Reply to Reviewer 2:

We would like to thank the reviewer for their careful reading and suggestions. Please, find below a point-by-point response to all comments. For ease of reference, the reviewer's comments are presented in blue font, while the authors' responses are presented in black font.

General comments

In this manuscript, the authors explore sea surface temperature data to analyze long-term changes in MHW characteristics, distinguishing the mean warming and SST variability impacts. The study is interesting but the authors should better clarify the motivations of the study, as well as the implications on marine ecosystems providing references. By comparing to the recent studies (cited by the authors), the novelty of the manuscript should be better highlighted.

Thank you for this valuable feedback. Our primary motivation lies in advancing scientific understanding of mean and extreme warming conditions and their drivers across the entire Mediterranean basin. In this context, expanding the analysis of Marin et al. (2021) beyond coastal locations provides a more holistic understanding of the basin. However, we recognize the need to emphasize broader motivations in the manuscript, especially concerning potential implications for marine biodiversity and ecosystem functioning.

Before applying the method of Marin et al. (2021) for attributing MHW trends, our study begins with an analysis of SST variability and extremes (99th percentile) across the Mediterranean Sea. This part aims to provide essential context on how long-term changes in extremes and variability are distributed spatially throughout the basin. This part sets the stage for the subsequent MHW analysis but also highlights areas of the basin where extreme warming is particularly pronounced and therefore might be disproportionately impacted.

For example, we find that the Adriatic, Aegean and northern Levantine Seas show the highest trends of both SST and its 99th percentile, suggesting higher vulnerability in terms of both accumulated warming and extreme SST occurrences. Such evidence is potentially useful for informing regional management strategies.

The Mediterranean Sea is a biodiversity hotspot and one of the most sensitive marine regions to climate change. By including the open sea, we account for areas that support key ecological processes which can be disrupted by MHWs. For example, pelagic species, critical to marine food webs, may be affected by MHWs, with potential repercussions for the fishery industry. A climate risk assessment by Hidalgo et al. (2022) finds the highest risks associated with impacts of ocean warming on fisheries resources (e.g., catch composition, distribution changes), highlighting the southeastern basin as the most impacted for both pelagic and demersal fisheries. Importantly, they find geographic differences in terms of drivers and impacts and recommend regionally tailored adaptation strategies.

Moreover, MHWs pose significant risks to aquaculture, which is a rapidly expanding industry in the Mediterranean Sea. Apart from fish mortality, MHWs affect aquaculture by facilitating the proliferation of pathogens and disease outbreaks, which can lead to unmarketable fish and substantial financial losses (Cascarano et al., 2021). Offshore aquaculture is increasingly being considered as an alternative to mitigate the effects of coastal warming, as it may help alleviate the impacts of extreme water temperatures (Mengual et al., 2021). In this context, a better understanding of MHWs is essential across both coastal and offshore areas.

Likewise, Marine Protected Areas (MPAs), which host vulnerable marine species, such as marine mammals and turtles (Chatzimentor et al., 2023), could benefit from a broader understanding of MHWs across the basin. Given the growing need for climate-based conservation strategies to protect marine life, it is important to enhance our understanding of extreme warming conditions at regional scale. Such insights could inform protective measures such as identifying spatial refugia and establishing new MPAs, strengthening the resilience of Mediterranean marine life to climate change (e.g., Zentner et al., 2023; Bates et al., 2019).

Considering the above, we will enrich the introduction of the revised manuscript making our motivations more explicit and addressing the ecological and socio-economic relevance of the study. Possible implications on marine ecosystems and marine economic activities will be included providing references.

Bates, A. E., Cooke, R. S. C., Duncan, M. I., Edgar, G. J., Bruno, J. F., Benedetti-Cecchi, L., Côté, I. M., Lefcheck, J. S., Costello, M. J., Barrett, N., Bird, T. J., Fenberg, P. B., and Stuart-Smith, R. D.: Climate resilience in marine protected areas and the 'Protection Paradox,' https://doi.org/10.1016/j.biocon.2019.05.005, 1 August 2019.

Cascarano, M. C., Stavrakidis-Zachou, O., Mladineo, I., Thompson, K. D., Papandroulakis, N., and Katharios, P.: Mediterranean aquaculture in a changing climate: Temperature effects on pathogens and diseases of three farmed fish species, https://doi.org/10.3390/pathogens10091205, 1 September 2021.Chatzimentor, A., Doxa, A., Katsanevakis, S., & Mazaris, A. D. (2023). Are Mediterranean marine threatened species at high risk by climate change? Global Change Biology, 29(7), 1809–1821. https://doi.org/10.1111/gcb.16577

Chatzimentor, A., Doxa, A., Katsanevakis, S., and Mazaris, A. D.: Are Mediterranean marine threatened species at high risk by climate change?, Glob. Chang. Biol., 29, 1809–1821, https://doi.org/10.1111/gcb.16577, 2023.

