

Response to Reviewer #3

Dear Reviewer #3, 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 Establishing a monitoring approach for marine heatwaves in the Black and Mediterranean Sea by Lima et al.

The manuscript provides a useful update of MHW indicators for the Mediterranean and introduces new OHC-based diagnostics. The development of indicators for the Black Sea is timely and fills a gap in the study of MHW. The idea of combining SST and upper-ocean OHC into a potential monitoring index is promising and could be published after revision.

However, several methodological gaps and missing justifications weaken the robustness of the results.

Some aspects require clarification and particularly the seasonal dependence of events, the physical meaning of OHC-based MHWs, the calculation of climatologies, and the quantification of uncertainties.

I found some very important points :

- The use of multiple products (regional reanalyses, global reanalysis, and SST L4) even if some discussions are essential on their limitations.
- The computation of an upper-ocean OHC indicator (0–40 m) offers additional insight into the vertical structure of events, especially in the Black Sea. I would advocate for a more in-depth analysis of the propagation of surface MHW into subsurface layer.
- Regional descriptions (Sicily Channel, CIL, Rim Current, etc.) and case studies (2011–2012, 2017, 2024) are relevant and illustrate contrasting conditions.

Here are some thoughts to improve this study :

- Lack of seasonal decomposition : it is unclear whether MHW detection is performed separately for summer and winter. In my opinion, this distinction is essential because impacts differ strongly from one season to another. Impacts of MHW are the main justification of establishing a monitoring approach. In addition, upper-ocean stratification varies strongly. I suggest to provide season-specific analyses for all metrics.

We thank the reviewer for this relevant comment. We agree that a seasonal perspective is essential, as MHW impacts and upper-ocean stratification differ markedly between winter and summer.

In response, 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.

- Unclear physical link between SST and OHC : The manuscript applies HD2016 method (designed for surface anomalies) to the integrated 0–40 m OHC variable. OHC has different variability, autocorrelation and distributions compared to SST. Furthermore, in strongly stratified summer conditions, the 0–40 m layer comprise two different layers. The resulting OHC-MHW mix surface and subsurface processes without clear justification. I recommend to justify why this method is appropriate and can be apply to this layer even in summer. Maybe normalize OHC anomalies before thresholding. Moreover, SST-OHC relationship is region-specific (e.g., ventilated vs strongly stratified areas) and dependent on the season/stratification/internal variability. Maybe provide a seasonal SST-OHC correlation maps and discuss mechanisms controlling both variables.

We thank the reviewer for this comment and agree that further clarification is needed regarding the physical link between SST and OHC and the applicability of the Hobday et al. (2016) framework to the 0–40 m layer.

In this study, the Hobday et al. (2016) detection framework is applied directly to the OHC fields, following its original formulation, rather than to pre-computed OHC anomalies. The method defines extreme events relative to a daily percentile threshold computed from a daily climatology. As a consequence, OHC-based heatwaves are inherently characterized in terms of anomalies relative to this threshold, consistent with the definition of MHW intensity (e.g., maximum intensity defined as the highest anomaly relative to climatology). Therefore, the application of an additional normalization or anomaly pre-processing step is not required.

While OHC exhibits different variability, persistence, and autocorrelation compared to SST, this detection framework has been successfully extended in recent studies to subsurface temperatures and vertically integrated thermal quantities (e.g., Dayan et al., 2023; McAdam et al., 2023). The physical connection between SST-based MHWs and upper-layer OHC arises from the dominant role of surface heat fluxes in controlling upper-ocean thermal variability. Under strongly stratified summer conditions, the 0–40 m layer may encompass both the surface mixed layer and the upper thermocline, capturing the vertical penetration and persistence of surface-driven thermal anomalies. As such, the resulting OHC-based events reflect coupled surface–subsurface processes rather than purely surface anomalies. As the integration depth increases, the coupling with SST is expected to weaken, consistent with the inclusion of variability less directly driven by surface forcing.

Finally, to address the region- and season-dependent nature of the SST–OHC relationship, we now provide seasonal SST–OHC correlation maps (see new Figures 1y–1ad). These results are presented and discussed in the revised manuscript, highlighting the outcomes of the new analyses of surface and subsurface MHW variability under different stratification and seasonal conditions.

- Insufficiently motivated choice of 0–40 m for OHC: The choice of 0–40m is justified only briefly but in stratified regions this layer may represent different processes. Moreover, this layer aggregate a lot of different ecosystems and even more in complex basins such as Med and Black Sea. I recommend to test alternative integration depths (0–20, 20–40, 0–60 or 0–100 m) and compare the resulting MHW statistics.

We thank the reviewer for this comment. The rationale for selecting the 0–40 m integration depth has been clarified and strengthened in the revised manuscript. This choice is primarily biologically motivated, as the 0–40 m layer encompasses the biologically productive upper epipelagic zone and is particularly relevant for ecology and coastal management, including fisheries and aquaculture, in the Mediterranean and Black Seas (Granata et al., 2010; Cheminée et al., 2021; Macias et al., 2019; Nenciu et al., 2023).

