

Response to Reviewer #4

Dear Reviewer #4, thank you for reading and suggesting modifications to our manuscript entitled “Establishing a Monitoring Approach for Marine Heatwaves in the Black and Mediterranean Seas”.

We believe that your review has helped to substantially improve the revised manuscript. The changes in the manuscript have been highlighted in red. Additionally, please find below a list with our point-by-point answers (*in italic*) to your comments and suggestions.

Review of the manuscript sp-2025-6 “Establishing a Monitoring Approach for Marine Heatwaves in the Black and Mediterranean Seas” by Lima et al. (December 2025)

This manuscript provides a comprehensive description and analysis of MHWs from surface to 40m depth in the Mediterranean and Black Seas. MHWs propagate in depth making the development and implementation of the proposed indicators relevant. While MHWs in the Mediterranean have been studied in the last years, results in the Black Sea are novels.

The manuscript is very well-written. The study and results are relevant for the scientific community, as well as for society given the needs of adaptation to face the multiple climate-change impacts. However, some information is missing and clarifications are needed. I would recommend the publication of the manuscript after revisions, in particular, clarifications and justifications required for methodology. Please, find the comments below.

General scope

- **Novelty of the study.** The authors should better highlight the novelty for the Mediterranean Sea. Indeed, SST and OHC within 0-40m have been already addressed in Dayan et al., 2023. In addition, recent studies have analysed subsurface MHWs in the Mediterranean (Juza et al., 2022; Dayan et al., 2023; Martinez et al., 2023; Pirro et al., 2024) addressing deeper layers for some of them. Maybe, the use of multiple products could be better highlighted as novelty. Finally, comparisons or similarities between the two basins could be addressed in terms of drivers, mechanisms, impacts if relevant.

We thank the reviewer for the suggestion. Building on previous work (e.g., Dayan et al., 2022, 2023), our study uses an updated reference climatology and applies a consistent multi-dataset monitoring framework to both the Mediterranean and Black Seas. This includes an uncertainty assessment of key MHW metrics and integrates indicators for MHW based on SST and upper-OHC to jointly assess surface and subsurface expressions of MHWs. While multiple observational and reanalysis products have been used previously for the Mediterranean, the consistent application across both basins and the resulting comparison of historical MHW characteristics represent the main novelty of our study. These aspects are now more clearly highlighted in the revised manuscript (lines 96-109).

- **MHW in subsurface.** The authors could better highlight the importance of monitoring subsurface MHW. Developing such related indicators are essential to face socio-economic and environmental challenges in the context of accelerated climate change.

We thank the reviewer for the suggestion. In our study, we monitor subsurface MHWs in the upper 0–40 m, which includes the biologically productive epipelagic zone and the upper mixed layer. Indicators for MHW based on SST and upper-OHC allow us to jointly assess surface and subsurface expressions, providing insights for ecosystem management and early warning systems. Monitoring subsurface MHWs helps anticipate thermal stress on sensitive habitats, aquaculture sites, or commercial fisheries before it becomes apparent at the surface. These points are mentioned in the Introduction (lines 96-100) and are now more clearly highlighted in the revised manuscript, including in the Conclusions (lines 587-593).

Methodology

- **Indicators.** The authors propose OHC within the upper layer 0-40m. They should explain why in the introduction (not in the last sentence of the manuscript). Why this layer, specifically? Why OHC rather than temperature at 40m? Why not deeper? What about OHC within the mixed layer? I would need some justifications in the introduction and in the discussion. Given the seasonal variability of the mixed layer and stratification, would seasonal metrics be relevant? Could the authors provide seasonal indicators and have (at least) a discussion about this aspect?

We thank the reviewer for this suggestion. We focus on OHC integrated over the upper 0-40 m layer, which encompasses the biologically productive epipelagic zone and the upper mixed layer in both the Mediterranean and Black Seas. This depth range is particularly relevant for ecology and coastal management, as it includes the main habitat of commercially important species and most aquaculture operations, where organisms are directly exposed to heat anomalies (Granata et al., 2010; Cheminée et al., 2021; Macias et al., 2019; Nenciu et al., 2023). Support for this choice has now been included in the Introduction and the Methodology section of the revised manuscript.

