

RC1 :

Summary

The authors of this work introduce a new ocean monitoring indicator to track the temporal evolution of seven marine bioregions—characterized by similar phytoplankton biomass seasonality—using satellite chlorophyll-a data from 1998 to 2024. They observe a long-term poleward shift of less seasonal phytoplankton patterns, linked to climate change. This approach offers insights into how marine ecosystems are adapting over time.

General comments

I acknowledge the substantial work and the effort made to synthesise complex information. The analysis conducted by the authors is robust, and the results obtained are meaningful. I believe that the proposed indicator could provide added value to the set of indicators currently available in the Copernicus Marine Service Catalogue. I also appreciate the effort to estimate a form of associated uncertainty, as well as the discussion of the indicator's limitations and its potential for further integration with other products. I recommend minor revisions before the publication in Ocean State Report 10. In particular, since the present paper is an extension of a companion study (i.e., Baudena et al., 2025), I suggest briefly recalling some key concepts from that work and making more explicit the differences between the two studies. In addition, I recommend improving the presentation of the results, both in the main text and in some figures and their captions. These issues, along with other minor points, are addressed in the Specific Comments section below. Finally, although I am not a native English speaker, I believe the manuscript could benefit from a language revision to improve clarity and fluency.

We sincerely thank the reviewer for his thorough evaluation of our manuscript. The comments have greatly contributed to improving the clarity, rigor, and overall presentation of our work. We have carefully addressed each point raised and revised the manuscript accordingly. Complete re-reading and language verification have also been performed to improve the manuscript's readability and consistency. Below, we provide a detailed, point-by-point response to all comments and describe the corresponding manuscript revisions. Our responses are highlighted in blue.

Specific Comments

- Line 58: Does the term “update” refer to the climatology derived from Baudena et al. 2025? In that paper the climatology used is 1998-2022 (Figure 1 of that paper), whereas in your study you are considering 1998-2024. If so, I suggest making the different time periods explicit.

The update term does refer to the climatological period extent and to the method which was climatological in Baudena et al., 2025 and which is here at annual resolution. This paragraph was rewritten as follow:

Line 65: “We introduce here a proof of concept for such an approach using the supervised clustering method introduced in Baudena et al., 2025. Annual time series of remotely sensed chlorophyll-a seasonal concentration of one ocean color product (Copernicus-Globcolor) are sorted into bioregions that partition the global ocean (between 56°S-56°N) from 1998 to 2024.

- Line 66: “therefore compensating for the lack of observation inherent to satellite ocean color (Stock et al., 2020).” I understand the advantage of using L4 for this kind of study, but Baudena et al. 2025 use L3 satellite, along with an interpolation method. The authors declare in the Introduction that this study is an extension of Baudena et al 2025, since it is finalized to track variations in time in the extension of the bioregions, therefore I think that the choice of using L4 instead of L3 data should be (at least shortly) discussed in connection with that paper. I suppose that any possible differences are small, but I suggest clearly addressing this aspect in the text. Finally, I suggest specifying the spatial resolution of the product used.

The details were added according to the reviewers suggestion:

Line 78: “This product offers cloud free remotely sensed surface chlorophyll-a concentration at a 4 km spatial resolution and daily intervals. Using such a L4 product (an optimally interpolated, merged satellite dataset), as compared to L3 (merged product) in Baudena et al., (2025), compensates for the lack of observation inherent to satellite ocean color (Stock et al., 2020) and ensures a maximal spatialization of the bioregions at an annual temporal resolution.”

- Line 79: “within 111 km” I suggest an explicit reference to the 1° grid box mentioned in line 72.
A reference to the 1° grid box was added.
Line 96: “Coastal pixels located within 111 km (~1°) from the coast were also discarded”
- Line 97-98: Here, as in other lines of the 2.3 paragraph, the authors cite some figures they show only in Section 3. I understand that, in some cases, it can help to illustrate some specific choices adopted in the methods (as done at lines 110-116, for Figure 1b), but I suggest doing it only if it is strictly necessary. In particular, I think that the citation of Fig. 2b here can be deleted, as well as the ones at line 102 for Fig. 2a and Fig. 4a. This would also allow to cite Fig.1b as the first one in the paper, i.e., it would avoid citations of Figures that do not follow the order Fig.1, Fig.2, and so on.
References to the figures were adjusted according to this suggestion.
- Finally, I suggest formally rephrasing the sentence at 97-98 as: “The frequency of phenology change refers to the number of years within the last 26 years during which a pixel changed its assigned bioregion”.
The sentence was rephrased.
Line 123: “For a given pixel, the frequency of phenology change is defined as the total sum of these changes over the study period”.
- Line 117: In the short paragraph 2.4 authors discuss not only the uncertainties related to the clustering method, but also the approach to identify long-term changes. I suggest modifying the title of the paragraph accordingly to better reflect its content.
The paragraph title is now “Uncertainties estimation”.
- Line 129 (general comment on paragraph 3.1): Even if the seven bioregions are illustrated in detail in the companion paper, I think that it could be useful just to recall the biogeochemical interpretation of the bioregions when they are mentioned in the paragraph, as done in the

