

We thank Reviewer #1 for the constructive and helpful comments. The manuscript has been revised accordingly, with changes aimed at clarifying the methodological role of the MEOF analysis, better justifying the use of OASIM-derived irradiance, adding the requested references, and improving figure accessibility. Point-by-point responses are provided below.

1. Scientific Content

1.1. Added Value of Multivariate EOF (MEOF) Analysis

The authors successfully explain the spatial and temporal dynamics of primary production (PP) using EOF analysis, which helps identify the physical and/or biological drivers of PP variability in the Mediterranean. However, the specific added value of the Multivariate EOF (MEOF) approach compared to univariate EOF analyses is not clearly demonstrated.

Author's reply: *We have revised Section 2.5 to explicitly state that univariate EOFs and MEOFs optimize different variance structures: univariate EOFs describe the dominant variability of each individual field, whereas MEOF modes identify the variability shared by the combined standardized dataset. Accordingly, similarities between univariate EOFs and MEOFs are now discussed only in terms of consistency among variability patterns, and not as evidence of a one-to-one correspondence between modes of the same order. The MEOF analysis is instead used as the formal basis for defining coupled basin-scale modes. We also revised the wording in the MEOF section to avoid implying a direct correspondence between individual EOF modes and MEOF modes.*

1.2. Use of the OASIM Model for PAR

The authors use the OASIM model to estimate PAR, while satellite data are available. Suggestions:

- Justify the choice of OASIM over satellite data (e.g., longer temporal coverage, higher resolution, specific bias corrections).
- Indicate, in the manuscript, that OASIM description is given in the appendix.
- Add a sentence indicating that further details on primary production calculations (including the use of OASIM) are provided in the appendix.

Author's reply: *The choice was mainly driven by the need for consistency with the primary production model, which is wavelength-resolved and requires spectral direct and diffuse irradiance to compute light absorption, scattering and propagation through the water column. Standard satellite PAR products provide an integrated 400–700 nm surface quantity, whereas OASIM provides the spectral irradiance used directly in the PP calculation. In addition, OASIM ensures a homogeneous radiative forcing over the full 27-year period, avoiding potential discontinuities associated with merging PAR estimates from different satellite sensors. The Mediterranean implementation of OASIM has also been evaluated with good results against independent in situ radiometric observations (Lazzari et al., 2021). We have added a short clarification in the Methods section and explicitly indicated that further details on the PP calculation, including the use of OASIM, are provided in Appendix A*

1.3. Missing References

- Nutrient concentration and primary production: The authors should cite Cossarini et al. (2020) to support their discussion on the impact of nutrients on primary production in the Mediterranean.

Author's reply: *We have added Cossarini et al. (2020) to support the discussion on Mediterranean primary production patterns in the Copernicus Marine framework. We have*

also included Reale et al. (2020), co-authored by Cossarini, to strengthen the mechanistic interpretation of the role of nutrient availability, mixed-layer dynamics and atmospheric forcing in productive and convective Mediterranean regions. The revised text now explicitly links enhanced PP variability in river-influenced and convective areas to nutrient supply from river inputs, lateral advection and winter mixing.

- Tropical-like behavior (line 1332): A reference supporting this behavior in the Mediterranean would strengthen the argument.

Author's reply: sentence has been revised as detailed below.

- Competitiveness of larger cells in high-mixing areas (line 1395): Please add a reference to support this statement (e.g., Margalef, 1978, or more recent work on phytoplankton cell size theory).

Author's reply: We have added references to both the classical Margalef framework and more recent trait-based phytoplankton size theory to support the statement that larger cells are generally favored under nutrient-rich and turbulent/mixed conditions. The sentence has been rephrased to make the interpretation more explicit and less assertive.

1.4. Clarifications Needed

Line 1332: the authors mention a “tropical-like behavior,” please clarify if this behavior has already been observed in the Mediterranean, if this is expected and what the implications are for the Mediterranean.

Author's reply: In the revised manuscript, we have removed the statement referring to a “tropical-like behavior”. This revision is consistent with our more cautious interpretation of the second PAR EOF mode: since this mode explains only a very small fraction of the total variance, it cannot be robustly used to support the interpretation of the second mode as a deep-convection/spring-bloom signal. We therefore no longer interpret this PAR mode in terms of a Mediterranean analogue of tropical PAR dipole variability, and the discussion of the second mode is now based primarily on the coherent MLD, CHL and PP patterns.

2. Form and Accessibility

2.1. Figure Accessibility

- Figures should be made accessible to visually impaired readers. This includes:
- Adding detailed captions describing the main content and trends.
- Using appropriate colorpalette for colorblind person.

Author's reply: DONE

We thank Reviewer #2 for the careful re-reading of the manuscript and for the constructive methodological comments. We have addressed all the reviewer's comments and concerns. In particular, we re-ran the EOF and MEOF analyses after consistently masking the main Case II water regions (Po, Nile and Gabès) from the entire dataset, and we revised all figures using colourblind-friendly palettes. We also clarified the role of the univariate and multivariate EOF approaches, specified the treatment of PSC in the MEOF analysis, and revised the text where needed to improve clarity and address the reviewer's concerns. Detailed point-by-point responses are provided below.

