<u>Reply to Reviewer 2:</u>

We would like to thank the reviewer for their valuable feedback on our manuscript. 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

The authors examine the role of air-sea heat flux during Marine Heatwaves (MHWs) events in the Mediterranean Sea over the last 30 years. These events were identified using satellite-derived Sea Surface Temperature (SST) data from 1993 to 2022. An analysis of the ocean mixed layer heat budget was conducted to determine the change in SST attributed to the net surface heat budget during onset and decline phases of MHWs. Air-sea heat fluxes are found to be the primary driver of most MHW onsets, particularly in warmer months and during onset phases, while oceanic processes play a key role in regulating SST during decline periods. A progressively decreasing mixed layer depth (MLD) is observed over the entire event duration, particularly for shorter-lasting events, with significant mixed layer deepening occurring after the end of the decline period. This study underscores the importance of considering subsurface information to better describe the evolution of these extreme events. Combining observations and ocean reanalysis systems appears promising for improving monitoring and early warning of MHWs.

In general, this paper is well-organized and presented in a coherent manner. While the findings may not be groundbreaking, they are relevant within the context of the Mediterranean Sea and can contribute to the advancement of knowledge on this topic.

My main concern, however, is the emphasis placed by the authors on oceanic processes, such as horizontal advection and vertical mixing. Specifically, some findings are just deduced by the authors without conducting a thorough analysis of these processes (e.g., lines 12-13; 227-229; 231-233; 265 268 and so on). Hence, I suggest either revising the sentences highlighting oceanic processes or providing additional analysis to support the findings.

We thank the reviewer for this comment. Indeed, the heat budget analysis performed in this work quantifies the role of air-sea heat flux in the evolution of MHWs in the Mediterranean basin. This role is assessed in relation to a single residual term (i.e., the non-heat flux terms merged into a single one), representing the cumulative effect of all other (oceanic) factors influencing the SST tendency during a MHW phase. Therefore, the role of oceanic processes is deduced from this analysis and is not directly examined. We agree on rephrasing the sentences that highlight the relevant role of oceanic processes putting more focus on the actually quantified contribution. Our answers are provided under your specific comments below.

Specific Comments

[Lines 12-13]. "Our findings suggest that oceanic processes…". Based on my last comment given in the General Comments, I would rephrase this sentence giving more emphasis to the role of heat fluxes, which is the topic of this work.

Thank you for your comment. We agree on re-orienting the presentation of these results. We have revised this sentence (Lines 12-13) as follows: *Results show that air-sea heat flux is the major driver in 44% of the onset and only 17% of the decline MHW phases. Thus, these findings suggest that oceanic processes play a key role in driving SST anomalies during MHWs, particularly during declines.*

[Line 44]. I suggest the authors the following reference that investigates the role of atmospheric forcing and wind-driven mixing during the 2022/2023 MHW event in the Mediterranean Sea.

Marullo, S., Serva, F., Iacono, R., Napolitano, E., di Sarra, A., Meloni, D., ... & Santoleri, R. (2023). Record-breaking persistence of the 2022/23 marine heatwave in the Mediterranean Sea. Environmental Research Letters, 18(11), 114041. https://doi.org/10.1088/1748-9326/ad02ae

Thank you for this suggestion. This paper has been included in the reference list.

[Line 59]. Please, expand acronyms: NRT CMEMS.

Thank you for your comment, acronyms have been expanded.

[Line 68-69]. Please, clarify how the climatology was computed (is it just an average or did you apply a smoothing window?)

Thank you for your comment. To compute the climatology at each grid point, a time-window of 11 days was employed, centered on the day when each daily climatological value was computed. Additionally, a 30 day-window was applied for smoothing the daily threshold time series.

We added this information in the revised manuscript.