Conclusion section of Baudena et al., 2025 (e.g., bioregion 3 can be interpreted as “subtropical winter nutrient-limited”, or bioregion 4 as “bloom”). I think it could help to even more appreciate the importance of the detected cascading changes (e.g., from bioregion 4 to 3) highlighted in the Discussion and conclusion Section.

We do acknowledge the reviewer comment as the biogeochemical interpretation is of importance for the subsequent study. The oceanographic interpretation of the bioregions is now recalled in the manuscript.

Line 181: “Baudena et al. (2025) offered a biogeochemical interpretation of the bioregions, summarized as follows. Bioregions 6 and 7 correspond to Longhurst’s (1995) model 1 (polar, irradiance-limited). Bioregion 5 exhibits features of both model 1 and model 2 (mid-latitude, nutrient-limited spring production peak). Bioregion 4 closely aligns with the Bloom bioregion identified by D’Ortenzio et al. (2012). Bioregion 3 matches Longhurst’s (1995) model 3 (subtropical, winter nutrient-limited), whereas Bioregion 2 closely resembles the Tropical bioregion described by D’Ortenzio et al. (2012). Finally, Bioregion 1 corresponds to Longhurst’s model 4 (tropical). The additional subdivision introduced here produces spatially coherent domains that distinguish between oligotrophic regions in the centers of subtropical gyres and mesotrophic regions primarily distributed around the equator.”

- Lines 135-136: The citation of Fig. 2a is not clear to me here. I suggest deleting “(Fig. 2a) ,”.
The citation was deleted.
- Lines 137-138: I suggest replacing “bioregion 1” with “cluster 1” and rephrasing “to those with pronounced single or double peak events typical of blooms in temperate and high-latitude systems (bioregion 4-7)” as “to those with pronounced single or double peak events (clusters 4-7), which are typical of blooms in temperate and high-latitude system, as we found in Fig. 2a”.
The rephrasing suggestion was considered but not the substitution of “bioregion” to “cluster”. To us, the term cluster refers to the mathematical (or numerical) object dividing the ensemble of annual time series, while the term bioregion acknowledges their spatial distribution projected

onto the ocean. Hence, as this sentence refers to their latitudinal distribution, we find the term bioregion to be more adequate.

- Line 139: I suggest replacing “As demonstrated by Baudena et al. (2025)” with “In agreement with Baudena et al., 2025”.

The suggestion was accounted for.

Line 173: “In agreement with Baudena et al. (2025), the climatological distribution ...”

- Line 144 “and the highest in the high-latitude bloom regions”: please add the reference to the corresponding bioregions. Moreover, since the authors (rightly) distinguish between the oligotrophic and mesotrophic group of cluster 1, I suggest adding here (i.e., in the part of general illustration of Figure 2a) also a sentence in the text about their spatial distributions. This is a (small) difference with respect to the corresponding Figure 1 in Baudena et al., 2025 and I think that it should be at least mentioned.

This was done after the biogeochemical interpretation of the clusters.

Line 186: “ Finally, Bioregion 1 corresponds to Longhurst’s model 4 (*tropical*). Its additional subdivision, introduced here, produces spatially coherent domains that distinguish between oligotrophic regions in the centers of subtropical gyres and mesotrophic regions primarily distributed around the equator.”

- Line 154: I suggest rephrasing the first sentence as: “The boundaries of bioregions in Fig. 2a are not static” and replacing “changes of bioregions” as “changes in the bioregion of affiliation” or something similar.

The recommendations were considered.

Line 198: “The boundaries of bioregions in Fig. 2a are not static. Fig.2b displays the frequency of changes in each pixel bioregion's affiliation”

- Line 159: Since black dots in Figure 3 represent estimates of the bioregions’ areas along the years

and with varying acceptance threshold, I suggest specifying here “(time evolution of black dots)” instead of simply “(black dots)”.

The correction was added in the caption of figure 3.

- Line 161-162: Please better clarify the comment about bioregions 6 and 7, e.g., quantifying the temporal variabilities.