Hidalgo, M., El-Haweet, A. E., Tsikliras, A. C., Tirasin, E. M., Fortibuoni, T., Ronchi, F., Lauria, V., Ben Abdallah, O., Arneri, E., Ceriola, L., Milone, N., Lelli, S., Hernández, P., Bernal, M., and Vasconcellos, M.: Risks and adaptation options for the Mediterranean fisheries in the face of multiple climate change drivers and impacts, ICES J. Mar. Sci., 79, 2473–2488, https://doi.org/10.1093/icesjms/fsac185, 2022.Mengual, I. L., Sanchez-Jerez, P., and Ballester-Berman, J. D.: Offshore aquaculture as climate change adaptation in coastal areas: sea surface temperature trends in the Western Mediterranean Sea, Aquac. Environ. Interact., 13, 515–526, https://doi.org/10.3354/AEI00420, 2021.

Mengual, I. L., Sanchez-Jerez, P., and Ballester-Berman, J. D.: Offshore aquaculture as climate change adaptation in coastal areas: sea surface temperature trends in the Western Mediterranean Sea, Aquac. Environ. Interact., 13, 515–526, https://doi.org/10.3354/AEI00420, 2021.

Zentner, Y., Rovira, G., Margarit, N., Ortega, J., Casals, D., Medrano, A., Pagès-Escolà, M., Aspillaga, E., Capdevila, P., Figuerola-Ferrando, L., Riera, J. L., Hereu, B., Garrabou, J., and Linares, C.: Marine protected areas in a changing ocean: Adaptive management can mitigate the synergistic effects of local and climate change impacts, Biol. Conserv., 282, https://doi.org/10.1016/j.biocon.2023.110048, 2023.

Specific comments

Introduction

L.28: reference in 2014 does not seem to me adequate when addressing the period 1982-2022, especially knowing the acceleration in global warming in the last decade and recent years. More recent publications: Martinez et al. (2023) 1982-2021, Juza et al. (2021)→ 1982-2020.

Thank you for your comment. We will update this part to better align with the period examined in this study, including the most recent publications you mention.

l. 30: I would suggest "warm oceanic events"

Thank you for this suggestion, it will be included in the revised manuscript.

l. 30 replace "Marine Heatwaves (MHW)" by "marine heatwaves (MHWs)"

Thank you for this suggestion, it will be included in the revised manuscript.

2.1 SST observations

The authors "re-gridded" the datasets to coarser resolution, for computational reasons. I do not understand such an exercise and degradation of the datasets.

Thank you for raising this point. The dataset was regridded to a coarser resolution to ensure efficient processing and analysis of results across the basin, given the large data volume and the multiple experiments conducted. Importantly, this step did not compromise the accuracy of the results or the ability to capture the spatial patterns of interest, as the key features and variability relevant to the objectives of our analysis are effectively represented.

The authors could provide a table or list of the derived datasets for clarity.

Thank you for your comment. Please, note that we use a single dataset in this study, so there is not a list of datasets to provide.

Are these datasets available in open access? It would be a real added value of the paper.

Thank you for noting this. The used dataset is a gridded observational dataset (L4, reprocessed) for SST in the Med Sea, available (open access) through the Copernicus Marine Catalogue, as shown in Table 1. All information included in Table 1 for this Copernicus product (official product name (ID), source, links for associated documentation), follow the guidelines provided for product references in the context of this special issue (Copernicus Ocean State Report #9). Despite the details that a reader may find in the documentation of Table 1, we agree that some further information on this SST satellite dataset can be provided within the text. We will enrich this part in the revised manuscript.

Maybe the authors could be interested by the paper from Amaya et al., 2023 Amaya 2023https://www.nature.com/articles/d41586-023-00924-2

Thank you for mentioning this valuable publication which highlights the importance of clearly articulating detection methodologies as regards the climatological baselines. We agree that this clarity is essential for understanding warm extremes and their impacts on marine life. Our choice for the climatological baseline used for MHW detection is currently described in the manuscript in L. 97-101. Nevertheless, we will enrich the description of our approach and motivation for the employed climatology to improve clarity.