One main methodological concern remains. I continue to struggle with the interpretation of how correlated the univariate EOF modes are. To me, mode ordering is not inherently comparable across variables, and Sections 3.2.1 and 3.2.2 appear more as descriptions of statistical diagnostics. From this perspective, I find the addition of the MEOF method adequate, as it allows, more rigorously than intuitively, to highlight the structural coupling between variables. While I do agree with the authors' description and interpretation of the MEOF modes and their coupling, I still fail to see how they support or correlate with the univariate EOFs. Most of my specific comments below support this observation. I think that a manuscript rearrangement, such as inverting the subsection ordering within Section 3 (MEOF before EOF), would be sufficient to highlight the statistical derivation of the basin's modes.

Author's reply: *We agree with the reviewer that the ordering of univariate EOF modes is not necessarily comparable across variables. We also agree that the distinction between the roles of the univariate and multivariate approaches needed to be made clearer and linked to the general paper objectives. We have therefore revised Section 2.5 to explicitly state that univariate EOFs and MEOFs optimize different variance structures: univariate EOFs describe the dominant variability of each individual field, whereas MEOF modes identify the variability shared by the combined standardized dataset. Accordingly, similarities between univariate EOFs and MEOFs are now discussed only in terms of consistency among variability patterns, and not as evidence of a one-to-one correspondence between modes of the same order. The MEOF analysis is instead used as the formal basis for defining coupled basin-scale modes. We also revised the wording in the MEOF section to avoid implying a direct correspondence between individual EOF modes and MEOF modes. We kept the current subsection order because the univariate EOFs first provide a variable-specific diagnosis of the dominant variability, while the subsequent MEOF section synthesizes these patterns into formally coupled multivariate modes.*

Specific comments

line 150: *However, these areas represent a small fraction of the Mediterranean basin. Small in surface area yes but are they small in terms of productivity? Furthermore, their small surface area might result in them having a smaller weight in the statistical methods (EOF/MEOF). However, in the end, they might have their own modes of variability, decoupled from the entire basin modes. This observation is reinforced by looking at Fig. 3e, where PP is masked in some coastal areas.*

Author's reply: *As mentioned in the general comment, we have masked out the three most relevant sites in terms of Case 2 water persistence: the Po river, the Nile river mouth and the Gulf of Gabès. Afterwards, we have re-computed the EOF and MEOF analyses. Results do not significantly change, substantially supporting the idea that the basin scale variability is not affected by these three spots. We have updated the figures with the last analyses.*

The author raises the inclusion of mesoscale structure to contextualize the choice of spatial dimension. I agree that the 4×4 km size is well suited to capture mesoscale structure in the Mediterranean Sea, but I wonder how the one-month period compares to the temporal scale of mesoscale structure (e.g., movement, dissipation, etc.).

Author's reply: *Reviewer is right. We changed the sentence to explicitly refer to numerous permanent or semi-permanent mesoscale features.*

line 174: Are PSC considered in the MEOF, or only Chl, SST, MLD, and PAR?

Author's reply: *Given the PSC strong dependence on Chl we deemed not necessary to include PSC in the MEOF analysis. We added a sentence in par 2.5 to clarify this point.*

Figures: I found the usage of the same jet palette for all figures confusing, especially in the interpretation of the spatial variability of the modes. I suggest keeping the jet palette for the mean states (Figures 1 and 2) and using a diverging colormap centered on 0 (e.g., red-white at 0 and blue) for the mode variability (Figures 3, 5, 7, and 8).

Author's reply: *Palettes are changed using colourblind friendly colorbar. Following the reviewer suggestion, we used a blue-white-red palette for figures 3, 5, 7 and 8.*

Figure 3 caption: I feel that a reminder of what positive/neutral/negative variability means would help better correlate the visible spatial patterns with the identified modes. For instance, in Figure 3, it is stated that small variability (~ 0) indicates areas in opposition of phase with the mode and are removed (e.g., white areas). Meanwhile, in Figures 7a–b, the MLD and Chl variability are described as negative, revealing that they are *in anti-phase with the seasonal solar-thermal forcing embedded in the temporal amplitude* (i.e., the 1st MEOF mode).

Author's reply: *Since case 2 areas were masked out in the analysis (not only for graphical purpose as it was in the previous version), that sentence is no longer needed and has been removed. In section 2.5 we added a few sentences with caveats to better interpret EOF results.*

Section 3.2.1 / 3.2.2: Line 253 / 352: The first mode is presented as the classical annual cycle of the basin, and the second mode as deep water formation and spring bloom variability. I wonder what makes the latter, especially the second modes for Chl and PP, not equally specific as an "annual" or "seasonal" cycle dominant in a specific region (e.g., the Gulf of Lion area). I acknowledge that this mode also presents stronger interannual variability, as well depicted by the authors, particularly for MLD.