We apply the Hobday et al. (2016) framework directly to OHC over 0–40 m rather than using temperature at a single depth because many marine species move vertically during the day, and choosing a single fixed depth would limit the monitoring of upper-ocean MHW events that could affect organisms in the biologically productive epipelagic zone.

From a physical perspective, the mixed layer depth (MLD) in the Mediterranean Sea is typically much shallower than 40 m, particularly between spring and autumn and during surface MHWs (Houpert et al., 2015; Darmaraki et al., 2025). Therefore, the 0-40 m range captures upper-ocean events that are not reflected by surface-only monitoring (Juza et al., 2022; Dayan et al., 2023). We further explore this assumption during winter, when the MLD can extend beyond 40 m. While seasonal variability of the mixed layer and stratification is important, we focus here on the integrated 0-40 m layer; seasonal SST–OHC correlation maps are provided in the revised manuscript (Figures 1y–1ad) to illustrate region- and season-dependent variability, as explained below.

We extended part of the original annual analyses to include season-specific assessments. MHWs are now analyzed separately for winter and summer, and we added correlations between MHW metrics derived from SST and OHC for each season (Figures 1y–1ad). In addition, we performed the same analyses previously conducted using annual MHW metrics separately for summer and

winter, including the calculation of discrepancies between the regional and global reanalyses relative to the SST-L4 product (Table 2).

These additions strengthen the proposed monitoring framework by explicitly accounting for seasonal variability in MHW characteristics and impacts.

- **Climatology.** Explanations about the reference period 1993-2022 for climatology are needed. It seems to me that the last recommendation at international and OSR levels is the use of the longest period available. Do not the datasets start earlier than 1993? In any case, please, justify your choice.

We recognize that the choice of the climatological reference period for detecting MHWs is a key methodological decision. We also acknowledge that recent discussions within the Ocean State Report (OSR) community recommend using the longest period available to construct climatologies. In this study, the reference period was set to 1993–2022 because the Black Sea reanalysis starts in 1993. To ensure methodological consistency across all variables and analyses, the same reference period was adopted for the detection of MHW throughout the study.

- **Metrics.** MHW mean and maximum intensities are more usually provided above the mean climatology rather than above the threshold. It would facilitate the intercomparisons with others studies. Concerning the spread, could you better explain this metric in the methodology?

Regarding the spread, MHW metrics were first computed independently for each product. The spread was then estimated as the standard deviation across products for each metric. The ensemble spread is defined in Table 1 in the revised manuscript.

- **Model validation.** Providing percentages of error would facilitate the quantification in model assessment. Also, could you explain why you process model assessment. To justify their use in OHC-MHW metrics and/or in uncertainties?

We have now included the errors expressed as percentage discrepancy in Table 2, and the definition of percentage discrepancy has been added to Table 1.

We emphasize that this is not a full model assessment. The comparison is performed to assess the accuracy of the global and regional reanalyses at the level of MHW metrics (duration, number, and intensity), based on differences with respect to the SST-L4 product.

An analogous analysis is not carried out for OHC due to the lack of high-resolution gridded three-dimensional objective analyses from which MHW-related metrics could be estimated in a similar manner, providing an observation-based reference for uncertainty assessment.

Results and discussion

- **Key findings.** The subsections are a bit long. It would be strongly appreciated to add concise outcomes/conclusions at the end of each of them.

We agree with the reviewer's suggestion. To improve clarity and readability, we have added one or two (or more) plain-language sentences at the end of each relevant section of the manuscript to emphasize the key findings and clearly state what the results mean for the reader.

- **Gulf of Lion.** It is a place of deep convection (sometimes bottom sea convection), so it would be an interesting region to add in section 3.3.2.

In this study, the South Adriatic Pit region was selected based on the Ocean Monitoring Indicator (OMI) framework published within the Copernicus OSR. In particular, the OSR2 (Simoncelli and Pinardi, 2018), evaluates Mediterranean water mass formation rates in four reference areas, including the Adriatic and Gulf of Lion regions, providing a well-established and consistent basis for our regional analysis.

