nature portfolio

Peer Review File

Mediterranean marine heatwaves intensify in the presence of concurrent atmospheric heatwaves.

Corresponding Author: Dr Francisco Pastor

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Dr Pastor,

Your manuscript titled "Mediterranean marine heatwaves intensification in the presence of concurrent atmospheric heatwaves." has now been seen by 3 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication, but would be interested in considering a revised version that fully addresses these serious concerns. In particular, we would want the revised manuscript to meet the following editorial thresholds:

1. The manuscript should show how the results are robust against methodological choices (such as reference period) and the sensitivity to thresholds used.

2. The manuscript should better highlight the novelty in the context of previous studies.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to address these criticisms, we would be happy to look at a substantially revised manuscript. If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

When resubmitting, please provide a point-by-point response to the reviewers' comments. Please submit your responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

If the revision process takes significantly longer than three months, we will be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the reviewers' comments with a list of your changes to the manuscript text (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and any completed checklist:

Link Redacted

** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

Please do not hesitate to contact us if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Joy Merwin Monteiro, PhD
Editorial Board Member
Communications Earth & Environment
orcid.org/0000-0002-3932-3603

Alireza Bahadori, PhD
Associate Editor
Communications Earth & Environment

EDITORIAL POLICIES AND FORMAT

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• Ecological, evolutionary & environmental sciences
• Life sciences
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You can download the form here:
https://www.nature.com/documents/nr-reporting-summary.zip

For your information, you can find some guidance regarding format requirements summarized on the following checklist: (https://www.nature.com/documents/commsj-phys-style-formatting-checklist-article.pdf) and formatting guide (https://www.nature.com/documents/commsj-phys-style-formatting-guide-accept.pdf).

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

The authors have implemented a new method for the detection of atmospheric heat waves (AHWs) and marine heatwaves (MHWs) and applied their algorithm to long-term timeseries in the Mediterranean over the period 1940-2022. The study aims to investigate the spatio-temporal concurrency of AHWs and MHWs and changes in their characteristics, and thus to increase our knowledge about extreme events, whose impacts are becoming devastating.
The manuscript is interesting, well documented and well written. It implies important computational work and provides new results. However, I would need some clarifications and justifications about the methodology and its use as well as better highlights on the novelty brought by this study, that would require major revisions. The authors will find below, general and specific comments.

Introduction

The authors provide well-documented state-of-the-art. However, I would suggest being more concise in the introduction, in particular in the two first paragraphs.

The authors are a bit too “Europe/Spain”-oriented since they refer specifically to Southern Europe, Iberian or Spanish conditions several times (l.99, 115,116, 563…) whereas the study addresses all the Mediterranean Sea.

L.110-111. Please rephrase this sentence.

L.112. “largest trends for summer”. I suppose the authors precise “summer” because it is not the case for the rest of the year, is it true?

L.123. I would replace “intensification trend” by “increasing trend”.

L.114, 214 217, 506: please use the acronyms AHWs and MHWs, already defined.

L.153-155: the authors state “Although the mentioned studies have investigated the concurrence between AHWs and MHWs, they are limited to terrestrial AHWS and no concurrent assessments have been run, to our knowledge, over the ocean.” but then, L.185-188 they write “They found a statistically significant correlation between AHWs and MHWs frequencies and total days in the Eastern Mediterranean, but with regional differences; they also found an increase in the co-occurrence of AHW and MHW events frequency and total days”. It seems contradictory to me, it has been done in the eastern Mediterranean. Maybe the 3rd, 4th and 5th paragraphs could be better reorganized.

L.190: I am not sure that the wording “not a single universally accepted” is appropriate. I would is that there is a commonly used methodology that allows addressing and comparing extreme events worldwide. However, given the global and ocean warming, new and complementary definitions are being used. Again, L. 196 “fully universal”, I suggest to rephrase and avoid repetitions when possible.

L.192: the authors write 90th percentile. But then, they use the 95th for AHWs. Please clarify.

L.205: “Could you precise the “minimum overlapping” ?

L.216-219: The conclusion should not be stated in the introduction.

L.208-220: I strongly recommend to better highlight the novelty of this study.

Results and discussion

L.225-227: A new methodology is not an aim, it is a tool to reach the scientific objective(s). I suggest rephrasing/clarifying.

L.235-238: “Our ImeanM and IcumM values are comparable but somewhat lower than the 1.60ºC and 24.70ºC values for the shorter 1982-2021 period which could indicate that the MHW intensity is not dependent on the detection algorithm, while the mean duration of MHWs is almost three many times larger in this new approach, as expected.” Given the warming trend basis, I would think the contrary. In addition, the difference could be explained by the different periods of reference, not (only) the detection method.

L.238: three times larger

L.246-248: I am not sure to understand why both mean and median are indicated.

L.253-258: It is in agreement with results from previous studies using the “classical” method.

L.288-290: “This divergence from values previously obtained in the scientific literature was foreseeable as the new methodology necessarily implied an increase in the duration of events and a consequent decrease in annual frequency. As said before, I think that the differences could also be explained by the reference period used.

L.294-303: Why do the authors not address the duration here whereas the duration trends are introduced and commented on in the previous paragraph?

L.318: “is a consequence of the new dynamical definition used in the MHW detection applied in this work.” See the previous comment about the reference period. Same concern L. 444.

L.319: “longer lasting and larger MHW events which then reduce the annual count”.

L. 322: associated with

Discussion

L. 431: Could you explain the choice of the number 5%?

L.482-488: Why do the authors not address the total days since frequency decreases when duration increases? In addition to the indicator “concurrency”, it would be great to address the time of MHW response and persistence after AHW. It seems the authors have developed the tools for that, it would provide interesting information.

L.522: “Future studies’” could be precised a bit, if possible.
Methods

ERA5 data

Mentioning monthly data is not useful since they are not used, right?

Detection

I do not understand why the AHWs are addressed only in summer when MHWs throughout the year.

L. 586: the reference period used is 1961-1990, “following the recommendations of the WMO”. Could you provide the source of such information? In a warming ocean, recommendations may have changed.

L.589: Please correct 1960-1990 to 1961-1990

L.591: “following the recommendation for the Mediterranean”. Could you explain in 1-2 sentences?

L.594-596: “Following the Hobday definition, we have also considered that two MHWs separated by less than three days are the same event”. I think that Hobday recommends two days, right? Please correct or explain.

L.611: why not use the same reference for AHW and MHW intensity to facilitate the comparison in this study?

Concurrence

L.631. Could you explain the choice of three days?

Table 1. I am not sure that this table is necessary since it is clear in the text.

Reviewer #2 (Remarks to the Author):

REVIEW
COMMSENV-24-1251

Title: Mediterranean marine heatwaves intensification in the presence of concurrent atmospheric heatwaves

This paper focuses on the changes of concurrence of marine and atmospheric heatwaves in the Mediterranean area. In this study, the authors propose an adaptation of the method introduced at Sun et al. (2023) for the Mediterranean. The subject discussed in the present article is of great importance, and the paper is well structured and easy to follow. Nevertheless, there are some minor points that need further detail. The introduction is very well written, and the references are recent, relevant, and well referred. The caveat of prior compound studies needs to be emphasized, and the main goal highlighted. Particularly, the differences to Sun et al. (2023) need emphasizing, and the novelty highlighted. Although the approach is not cpmpletely novel, it will be of interest to others in the community and the wider field. The discussion is very detailed and elucidating. A final paragraph reinforcing the main outcomes is lacking. The statistical approach is sound but needs some minor clarifications and tests. I truly congratulate the authors for this manuscript, which I believe that should be considered for publication after minor changes.

Below I discuss main comments and suggestions, which hopefully can help the authors to enhance the manuscript.

Major comments:

1. Introduction: The caveat on prior studies analysing compound MHW and AHW in the Mediterranean should be highlighted so the goal of the study is more evident. Is the main goal the new spatio-temporal approach or the analysis, or both? This is stated in the Methods section
“Definition and detection of concurrence for AMHWs
A previous definition of concurrent events47 that an AHW had to be encompassed by an MHW in coastal and land-adjacent grid points to be considered as concurrent while others62 do not introduce any explicit spatial requirement by using a grid-point-based approach, aggregating or averaging over all grid cells across the whole study area.”
and should be highlighted in the introduction.
2. Introduction: Remove the last sentence on the results.
3. Methods: How different would the results be if instead of using as reference for marine all year and and May-September period selection for AHW?
4. Methods: Why did you use 1961-1990 as a reference for AHW? Using a more recent period would significantly change the results. I understand that is one of the climatologies used as reference (https://community.wmo.int/en/wmo-climatological-normals). Please comment on this choice.
5. Methods: Did you test how using >P90 or >P95 for both MHW and AHW days would affect the results, instead of using P90 for MHW and P95 for AHW? Your approach is not comparing the same amount of days and that influences the overlap.
6. Methods: Table 1 could be substitute by a schematic diagram of the procedure.
7. Figure 1: the legend it is not self-explicative (Imean and Imax are only defined in the text and need to be here also), the fonts are too small. I can’t the shadowed area in the a) panel.
8. Figure 2: Acronyms not identified in the legend and font sizes too small.
9. Figure 2: Did you produce a similar figure but with points size denoting event intensity? What would that show?
10. Figure 3: The high percentages seen by compound events and AHW might reflect the fact that MHW are calculated using the all period of the year and not only the May-September period. Please check.

11. Abstract: Remove “due to anthropogenic climate change” as you do not test for it.

Minor comments:

1. Introduction: When you give examples of impacts on health,

“Public health is another crucial sector that has been impacted by temperature rise and AHW intensification in the Mediterranean; an evaluation of the mortality attributable to heat in Spain in the summer of 2022 showed excess mortality due to extreme heat around 4600 deaths26.”
reducing to what happens in Spain covers a minor part of the study area. Please give a couple of examples in the Mediterranean region.
2. Introduction: two important works from Simon et al. use different metrics and would be an important addition in terms of methods used to identify MHW:
- https://doi.org/10.1016/j.wace.2023.100619
- https://doi.org/10.3389/fmars.2022.892201

3. Methods: Mention the colors used in figure 8 in the text in section “Definition and detection of concurrence for AMHWs” so the reading is more intuitive.