2.2 MHW analysis

l.78 “for a 5-day period” → add “at least” or “or more”

Thank you for noting this, it will be added in the revised manuscript.

l.100: the authors want to directly compare their results to Marin et al. (2021). They will obviously find differences when using different periods…

Thank you for this comment. We totally agree, and this is expected also due to the different dataset used in the current study. However, despite these differences, our results for the coastal locations agree with Marin et al. 2021 for all MHW metrics, which suggests that there is not large sensitivity to these methodological choices. Most importantly, the differentiation of mean intensity among the other metrics is observed in both studies. In addition, the experiments testing the sensitivity of results to climatological baselines further support that a less predictable behavior should be expected for mean intensity, in agreement with Marin et al. 2021.

l.105: I do not feel comfortable with the reference period 1982-2002, since it does not respect the 30-year period recommendation (Hobday et al., 2016).

Thank you for pointing this out. We acknowledge that the reference period 1982–2002 does not follow the 30-year period recommendation by Hobday et al. (2016). However, the use of this shorter period (21 years) in EXP3 was intentional, serving as part of a sensitivity test to evaluate how TAR values are affected by changes in the reference period length. This experiment is not intended as an alternative climatological baseline but as a methodological sensitivity test. Additionally, we note that the differentiation of mean intensity from other metrics is consistently observed across the three experiments and aligns with the findings of Marin et al. (2021), who based their analysis on a 25-year period.

To address your concern, we will enhance the description of EXP3 in the revised manuscript to clarify that it aims to explore the impact of using a shorter reference period on the attribution of trends.

l. 122-125: It could be great to provide some references. The choice of the metrics is driven by marine ecosystems implications. It should be clarified.

Thank you for this suggestion. Although our primary motivation is advancing scientific understanding of the drivers of MHW trends across the basin, we agree that linking the selected metrics to implications for marine ecosystems adds valuable context.

The yearly cumulative intensity (CI_{yearly}) not only integrates the effects of MHW duration and intensity but also serves as a measure of the long-term thermal stress induced by MHWs. Including the cumulative effect of multiple events may be relevant for several species in the Mediterranean basin, such as gorgonian populations which are severely impacted by recurrent MHWs in the basin (Orenes-Salazar et al., 2023) or fish species such as the gilthead seabream whose thermal tolerance can be affected by past exposure to thermal stress (Kir, 2020). The limited acclimatization capacity of the latter and its relatively narrow temperature range challenge its survival where strong temperature variations occur. Areas with the highest event extremity (as represented by SI_{max}) may therefore pose severe risks to such species. In addition, wild marine species can often escape unfavorable aquatic conditions, whereas farmed species confined to aquaculture environments are more vulnerable to warm extremes (Beever et al. 2017). Such distinctions in behavioral flexibility are also important for the selection of appropriate metrics for assessing impacts on different marine populations and environments.

Following your suggestion, we will add a short discussion in the Methods subsection ("Selected MHW metrics") based on the above.

Beever, E. A., Hall, L. E., Varner, J., Loosen, A. E., Dunham, J. B., Gahl, M. K., Smith, F. A., and Lawler, J. J.: Behavioral flexibility as a mechanism for coping with climate change, Front. Ecol. Environ., 15, 299–308, https://doi.org/10.1002/fee.1502, 2017.

Kır, M.: Thermal tolerance and standard metabolic rate of juvenile gilthead seabream (Sparus aurata) acclimated to four temperatures, J. Therm. Biol., 93, 102739, https://doi.org/10.1016/j.jtherbio.2020.102739, 2020.

Orenes-Salazar, V., Navarro-Martínez, P. C., Ruíz, J. M., & García-Charton, J. A. (2023). Recurrent marine heatwaves threaten the resilience and viability of a key Mediterranean octocoral species. Aquatic Conservation: Marine and Freshwater Ecosystems, 33(11), 1161–1174. https://doi.org/10.1002/aqc.3997

Trends: uncertainties are missing in the text. Could you precise which method is used and the level of significance?

Thank you for pointing this out. Trends were computed using linear regression, and their statistical significance was assessed using the Mann-Kendall test at the 95% confidence level. Confidence intervals for the trend estimates were calculated based on the standard error of the regression coefficients, using the Student's t-distribution (α=0.05). We will include this information in the Methods section and the legend of Table 2.

Results

l. 189: "mean intensity seems to increase" → are they statistically increasing? or not?

Yes, this trend is statistically significant. We provide the entire sentence here for clarity: *"Mean intensity seems to increase basin-wide when the long-term warming trend of the Mediterranean Sea is removed (Fig. 2f), with statistically significant trends of 0.12, 0.08, and 0.05 degC.dec^{-1} for the western, central and eastern sub-basins, respectively."* In addition, detailed information on the statistical significance of MHW trends for the basin and sub-regions is provided in Table 2.

l. 222: "forced by interannual variability": what would be the results when distinguishing the seasons?

