_GLO_<br>BGC_L4_MY_009_104,<br>Satellite observations | EU Copernicus<br>Marine Service<br>Product (2024) | Quality<br>Information<br>Document<br>(QUID):<br>Garnesson <i>et al.</i><br>(2025)<br>Product User<br>Manual (PUM):<br>Colella et<br>al. (2024) |

83 **Table 1: Product table**

84 **2.2 Supervised Clustering**

85 Annual ensembles of seasonal time series of chlorophyll-a concentration were built from 1998 to 2024.  
86 The time series composing them were all processed similarly to allow subsequent classification  
87 according to Baudena *et al.* (2025) supervised clustering method. In short, within each annual ensemble,  
88 each individual time series characterizes the seasonal evolution of chlorophyll-a concentration over a  
89 1° × 1° grid. Following the method detailed in supplementary section S1, the time series were obtained

90 averaging all available observations within each 1x1° pixel over a 8-day temporal window. To dampen  
91 sub-seasonal variations, time series were all smoothed with a 5 weeks centered rolling average method.  
92 Finally, all annual time series were normalized by their maximum to ensure that the clustering method  
93 focuses on their shape rather than on their magnitude.

94 Time series associated with pixels in the Arctic and Southern Oceans (respectively above 56°N and below  
95 56°S) were removed from every annual ensemble due to lack of continuous satellite observation through  
96 winter in relation to permanent cloud presence and polar night. Coastal pixels located within 111 km  
97 (~1°) from the coast were also discarded due to the uncertainty in chlorophyll-a concentration  
98 estimations within optically complex waters (Case 2 waters). As a result 80% of the global ocean area is  
99 considered. In the southern hemisphere, time series were all shifted six months backward, to ensure  
100 identical sequencing of seasons in the time series of all pixels.

101 Each annual ensemble was then partitioned into the seven clusters of Baudena *et al.*, 2025 based on their  
102 seasonality patterns. These seven clusters were found to optimally partition open ocean seasonal cycles  
103 of surface chlorophyll-a concentration in respect of multiple statistical tests discussed in the companion  
104 study. The assignment of a given time serie into one of the clusters was done according to its minimal  
105 euclidean distance (maximal similarity) with the central time series of Baudena *et al.*, 2025 clusters. To  
106 prevent assignment of too dissimilar seasonal patterns, a threshold distance was considered to accept  
107 (distance below the threshold) or refuse (distance above the threshold) an assignment. To account for the  
108 method's sensitivity to this hyperparameter, we discretized a range of possible values, defined by the  
109 minimum and maximum classification distances found among the most deviating elements of any  
110 cluster, from 1.33 (cluster 1) to 2.60 (cluster 7), based on the unsupervised clustering of Baudena *et al.*,  
111 (2025). Each annual ensemble was partitioned several times from a low (strict definition of the clusters)  
112 to high threshold values (lax definition of the clusters) selected within this range with a regular step of  
113 0.05 (see sensitivity analysis in supplementary section 2). At least 88 % of the time series were always  
114 successfully sorted within the seven clusters (see Fig. S2b). Unclassified time series, mostly located in  
115 regions of low satellite data availability region (see Fig. S2a), were all excluded from ulterior analysis.

## 116 2.3 Bioregions

117 The spatial projection of each pixel's membership over the global ocean forms large coherent spatial  
118 domains similarly classified. These oceanic domains correspond to the bioregions as defined by Baudena  
119 *et al.* (2025). As a reminder, bioregions share similar seasonal patterns in phytoplankton phenology  
120 suggesting a common biogeochemical functioning (Longhurst, 1995). Over time, the spatial definition of  
121 the bioregion might change with annual time series characteristic of a given pixel being attributed to  
122 different clusters over different years. A change of phytoplankton phenology is attributed to a pixel when  
123 its bioregion changes from one year to another. For a given pixel, the frequency of phenology change is  
124 defined as the total sum of these changes over the study period. These changes might present oscillating

125 patterns from annual to decadal period or long term trends.

126 Three climatological partitions of the global ocean were considered hereafter. They were constructed by  
127 keeping, in each pixel, the most frequent bioregion over the selected temporal extent. The three  
128 considered periods are: from 1998 to 2024 and two decadal periods from 1998 to 2007 and from 2015 to  
129 2024. The former climatological period supports the documentation of the average bioregion extent  
130 while the latter two decadal periods were chosen at the edge of the temporal span to support the  
131 documentation of long term changes in the bioregion's extent. The use of decadal bioregions also  
132 dampens interannual variability.

133 When comparing the decadal bioregions' extent between the 1998-2007 and the 2015-2024, we attribute a  
134 stable phenology change to a given pixel when its classification changed between the two periods and if  
135 this assignment remained identical for more than six years in each of the two decades. This temporal  
136 criterion was chosen strictly above half a decade to grant a reasonable and robust indicator of the  
137 bioregion persistence while remaining permissive in respect of inter annual climate variability.