We agree that the Gulf of Lion, as a region of deep convection, would be an interesting area to compare surface and subsurface MHW. However, this analysis was not conducted in the present study due to space limitations and in order to better align with the scope and requirements of the OSR framework. We now clarify in the manuscript that the winter MHW analysis performed in the Adriatic can be extended to other deep convection regions, such as the Gulf of Lion, in future work.

- **Methodology sensitivity.** It could be discussed (choice of the climatology, datasets, seasonal vs annual metrics etc).

Regarding methodology sensitivity, the Black Sea reanalysis used in this study starts in 1993. To ensure consistency across regions and datasets, we adopted 1993 as the common starting year for the climatology and MHW detection in both the Mediterranean and Black Seas.

To account for the region- and season-dependent nature of the SST–OHC relationship, we now provide seasonal SST–OHC correlation maps (see new Figures 1y–1ad), which are discussed in the revised manuscript with emphasis on the mechanisms controlling SST and OHC variability and their dependence on stratification and seasonal conditions. Additionally, percentage discrepancies between MHW metrics derived from the reanalysis SST and those computed from the SST-L4 products are provided in Table 2

- **Conclusions.** Environmental and socio-economic impacts of the main findings are missing. Also, based on the results, some recommendations in terms of observing systems would be really appreciated. It is essential to improve our knowledge and forecasting systems in order to better support the adaptation of our societies.

In the revised manuscript, the last paragraph of the Conclusions emphasizes the importance of detecting both surface and subsurface MHWs (0–40 m) to monitor thermal extremes within the biologically productive upper epipelagic zone, which supports key ecological functions and socio-economic activities. Incorporating subsurface indicators provides valuable insights for ecosystem management and early warning systems, while monitoring OHC-based heat anomalies can help anticipate thermal stress on sensitive habitats, aquaculture sites, or commercial fisheries before it becomes apparent at the surface.

Future studies are suggested to explore region-specific depth thresholds that account for local oceanographic dynamics and ecological sensitivities.

Figures

- **Figure 1.** I would replace “Number” by “Frequency”, and “Intensity” by “Maximum intensity”. Units should be in the legend or subtitles of the figure.
- **Figures 4 and 5.** These figures have a very low quality. They should be improved.

We thank the reviewer for the suggestions regarding the figures. Figure 1 has been updated to replace “Number” with “Frequency” and “Intensity” with “Maximum intensity,” and the units have been added to the legend. Figures 4 and 5 have been improved to enhance their quality and readability in accordance with your recommendations.

Suggestions for additional references (subsurface MHWs)

- Zhang, Y., Du, Y., Feng, M., & Hobday, A. J. (2023). Vertical structures of marine heatwaves. *Nat. Commun.*, 14(1), 6483. doi: 10.1038/s41467-023-42219
- Juza, M., Fernández-Mora, À., & Tintoré, J. (2022). Sub-Regional Marine Heat Waves in the Mediterranean Sea From Observations: Long-Term Surface Changes, Sub-Surface and Coastal Responses. *Front. Mar. Sci.*, 9, 785771. doi:10.3389/fmars.2022.785771
- Pirro, A., Martellucci, R., Gallo, A., Kubin, E., Mauri, E., Juza, M., et al. (2024). Subsurface warming derived from Argo floats during the 2022 Mediterranean marine heat wave. of the Copernicus Ocean State Report (OSR8), edited by: von Schuckmann, K., Moreira, L., Grégoire, M., Marcos, M., Staneva, J., Brasseur, P., Garric, G., Lionello, P., Karstensen, J., and Neukermans, G., Copernicus Publications, State Planet. doi:10.5194/sp-4-osr8-18-2024

Thank you for the suggested references. We included Juza et al. (2022) because it directly relates to the seasonal patterns in our correlation analysis (lines 317-319).

References

Simoncelli, S. and Pinardi, N. 2018. Water mass formation processes in the Mediterranean sea over the past 30 years. In: Copernicus Marine Service Ocean State Report, Issue 2, Journal of Operational Oceanography, 11:sup1, s13–s16, DOI: 10.1080/1755876X.2018.1489208.