4. Results and Figure 2: Acronyms of WMED, ASEA, EMED and MEDSEA appear the first time and are not introduced previously, nor even in the supplementary material.

5. Figure 3: Change the caption to easier interpretation (see underlined suggestions):

“Fig. 3: Percentage of May-September AHW-MHW concurrent days. Regional distribution of AHW and MHW concurrent days from the total AHW (top panel) and MHW (bottom panel) days in the May-September period (from left to right) for 1940-2022 and three 29-year periods (1940-1969,1966-1995 and 1993-2022).”
6. Results and Figure 4:
The text says: “Figure shows the boxplot and density distribution for Imean, Imax and ronset,” and the figure shows the variables written in full. Please check.

7. Spatiotemporal is written differently throughout the manuscript

Reviewer #3 (Remarks to the Author):

Subject: Review Report Submitted for Manuscript COMMSENV-24-1251
Dear Dr. Joy Merwin Monteiro and Dr. Heike Langenberg,
Thank you for the opportunity to review the manuscript titled "Mediterranean marine heatwaves intensification in the presence of concurrent atmospheric heatwaves" by Dr. Pastor and colleagues. I have completed my review and submitted my report through the system.
I appreciate the clear guidance provided on the review process and the focus on the scientific content. The manuscript presents a thorough analysis of the interplay between atmospheric and marine heatwaves, and I have provided detailed feedback and raised several questions, particularly regarding the availability of the code and data used in the study, which are crucial for ensuring the reproducibility of the results.
Please let me know if there is anything further required from my side.
Thank you once again for the opportunity to contribute to the review process.
Best regards,

Detailed Review Questions:
Abstract and Introduction
• Line 45-52 (Abstract): The abstract states that concurrent atmospheric and marine heatwaves (AHW and MHW) lead to an intensification of marine heatwaves but not atmospheric ones. Can the authors clarify the mechanisms or processes that specifically cause this intensification in MHWs? Is there any observational or model-based evidence that supports this differential impact?

• Lines 89-113 (Introduction, Pages 1-2): The introduction outlines the increased frequency and intensity of both AHWs and MHWs in the Mediterranean. However, it seems to rely heavily on previous studies. How does this study uniquely contribute to the existing body of knowledge? Could the authors explicitly highlight the novel aspects of their methodology or findings in relation to earlier work?

Methodology
• Line 225-240 (Methodology, Page 7): The authors introduce a new methodology for detecting MHWs based on their spatiotemporal evolution. How does this new method compare with existing methods in terms of accuracy and reliability? Are there any potential biases or limitations introduced by this new approach that could affect the results?

• Lines 537-622 (ERA5 Data and Detection Methods, Page 24): The study uses ERA5 data for temperature and SST analysis. Given the known limitations of reanalysis datasets, especially in representing extreme events, how do the authors account for these potential discrepancies? Have they performed any sensitivity analyses to assess the impact of data uncertainties on their findings?

Results and Interpretation
• Lines 223-258 (MHW and AHW Characterization, Page 8): The authors present basin-wide averages for MHWs and AHWs but acknowledge that these may mask regional variability. Could the authors provide more detailed regional analyses, particularly in areas like the Adriatic Sea, where the results indicate higher intensities? How do local oceanographic and atmospheric conditions contribute to these regional differences?

• Lines 269-302 (Trend Analysis, Page 10-11): The manuscript reports a significant positive trend in MHW maximum intensity, particularly in the last decades. Is this trend consistent across all subregions, or are there areas where the trend is weaker or even negative? How do the authors reconcile any discrepancies between their findings and those of previous studies?

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•Lines 422-535 (Discussion, Pages 20-22): The discussion centers on the intensification of MHWs during concurrent AHW events. Can the authors elaborate on the potential feedback mechanisms that might exist between these concurrent events? Could such feedbacks exacerbate the intensity or duration of future heatwaves in the Mediterranean or similar regions?
• Lines 503-531 (Impact on Surrounding Areas, Page 22): The manuscript suggests that the impact of MHW intensification could extend to surrounding non-concurrent areas. Could the authors quantify this extension? What are the potential ecological and socio-economic implications for these surrounding regions?

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• Lines 524-531 (Future Research Directions, Page 22): The authors mention future work on the physical processes at the sea-atmosphere interface. Could they provide more details on the specific questions or hypotheses they aim to test? How will these future studies build on the findings presented in this manuscript?

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• Line 702-870 (References, Pages 25-28): Ensure that all references are correctly formatted according to the journal's guidelines. Also, consider including a discussion of any recent studies that might have emerged since the manuscript was first submitted.

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Version 1:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

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Your revised manuscript titled "Mediterranean marine heatwaves intensification in the presence of concurrent atmospheric heatwaves." has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

EDITORIAL REQUESTS:

Please review our specific editorial comments and requests regarding your manuscript in the attached "Editorial Requests Table".

*****Please take care to match our formatting and policy requirements. We will check revised manuscript and return manuscripts that do not comply. Such requests will lead to delays. *****

Please outline your response to each request in the right hand column. Please upload the completed table with your manuscript files as a Related Manuscript file.

If you have any questions or concerns about any of our requests, please do not hesitate to contact me.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Alireza Bahadori, PhD
Associate Editor
Communications Earth & Environment

Joy Merwin Monteiro, PhD
Editorial Board Member
Communications Earth & Environment
orcid.org/0000-0002-3932-3603

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

I have really appreciated the detailed responses of the authors as well as the important work performed to revise the manuscript. I thank the authors very much for their rigorous work and scientific contribution. I recommend the publication of the manuscript without additional revision.

Reviewer #2 (Remarks to the Author):

The authors addressed all my comments and suggestions. I fully agree with the publication of the manuscript.

Reviewer #3 (Remarks to the Author):

Dear Authors,
Thank you for your comprehensive responses to the review comments and for addressing the suggestions thoughtfully. Your clarifications on the methodology, particularly regarding the spatiotemporal evolution of heatwaves and the choice of reference periods, have enhanced the robustness of the study. The adjustments made to the introduction, methodology explanations, and the additional references added provide further clarity and strengthen the manuscript.

I appreciate the detailed consideration you've given to ensure transparency and reproducibility, particularly in relation to data availability and the plans for code sharing. These efforts will undoubtedly be valuable for the research community and support future studies in this area.

Based on the revisions and responses provided, I am pleased to accept your responses and commend the improvements made to the manuscript.

Best regards,

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COMMSENV-24-1251: Answer to reviewers

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We would like to thank the reviewer for his general positive opinion on the work presented in our manuscript. We hope the answers and clarifications provided below will satisfy the questions raised contributing to an improved quality of the manuscript.

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The authors provide well-documented state-of-the-art. However, I would suggest being more concise in the introduction, in particular in the two first paragraphs.

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We thank the reviewer for pointing this out. We would like to point out that even though in this manuscript we analysed atmospheric and marine heatwaves in the whole Mediterranean as a well-known climate change hotspot and focus of some of our previous studies, our methodology and analysis can also be run in any other oceans.

Following the reviewer's suggestion we have included references for the readers in relation to the state-of-the-art in surrounding areas; there is abundant scientific literature on atmospheric heat waves in the mediterranean Europe, and to lesser extent in middle eastern countries and northern Africa. Thus, in order to expand the regional focus, new references have been added on this issue.

- Engdaw, M. M., Ballinger, A. P., Hegerl, G. C., & Steiner, A. K. (2022). Changes in temperature and heat waves over Africa using observational and reanalysis data sets. International Journal of Climatology, 42(2), 1165–1180. https://doi.org/10.1002/joc.7295
- Wu, Y., Li, S., Zhao, Q., Wen, B., Gasparrini, A., Tong, S., Overcenco, A., Urban, A., Schneider, A., Entezari, A., Vicedo-Cabrera, A. M., Zanobetti, A., Analitis, A., Zeka, A., Tobias, A., Nunes, B., Alahmad, B., Armstrong, B., Forsberg, B., … Guo, Y. (2022). Global, regional, and national burden of mortality associated with short-term temperature variability from 2000–19: a three-stage modelling study. *The*

Lancet Planetary Health, *6*(5), e410–e421. https://doi.org/10.1016/S2542-5196(22)00073-0

- Perkins-Kirkpatrick, S. E., & Lewis, S. C. (2020). Increasing trends in regional heatwaves. Nature Communications, 11(1), 1–8. https://doi.org/10.1038/s41467-020-16970-7

L.110-111. Please rephrase this sentence. Done

L.112. “largest trends for summer”. I suppose the authors precise “summer” because it is not the case for the rest of the year, is it true?

In the cited reference *“Dunn, R. J. H. et al. Development of an Updated Global Land In Situ-Based Data Set of Temperature and Precipitation Extremes: HadEX3. Journal of Geophysical Research: Atmospheres* ***125****, (2020)”* the *“Seasonal temperature indices”* section states:

“In Europe, MAM and JJA show the strongest increases, ***with the focus of the JJA increases being around the Mediterranean and Black Seas****, but for MAM it is western/Atlantic Europe that sees the largest increases”*

indicating the strength of temperature increase in the mediterranean area.

Additionally, we were interested in summer trends as it is the season encompassing the most intense and frequent atmospheric heatwaves (although AHWs can also appear in winter) in the Mediterranean area, especially because of their important impacts on human health. In the following sections we select the extended summer season (May-September) for our analysis based on previous work of the authors on AHW and health impact correlation. Other authors selected a different “extended summer season” depending on their study interests, such as Russo et al (2024) who were interested in summer season because of the high fire activity in the Mediterranean but decided to extend to the May-October period following the recent trends in the temporal expansion of the fire season.