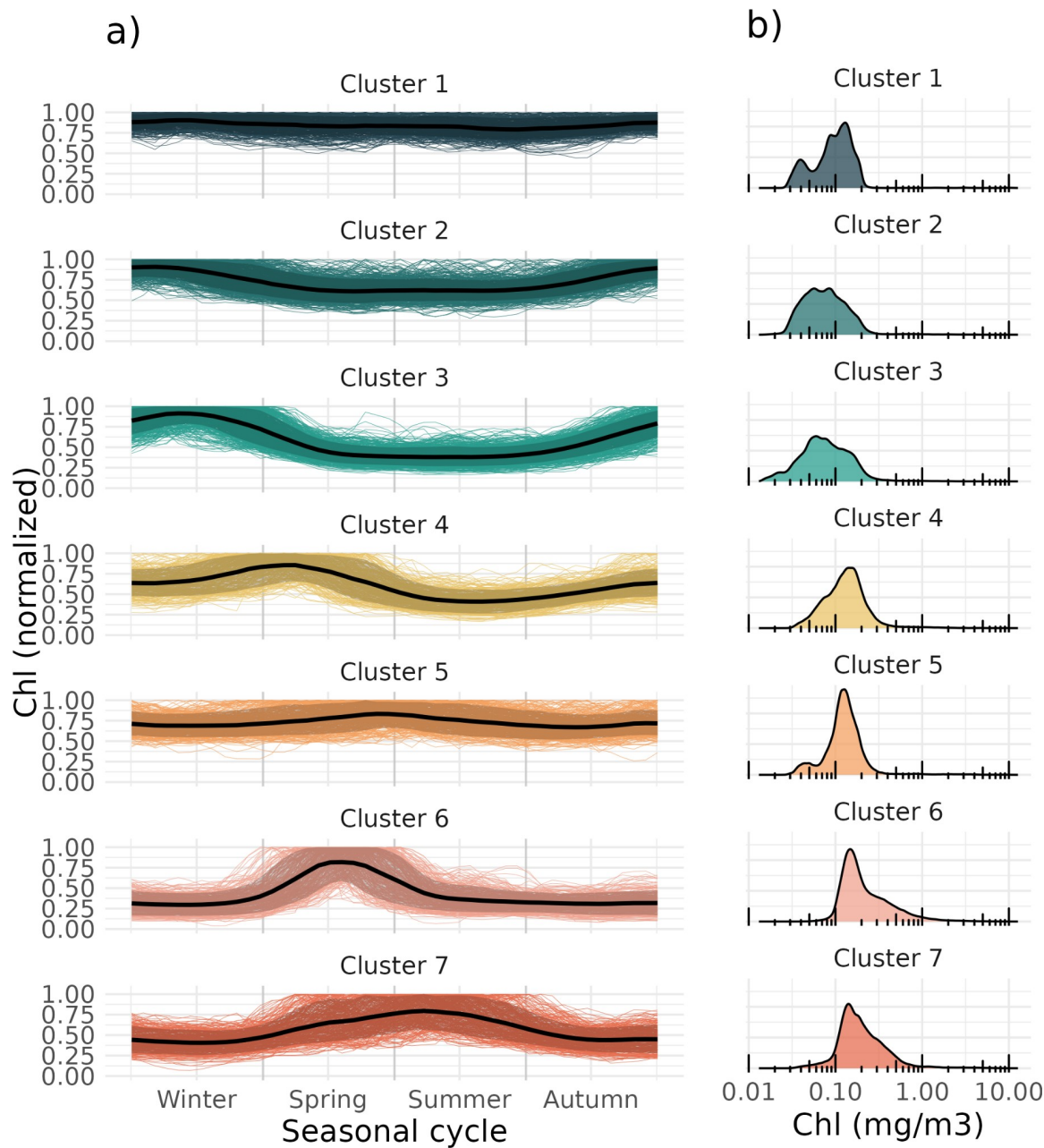
138 To assess phytoplanktonic biomass across the bioregions, we analyzed their chlorophyll-a  
139 concentrations, presented as probability distribution functions in Fig. 1b. The distribution for bioregion 1  
140 is notably bimodal, showing a minor peak near  $0.03 \text{ mg.m}^{-3}$  and a dominant one just above  $0.1 \text{ mg.m}^{-3}$ .  
141 This finding prompted us to subdivide bioregion 1, after the clustering, based on a threshold of  $0.06$   
142  $\text{mg.m}^{-3}$  for yearly average chlorophyll-a, creating an oligotrophic group (below the threshold) and a  
143 mesotrophic group (above the threshold). Although both sub-regions exhibit a similar non-seasonal  
144 pattern, this subdivision reveals distinct phenologies, suggesting they are controlled by different  
145 environmental forcings that either sustain or inhibit year-round phytoplankton growth.