[Table 1]. For your information, here are the references for products n.1 and n.2:

(a) Product n.1. Pisano, A., B. Buongiorno Nardelli, C. Tronconi, and R. Santoleri (2016). The new Mediterranean optimally interpolated pathfinder AVHRR SST Dataset (1982 – 2012). Remote Sensing of Environment, Vol. 176, pg. 107-116. http://dx.doi.org/10.1016/j.rse.2016.01.019

(b) Product n.2. Buongiorno Nardelli, B., Tronconi, C., Pisano, A., and Santoleri R. (2013). High and Ultra-High resolution processing of satellite Sea Surface Temperature data over Southern European Seas in the framework of MyOcean project. Remote Sensing of Environment, Vol. 129, pg. 1-16. http://dx.doi.org/10.1016/j.rse.2012.10.012

Thank you for sharing these references. However, the reference format currently included in the manuscript for the Copernicus Marine products follows the specific guidelines provided in the context of the Ocean State Report.

[Line 113]. "Events tend to last longer in eastern part…". I recommend to include the central-western region of the Mediterranean into this consideration as well.

Thank you for noting this, it has been added in the revised manuscript.

[Line 114-115]. "…frequency…closely follows intensity…". Honestly, I do not see this 'high correlation'. I recommend to quantify the correlation or rephrase the sentence.

We thank the reviewer for this comment. Figure 1a shows that the northwestern Mediterranean Sea (around the Gulf of Lions, and to the east of Corsica) and the northern Adriatic Sea, followed by the Aegean Sea, present the higher MHW frequency. These are the areas where MHW intensity also shows its higher values across the basin (Fig. 1b). In addition, the lowest intensity values are observed across the African coasts (10^{o}E eastwards) and it is in several spots within this extended area that the lowest frequency values are also encountered. We agree that "closely follows" written in the manuscript implies a strong spatial correlation among these quantities which is not correct and should be rephrased. To report the observed similarities in the spatial patterns of the discussed fields without overstating their correspondence, we have revised the sentence as follows:

The mean event frequency over the study period shows some similarities with the mean intensity spatial distribution, suggesting that the most (least) intense and most (least) frequent MHWs are encountered in the northernmost (southernmost) flanks of the Mediterranean Sea (Fig. 1a,b).

[Line 121-125]. I recommend to quantify the trends of intensity, duration and frequency with confidence intervals as well.

Thank you for your comment. Mean-basin trend values for the examined parameters have been included in the revised manuscript in addition to the existing trend values discussed in this paragraph.

[Figure 1]. Concerning the trend maps (d-e-f), I would suggest to put black dots over non significant pixel values (that is, just switch the overlapping criterion).

Thank you for this suggestion. We have incorporated your suggestion for Fig. 1 in the revised manuscript.

[Figure 2]. The label for x-axis is DSSTQnet/DSSTA while you used ΔSSTQnet/ΔSSTA in eq. 3. I recommend to adopt the same notation. Same comment for Figures 3 and 4.

Thank you for noting this, this typo has been corrected in the revised manuscript.

[Line 166-167]. This sentence is somewhat misleading and complex ("are not the primary driver in..."). It appears to contradict what is stated at line 129. I would suggest rephrasing it. Overall, I recommend greater clarity when distinguishing between the roles of heat fluxes and oceanic processes, as in some cases one is more significant than the other and, in other cases, the opposite.

We thank the reviewer for this comment. We agree that this sentence should be rephrased for clarity. Line 129 states that there is a positive contribution of surface heat flux in 92% of the onset phases. As explained in Methods (Lines 96-98), a positive heat flux contribution during a MHW phase means that the heat flux promotes the observed change in SST anomaly during that phase ($\Delta SST_Q > 0$ & $\Delta SST'_{obs} > 0$ for onset). However, this does not suggest that heat flux is the primary driver during that phase (in terms of explaining at least half of the observed change in SST anomaly), so there is no actual contradiction with Lines 166-67.