- Santos, R., Russo, A., & Gouveia, C. M. (2024). Co-occurrence of marine and atmospheric heatwaves with drought conditions and fire activity in the Mediterranean region. *Scientific Reports*, *14*(1), 19233. https://doi.org/10.1038/s41598-024-69691-y

L.123. I would replace “intensification trend” by “increasing trend”. Done

L.114, 214 217, 506: please use the acronyms AHWs and MHWs, already defined. Done

L.153-155: the authors state “Although the mentioned studies have investigated the concurrence between AHWs and MHWs, they are limited to terrestrial AHWS and no concurrent assessments have been run, to our knowledge, over the ocean.” but then, L.185-188 they write “They found a statistically significant correlation between AHWs and MHWs frequencies and total days in the Eastern Mediterranean, but with regional differences; they also found an increase in the co-occurrence of AHW and MHW events frequency and total days”. It seems contradictory to me, it has been done in the eastern Mediterranean. Maybe the 3rd, 4th and 5th paragraphs could be better reorganized.

The reviewer is right to point out that the reading of these paragraphs may seem contradictory in this respect. The authors want to highlight that, unlike the relationship between terrestrial and marine atmospheric heat waves, in which spatial coincidence is neither required nor possible, but only temporal coincidence in nearby areas from coastal waters and coastal areas (Pathmeswaran et al, 2022) or sea-land at regional scales (Santos et al, 2024), which has been more extensively studied, the case of the concurrence of these phenomena over the sea, with a strict requirement of spatial coincidence, has been very scarcely analysed (Aboelkhair et al 2023). Moreover, the mentioned references, all of them not included in the introduction section, do not address the impact that concurrence has in AHWs and/or MHWs but just look for statistical and/or causal relationships between them, for common drivers or linkage, also with other extreme events such as droughts of wildfires.

A new reference to terrestrial AHW and MHW has been included (Santos et al 2024) and the reference Aboelkahir et al (2022) reference has been moved to the end of the third paragraph to avoid for such contradiction and try to show the paucity of scientific work on the subject.

L.190: I am not sure that the wording “not a single universally accepted” is appropriate. I would is that there is a commonly used methodology that allows addressing and comparing extreme events worldwide. However, given the global and ocean warming, new and complementary definitions are being used. Again, L. 196 “fully universal”, I suggest to rephrase and avoid repetitions when possible.

Following the reviewer’s suggestion we have removed the terms “universal” and “universally accepted”.

In this paragraph, we have tried to show the variety of (very similar) HW definitions that are in use in the scientific literature, that are also different to the ones used by the national meteorological services.

L.192: the authors write 90th percentile. But then, they use the 95th for AHWs. Please clarify.
To avoid confusion the reference to 90th percentile has been removed. Following the answer to the previous question, for AHWs we have used one of the many definitions used to assess atmospheric heat waves. In our case we have chosen the Spanish Met Service (AEMET) definition and applied the 95th percentile stated there. The mention to 90th percentile comes from Perkins et al (2013) as it is commonly, but not always, used. The authors have used this definition in previously published studies of AHWs as

- Paredes-Fortuny, L., Salvador, C., Vicedo-Cabrera, A. M., & Khodayar, S. (2024). Geographical Patterns in Mortality Impacts Due To Heatwaves of Different Characteristics in Spanish Cities. *GeoHealth*, *8*(8), e2024GH001092. https://doi.org/10.1029/2024GH001092
- Khodayar, S., & Paredes-Fortuny, L. (2024). Uneven evolution of regional European summer heatwaves under climate change. *Weather and Climate Extremes*, 43, 100648. https://doi.org/10.1016/j.wace.2024.100648
- Paredes-Fortuny, L., & Khodayar, S. (2023). Understanding the Magnification of Heatwaves over Spain: Relevant changes in the most extreme events. *Weather and Climate Extremes*, *42*. https://doi.org/10.1016/j.wace.2023.100631

L.205: “Could you precise the “minimum overlapping”?

In Sun et al (2023), they calculate *"the fraction of overlapped domain (FOD) between MHW units at two consecutive time steps"* that should not exceed a predefined threshold α. Then, for this parameter *"The value of α plays a central role in MHW tracking. On one hand, an overly large α may tend to incorrectly end the tracking process, making the duration of MHW events bias short but the number of MHW events bias high. The opposite is true for an overly small α. This is confirmed by the dependence of computed number and mean duration of MHW events on α derived from the OISST in the global ocean (Fig. 4). In this study, we set α = 0.5. Although such a single choice is unlikely to be optimal for all the MHW events, it is found that the number and mean duration of MHW events in the global ocean stay relatively stable for α < 0.7. Therefore, the uncertainty in α is unlikely to exert a substantial impact on the global MHW analysis."*

In our study we do not prescribe a minimum overlapping as the spatial continuity requirements in the MHW identification, and the minimum 5% of the basin spatial extensions assured the spatio-temporal continuity of the MHW events (see Methods section). In the supplementary material of our first submission (figure S4), the authors included a figure showing that the daily overlap of AHWs and MHWs was clearly above 75% in most cases.

L.216-219: The conclusion should not be stated in the introduction.

We agree with the reviewer and have removed these lines.

L.208-220: I strongly recommend to better highlight the novelty of this study.

The final introductory paragraph has undergone modification to clarify more explicitly the primary contribution of this study, which relates to the examination of the AHW and MHW compounding phenomenon itself.

Results and discussion

L.225-227: A new methodology is not an aim, it is a tool to reach the scientific objective(s). I suggest rephrasing/clarifying.

We agree with the reviewer that the development of a methodology is a tool to achieve a scientific objective. This line has changed from "The first aim of our study" to "The first step of our study".

L.235-238: "Our ImeanM and IcumM values are comparable but somewhat lower than the 1.60ºC and 24.70ºC values for the shorter 1982-2021 period which could indicate that the MHW intensity is not dependent on the detection algorithm, while the mean duration of MHWs is almost three many times larger in this new approach, as expected." Given the warming trend basis, I would think the contrary. In addition, the difference could be explained by the different periods of reference, not (only) the detection method.

We agree with the reviewer that the use of different reference period leads, inevitably, to different intensity values for MHWs but the results obtained are in good agreement with the values found in recent literature. It must be noted that the values discussed are mean and cumulative intensity which present lower temporal trends, both in our longer (1940-2022) temporal series and in the 1982-2021 period analysed in Pastor et al (2023). Major, and significant, changes in Mediterranean MHW intensity have been found (in our work but also in the cited literature in the manuscript) for the maximum intensity. Hence, our conclusion is that the main characteristics and tendencies associated with the intensity of marine heatwaves are not influenced by the employed detection algorithm.

Regarding the duration of MHWs, the conceptual framework of the new methodology (including the minimum spatial extent of 5% of the Mediterranean basin) forces a major duration as it follows the spatio-temporal evolution of the events.

Following the reviewer suggestion we have run the analysis with a different reference period (1991-2020) for MHWs; results are shown in the supplementary material Table S2. Most of the main characteristics show as expected slight differences, but comparable results to the previously found. The main impact of the new reference period yields a lower number of detected events (214 vs 344) as the threshold detection values are higher than the previous period and less days will exceed the detection threshold. Consequently, mean duration (22 vs 42) and persistence (11 vs 16) have also lower values. Mean and maximum size have also slightly reduced. With the new reference period the intensity related values are slightly higher than for the previous one, 10-15% for I_{mean} and 5%-11% for I_{max} depending on the subbasins. In a previous work by the authors (Pastor et al, 2020) it was determined that warming in the Mediterranean was mostly due to a stronger increase of the number of days with SST exceeding the higher percentiles for the 1982-2021 period (1982-2011 reference period), i.e. there are more extreme days in terms of SST in the last decades and less days with low intensity will be present during MHWs. Therefore, the global mean values for mean and maximum intensity of the associated MHWs will be higher (with higher increase for mean than maximum intensity), especially in the last decades when a higher intensity of MHWs has been detected, also with our methodology. Notably, the trends for I_{mean}/I_{max} show slightly lower/higher values but still positive and greater for Imax than Imean.

	1961-1990	1991-2020
Imax trend (ºC/decade)	0.13 +- 0.02	0.09 +- 0.01
Imean trend (ºC/decade)	0.04 +-0.01	0.06 +-0.01

L.238: three times larger

Changed

L.246-248: I am not sure to understand why both mean and median are indicated.

Median value has been removed from the text.

L.253-258: It is in agreement with results from previous studies using the “classical” method.

The reference from Pastor et al (2023) using the “classical” method for MHWs has been added.

L.288-290: “This divergence from values previously obtained in the scientific literature was foreseeable as the new methodology necessarily implied an increase in the duration of events and a consequent decrease in annual frequency”. As said before, I think that the differences could also be explained by the reference period used.

As discussed in the previous comment the use of different reference periods (table S2) shows principally an impact on detecting a lower number of MHW events with a shorter mean duration. Please see a more detailed discussion in the aforementioned answer.

Looking specifically at MHW duration, point-based methodologies without any minimum spatial requirement, can yield a notably greater number of events including small areas or isolated pixels that could be considered more warm spikes than impactful MHW events. In Pastor et al (2023) it was shown that considering events smaller than 5% of

the basin had a minor impact on the characterization of mean MHW magnitudes nor in their trends.

Our methodology follows the spatiotemporal evolution of MHW events that evolve, change shape, extend, or move through the basin. This necessarily implies a longer duration as, i.e. a spatially minor event that could be considered as a different and shorter one can be merged into a bigger one that evolves through the basin. MHW events can dissipate far apart from their onset area by moving across the basin having a longer duration than if different events were considered from a point-based detection.