## 146 2.4 Uncertainties estimation

147 Following the set of threshold distance, each annual ensemble is partitioned twenty six times (see section  
148 2.2). In each of these partitions, the distribution of the bioregion surface area relative to the set of  
149 threshold distances is characterised hereafter by its central value (the median) within its interquartile  
150 range (Q1–Q3). The interquartile range of surface area estimates accounts for the bioregionalization  
151 method uncertainty. All surface areas are reported relative to the total global ocean area. To identify  
152 long-term changes, we fitted a linear model to the central surface area estimates in respect of time. The  
153 statistical significance of these linear trends was determined using a Spearman rank correlation, with a  
154 trend considered significant at  $p < 0.1$ .

155    **3 Results**

156    Our analysis is presented in three parts. First, we recall the phytoplankton phenology and climatological  
157    repartition of the seven marine bioregions (described in more details in Baudena *et al.*, 2025). Second, we  
158    assess the interannual variability and long-term trends in the surface area evolution of each bioregion  
159    from 1998 to 2024. Finally, we identify the locations of stable phenological changes by comparing two  
160    distinct decades at the edges of the period.



162

163 **Figure 1: Clusters resulting from the supervised clustering of the ensemble of year 2024 from product ref. no.**  
164 **1 according to the strictest threshold. The left panel (a), shows the mean normalized seasonal cycles within**  
165 **each cluster (thick continuous black line) within its 10% and 90% percentiles (transparent black bands). In the**  
166 **background, examples of time series within that cluster are represented. The right panel (b), displays the**

13  
14

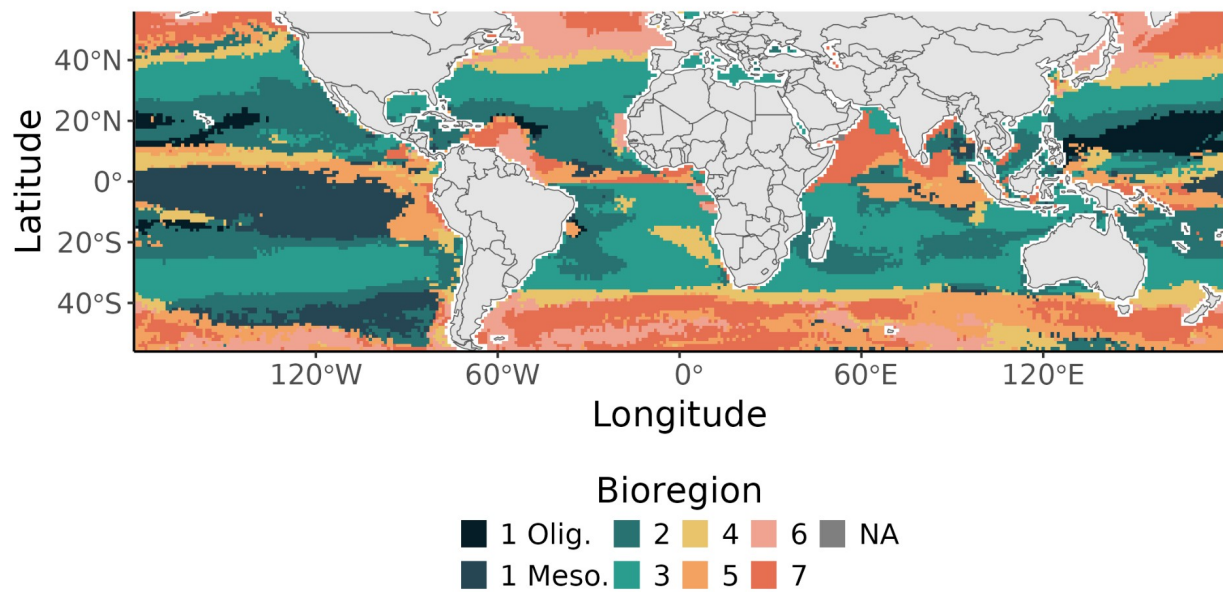
167 **distribution of chlorophyll concentration within each cluster.**

168 For each year, the supervised clustering method subdivides the ensemble into the seven clusters  
169 identified in Baudena *et al.* (2025). These clusters outline specific phenological patterns inferred from the  
170 mean seasonal cycle of chlorophyll-a concentration (Fig. 1a). These patterns, corresponding to the  
171 bioregions in Fig. 2a, range from no clear seasonality (bioregion 1) to those with pronounced single or  
172 double peak events (bioregions 7-6-4), which are typical of blooms in temperate and high-latitude  
173 systems, as we found in Fig. 2a.

