

1 **Three decades of marine bioregions evolution through**
2 **analysis of phytoplankton phenology**

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8 **Abstract**

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

22 **1 Introduction**

23 Phytoplankton, the main primary producers in the ocean, sustain marine food webs (Fenchel, 1988;
24 Kjørboe, 1993) and play a central role in regulating oceanic carbon fluxes (Falkowski *et al.*, 1994).
25 Environmental conditions shape phytoplankton growth and losses through “bottom-up” (e.g., light and
26 nutrients availability) and “top-down” (e.g., grazing) processes. Over the past three decades, satellite
27 ocean color measurements make it possible to estimate phytoplankton biomass (Behrenfeld *et al.*, 2005)
28 proxied by chlorophyll-a concentration (Huot *et al.*, 2007). This, in turn, has enabled the study of
29 phytoplankton phenology (i.e. the temporal succession of main biological events) (Longhurst, 2007;
30 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_ BGC_L4_MY_009_104, Satellite observations	EU Copernicus Marine Service Product (2024)	Quality Information Document (QUID): Garnesson <i>et al.</i> (2025) Product User Manual (PUM): Colella et 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.

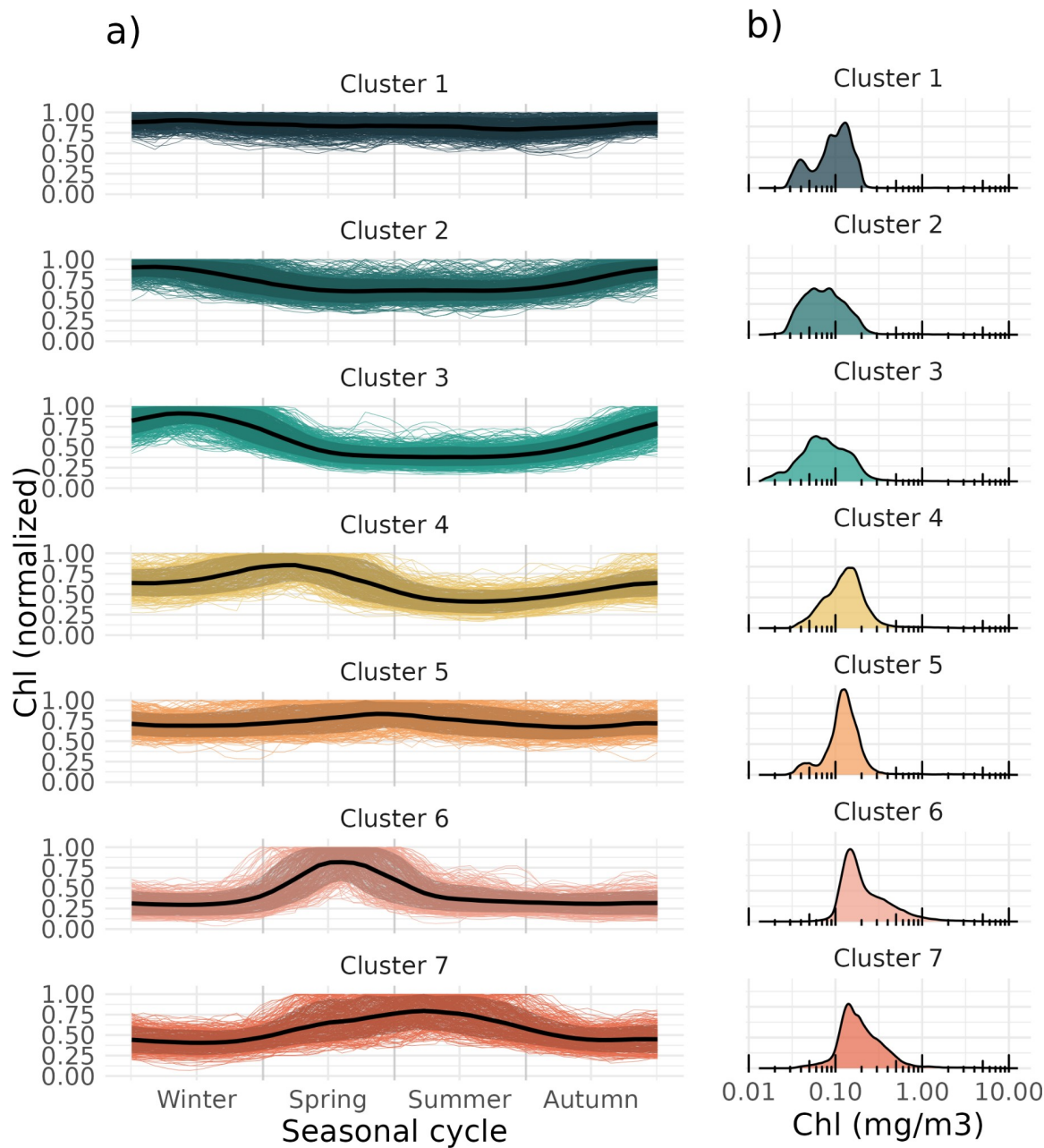
138 To assess phytoplanktonic biomass across the bioregions, we analyzed their chlorophyll-a
139 concentrations, presented as probability distribution functions in Fig. 1b. The distribution for bioregion 1
140 is notably bimodal, showing a minor peak near 0.03 mg.m^{-3} and a dominant one just above 0.1 mg.m^{-3} .
141 This finding prompted us to subdivide bioregion 1, after the clustering, based on a threshold of 0.06
142 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