The sentence was changed, it now indicates that the surface area of these two bioregions visually display variations in respect of time.

Line 208: “While surface areas of bioregions 6 and 7 exhibit large changes from one year to the other, their surface area estimates are associated with large method uncertainties (~50%), precluding the consideration of the trend significance.”

- Figure 3 (plot): I suggest using “Area of Global Ocean (%)” in the label of the y axes. Moreover, to better highlight interannual variabilities, I also suggest zooming the y axis of the single panels around the dots and lines represented, instead of making it always start from zero: I think that it could help the readability of the figure (which also has many panels).

The reviewer comment was considered and Figure 3 is now “zoomed in” as mentioned in the figure caption (“Note the varying y-scale across panels”). We did consider this display prior to submission and eventually settled for the other option. Please note that the figure theme was changed to match other figures.

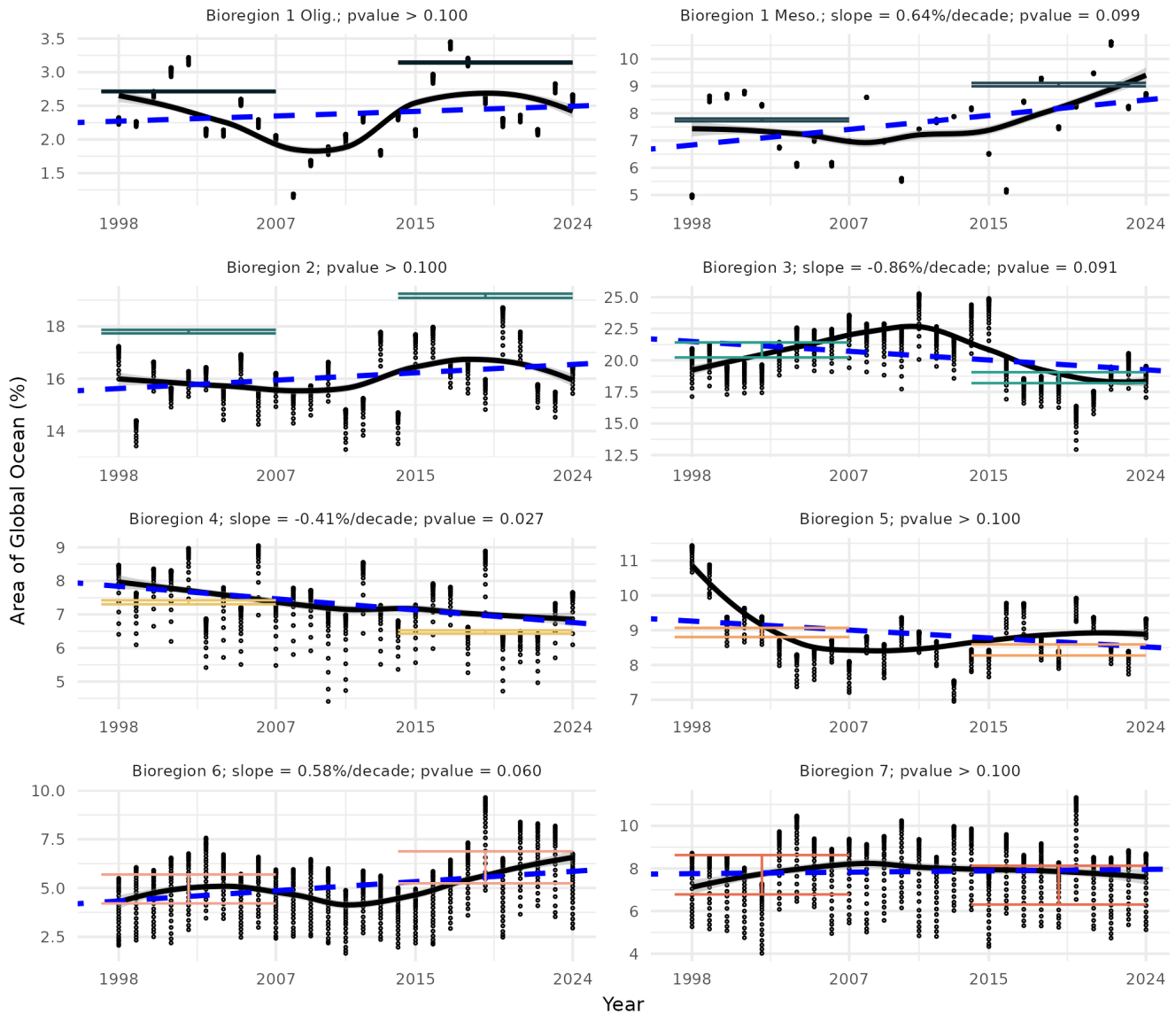


Figure 3 : Evolution of bioregions' surface area from 1998 to 2024. The time evolution of black dots represent estimates of the areas following the varying acceptance thresholds. The black trend line displays the smoothed centered 10-year rolling average, the blue dotted line corresponds to the linear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

- Line 164: I suggest using “bioregions’ surface areas” or “bioregions’ areas” instead of “bioregions’ surfaces” and “bioregion area” instead of “bioregion surface”.