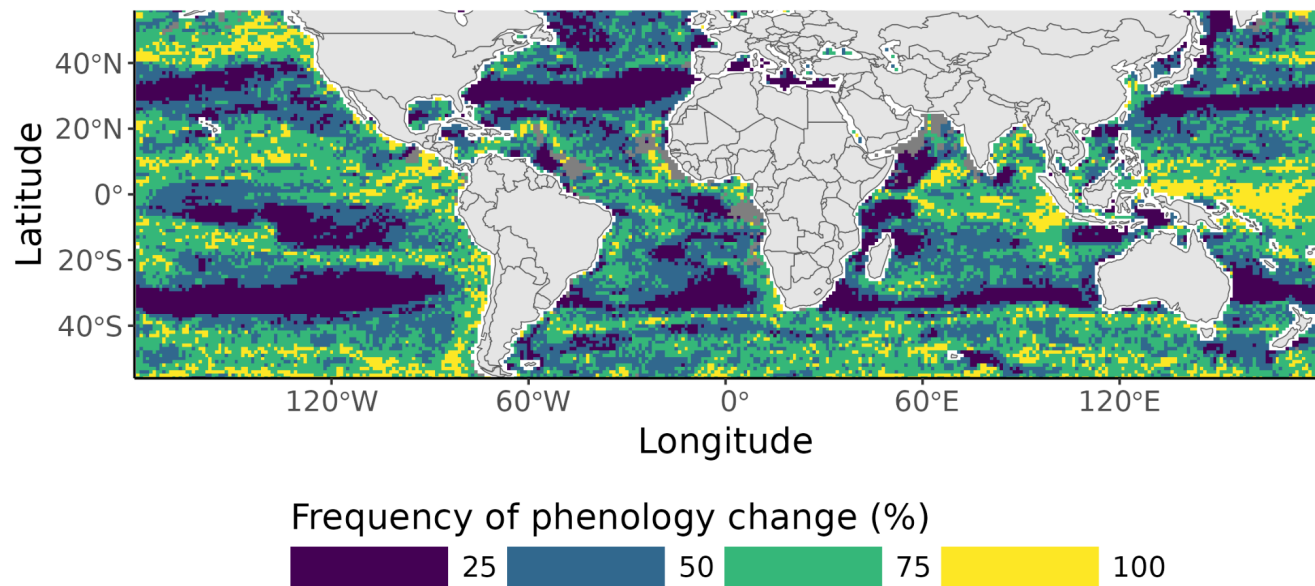
174 In agreement with Baudena *et al.* (2025), the climatological distribution of the related bioregions over the  
175 1998-2024 period (Fig. 2a) follows a meridional distribution sketching coherent, large-scale structures  
176 corresponding to major oceanic domains, such as the subtropical gyres (bioregions 1 Olig., 2 and 3) and  
177 convergences zones (bioregion 4). The biogeochemical relevance of this partitioning is reinforced by the  
178 distribution of chlorophyll-a concentrations within each bioregion (Fig. 1b). A clear poleward  
179 productivity gradient emerges, with the lowest surface biomass in the perpetually stratified regimes of  
180 the subtropical band and the highest in the high-latitude bloom regions (bioregion 6-7). This aligns with  
181 established knowledge of global ocean productivity patterns (Behrenfeld *et al.*, 2005).

182 Baudena *et al.* (2025) offered a biogeochemical interpretation of the bioregions, summarized as follows.  
183 Bioregions 6 and 7 correspond to Longhurst's (1995) model 1 (*polar, irradiance-limited*). Bioregion 5  
184 exhibits features of both model 1 and model 2 (*mid-latitude, nutrient-limited spring production peak*).  
185 Bioregion 4 closely aligns with the Bloom bioregion identified by D'Ortenzio *et al.* (2012). Bioregion 3  
186 matches Longhurst's (1995) model 3 (*subtropical, winter nutrient-limited*), whereas Bioregion 2 closely  
187 resembles the Tropical bioregion described by D'Ortenzio *et al.* (2012). Finally, Bioregion 1 corresponds  
188 to Longhurst's model 4 (*tropical*). Its additional subdivision, introduced here, produces spatially coherent  
189 domains that distinguish between oligotrophic regions in the centers of subtropical gyres and  
190 mesotrophic regions primarily distributed around the equator.