L.294-303: Why do the authors not address the duration here whereas the duration trends are introduced and commented on in the previous paragraph?

Since the spatiotemporal evolution of a MHW event is considered in our methodology, we believe that it is not feasible to assess the spatial variability of the duration. In our framework, duration is not associated with a grid point, but it is a "moving" parameter following the event, unlike intensity, which depends on the warming experienced at a particular location, although the subsequent characterisation of MHW requires spatial averaging.

L.318: "is a consequence of the new dynamical definition used in the MHW detection applied in this work." See the previous comment about the reference period. Same concern L. 444.

The same argumentation in the previous answer for the increased duration of MHWs can be applied to the consequently reduced annual frequency. Changing the reference period has led to a lower number of events detected but still with a higher duration (see supplementary table S2) than in previous work of the authors in Mediterranean MHWs, with a different reference period (1982-2011) and with the mostly used Hobday methodology, and consequently with lower annual frequency.

L.319: "longer lasting and larger MHW events which then reduce the annual count". The same argumentation in the previous answer for the increased duration of MHWs can be applied to the consequently reduced annual frequency.

L. 322: associated with

Changed

Discussion

L. 431: Could you explain the choice of the number 5%?

This threshold is based on previous work by Pastor and Khodayar (2023) where they state:

"Different area thresholds were checked, 2.5% and 10%, to evaluate their suitability. In the latter case, too many MHW events were removed hence reducing too much of the data population, so no adequate analysis was possible. With respect to the 2.5 % threshold, the 5 % threshold reduced the number of MHW to almost 23 % with a 65 % increase in the mean number of grid points affected. Primary MHW characteristics did not show noticeable changes for 2.5 and 5 % thresholds with mean duration only increasing by 3% and mean intensities changes ranging from 6 to 8%. The authors

understand that these minor changes in MHW characteristics would not affect the assessment of long-term trends."

"In our work, we have established a 5 % area threshold for the whole Mediterranean, that has also been applied to the different sub-basins. The application of this limit drastically reduced the MHW population by retaining the major events that could have a significant impact on the air-sea fluxes or on marine life in the basin. In our study, the number of possible MHWDs, understood as the sum of the number of days on which some point(s) in the catchment show SST exceeding its local 90th percentile likely to be part of a MHW, for the whole Mediterranean basin is reduced from 16 % to 0.005 %. The authors consider that this limit considerably reduces noise signal in the MHW data series and focuses the analysis on those events whose impact is of interest."

- Pastor, F., & Khodayar, S. (2023). Marine heat waves: Characterizing a major climate impact in the Mediterranean. *Science of the Total Environment*, *861*. https://doi.org/10.1016/j.scitotenv.2022.160621

L.482-488: Why do the authors not address the total days since frequency decreases when duration increases? In addition to the indicator "concurrency", it would be great to address the time of MHW response and persistence after AHW. It seems the authors have developed the tools for that, it would provide interesting information.

Referring to MHWs, independently from concurrence, we defined duration as the sum of total days. As MHWs evolve in time and space, duration accounts for the total number of days when points included in the event experienced SST above the corresponding threshold, at some time. In this work, our main aim is to assess the concurrency and its possible impacts on AHWs and MHWs so the relevant trend, for us, is the concurrency trend.

The analysis of the processes of MHW response to AHW concurrence is out of the scope of this work. The authors have been working on this issue and are now preparing a new manuscript for publication which we hope will be published in the next months and will provide interesting information on the interactions between MHWs and AHWs in the case of concurrency, with a main focus in energy and moisture fluxes in the air-sea interface.

L.522: "Future studies'" could be precised a bit, if possible.

Please see the last part of the answer to the previous question.

Methods

ERA5 data

Mentioning monthly data is not useful since they are not used, right?

Mention to monthly data has been removed.

Detection

I do not understand why the AHWs are addressed only in summer when MHWs throughout the year.

This was done following previous works in which AHWs were assessed at the Iberian Peninsula and European scales. The majority of AHWs were recorded in the "extended summer period" from May to September. AHWs are typically investigated over land, as

the authors did in recently published studies, where the largest impact on society and the ecosystems is observed in summer. In the present study, we aim to extend the AHW land analysis to the sea with an analogous definition based on the exceedance of a threshold defined as the 95th percentile of May-Sep temperatures. This threshold is rarely exceeded outside the May-Sep period. Other authors selected a different "extended summer season" depending on their study interests, such as Russo et al (2024) who were interested in the summer season because of the high fire activity in the Mediterranean but decided to extend to the May-October period following the recent trends in the temporal expansion of the fire season.

MHWs are events with much longer duration than AHWs and our methodology follows the whole event life cycle that could easily extend far beyond the "extended summer season". Excluding the rest of the year could affect the results, in terms of MHW characterization and trends, and would not be consistent with our methodology.

L. 586: the reference period used is 1961-1990, "following the recommendations of the WMO". Could you provide the source of such information? In a warming ocean, recommendations may have changed.

The WMO climatological normal (https://community.wmo.int/en/wmo-climatological-normals) states that, although the most-recent 30-year period finishing in a year ending with 0 should be used in recent climate analysis, "the period from 1961 to 1990 has been retained as a standard reference period for long-term climate change assessments". As we were interested in the concurrence of atmospheric and oceanic events and their long-term changes, we applied the same reference period for both phenomena.

Following the reviewers' advice, we have also run the analysis by changing the reference period to 1991-2020 recommended by the WMO for recent climate analysis. Please see the discussion on the new results above (question on lines 235-238). The use of a second reference period has mainly affected the number of detected MHWs and their mean duration, with less impact on their intensity.

L.589: Please correct 1960-1990 to 1961-1990

Changed

L.591: "following the recommendation for the Mediterranean". Could you explain in 1-2 sentences?
As mentioned in previous answers, the 5% threshold selection is based on the work by Pastor and Khodayar (2023) that discussed the adequacy of this minimum spatial requirement for the assessment of MHWs in the Mediterranean.

- Pastor, F., & Khodayar, S. (2023). Marine heat waves: Characterizing a major climate impact in the Mediterranean. *Science of the Total Environment*, *861*. https://doi.org/10.1016/j.scitotenv.2022.160621

L.594-596: "Following the Hobday definition, we have also considered that two MHWs separated by less than three days are the same event". I think that Hobday recommends two days, right? Please correct or explain.

Indeed, Hobday et al (2016) state that "*gaps between events of two days or less with subsequent five day or more events will be considered as a continuous event"* which is what we meant to be "less than three days". The text has been changed to accurately reflect the statement in Hobday.

L.611: why not use the same reference for AHW and MHW intensity to facilitate the comparison in this study?

Our main objective was not to compare AHWs and MHWs, nor to characterize them or their trends, although it was done for completion, but to analyse their concurrence. For the detection of HW events we have followed AHW and MHW definitions already present in the literature and the magnitudes usually used for their characterization, so our results could be compared with other studies from different authors both for AHWs and MHWs independently.

Concurrence

L.631. Could you explain the choice of three days?

We chose three days as it was the minimum duration of stablished for AHWs, in this way, we ensure that AHW events considered in the concurrency always meet the requirements of their definition within the concurrency period. A short AHW event of three days encompassed in an MHW will be considered but the 1-2 days head or tail of an AHW will not. This is intended to avoid spurious results where there is hardly any concurrency.

Table 1. I am not sure that this table is necessary since it is clear in the text.

Table 1 has been removed

New references added

- Santos, R., Russo, A., & Gouveia, C. M. (2024). Co-occurrence of marine and atmospheric heatwaves with drought conditions and fire activity in the Mediterranean region. *Scientific Reports*, *14*(1), 19233. https://doi.org/10.1038/s41598-024-69691-y
- Perkins, S. E. (2015). A review on the scientific understanding of heatwaves—Their measurement, driving mechanisms, and changes at the global scale. Atmospheric Research, 164–165, 242–267. https://doi.org/10.1016/j.atmosres.2015.05.014
- Mistry, M. N., Schneider, R., Masselot, P., Royé, D., Armstrong, B., Kyselý, J., Orru, H., Sera, F., Tong, S., Lavigne, É., Urban, A., Madureira, J., García-León, D., Ibarreta, D., Ciscar, J.-C., Feyen, L., de Schrijver, E., de Sousa Zanotti Stagliorio Coelho, M., Pascal, M., … Gasparrini, A. (2022). Comparison of weather station and climate reanalysis data for modelling temperature-related mortality. *Scientific Reports*, *12*(1), 1–14. https://doi.org/10.1038/s41598-022-09049-4
- Santos, R., Russo, A., & Gouveia, C. M. (2023). *Concurrent Marine and Atmospheric Heatwaves and Droughts and their Influence on Fire Activity in the Mediterranean Region* (M. G. Pereira, R. Oliveira, P. Navarro, & L. Bugalho, Eds.).
- Simon, A., Plecha, S. M., Russo, A., Teles-Machado, A., Donat, M. G., Auger, P. A., & Trigo, R. M. (2022). Hot and cold marine extreme events in the Mediterranean over the period 1982-2021. Frontiers in Marine Science, 9. https://doi.org/10.3389/fmars.2022.892201

- Simon, A., Pires, C., Frölicher, T. L., & Russo, A. (2023). Long-term warming and interannual variability contributions' to marine heatwaves in the Mediterranean. *Weather and Climate Extremes*, *42*. https://doi.org/10.1016/j.wace.2023.100619
- Gallo, E., Quijal-Zamorano, M., Méndez Turrubiates, R. F., Tonne, C., Basagaña, X., Achebak, H., & Ballester, J. (2024). Heat-related mortality in Europe during 2023 and the role of adaptation in protecting health. Nature Medicine. https://doi.org/10.1038/s41591-024-03186-1
- Vicedo-Cabrera, A. M., Scovronick, N., Sera, F., Royé, D., Schneider, R., Tobias, A., Astrom, C., Guo, Y., Honda, Y., Hondula, D. M., Abrutzky, R., Tong, S., Coelho, M. de S. Z. S., Saldiva, P. H. N., Lavigne, E., Correa, P. M., Ortega, N. V., Kan, H., Osorio, S., … Gasparrini, A. (2021). The burden of heat-related mortality attributable to recent human-induced climate change. Nature Climate Change, 11(6), 492–500. https://doi.org/10.1038/s41558-021-01058-x
- Wu, Y. *et al.* Global, regional, and national burden of mortality associated with short-term temperature variability from 2000–19: a three-stage modelling study. *Lancet Planet Health* **6**, e410–e421 (2022).