As stated in lines 166-176, the air-sea heat flux is found to be the primary driver of 44% of the onset phases. In other words, heat flux is not the primary driver in 56% of the onset phases. This suggests that in 56% of the onsets, oceanic processes have a dominant role. To increase clarity and avoid misleading the reader, we have rephrased Lines 166-69, as follows:

Results show that the air-sea interaction, with a dominant role of LH flux, plays a major role in the development of nearly half (44%) of the MHWs in the Mediterranean Sea. This finding suggests that oceanic processes play a key role during 56% of the onset cases. A further weakened role of heat flux is found during decline periods (being the major contributor in only 17% of declines), indicating that MHWs decay is also primarily driven by oceanic processes.

[Line 186-188]. This sentence is a repetition of what already stated above. I suggest to rephrase or remove it.

Thank you for noting this. Our intention was to introduce to the reader the information merged in Fig. 3, briefly relating its content with the previous results.

We suggest rephrasing lines 187-190 as follows:

Whereas during onset, MHWs are largely driven by heat flux exchange and most of them are accompanied by mixed layer shoaling, there are cases where MLDA are strongly positively correlated with SSTA during onset, indicating surface warming evolves while the mixed layer deepens (Fig. 3a-top).

The revised sentence provides additional information on the already discussed results for onset periods, reporting the existence of cases with positive heat-flux contribution and mixed layer deepening.

[Line 192]. "a significant MLDA-SSTA correlation is absent…". What do you mean with this sentence? To me is not clear.

Thank you for your comment. In Fig. 3a, the correlation coefficient (CC) values of the x axis range from -1 up to 1. The highest concentration of events in the heatmap of Fig. 3a-bottom is observed in the right area of this panel that corresponds to large positive correlation (CC close to 1) between the MLD and SST time-series during declines (i.e., SST decrease and MLD decrease). However, looking at the entire panel Fig. 3a-bottom we see that all different cases exist, including cases with very small (non-significant) positive or negative CC values. We therefore report (Line 192) that apart from the most commonly observed finding for declines, there are several cases with no significant MLD-SST correlation.

[Line 248]. "…and oceanic processes". I would suggest to substitute oceanic processes with mixed layer heat budget analysis (or something equivalent).

Thank you for this suggestion. The part " and oceanic processes" has been entirely removed from the sentence.

Comments on the example lines mentioned by the Reviewer in General Comments:

Lines 12-13: Answer included in specific comment for these lines

Lines 231-233 and Lines 265-268

Our results show that the SST decrease during decline is primarily driven by air-sea heat flux in only 17% of the declines. On top of this, during most declines, a continuation of the mixed layer shoaling is found, suggesting that in these cases the SST decrease is not driven by mixing in the vertical. Based on the above, we assume that the SST decrease right after the peak intensity day of most events is probably due to heat advection. In turn, the significant increase in MLD after the MHW end day found in most cases suggests that vertical mixing becomes important for the MHW decay after the end of the decline phase.

The contribution of oceanic advection in Lines 231-233 and Lines 265-268 is deduced from our analysis and is not investigated. For this reason, we briefly discuss this factor solely in terms of its potential role right after the peak-intensity day, as implied from our actually quantified results (i.e., the contribution of surface heat flux, and the enhanced/suppressed vertical mixing as indicated from MLD increase/decrease).

Our comment that this hypothesis applies especially for shorter decline periods (Line 268) is based on the higher SST-MLD correlation found for decline phases of shorter durations. This suggests that the progressively decreasing MLD during decline is more common during shorter declines. In line with the weak contribution of air-sea heat flux during declines (found to be weaker for shorter declines), this suggests a higher probability of advection being responsible for the observed surface cooling in such cases.

Lines 227-229:

The calculated percentage change in the MLD between the onset and the selected post-decline period (shown in histogram of Fig. 3c) reveals that a significant mixed layer deepening occurs after the MHW end day in most cases. We therefore believe that this finding supports the conclusion reported in the discussed lines "…*suggesting that vertical mixing eventually contributes to the heat dissipation.*" Let it be noted here that the examined post-decline period starts at the end day of the event, which means that SST will continue to decrease (by definition, as the end-day of the event is the last day when SST is above threshold).