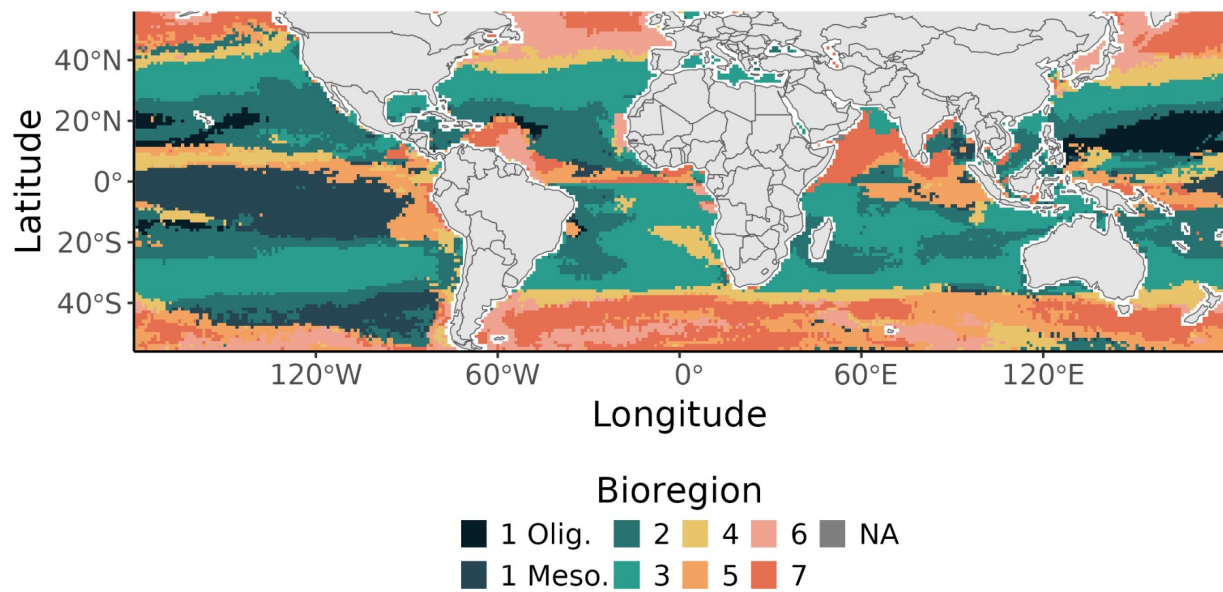
167 **distribution of chlorophyll concentration within each cluster.**