This biological motivation is now supported by physical considerations in the revised manuscript. In the Mediterranean and Black Seas, the mixed layer depth is typically shallower than 40 m for most of the year, particularly from spring to autumn and during surface MHWs. Integrating OHC over 0–40 m therefore captures the upper ocean most directly influenced by atmospheric forcing, while also allowing the detection of subsurface heat accumulation not evident from SST alone.

We acknowledge that alternative depth ranges could provide additional insights for ecosystem- or process-specific applications. However, a systematic comparison across multiple integration depths is beyond the scope of this study, which aims to define a robust and spatially consistent upper-ocean MHW indicator for monitoring purposes. Nevertheless, we emphasize in the revised manuscript that the optimal depth range is region- and application-dependent and should be explored in future studies.

- Insufficient methodological description : I found the method to lack from essential details. How is the climatology computed (running mean, harmonic filtering). How do you compute the MLD ? Can you explain why do you start your reference period in 1993? I found the linear detrending to be quite limiting knowing the warming trend in the Med Sea and the regional dependencies (influence of the AMV, aerosol-forced variability, nonlinear internal variability).

We thank the reviewer for this comment and agree that additional methodological details were required. Regarding the climatology used for MHW detection, it is computed following the original Hobday et al. (2016) formulation, as a daily climatology defined for each calendar day (1 January, 2 January, ..., 31 December) using all available years within the reference period. No running mean or harmonic filtering is applied.

Concerning the MLD, this variable is only analyzed in Section 3.3.2 (Southern Adriatic Sea Pit and the Eastern Mediterranean Deep Water), where its definition and estimation method are now explicitly mentioned. Since MLD is not used elsewhere in the analysis, we did not include its definition in the general methodology section.

With respect to the climatological reference period, the Black Sea reanalysis employed in this study starts in 1993. To ensure methodological consistency across regions and datasets, we therefore adopted 1993 as the common starting year for the climatology and MHW detection in both the Mediterranean and Black Seas.

Finally, regarding detrending, a linear detrend was applied prior to MHW detection

to isolate the contribution of the long-term warming signal to MHW statistics. This approach, commonly adopted in recent studies (e.g., Martinez et al., 2023), allows assessing whether changes in MHW metrics arise primarily from the background temperature trend. Detrended analyses were performed separately for different Mediterranean subregions and for the Black Sea to account for regional variability; the corresponding results are presented in Appendix A.

- Limited uncertainty quantification : Multiple products are compared but there is no formal propagation of uncertainties, no sensitivity testes, no confidence intervals associated with trends or metrics. Some suggestions could be to include bootstrap ranges, product statistics to inform on the spread and sensitivity analyses to percentile choices, detrending methods.

We thank the reviewer for the comment regarding uncertainty quantification. The products used in this study (global and regional reanalyses and objective analysis) are individually evaluated in their respective Quality Information Documents (QUIDs). Inter-product spread is explicitly quantified for SST using three independent products ($N = 3$). While this approach could be extended to additional SST datasets, a more comprehensive uncertainty propagation is not the primary focus of this study.

For SST-based MHW metrics, discrepancies between global and regional reanalyses relative to the observation-based SST-L4 product are quantified for the Mediterranean (and subregions) and Black Sea and reported in Table 2, for annual metrics and, in the revised version, also for seasonal metrics. These results document the differences between reanalysis products and an observation-based reference. Comparable inter-product comparisons, whether based on spread or differences, could not be performed for OHC-based metrics, as the analysis relies exclusively on reanalysis products due to the limited spatial resolution of observation-based three-dimensional temperature datasets.

Statistical significance and confidence intervals are explicitly reported throughout the manuscript. Trends and correlations shown in Figure 1 are evaluated for statistical significance, and only statistically significant results ($p < 0.05$) are displayed in the spatial maps. Appendix A further documents long-term trends (1993–2024), including 95% confidence intervals shown by brown lines in the bar plots of Figures A1 and A2 and reported in brackets in the tables; non-significant trends are omitted and therefore not reported.

Finally, regarding sensitivity to percentile choices and detrending methods, we emphasize that the 90th percentile threshold was deliberately selected to support the development of a consistent MHW monitoring indicator. Higher percentile thresholds would naturally reduce the number of detected events. Sensitivity to detrending is addressed through parallel analyses performed after detrending both SST and OHC, with results presented in Appendix A.

- Introduction : The introduction sometimes reads as a list of ideas lacking cohesion, and several important references are missing. Moreover, what is the impact of ENSO on the Med Sea? There is also a strong influence of the NAO and AMV on the western basin.

We thank the reviewer for this comment. We have improved the introductory section to better support the objectives and methodological choices of the study, particularly the selection of the 0–40 m layer for defining upper-OHC in the detection of subsurface MHWs. The Introduction provides a general overview of the main drivers of MHW variability, including both local and remote influences, without aiming for a detailed assessment of their impacts. Instead, it focuses on motivating the need to

monitor both surface and subsurface events in the Mediterranean and Black Seas. We therefore chose to keep the introductory contextualization of MHW drivers concise and at a general level, by citing the main references.