Reviewer #2 (Remarks to the Author):

REVIEW
COMMSENV-24-1251

Title: Mediterranean marine heatwaves intensification in the presence of concurrent atmospheric heatwaves

This paper focuses on the changes of concurrence of marine and atmospheric heatwaves in the Mediterranean area. In this study, the authors propose an adaptation

of the method introduced at Sun et al. (2023) for the Mediterranean. The subject discussed in the present article is of great importance, and the paper is well structured and easy to follow. Nevertheless, there are some minor points that need further detail. The introduction is very well written, and the references are recent, relevant, and well referred. The caveat of prior compound studies needs to be emphasized, and the main goal highlighted. Particularly, the differences to Sun et al. (2023) need emphasizing, and the novelty highlighted. Although the approach is not cpmpletely novel, it will be of interest to others in the community and the wider field. The discussion is very detailed and elucidating. A final paragraph reinforcing the main outcomes is lacking. The statistical approach is sound but needs some minor clarifications and tests. I truly congratulate the authors for this manuscript, which I believe that should be considered for publication after minor changes.

Below I discuss main comments and suggestions, which hopefully can help the authors to enhance the manuscript.

We thank the reviewer for the positive feedback on our manuscript. We have considered thoroughly all the questions and comments that for sure will improve the final version of the manuscript.

In relation to the previous work on Sun et al. we found this reference once our methodology was developed, results obtained, and we had started writing the article. Both the conception of the methodology and the work carried out subsequently are independent of the work of Sun et al. Once we became aware of this work, we considered that it should be included among the references, even at the risk of the reviewers calling into question the novelty of our methodology. In any case, we recall its originality and novelty as it was developed without any previous knowledge of the work of Sun. This will allow for future comparison and validation of results from both methodologies. This comparison cannot be carried out in this work due to the spatial conditions of Sun's method which do not make it applicable to a marginal sea such as the Mediterranean. The development of a methodology is not the main aim of our study but a necessary step towards the actual objective of analysing the concurrence between AHWs and MHWs.

Differences between the two methodologies are explained below in the answer to the reviewer. The main differences between Sun and our methodology have also been highlighted in the *Methods-Detection of AHW and MHW events* section:

"Although we follow a similar spatiotemporal approach to the proposed by Sun[77] there are some differences that should be highlighted. For the spatial continuity Sun uses the K nearest neighbour algorithm, dependent on non-predefined optimal K-parameter, considering an event if more than half of its k-nearest grid cells are identified as MHW irrespective of the total event size but then applying a 5ºx5º filtering to discard small scale events, while in our methodology we look for clusters of contiguous points, without requiring any minimum amount of points, meeting MHW conditions and occupying at least 5% of the Mediterranean basin. To assess the temporal continuity of MHWs Sun's method is based on the calculation of the event overlapping area between consecutive days that has to exceed a parameter value ranging from 0 to 1, set to 0.5 in their work but that should not exceed 0.7 as a universal single choice would not be optimal for all MHW events. In our methodology no minimum spatial overlapping is required between consecutive days. The iterative application of the algorithm requiring the minimum spatial size for the MHW event ensures the continuity of the events; the calculation of the probability density function of the overlap yields overlapping areas bigger than 75% (see supplementary figure S4). The application of our methodology relies on the determination

of the minimum extent to consider an event, in our case 5% of the Mediterranean, which will have to be re-evaluated especially in larger basins."

Major comments:

1. Introduction: The caveat on prior studies analysing compound MHW and AHW in the Mediterranean should be highlighted so the goal of the study is more evident. Is the main goal the new spatio-temporal approach or the analysis, or both? This is stated in the Methods section

"Definition and detection of concurrence for AMHWs

A previous definition of concurrent events47 that an AHW had to be encompassed by an MHW in coastal and land-adjacent grid points to be considered as concurrent while others62 do not introduce any explicit spatial requirement by using a grid-point-based approach, aggregating or averaging over all grid cells across the whole study area." and should be highlighted in the introduction.

The main objective of this manuscript is to analyze the interaction between AHW and MHW events assessing the potential implications that their simultaneous spatiotemporal occurrence may have on their primary attributes. For this analysis, following the previous work of the authors on MHW and considering the existing gap in related scientific research, we considered that it was necessary to develop a new methodology for the detection of MHWs that would consider their spatiotemporal evolution. In the same way, we did not find references to the concurrence of both phenomena over the oceans, so we developed a new definition for concurrence. The definition in Pathmeswaran et al (2022) was devoted to AHWs over land, which is different from the phenomenon analysed in our work, while Aboelkahir et al (2023) use the same definition of Pathmeswaran but from a point-based approach and taking into account any spatial/size restriction and aggregating results over the whole Eastern Mediterranean.

Changes have been made to the Introduction section to reflect the lack of studies on HW concurrence in the Mediterranean to highlight the novelty of our work. We have also cited recent works on HWs, and their health impacts, in the Mediterranean area to expand the focus from a more southern European point of view to the whole region. We have also removed the last lines of the section that showed some results discussed later in the manuscript.

2. Introduction: Remove the last sentence on the results.

Removed.

3. Methods: How different would the results be if instead of using as reference for marine all year and and May-September period selection for AHW?

The May-September period encompasses the vast majority of AHWs in Southern Europe/Iberian Peninsula, from previous works from the authors (see below), and extending the analysis to the whole year will not significantly change main results on AHWs. The May-September period for the AHWs is chosen based on the AHW definition used in the present study. AHWs are identified as three or more days of air temperature exceedance of the 95th percentile of May-September temperature, which makes it highly unlikely to find AHWs outside this period. Therefore, considering the temperature distribution through the year, the number of cases when air temperature would surpass

this threshold (and the other AHW requirements would be simultaneously met) is so small that would not have an impact in our statistics.

MHWs need to be analysed for the whole year as they have been progressively increasing their duration and frequency, especially in the last years, extending far beyond the May-September period. As MHWs have usually longer duration than AHWs, a strict temporal restriction from May to September would lead to an artificial shortening, without a solid justification behind, of continuous events starting before or ending after the period under analysis which would make the results less reliable, especially in recent years.

- Paredes-Fortuny, L., Salvador, C., Vicedo-Cabrera, A. M., & Khodayar, S. (2024). Geographical Patterns in Mortality Impacts Due to Heatwaves of Different Characteristics in Spanish Cities. *GeoHealth*, *8*(8), e2024GH001092. https://doi.org/10.1029/2024GH001092
- Khodayar, S., & Paredes-Fortuny, L. (2024). Uneven evolution of regional European summer heatwaves under climate change. *Weather and Climate Extremes*, 43, 100648. https://doi.org/10.1016/j.wace.2024.100648
- Paredes-Fortuny, L., & Khodayar, S. (2023). Understanding the Magnification of Heatwaves over Spain: Relevant changes in the most extreme events. *Weather and Climate Extremes*, *42*. https://doi.org/10.1016/j.wace.2023.100631

In different studies from other authors, different analysis periods have been used for the analysis of MHWs depending on their objectives.

- Simon, A., Pires, C., Frölicher, T. L., & Russo, A. (2023). Long-term warming and interannual variability contributions' to marine heatwaves in the Mediterranean. *Weather and Climate Extremes*, *42*. https://doi.org/10.1016/j.wace.2023.100619
- Simon, A., Plecha, S. M., Russo, A., Teles-Machado, A., Donat, M. G., Auger, P. A., & Trigo, R. M. (2022). Hot and cold marine extreme events in the Mediterranean over the period 1982-2021. Frontiers in Marine Science, 9. https://doi.org/10.3389/fmars.2022.892201
- Darmaraki, S., Somot, S., Sevault, F., & Nabat, P. (2019). Past Variability of Mediterranean Sea Marine Heatwaves. Geophysical Research Letters, 46(16), 9813–9823. https://doi.org/10.1029/2019GL082933

and the most intense events dominantly occur in summer

- sen Gupta, A., Thomsen, M., Benthuysen, J. A., Hobday, A. J., Oliver, E., Alexander, L. v., Burrows, M. T., Donat, M. G., Feng, M., Holbrook, N. J., Perkins-Kirkpatrick, S., Moore, P. J., Rodrigues, R. R., Scannell, H. A., Taschetto, A. S., Ummenhofer, C. C., Wernberg, T., & Smale, D. A. (2020). Drivers and impacts of the most extreme marine heatwaves events. *Scientific Reports*, *10*(1). https://doi.org/10.1038/s41598-020-75445-3

4. Methods: Why did you use 1961-1990 as a reference for AHW? Using a more recent period would significantly change the results. I understand that is one of the climatologies used as reference (https://community.wmo.int/en/wmo-climatological-normals). Please comment on this choice.

In the WMO climatological normal (https://community.wmo.int/en/wmo-climatological-normals) it is stated that, although the recent 30-year period finishing in a year ending with 0 should be used in recent climate analysis, "the period from 1961 to 1990 has been

retained as a standard reference period for long-term climate change assessments". As we were interested in the concurrence of atmospheric and oceanic events, and their long-term changes, we have applied the same reference period for both types of events.