(a) 1998-2024



(b) 1998-2024



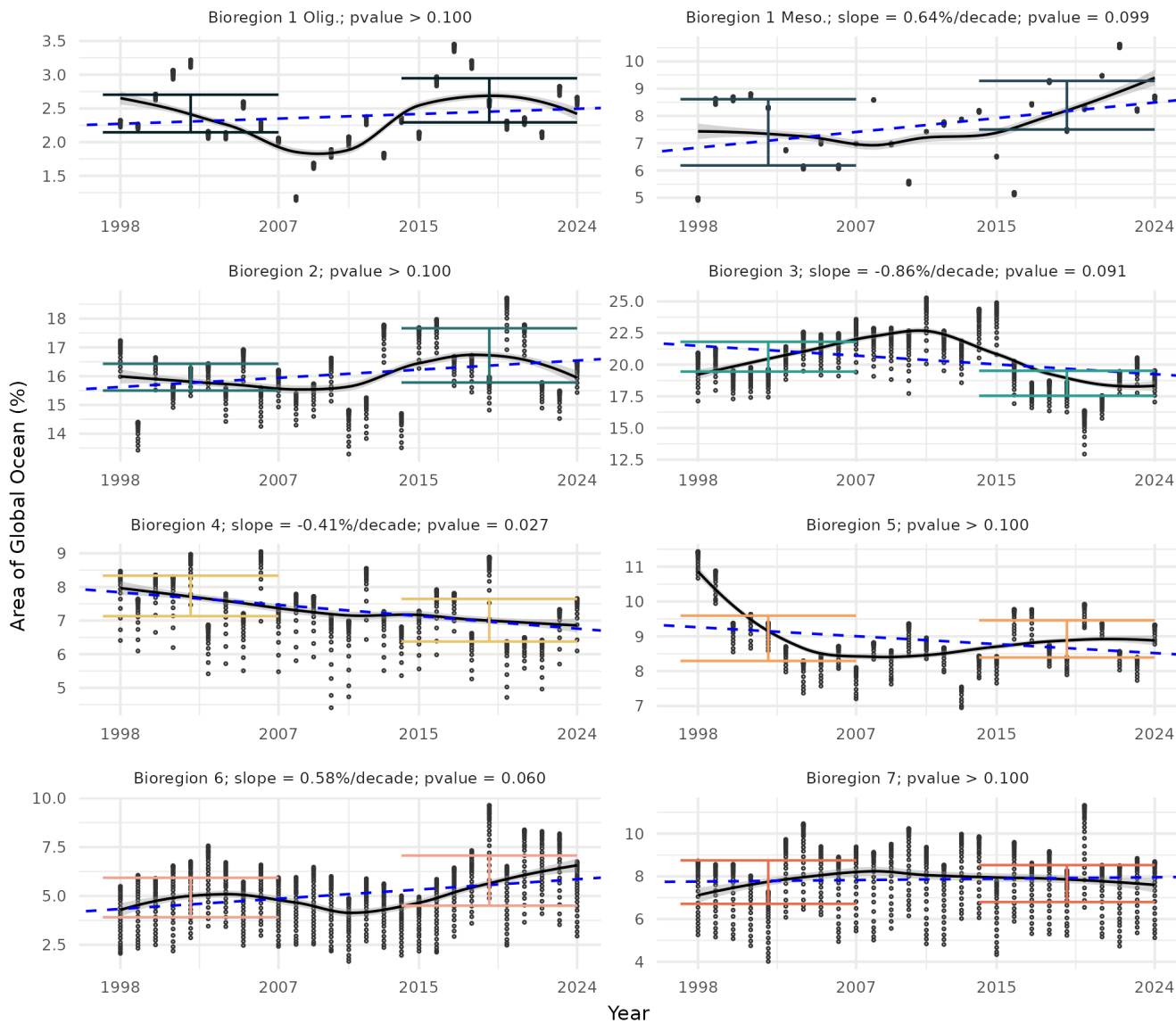
**Figure 2: (a) Climatological distribution of the bioregions in the 1998-2024 period. (b) Amount of phenology change per pixel over the 1998-2024 period given in % of the total number of considered years. Both panels display the results obtained using the least strict clustering criteria on the ensemble processed from product ref. no. 1. Pixels designated as NA (in grey) refer to the position of the time series that were not successfully**