Thank you for raising this question. In this study, we use deseasonalized SST data in the entire analysis. Our aim is to focus on interannual variability and long-term trends without the effect of seasonal fluctuations, as described in Methods. Distinguishing the seasons could provide additional insights and is undoubtedly an interesting direction for future research, it lies however outside the scope of the present work where seasonal variations are removed closely following the approach of Marin et al. (2021).

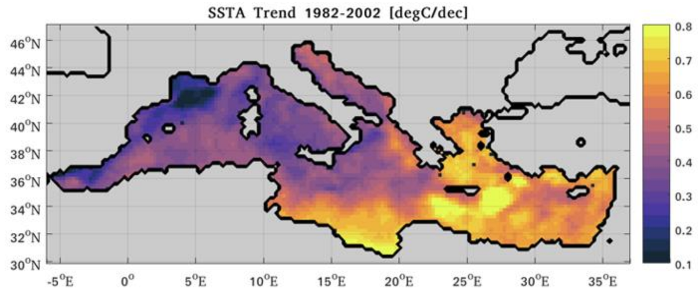
l.229: "opposing trend of the (reduced) variability → decreasing trend of the variability

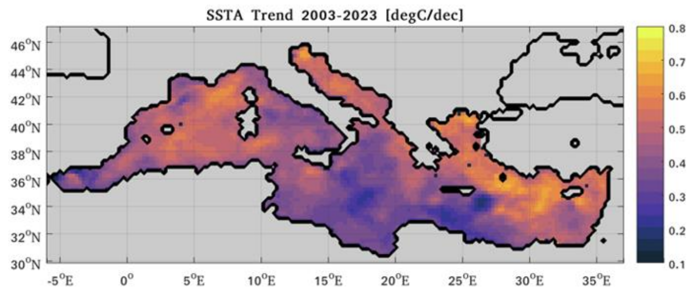
Thank you for noting this. It will be rephrased in the revised manuscript as suggested.

Conclusions

l.284 "results potentially suggest"... A study over a more recent period could lead to different results. In particular, I think that the warming rate in WMED is higher than in EMED in the last decade… Have the two periods proposed in introduction/methodology been explored and analyzed to state such a conclusion?

Thank you for giving us the chance to comment on this. You are correct in noting that the warming rate in western is higher than in eastern basin over the most recent years. SST trends for the first and second half of the study period (1982-2002 and 2003-2023) reveal increased (decreased) warming rates over the western (eastern) basin for the second period, as shown in the figure below:





However, the conclusion in the quoted sentence is based on the entire study period (1982–2023), during which cumulative warming in the eastern basin is indeed larger than in the western basin as shown in Fig. 1 of the manuscript. Therefore, we believe that the statement remains accurate and not misleading within the context of the full study period. Using different time periods naturally results in varying trends, and we specifically chose to present the analysis over the longest available satellite record to ensure consistency and a comprehensive view of the trends. This was the focus of our study, as the main objective was to attribute MHW trends, rather than focusing on shorter-term trends.

For clarity, in the introduction/methodology we do not propose examining two periods. A different period than the entire 42-year period is used only within one of the sensitivity tests (EXP3), in order to understand how the choice of the reference climatology period (i.e., its temporal coverage for EXP3) affects the trend attribution results.

l.290: I would delta “in most of the basin, mainly”

Thank you for your comment. We agree, this will be corrected in the revised manuscript.

l.293: I would delete the parenthesis

Thank you for your comment. We agree, this will be corrected in the revised manuscript.

l.303-305: see my previous comments concerning the seasons.

Thank you for your comment. As explained in our answer to your relevant comment, this study aims to provide an annual perspective, in contrast to prior studies focusing on summer MHWs (e.g., results of Simon et al. 2022 for summer MHW Activity discussed in these lines).

l.313-315: to be referred.

Thank you for your comment. We agree, this will be corrected in the revised manuscript.

l.316-317: this statement has been repeated several times I think…

Thank you for your comment. You are right that there is a repetition of this statement. We believe however it is not redundant in the context of the conclusions section, as it constitutes the key finding of this work.

Figures

Figure 2: Could you define somewhere the boxes WMED, CMED, EMED? Maybe boxes could be added in Figure 1.

Thank you for your suggestion. We agree that it is better to show the geographical areas in the first panel of Fig. 1, making it easier for readers to refer to. We will adjust Fig. 1a in the revised manuscript, as suggested.

Figure 4 is not necessary

Thank you for your comment. We understand that key findings from the sensitivity experiments (EXP1-3) are described in L253-267. Nevertheless, we believe that Fig. 4 adds value by presenting these results in a more immediately interpretable format. The bar graphs, shown separately for each experiment, allow for clear visual comparisons both among the examined metrics within each experiment and across experiments. For this reason, we would prefer to keep this figure in the manuscript.