Following the reviewer's suggestion we have run the analysis with a different reference period (1991-2020); results are shown in the supplementary material Table S2. Most of the main characteristics show slightly different, but comparable, results to the previously found. The main impact of the new reference period is a lower number of detected events (214 vs 344) and reduced duration (22 vs 42) and persistence (11 vs 16). Mean and maximum size also slightly reduced while the intensity-related values are higher for the new reference period. Notably, the trends for Imean/Imax show slightly lower/higher values but are still positive and greater for Imax than Imean.

5. Methods: Did you test how using >P90 or >P95 for both MHW and AHW days would affect the results, instead of using P90 for MHW and P95 for AHW? Your approach is not comparing the same amount of days and that influences the overlap.

We agree that the use of different percentiles would affect the results in the identification of HW events, especially the number of events. When building the detection methodology our focus was on the spatiotemporal evolution rather than on the adequacy of the thresholds, which is addressed in the literature. We decided to strictly follow MHW and AHW definitions already described and established in previous scientific literature. To assess the effect of these or other adjustments to the definition of HW events, a review and comparison of the different definitions in the scientific literature should be carried out. It was not our aim to set a new definition of HW events regarding temperature thresholds, extensively studied in the literature, but to study the impact of concurrency. As the conceptualization of the work was being carried out, and based on previous research (Pastor and Khodayar, 2023) we decided to develop a new approach to MHW identification to consider the event spatio-temporal evolution.

- Pastor, F., & Khodayar, S. (2023). Marine heat waves: Characterizing a major climate impact in the Mediterranean. *Science of the Total Environment*, *861*. https://doi.org/10.1016/j.scitotenv.2022.160621

Regarding the different number of days for AHW and MHW events, once the events are observed in the same temporal period, we strictly check their concurrence and overlap to identify them as concurrent events without taking into account the difference in their definitions. We overlap AHW days with MHW days, irrespective of the definition used to define them. We established a minimum of three days overlap, independent of the event duration, as it is the minimum duration for an atmospheric temperature event to be considered such as AHW. In this case, the shortest possible AHWs encompassed by an MHW are included in the analyses while just the head or tail of an AHW, which could not be independently considered as AHW, but coinciding with the MHW are removed from the analysis.

6. Methods: Table 1 could be substitute by a schematic diagram of the procedure.

Table 1 has been removed as the algorithm is well explained in the text (suggestion from reviewer 1).

7. Figure 1: the legend it is not self-explicative (Imean and Imax are only defined in the text and need to be here also), the fonts are too small. I can't the shadowed area in the a) panel.

All graphs have been developed following the same graphical standard. To improve readability, we have enlarged axis fonts. Shadowed area is very narrow, especially in the case of MHWs, and mostly overlapped by the red line. Trend line (red) is narrower in this version so the shadowed area (now changed to represent 95% confidence interval) can be more clearly seen in the upper left panel.

8. Figure 2: Acronyms not identified in the legend and font sizes too small.

Acronyms now included in the caption and font sizes are now larger

9. Figure 2: Did you produce a similar figure but with points size denoting event intensity? What would that show?

We thank the reviewer for this suggestion and have included the suggested plot as Figure 5 and discussed in *"Intensification of MHWs in the presence of AHWs"* section

"The HWs global intensification presents a growing trend for AHWs and MHWs for the whole Mediterranean and subbasins (Figure 5) during the study period. Maximum intensity shows a global increase from the beginning of the study period which is more intense since 2000 for the concurrent events and especially for MHWs. For AHWs a similar variability can be seen for non-concurrent events throughout the study period in all basins, but concurrent ones present larger variability, towards higher values, in the last decades. MHWs non concurrent events show almost no trend in the long-term while a notable positive trend has been found for concurrent ones since the late 90's decade or 2000, especially in the ASEA where the highest values were observed."

10. Figure 3: The high percentages seen by compound events and AHW might reflect the fact that MHW are calculated using the all period of the year and not only the May-September period. Please check.

Figure 3 shows percentages of days only in the May-September period, the only months when concurrence is possible because of the AHW period detection, so MHWs outside this period do not affect this percentage. We believe that the higher percentages in the last decades are mostly due to the Mediterranean Sea warming and the consequent increase of MHW days frequency, and MHW duration, rather than the May-September period.

11. Abstract: Remove "due to anthropogenic climate change" as you do not test for it. Removed

Minor comments:

1. Introduction: When you give examples of impacts on health,

"Public health is another crucial sector that has been impacted by temperature rise and AHW intensification in the Mediterranean; an evaluation of the mortality attributable to heat in Spain in the summer of 2022 showed excess mortality due to extreme heat around 4600 deaths26." reducing to what happens in Spain covers a minor part of the study area. Please give a couple of examples in the Mediterranean region.

New references on temperature health impact in the Mediterranean region have been included in the introduction section.

- Gallo, E. *et al.* Heat-related mortality in Europe during 2023 and the role of adaptation in protecting health. *Nat Med* (2024) doi:10.1038/s41591-024-03186-1.
- Wu, Y. *et al.* Global, regional, and national burden of mortality associated with short-term temperature variability from 2000–19: a three-stage modelling study. *Lancet Planet Health* **6**, e410–e421 (2022).
- Vicedo-Cabrera, A. M. *et al.* The burden of heat-related mortality attributable to recent human-induced climate change. *Nat Clim Chang* **11**, 492–500 (2021).

2. Introduction: two important works from Simon et al. use different metrics and would be an important addition in terms of methods used to identify MHW:
- https://doi.org/10.1016/j.wace.2023.100619

-https://doi.org/10.3389/fmars.2022.892201
References have been included in the introduction section

3. Methods: Mention the colors used in figure 8 in the text in section "Definition and detection of concurrence for AMHWs" so the reading is more intuitive. Done

4. Results and Figure 2: Acronyms of WMED, ASEA, EMED and MEDSEA appear the first time and are not introduced previously, nor even in the supplementary material. Revised

5. Figure 3: Change the caption to easier interpretation (see underlined suggestions): "Fig. 3: Percentage of May-September AHW-MHW concurrent days. Regional distribution of AHW and MHW concurrent days from the total AHW (top panel) and MHW (bottom panel) days in the May-September period (from left to right) for 1940-2022 and three 29-year periods (1940-1969,1966-1995 and 1993-2022)." Done

6. Results and Figure 4:

The text says: "Figure shows the boxplot and density distribution for Imean, Imax and ronset," and the figure shows the variables written in full. Please check.
Figure caption has been rewritten to better illustrate the figure

7. Spatiotemporal is written differently throughout the manuscript Revised

New references added

- Santos, R., Russo, A., & Gouveia, C. M. (2024). Co-occurrence of marine and atmospheric heatwaves with drought conditions and fire activity in the Mediterranean region. *Scientific Reports*, *14*(1), 19233. https://doi.org/10.1038/s41598-024-69691-y
- Perkins, S. E. (2015). A review on the scientific understanding of heatwaves—Their measurement, driving mechanisms, and changes at the global scale. Atmospheric Research, 164–165, 242–267. https://doi.org/10.1016/j.atmosres.2015.05.014
- Mistry, M. N., Schneider, R., Masselot, P., Royé, D., Armstrong, B., Kyselý, J., Orru, H., Sera, F., Tong, S., Lavigne, É., Urban, A., Madureira, J., García-León, D., Ibarreta, D., Ciscar, J.-C., Feyen, L., de Schrijver, E., de Sousa Zanotti Stagliorio Coelho, M., Pascal, M., … Gasparrini, A. (2022). Comparison of weather station and climate reanalysis data for modelling temperature-related

mortality. *Scientific Reports*, *12*(1), 1–14. https://doi.org/10.1038/s41598-022-09049-4

- Santos, R., Russo, A., & Gouveia, C. M. (2023). *Concurrent Marine and Atmospheric Heatwaves and Droughts and their Influence on Fire Activity in the Mediterranean Region* (M. G. Pereira, R. Oliveira, P. Navarro, & L. Bugalho, Eds.).
- Simon, A., Plecha, S. M., Russo, A., Teles-Machado, A., Donat, M. G., Auger, P. A., & Trigo, R. M. (2022). Hot and cold marine extreme events in the Mediterranean over the period 1982-2021. Frontiers in Marine Science, 9. https://doi.org/10.3389/fmars.2022.892201
- Simon, A., Pires, C., Frölicher, T. L., & Russo, A. (2023). Long-term warming and interannual variability contributions' to marine heatwaves in the Mediterranean. *Weather and Climate Extremes*, *42*. https://doi.org/10.1016/j.wace.2023.100619
- Gallo, E., Quijal-Zamorano, M., Méndez Turrubiates, R. F., Tonne, C., Basagaña, X., Achebak, H., & Ballester, J. (2024). Heat-related mortality in Europe during 2023 and the role of adaptation in protecting health. Nature Medicine. https://doi.org/10.1038/s41591-024-03186-1
- Vicedo-Cabrera, A. M., Scovronick, N., Sera, F., Royé, D., Schneider, R., Tobias, A., Astrom, C., Guo, Y., Honda, Y., Hondula, D. M., Abrutzky, R., Tong, S., Coelho, M. de S. Z. S., Saldiva, P. H. N., Lavigne, E., Correa, P. M., Ortega, N. V., Kan, H., Osorio, S., … Gasparrini, A. (2021). The burden of heat-related mortality attributable to recent human-induced climate change. Nature Climate Change, 11(6), 492–500. https://doi.org/10.1038/s41558-021-01058-x
- Wu, Y. *et al.* Global, regional, and national burden of mortality associated with short-term temperature variability from 2000–19: a three-stage modelling study. *Lancet Planet Health* **6**, e410–e421 (2022).