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

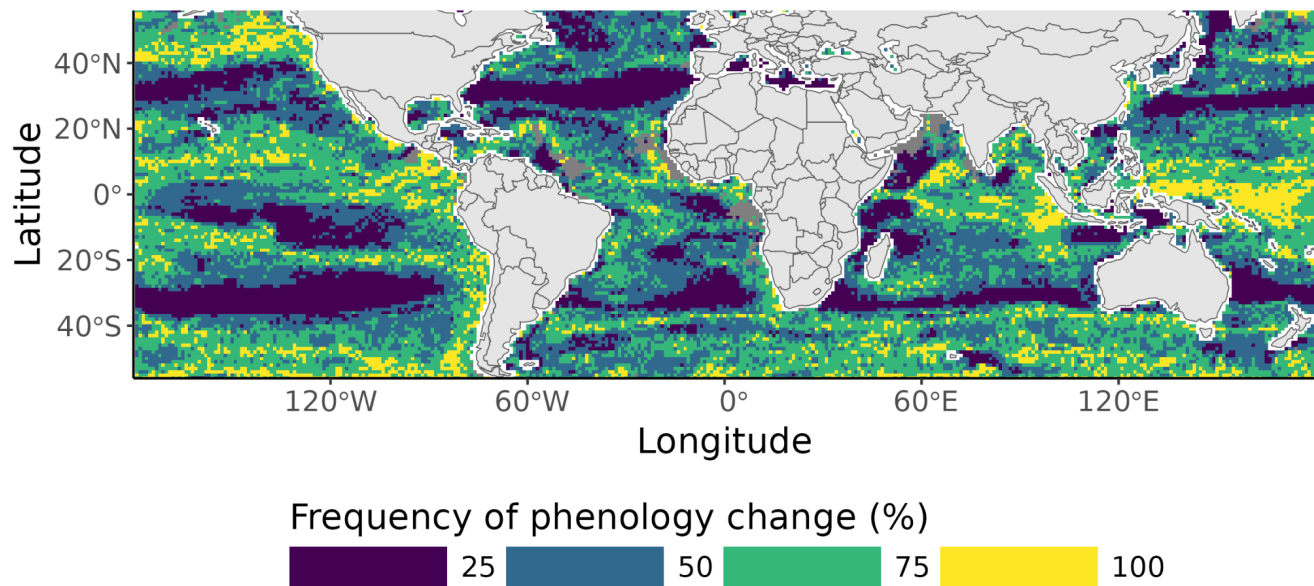


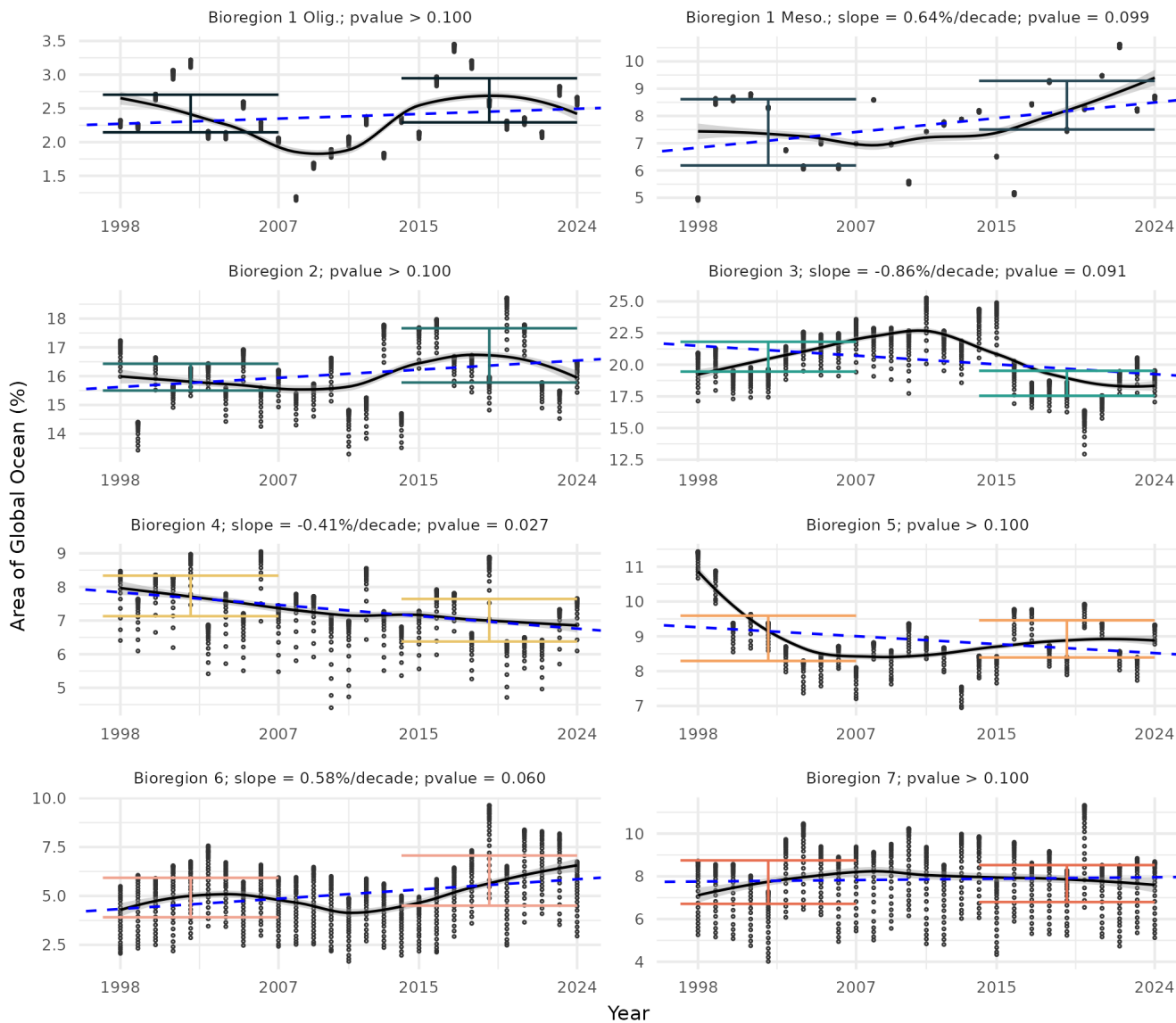
Figure 2: (a) Climatological distribution of the bioregions in the 1998-2024 period. (b) Amount of phenology change per pixel over the 1998-2024 period given in % of the total number of considered years. Both panels display the results obtained using the least strict clustering criteria on the ensemble 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**