The term “area” was added when necessary in the text, in the description of figure 3 and table 2. We thank the reviewer for pointing out this incomplete terminology.

- Line 168: I think that “Note the varying coordinate scale” could be ambiguous. I suggest using “Note the varying y-axis scale across panels”.

Done. Figure 3 caption: “...Note the varying y-scale across panels”

- Lines 170-172: Since here the authors are commenting Figure 4a, which is the starting point for the following considerations, I suggest moving within this (Results) section Figure 4, that is currently in the Discussion and conclusion Section. Moreover, I suggest moving here (i.e., within the Results Section) the comment to Fig. 4b which is currently in the Discussion and conclusion Section (lines 187-189). Finally, I suggest rephrasing “Stable changes... stable conditions”, as the use of the term “stable” in case of both phenological changes and “reference” conditions may cause ambiguity.

Following the reviewer comment, the figure changed section.

- Lines 180-182: Are these estimates reported as medians, along with interquartile ranges? The value for the South Atlantic Ocean is given as 0.20% within a 0.21%-0.21% range and this seems inconsistent or possibly a typo. What does the bold text indicate and why are the percentages associated with “3 to 2” in the Atlantic Ocean and in the South Pacific Ocean not in bold (they are similar to other percentages that are in bold)? I also suggest using “area” and “areas” instead of “surface” and “surfaces”, respectively, and “grouped by” instead of “divided per”.

Yes, the estimates are median within interquartile ranges. Numbers highlighted in bold indicate values greater than 0.1 % of the global ocean. This is now mentioned in the caption of Table 2. As mentioned before the term “area” was added when needed. The other corrections were considered. The value for the South Atlantic Ocean was wrongly rounded, after verification it is ~0.209 % within a 0.206%-0.212%

range, this has been corrected.

		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 as median within their first and third quartiles** and **grouped by** oceanographic basins. Minor changes, associated with **an area** inferior to 0.1% of the global ocean, are not represented. **Estimates highlighted in bold indicate values greater than 0.1 % of the global ocean.**

- Line 195: I would add here (or elsewhere in this Section) a comment on the uncertainties associated with the proposed indicator.

A sentence was added on the limitation paragraph to connect increased uncertainties at high latitude with data availability of ocean color satellites.

Line 251: “The robustness of our ocean indicator approach is further validated in the temperate North Atlantic, where despite high method uncertainties, the documented shift from a double to a single bloom

phenology (bioregion 7 to 6) linked to delayed autumnal mixing in Martinez et al. (2011) is successfully captured.”

Line 256: “First, satellite ocean color observations are sparse at high latitudes inducing increasing method uncertainties poleward and the exclusion of the subpolar and polar domains (above 60°)”.

- Line 201: I think it should be written “27-year time series” (since the time period is 1998-2024).

This was corrected.

- Line 211: Since also Global ocean hindcast is a 4D (modeling) product, I suggest “and other four dimensional products”.

The suggestion was accounted for.

- Line 217 (Figure 4): I suggest to better balance the dimensions of panel (a) and panel (b).

A new ordering and size of the panels is proposed now in Figure 4:

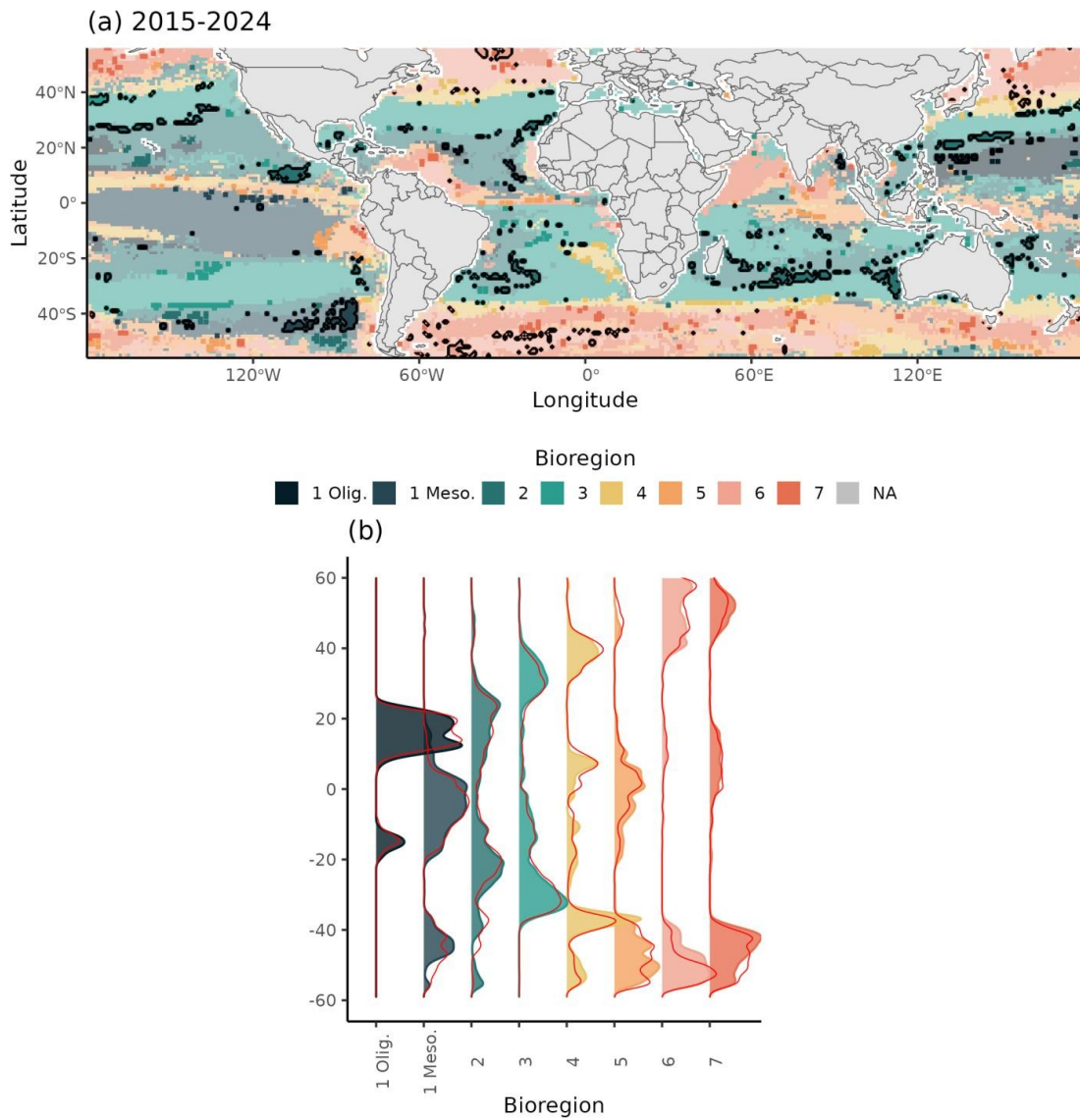


Figure 4: (a) Bioregions in the 2015-2024 decadal period with stable changes identified by black contours. (b) displays the latitudinal distribution of bioregions between the 1998-2007 decadal period, as red line, and the 2015-2024 period, with colored and filled distributions, respectively.

Technical corrections

- Lines 12-15 “While the bioregions’ extent... subtropical bands”: I suggest adding commas after “variability” and after “phenology” and replacing “are generally” with “is generally”. [ok](#)
- Line 55: I suggest using “dynamics” instead of “dynamic”. [ok](#)
- Line 61: The second time period indicated should be “2015-2024”. I also suggest that the comma be moved from before to after the parenthesis. [ok](#)
- Line 86: I suggest using “twenty-six” in place of “twenty six”. [ok](#)
- Line 100: I suggest replacing “partitioning” with “partitions”. [ok](#)
- Line 113: I suggest specifying “(below the threshold)”. [ok](#)
- Line 182: I suggest adding a comma after “less than 0.1% of the global ocean”. [ok](#)
- Lines 187-189: This sentence should be split in two. [ok](#)
- Line 208: I suggest replacing “is behaving” with “are unfolding” or something similar. [ok](#)
- Lines 218-219: I suggest replacing “identified contoured in black” with “identified by black contours” and rephrasing: “(b) Latitudinal distribution of bioregions between the 2015-2024 decadal period, filled, compared with the 1998-2007 decadal period, indicated by the red line.” [ok](#)