Reviewer #3 (Remarks to the Author):

Subject: Review Report Submitted for Manuscript COMMSENV-24-1251
Dear Dr. Joy Merwin Monteiro and Dr. Heike Langenberg,

Thank you for the opportunity to review the manuscript titled "Mediterranean marine heatwaves intensification in the presence of concurrent atmospheric heatwaves" by Dr. Pastor and colleagues. I have completed my review and submitted my report through the system.
I appreciate the clear guidance provided on the review process and the focus on the scientific content. The manuscript presents a thorough analysis of the interplay between atmospheric and marine heatwaves, and I have provided detailed feedback and raised several questions, particularly regarding the availability of the code and data used in the study, which are crucial for ensuring the reproducibility of the results. Please let me know if there is anything further required from my side.

Thank you once again for the opportunity to contribute to the review process. Best regards,

We appreciate the time and effort dedicated by the reviewer on revising our manuscript. We also want to thank the reviewer for the positive feedback on our work and will try to address all questions to improve the final version.

Detailed Review Questions:

Abstract and Introduction

• Line 45-52 (Abstract): The abstract states that concurrent atmospheric and marine heatwaves (AHW and MHW) lead to an intensification of marine heatwaves but not atmospheric ones. Can the authors clarify the mechanisms or processes that specifically cause this intensification in MHWs? Is there any observational or model-based evidence that supports this differential impact?

The mechanisms leading to the MHW intensification are out of the scope of this work. The authors have been working in the last months on the analysis of reanalysis and observational data to assess these processes which results are the basis of a new publication.

• Lines 89-113 (Introduction, Pages 1-2): The introduction outlines the increased frequency and intensity of both AHWs and MHWs in the Mediterranean. However, it seems to rely heavily on previous studies. How does this study uniquely contribute to the existing body of knowledge? Could the authors explicitly highlight the novel aspects of their methodology or findings in relation to earlier work?

In recent years, many studies have addressed the trends of AHWs and MHWs, separately, in the Mediterranean region, including relevant contributions previously published by the authors. The aim of this study goes beyond this aspect and focuses on understanding the impact of the concurrence of both extreme events on their characteristics. With this novel study, we contribute to bridging an existing gap in the literature, given the lack of similar studies over the whole Mediterranean basin and very few on the relationship between AHWs and MHWs, most related to terrestrial AHWs (see references cited in the introduction). Another novelty of our study which allows us to achieve our overarching aim is the development of a new tool for the MHWs detection that considers the spatiotemporal evolution tracking of HWs.

Methodology

• Line 225-240 (Methodology, Page 7): The authors introduce a new methodology for detecting MHWs based on their spatiotemporal evolution. How does this new method compare with existing methods in terms of accuracy and reliability? Are there any potential biases or limitations introduced by this new approach that could affect the results?

The authors believe that, as shown in the ***Results and Discussion – MHW and AHW characterization and trends in the Mediterranean*** section, our results are consistent in terms of accuracy and reliability by comparison with previous scientific literature. The major bias in our results from previous independent studies comes up for the MHW events duration because of the spatiotemporal tracking through the event lifecycle. The conceptual framework of the new methodology forces a major duration as it follows the

spatiotemporal evolution of the events, merging what other methodologies could consider different (smaller scale) events. To evaluate the impact of using a different reference period, we have run the analysis for the 1991-2020 period. Results are shown in the supplementary material Table S2. Most of the main characteristics show slightly different, but comparable, results to the previously found. The main impact of the new reference period yields a lower number of detected events (214 vs 344) and has reduced the duration (22 vs 42) and persistence (11 vs 16). Mean and maximum size has also slightly reduced while the intensity-related values are higher for the new reference period. Notably, the trends for Imean/Imax show slightly lower/higher values but are still positive and greater for Imax than Imean.

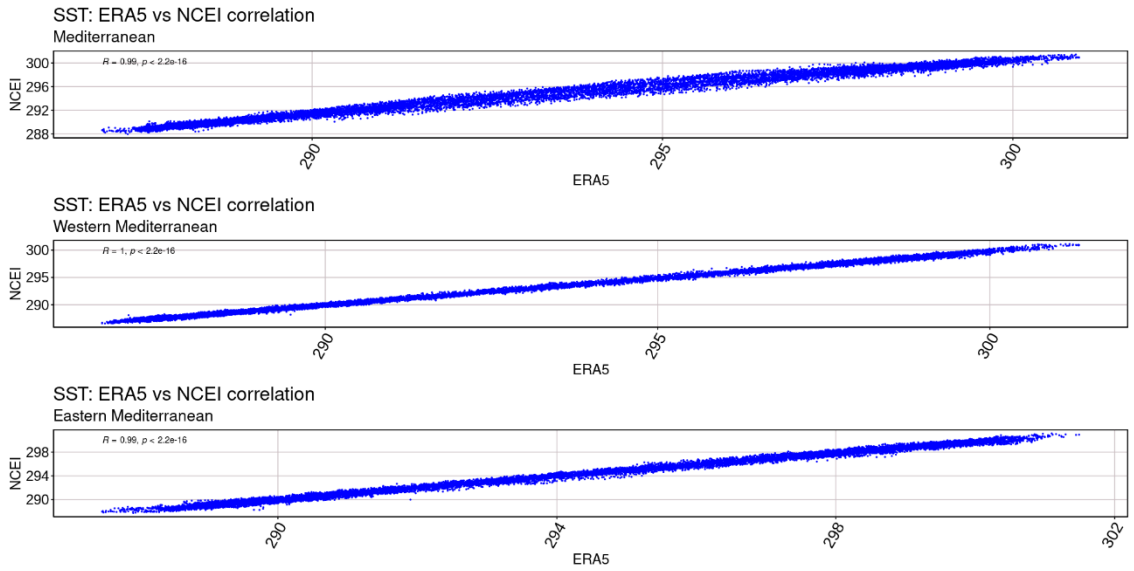
The novelty of our methodology relies on the spatial minimum extension requirement and the need for daily overlapping. The 5% area is appropriate for the Mediterranean basin, as shown in Pastor and Khodayar (2023), but will need to be assessed for other basins from a fixed value. The use of different reference periods, which are not on the basis of our methodology, should have no impact on the general character of the results but in their absolute values, as previously explained.

The main differences between Sun and our methodology have been highlighted in the *Methods-Detection of AHW and MHW events* section:

"Although we follow a similar spatiotemporal approach to the proposed by Sun[77] there are some differences that should be highlighted. For the spatial continuity Sun uses the K nearest neighbour algorithm, dependent on non-predefined optimal K-parameter, considering an event if more than half of its k-nearest grid cells are identified as MHW irrespective of the total event size but then applying a 5ºx5º filtering to discard small scale events, while in our methodology we look for clusters of contiguous points occupying at least 5% of the Mediterranean basin. To assess the temporal continuity of MHWs Sun's method is based on the calculation of the event overlapping area between consecutive days that has to exceed a parameter value ranging from 0 to 1, set to 0.5 in their work but that should not exceed 0.7 as a universal single choice would not be optimal for all MHW events. In our methodology no minimum spatial overlapping is required between consecutive days. The iterative application of the algorithm requiring the minimum spatial size for the MHW event ensures the continuity of the events; the calculation of the probability density function yields overlapping areas bigger than 75% (see supplementary figure S4). The application of our methodology relies on the determination of the minimum extent to consider an event, in our case 5% of the Mediterranean, which will have to be re-evaluated especially in larger basins."

• Lines 537-622 (ERA5 Data and Detection Methods, Page 24): The study uses ERA5 data for temperature and SST analysis. Given the known limitations of reanalysis datasets, especially in representing extreme events, how do the authors account for these potential discrepancies? Have they performed any sensitivity analyses to assess the impact of data uncertainties on their findings?

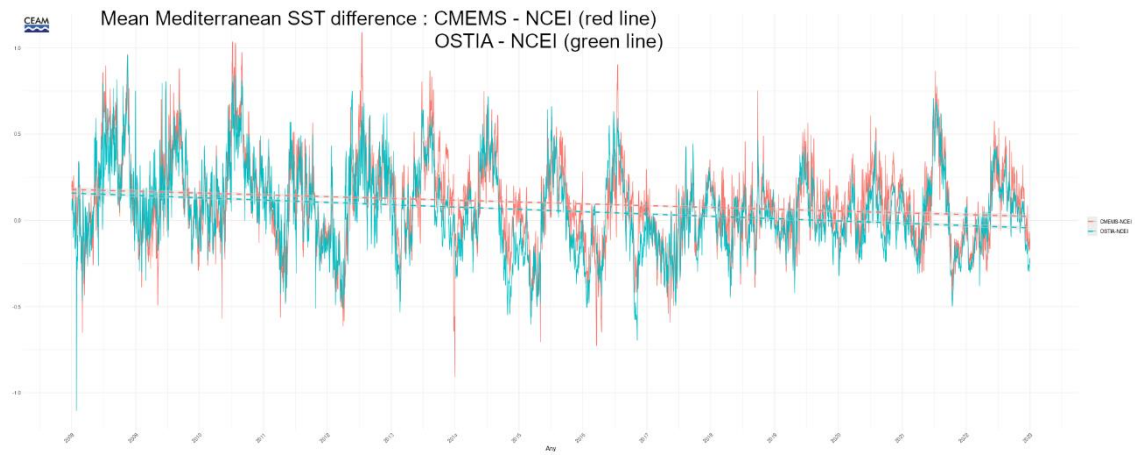
In previous works, the authors run a validation of ERA5 reanalysis for SST using observational satellite data of similar spatial resolution. The satellite dataset used for validation was the "GHRSST Level 4 AVHRR_OI Global Blended Sea Surface Temperature Analysis (GDS2)" from NCEI, which is recognized as an appropriate dataset for climatic analysis. Both datasets showed a high correlation for the mean daily SST (see figure below) for the whole Mediterranean basin and for the western and eastern subbasins.