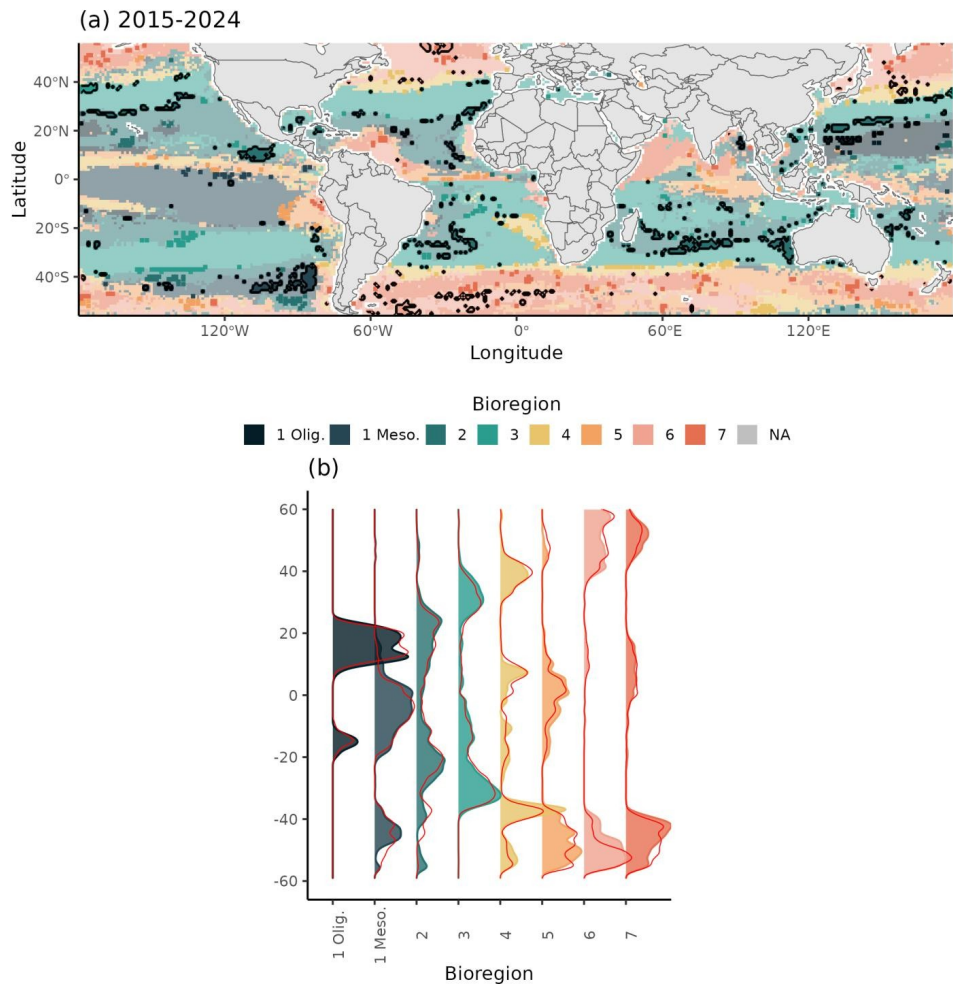
199 The boundaries of bioregions in Fig. 2a are not static. Fig. 2b displays the frequency of changes in each
200 pixel bioregion's affiliation, interpreted as changes in phytoplankton phenology, over the 1998–2024
201 period. These changes occur most frequently in transitional areas in-between major 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)**To isolate long-term trends from interannual variability, we identified areas with
224 stable phenological changes between the 1998–2007 and 2015–2024 decadal periods. As highlighted in
225 Fig. 4a, these regions are mostly located within the tropical and subtropical band. Overall 4.93% [4.56%,
226 5.06%] of the global ocean is affected suggesting slow transitions in essentially steady conditions. The
227 dominant pathways in phenology transition are summarized in Table 2. The most prominent change
228 (1.82% of the global ocean) is the transition from bioregion 3 to the less seasonal bioregion 2, occurring
229 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.	-	0.12 % [0.12, 0.12]	0.01% [0.01, 0.01]	0.03 % [0.03, 0.03]	-	0.16 % [0.16, 0.16]
	2 to 1 Meso.	0.03 % [0.03, 0.03]	-	0.36 % [0.36, 0.36]	0.07% [0.07, 0.07]	-	0.46 % [0.46, 0.46]
	3 to 2	0.67 % [0.66, 0.67]	0.55% [0.52, 0.55]	0.15 % [0.15, 0.15]	0.19 % [0.18, 0.19]	0.21 % [0.21, 0.21]	1.82 % [1.78, 1.83]
	4 to 3	0.01 % [0.01, 0.01]	0.16 % [0.14, 0.16]	0.02 % [0.01, 0.02]	0.02 % [0.02, 0.02]	0.06 % [0.06, 0.06]	0.27 % [0.24, 0.27]
	6 to 7	-	0.03 % [0.02, 0.06]	0.02 % [0.01, 0.02]	0.08 % [0.03, 0.10]	0.01 % [0.001, 0.10]	0.13 % [0.06, 0.19]
	7 to 6	0.01% [0.01, 0.01]	0.01% [0.01, 0.02]	-	0.17 % [0.13, 0.19]	0.23 % [0.19, 0.24]	0.43 % [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 bioregion 4 to 3, bioregion 3 to 2, and 2 to 1) identified above, are possibly driven by an intensification of upper-ocean stratification in relation to climate warming (Capotondi *et al.*, 2012). At these low latitudes (30°S-30°N), a shallower vertical mixing prevents entrainment of deeper nutrients (Vereshchaka and