Author's reply: *What makes the first mode to be associated with the annual cycle is that the basin is spatially in phase (all positive values) whose variability is shaped by the temporal amplitude. On the other hand, what makes the second mode (in particular Chl and PP) to be associated with the spring bloom dynamics at regional scale is that the basin presents highly positive values (for both Chl and PP) in the area of the Gulf of Lion while the rest of the basin is characterized by very low (close to zero) values. In the spatial pattern, the only area in which a significant, noteworthy signal can be appreciated is the Gulf of Lion. Moreover, the temporal signal is clearly associated with the dynamics of the spring bloom, with lows in the winter (associated with the formation of deep water) and highs in spring. We think this is fully explained in the current version of the main text that therefore does not need any amendments.*

Section 3.2.1 / 3.2.2 titles: Line 253 / 352: *Annual variability (1st mode)* and *Deep-water formation and spring bloom variability (2nd mode)*. I find the usage of the word "mode" to characterize the two main regimes of the Mediterranean Sea confusing and premature at this stage. These sections appear to be more of a presentation of statistical diagnostics, with the modes (or regimes) of the basin being highlighted later with the MEOF.

Author's reply: *Our original intention was only to provide concise interpretative titles summarizing the main variability patterns discussed in each subsection. To avoid confusion and to better distinguish the univariate EOF diagnostics from the multivariate modes, we have removed "mode" from the subsection titles.*

From line 256: Based on this observation :*The variability of these areas is low as compared to the rest of the fields and the uncertainty associated with satellite retrievals in shallow waters are known to be substantially larger than open waters (Volpe et al., 2012; Volpe et al., 2019; Brando et al., 2024).* I would expect all these regions to be masked consistently through the study at least for the related variables.

Author's reply: *As already stated, in the previous version these areas were only graphically masked out to improve the figure readability. In this new version the three case 2 water areas (Po, Nile, Gabès) were consistently masked out from the entire dataset also for the analysis. Results do not substantially change thus proving the three areas not to be relevant for the basin overall variability. This sentence was removed as from section 3.2.1.*

line 270: *The combination of the spatial pattern and of the temporal evolution points to winter deep-water formation in the Gulf of Lion, whose interannual variability is further isolated in the second EOF mode.*

This comment, which points to the first mode of the MLD, also refers to the 2nd mode of the basin. Is the first mode of MLD also linked to winter deep water formation, or just the second one

Author's reply: *The sentence has been rephrased as "The combination of the spatial pattern and temporal evolution indicates that the first MLD mode primarily represents the dominant basin-scale seasonal cycle of winter mixed-layer deepening, with the largest amplitude in the Gulf of Lion."*

line 334: *It is worth mentioning that nearly the total variability of light (98%) and temperature (97%) is linked to the annual cycle while there is still a substantial part of variability to be explained for MLD, CHL and PP.*

I still fail to see why the 2nd modes of PAR and SST are worth considering in the second mode of the basin, as they are statistically weak. For SST, I find it interesting that this mode aligns with Volpe (2012). For PAR (from line 380), the authors suggest a possible physical interpretation related to the modulation of cloud coverage, which I personally find interesting. However, I think the possibility that this mode is just noise remains high. I also fail to see why this second mode, interpreted as cloud presence, would be related to deep water formation and spring bloom (the 2nd mode of the basin).

Author's reply: *We share the reviewer concern and have rephrased the PAR section as "The second EOF mode of PAR (Figure 5.c) explains only 0.6% of the total variance, confirming that PAR variability is largely dominated by the annual cycle. Its spatial pattern shows a weak dipole-like structure between the northwestern Mediterranean and the Levantine sub-basin. This residual signal may partly reflect non-seasonal modulation of cloud cover and surface shortwave radiation by atmospheric circulation patterns, but its physical interpretation remains uncertain and a contribution from noise cannot be excluded.*

Therefore, the second mode of PAR is not considered a robust component of the deep-water formation and spring bloom mechanism discussed in this section.”

line 440: I fail to see how the MEOF 2nd mode captures the interannual modulation of the MLD, which was raised beforehand as the main difference between the MLD 1st and 2nd modes.

Author’s reply: *We have addressed this issue by removing the reference to deep-water formation from the description of MLD EOF1.*

Technical corrections

Line 8, 86: There is an inconsistency between PSC which refers to PHYtoplankton Size Class and Phytoplankton Size Structure (line 8-38 and 86).

Author’s reply: *Done*

Line 7-8: I would recommend specifying surface phytoplankton biomass and integrated primary production.

Author’s reply: *Done*

Line 25 and 36-37: From the GOOS, phytoplankton biomass and diversity are the *EOV* (or *subvariable of the EOV*) while productivity is a *derived product* and physical drivers are *supporting variables*. (<https://goosocean.org/what-we-do/framework/essential-ocean-variables/>)

Author’s reply: *Productivity has been deleted in this sentence*

line 87: I suggest mentioning that CHL comes from satellites (e.g. . *CHL fields are derived from a multi-sensor, gap-free Level-4 satellite product specifically developed for the Mediterranean Sea ...*) as it is for SST later on.

Author’s reply: *Both sentences are changed including “satellite”.*

line 174: multi variate EOF (MEOF)

Author’s reply: *Done*

Figure A1, A2: the x and y labels might be reversed.

Author’s reply: *Done*