197 **classified.**

### 198 **3.1 Temporal evolution of the bioregions**

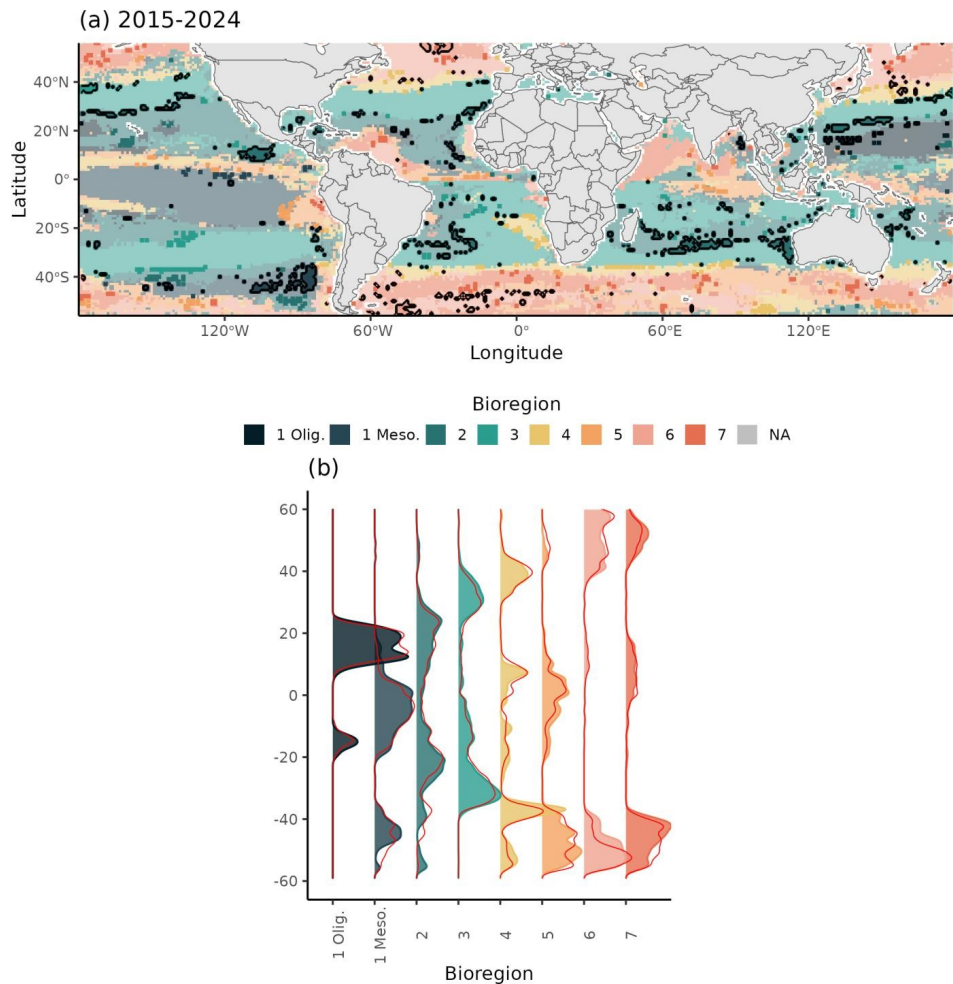
199 The boundaries of bioregions in Fig. 2a are not static. Fig. 2b displays the frequency of changes in each  
200 pixel bioregion's affiliation, interpreted as changes in phytoplankton phenology, over the 1998–2024  
201 period. These changes occur most frequently in transitional areas in-between major bioregions, as well  
202 as in coastal zones, over the equatorial band, and over high-latitude regions of the northern Pacific and  
203 Southern Ocean (Fig. 2b). Bioregion 3, centered at 30° in both hemispheres, appears as the most stable  
204 bioregion.

205 A visual analysis of the temporal evolution of each bioregion's surface area (Fig. 3) reveals strong  
206 interannual variabilities (time evolution of black dots) in all bioregions. Bioregions 1, 2, 3 and 6 also  
207 display high decadal variability (black lines). Linear trend analysis ( $p < 0.1$ ) indicates a significant  
208 reduction in the global surface area of bioregion 3 and bioregion 4. Conversely, the mesotrophic  
209 bioregion 1 shows a significant expansion. While surface areas of bioregions 6 and 7 exhibit large  
210 changes from one year to the other, their surface area estimates are associated with large method  
211 uncertainties (~50%), precluding the consideration of the trend significance.



212

213 **Figure 3 : Evolution of bioregions' surface area from 1998 to 2024. The time evolution of black dots represent**  
 214 **estimates of the areas following the varying acceptance thresholds. The black trend line displays the**  
 215 **smoothed centered 10-year rolling average, the blue dotted line corresponds to the linear tendency of the**  
 216 **annual median area estimate. Panel's titles show the linear trends on the condition that it was found**  
 217 **significant ( $p < 0.1$ ). First and third quartiles of the decadal bioregions (1998-2007 and 2015-2024) are indicated**  
 218 **as colored error bars. Note the varying y-scale across panels.**



220

221 **Figure 4: (a) Bioregions in the 2015-2024 decadal period with stable changes identified by black contours. (b)**  
222 **Latitudinal distribution of bioregions for the 2015-2024 decadal period (filled), compared with the 1998-2007**  
223 **decadal period (red line)(b) displays the latitudinal distribution of bioregions between the 1998-2007**  
224 **decadal period, as red line, and the 2015-2024 period, with colored and filled distributions, respectively.**