250 Shatravin, 2025) therefore hindering biomass accumulation of surface waters (Sarmiento *et al.*, 2004;
251 Polovina *et al.*, 2008). The robustness of our ocean indicator approach is further validated in the
252 temperate North Atlantic, where despite high method uncertainties, the documented shift from a double
253 to a single bloom phenology (bioregion 7 to 6) linked to delayed autumnal mixing in Martinez *et al.*
254 (2011) is successfully captured. The documented changes also echo the variations of micronekton
255 habitats provinces monitored from sea surface temperature, stratification index and net primary
256 production evolution in Albernhe *et al.* (2025).

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

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

279 Future work could integrate Global ocean hindcast, to overcome the limitations of remotely sensed ocean
280 color and extend monitoring to regions with poor satellite coverage (10.48670/moi-00019) and other four
281 dimensional products (10.48670/moi-00046) to account for in-depth process. Earth system models can
282 also help predict future states according to climatic projections (Yamaguchi *et al.*, 2022; Fisher *et al.*,
283 2025). The partitioning could also be refined by incorporating additional variables (e.g., the particulate
284 backscattering coefficient) to better delineate bioregions. However, the current method's simplicity

285 remains its main asset, ensuring a broad application range, ease of use, and making it an ideal candidate
286 for immediate operational implementation.

287 **Data availability**

288 Ocean color data were collected from the OCEANCOLOUR_GLO_BGC_L4_MY_009_104 product, provided
289 by the Copernicus Marine Environment Monitoring Service (CMEMS, <http://marine.copernicus.eu/>).
290 Cluster centroids resulting from Baudena *et al.* (2025) were obtained directly from the author.

291 **Author Contribution CRediT**

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

297 **Competing Interests**

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

300 **Acknowledgement**

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

308
309 **Financial Support**

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

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