- Discussion : I find the discussion too concise and not really discussing the limitations of the study. It may include explicit methodological limitations (detrending, assimilation influence, vertical resolution, depth choice). As an example, using reanalyses and L4 tend to smooth signal along the coast or in period of important cloud cover due to missing data.

We thank the reviewer for this comment. The role of detrending is addressed in Appendix A, where its impact on MHW statistics is explicitly evaluated. Regarding data assimilation, this is considered a strength rather than a limitation of the reanalysis products, as the assimilation of observations is designed to improve the representation of ocean thermal fields compared to free-running models.

The vertical resolution is an intrinsic characteristic of the reanalysis configurations and is documented in the referenced datasets. While such aspects can be discussed in more detail in process-oriented studies, they are not the primary focus of this work, which aims to develop a consistent monitoring framework. Within this context, the selection of the 0-40 m integration depth is primarily biologically motivated, as it encompasses the biologically productive upper epipelagic layer that is most relevant for assessing the ecological impacts of subsurface MHWs in the Mediterranean and Black Seas.

We acknowledge that the use of reanalysis and L4 SST products may smooth fine-scale coastal signals or periods affected by data gaps due to cloud cover. However, these products remain widely used and appropriate for basin-scale monitoring applications, which is the main objective of this study.

We also agree with the reviewer's suggestion to improve clarity and readability. Plain-language sentences have been added 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.

Minor comments :

- in the manuscript, I suggest to include + or – before the anomaly number
We have revised all numbers accordingly, following the reviewer's suggestion.
- several paragraphs (e.g., the beginning of Section 3.3.1) contain methodological or introductory material and should be moved to their appropriate sections
We chose to retain a brief introductory paragraph at the start of each subsection to guide the reader and provide context for the analyses discussed therein.
- L38 : England et al. (2025) is not about the Med/Black nor the disruptions of marine ecosystems.
England et al. (2025) has been removed from the manuscript.
- L192 : Maybe I'm wrong but it is expected that regional reanalyses perform better partly because they assimilate local data and often use SST relaxation. This may artificially improve skill and reduce variability especially in coastal regions.
We thank the reviewer. Both regional reanalyses do not assimilate SST (though they apply SST relaxation) and use configurations specifically tailored for each sea (particularly at the model component level), while the global reanalysis applies SST assimilation. The better performance of the regional products mainly reflects these specific configurations, physical parameterizations, and higher resolution, allowing a more accurate representation of mesoscale and submesoscale processes, as well as thermohaline fields.
- L349-352 : The suggested “combined approach” (SST + OHC intensities) is based purely on a statistical aspect and does not integrate ecological vulnerability or impacts. For a monitoring strategy, impact-based thresholds are essential.
The proposed combined SST–OHC approach is intended as a physically based monitoring metric and does not explicitly incorporate ecological vulnerability or impacts, as it relies on reanalysis products and analysis objectives focused on physical variables; integrating ecological impacts would require extended analyses and additional biological datasets, which are beyond the scope of this study and are left for future work.
- L453, the main drivers in the Med are now well-known.
While the main drivers in the Mediterranean are well-known, the revised Introduction provides only a general overview of local and remote drivers to give context (see our responses to the general comments above), keeping the focus on the study's primary objective of monitoring surface and subsurface MHWs.
- Figures are not self-reading and could be improved.
We thank the reviewer for this comment. Where possible, figures have been improved, and we opted for subfigures to respect the figure limits and guidelines set by the Copernicus Ocean Science Report. Specifically for Figure 1, all panels are now clearly labeled, and these labels are consistently referred to in the figure caption, in the Results section, and throughout the text.

References to consider :

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- Bensoussan, N., Chiggiato, J., Buongiorno Nardelli, B., Pisano, A., & Garrabou, J. (2019).

Insights on 2017 Marine Heat Waves in the Mediterranean Sea. *Journal of Operational Oceanography*, 12(SI).

- Estaque, T., Richaume, J., Bianchimani, O., Schull, Q., M rigot, B., Bensoussan, N., ... & Garrabou, J. (2023). Marine heatwaves on the rise: One of the strongest ever observed mass mortality event in temperate gorgonians.

- Estournel, C., Estaque, T., Ulses, C., Barral, Q. B., & Marsaleix, P. (2025). Extreme sensitivity of the northeastern Gulf of Lion (western Mediterranean) to subsurface heatwaves: physical processes and insights into effects on gorgonian populations in the summer of 2022. *Ocean Science*, 21(4), 1487-1503.

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We thank the reviewer for the helpful suggestion. Among the proposed references, we have incorporated two studies addressing the impacts of marine heatwaves in the Mediterranean: Estaque et al. (2023) and Estournel et al. (2025) (lines 58-59). We did not include all suggested references, as we also considered those recommended by other reviewers.

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