225 To isolate long-term trends from interannual variability, we identified areas with stable phenological  
226 changes between the 1998–2007 and 2015–2024 decadal periods. As highlighted in Fig. 4a, these regions  
227 are mostly located within the tropical and subtropical band. Overall 4.93% [4.56%, 5.06%] of the global  
228 ocean is affected suggesting slow transitions in essentially steady conditions. The dominant pathways in

phenology transition are summarized in Table 2. The most prominent change (1.82% of the global ocean) is the transition from bioregion 3 to the less seasonal bioregion 2, occurring primarily in the subtropical Pacific and Indian Oceans. Other significant shifts include the expansions at lower latitude of bioregion 1 at the expense of bioregion 2 (0.62%) and of bioregion 3 at the expense of bioregion 4 (0.27%). In the North Atlantic's temperate band, a notable net transition from bioregion 7 to 6 also occurred (0.09%). As summarized by Fig.4b, the most prominent trend is a poleward expansion of bioregions of weaker seasonality. These spatial patterns of change correspond to the surface area trends observed over the full time series (Fig. 3).

|                                      |              | Oceanic Basins               |                               |                               |                               |                               | Total                         |
|--------------------------------------|--------------|------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
|                                      |              | Indian Ocean                 | North Pacific Ocean           | South Pacific Ocean           | North Atlantic Ocean          | South Atlantic Ocean          |                               |
| Pathways of stable phenology changes | 2 to 1 Olig. | -                            | <b>0.12 %</b><br>[0.12, 0.12] | 0.01%<br>[0.01, 0.01]         | 0.03 %<br>[0.03, 0.03]        | -                             | <b>0.16 %</b><br>[0.16, 0.16] |
|                                      | 2 to 1 Meso. | 0.03 %<br>[0.03, 0.03]       | -                             | <b>0.36 %</b><br>[0.36, 0.36] | 0.07%<br>[0.07, 0.07]         | -                             | <b>0.46 %</b><br>[0.46, 0.46] |
|                                      | 3 to 2       | <b>0.67%</b><br>[0.66, 0.67] | <b>0.55%</b><br>[0.52, 0.55]  | <b>0.15 %</b><br>[0.15, 0.15] | <b>0.19 %</b><br>[0.18, 0.19] | <b>0.21 %</b><br>[0.21, 0.21] | <b>1.82 %</b><br>[1.78, 1.83] |
|                                      | 4 to 3       | 0.01 %<br>[0.01, 0.01]       | <b>0.16 %</b><br>[0.14, 0.16] | 0.02 %<br>[0.01, 0.02]        | 0.02 %<br>[0.02, 0.02]        | 0.06 %<br>[0.06, 0.06]        | <b>0.27 %</b><br>[0.24, 0.27] |
|                                      | 6 to 7       | -                            | 0.03 %<br>[0.02, 0.06]        | 0.02 %<br>[0.01, 0.02]        | 0.08 %<br>[0.03, 0.10]        | 0.01 %<br>[0.001, 0.10]       | <b>0.13 %</b><br>[0.06, 0.19] |
|                                      | 7 to 6       | 0.01%<br>[0.01, 0.01]        | 0.01%<br>[0.01, 0.02]         | -                             | <b>0.17 %</b><br>[0.13, 0.19] | <b>0.23 %</b><br>[0.19, 0.24] | <b>0.43 %</b><br>[0.33, 0.47] |

Table 2: Major pathways among stable phenology changes. Changes in surface area from one bioregion to another are given relatively to the global ocean. Estimates are given within their first and third quartiles and grouped by oceanographic basins. Minor changes, associated with an area inferior to 0.01% of the global ocean, are not represented. Estimates highlighted in bold indicate values greater than 0.1 % of the global ocean.

#### 4 Discussion and conclusion

Our analysis introduces a novel ocean indicator approach that distinguishes between intermittent, year-to-year variability and persistent, long-term shifts in phytoplankton phenology. While boundary regions exhibit frequent intermittent changes (Fig. 2b), our decadal analysis finds that nearly 5% (see Table 2) of the global ocean experienced a displacement of phytoplankton phenology suggesting persistent ecosystem reorganization over the past three decades. The cascading changes (i.e., transitions from

249 bioregion 4 to 3, bioregion 3 to 2, and 2 to 1) identified above, are possibly driven by an intensification of  
250 upper-ocean stratification in relation to climate warming (Capotondi *et al.*, 2012). At these low latitudes  
251 (30°S-30°N), a shallower vertical mixing prevents entrainment of deeper nutrients (Vereshchaka and  
252 Shatravin, 2025) therefore hindering biomass accumulation of surface waters (Sarmiento *et al.*, 2004;  
253 Polovina *et al.*, 2008). The robustness of our ocean indicator approach is further validated in the  
254 temperate North Atlantic, where despite high method uncertainties, the documented shift from a double  
255 to a single bloom phenology (bioregion 7 to 6) linked to delayed autumnal mixing in Martinez *et al.*  
256 (2011) is successfully captured. The documented changes also echo the variations of micronekton  
257 habitats provinces monitored from sea surface temperature, stratification index and net primary  
258 production evolution in Albernhe *et al.* (2025).

259 The proposed ocean monitoring approach is nevertheless subject to several limitations. First, satellite  
260 ocean color observations are sparse at high latitudes inducing increasing method uncertainties poleward  
261 and the exclusion of the subpolar and polar domains (above 60°). In these domains significant and rapid  
262 phenological changes are already documented (Kahru *et al.*, 2011; Thomalla *et al.*, 2023; Manizza *et al.*,  
263 2023), with potential propagating effects on higher trophic levels (Fossheim *et al.*, 2015). Second, because  
264 | satellites only measure the ocean surface, our analysis cannot capture **changes** in subsurface  
265 productivity patterns, such as the deepening of the deep chlorophyll maximum (Mignot *et al.* 2014,  
266 Cornec *et al.*, 2021). Finally, while the twenty seven year long time series is substantial, it remains  
267 challenging to definitively disentangle long-term climate-driven trends from the influence of natural  
268 decadal-scale climate modes (e.g., D'Ortenzio *et al.*, 2012; Zhai *et al.*, 2013; Li *et al.*, 2024).

269 Despite these limitations, the ocean indicator approach presented here provides a powerful and  
270 pragmatic tool to effectively map the locations of potential long-term ecosystem shifts. This makes it a  
271 crucial complement to established indicators, such as the ocean indicator method for chlorophyll-a  
272 concentration (10.48670/moi-00230). While such concentration-based indicators quantify how much  
273 biomass is present, our phenology-based approach reveals how the ecosystem's seasonal dynamics are  
274 unfolding. It can therefore detect critical shifts in ecosystem structure and function even when the total  
275 annual biomass remains unchanged. Furthermore, identifying long term trends in the distribution of  
276 chlorophyll-a concentration was shown to be dependent on the type of ocean color product (Zhai *et al.*,  
277 2024, Pauthenet *et al.*, 2024). Investigating the presence and variability of the bioregions based on ESA's  
278 Ocean Color Climate Change Initiative (Sathyendranath *et al.*, 2019) would further consolidate  
279 (invalidate) the highlighted trends. In this paper, we mainly propose an approach, a proof-of-concept,  
280 that could be further applied to other ocean colors time-series

281 Future work could integrate Global ocean hindcast, to overcome the limitations of remotely sensed ocean  
282 color and extend monitoring to regions with poor satellite coverage (10.48670/moi-00019) and other four  
283 dimensional products (10.48670/moi-00046) to account for in-depth process. Earth system models can

also help predict future states according to climatic projections (Yamaguchi *et al.*, 2022; Fisher *et al.*, 2025). The partitioning could also be refined by incorporating additional variables (e.g., the particulate backscattering coefficient) to better delineate bioregions. However, the current method's simplicity remains its main asset, ensuring a broad application range, ease of use, and making it an ideal candidate for immediate operational implementation.

#### **Data availability**

Ocean color data were collected from the OCEANCOLOUR\_GLO\_BGC\_L4\_MY\_009\_104 product, provided by the Copernicus Marine Environment Monitoring Service (CMEMS, <http://marine.copernicus.eu/>). Cluster centroids resulting from Baudena *et al.* (2025) were obtained directly from the author.

#### **Author Contribution CRediT**

**WR:** Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Visualization, Writing – Original Draft Preparation. **NM:** Conceptualization, Investigation, Methodology, Writing – Original Draft Preparation, Visualization, Writing – Review & Editing. **AM:** Conceptualization, Formal Analysis, Visualization, Writing – Review & Editing. **VT:** Conceptualization, Supervision, Writing – Review & Editing. **FDO:** Conceptualization, Funding Acquisition, Supervision, Writing – Review & Editing.

#### **Competing Interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### **Acknowledgement**

The authors gratefully acknowledge Karina von Schuckmann for her insightful guidance and valuable contributions throughout all stages of the present study. [They also sincerely thank the reviewers for their constructive comments and valuable feedback, which significantly enhanced the clarity and quality of this manuscript.](#) During the preparation of this work the authors used ChatGPT-4 from OpenAI (<https://chat.openai.com>) in order to improve the readability and language of the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

#### **Financial Support**

NM received in 2025 a postdoctoral research grant from the CNES (Centre National d'Etudes Spatiales). WR acknowledges the financial support from the CNES through the APR - 2022 (project SEASONS) and BRIDGES-AVATAR (grant ANR-22-EXBR-0004) integrated in France (2030) and managed by Agence Nationale de la Recherche.

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