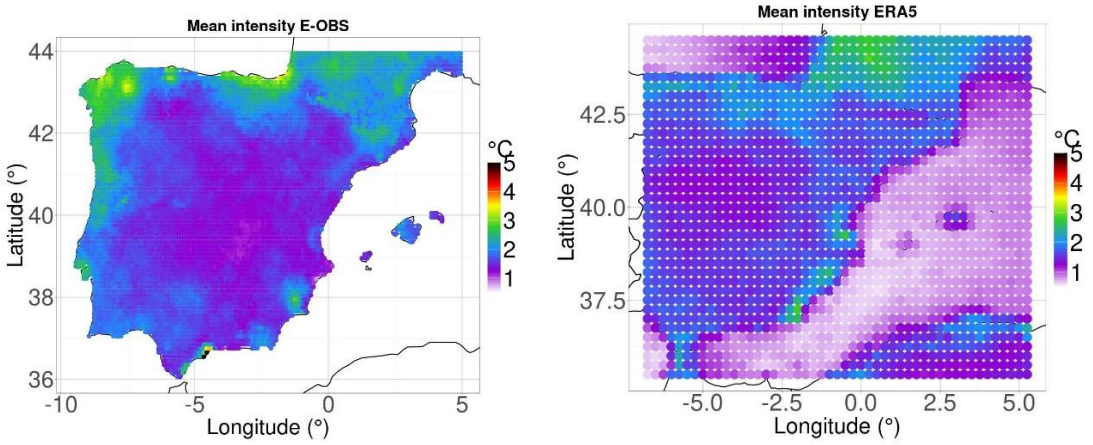
Additionally, the authors have validated NCEI by comparing its climatological analysis with two high resolution datasets:

- CMEMS: Copernicus Mediterranean Sea High Resolution and Ultra High-Resolution Sea Surface Temperature Analysis (https://doi.org/10.48670/moi-00172)
- OSTIA: Global Ocean OSTIA Sea Surface Temperature and Sea Ice Analysis (https://doi.org/10.48670/moi-00165)

The mean Mediterranean SST time series difference has been evaluated for the 2008-2022 period (shown below). The difference range was between -0.5 and 1ºC at the start of the time series and has reduced to (-0.5,0.5) in recent years.



Regarding the analysis of AHWs, ERA5 dataset has been extensively used and validated in the recent scientific literature in many different fields. It also has a long-time span, which is very useful for our work. In the past, the authors run a sensitivity analysis on ERA5 to assess its feasibility in atmospheric heat wave analysis by comparing the spatial variability of mean AHW intensity in the Iberian Peninsula to that obtained with the E-OBS gridded dataset. A good agreement between both datasets was revealed. In the figure below it can be seen that ERA5 mean AHW intensity spatial distribution shows similar results to those obtained with E-OBS.



E-OBS available at https://www.ecad.eu/download/ensembles/download.php

Cornes, R., G. van der Schrier, E.J.M. van den Besselaar, and P.D. Jones. 2018: An Ensemble Version of the E-OBS Temperature and Precipitation Datasets, J. Geophys. Res. Atmos., **123**. doi:10.1029/2017JD028200

ERA5 has been used for temperature, AHW, and their health impacts assessment in recent scientific papers:

- Mistry, M. N., Schneider, R., Masselot, P., Royé, D., Armstrong, B., Kyselý, J., Orru, H., Sera, F., Tong, S., Lavigne, É., Urban, A., Madureira, J., García-León, D., Ibarreta, D., Ciscar, J.-C., Feyen, L., de Schrijver, E., de Sousa Zanotti Stagliorio Coelho, M., Pascal, M., … Gasparrini, A. (2022). Comparison of weather station and climate reanalysis data for modelling temperature-related mortality. *Scientific Reports*, *12*(1), 1–14. https://doi.org/10.1038/s41598-022-09049-4
- Santos, R., Russo, A., & Gouveia, C. M. (2024). Co-occurrence of marine and atmospheric heatwaves with drought conditions and fire activity in the Mediterranean region. *Scientific Reports*, *14*(1), 19233. https://doi.org/10.1038/s41598-024-69691-y
- Santos, R., Russo, A., & Gouveia, C. M. (2023). *Concurrent Marine and Atmospheric Heatwaves and Droughts and their Influence on Fire Activity in the Mediterranean Region* (M. G. Pereira, R. Oliveira, P. Navarro, & L. Bugalho, Eds.).

Results and Interpretation

• Lines 223-258 (MHW and AHW Characterization, Page 8): The authors present basin-wide averages for MHWs and AHWs but acknowledge that these may mask regional variability. Could the authors provide more detailed regional analyses, particularly in areas like the Adriatic Sea, where the results indicate higher intensities? How do local oceanographic and atmospheric conditions contribute to these regional differences?

Characterizations of MHWs and AHWs for the different subbasins are shown in Table S1 provided in the supplementary material at the time of the first submission. The highest values for mean and maximum intensity are found in the Adriatic Sea for both AHWs and MHWs.

The analysis of physical processes, oceanic or atmospheric, is out of the scope of this work that the authors intend to address in future analysis. We have been working on the analysis of heat fluxes in the air-sea interface to identify processes involved in the MHW intensification when concurrent AHWs occur.

• Lines 269-302 (Trend Analysis, Page 10-11): The manuscript reports a significant positive trend in MHW maximum intensity, particularly in the last decades. Is this trend consistent across all subregions, or are there areas where the trend is weaker or even negative? How do the authors reconcile any discrepancies between their findings and those of previous studies?
Supplementary Figure S3 shows the regional distribution of the annual trend for maximum intensity. Almost all the Mediterranean basin shows a positive value with only some small areas in the Gulf of Lyons and close to the Algerian coast with neutral or negative values. The highest trends are found in the Adriatic and eastern Aegean seas and the Turkey coast.

No significant discrepancies are found from previous studies run by the authors on MHWs. Results in this work are comparable with those in the literature but with different numeric values because of the temporal series analyzed, different methodologies, and reference periods. An assessment has been run regarding the reference period by using the 1991-2020 climatology to assess the possible impact on our results. See some results on the MHW characterization in supplementary table S2.

Discussion and Broader Implications

•Lines 422-535 (Discussion, Pages 20-22): The discussion centers on the intensification of MHWs during concurrent AHW events. Can the authors elaborate on the potential feedback mechanisms that might exist between these concurrent events? Could such feedbacks exacerbate the intensity or duration of future heatwaves in the Mediterranean or similar regions?

We conclude that the demonstrated intensification of MHWs is due to changes in the actual interactions between AHWs and MHWs. After the completion of this manuscript, the authors have been investigating the energy and moisture exchanges in the air-sea interface to try to elucidate any differences between concurrent vs non-concurrent situations. But this work, already finished, is out of the scope of the present manuscript and will be sent for publication soon. From preliminary results, we conclude that the concurrency can exacerbate the intensity of HWs in the Mediterranean.

• Lines 503-531 (Impact on Surrounding Areas, Page 22): The manuscript suggests that the impact of MHW intensification could extend to surrounding non-concurrent areas. Could the authors quantify this extension? What are the potential ecological and socio-economic implications for these surrounding regions?

The author concludes that the MHW intensification “appears to be a transient local phenomenon in the concurrency area”. In the discussion section, the authors indicate that the MHW intensity progressively decreases apart from the concurrence area, at different paces depending on its intensity. This decrease is due more to the increase in higher values in the concurrent area, which becomes higher than the surrounding ones, rather than because of a real impact on the concurrence at some distance of the concurrent area.

The impacts of the MHW intensification are out of the scope of our study, however, we agree with the reviewer on the interest in this topic, which could be considered a topic for future analysis.

Conclusions and Future Work

• Lines 524-531 (Future Research Directions, Page 22): The authors mention future work on the physical processes at the sea-atmosphere interface. Could they provide more details on the specific questions or hypotheses they aim to test? How will these future studies build on the findings presented in this manuscript?

As it is a work still in progress, although almost finished, we prefer not to advance any hypothesis before it is well tested. In this work, we have analyzed energy balance in the air-sea interface to assess possible differences for the different concurrency phases.

Technical and Presentation Issues

• Figures 1-6 (Pages 10, 12, 14, 16, 17, 19): While the figures are informative, some of the captions lack sufficient detail. For instance, could the authors include more context in the captions, explaining what each figure illustrates and its significance to the study's findings?
More information has been added to the captions to include more context.

• Line 702-870 (References, Pages 25-28): Ensure that all references are correctly formatted according to the journal's guidelines. Also, consider including a discussion of any recent studies that might have emerged since the manuscript was first submitted.
New references have been added for recent studies.

Code Availability Questions:

1. Line 669-672 (Code Availability, Page 26): The manuscript mentions that the code used for this study is available upon request and will be uploaded to public repositories in the future. Given the increasing emphasis on transparency and reproducibility in scientific research, why was the decision made to delay the public release of the code? Could this delay impact the ability of other researchers to validate or build upon the findings presented in this study?

We agree with the need to share code for the sake of transparency and reproducibility in scientific research. At the time of writing, the code was functional but needed a major overhaul to achieve a final version that was clean, well-documented, and easily usable by other researchers. Our commitment is to make the code freely available when the manuscript is finally published, which will provide the scientific support necessary for it to be used with confidence. Most probably this code will be the first item in an institutional GitHub repository for the CEAM Meteorology and Climatology area. In the meantime, the corresponding author can be reached by mail for questions on the code.

The code has been developed under the R framework available under different computing environments. All scripts will be properly documented, and a list of required R packages will be listed and made available.

From its publication, we hope that the code will be used and validated by other researchers, as well as our results.

A technical publication is in preparation for the adequate description and identification including the code, that will be published in public repositories.

2. Line 669-672 (Code Availability, Page 26): The statement mentions that the code will be uploaded to public repositories "in brief." Could the authors clarify the expected timeline for this upload? What steps are being taken to ensure that the code is well-documented and accessible for future users?

Please see the answer to question 1 on code availability.

3. Line 669-672 (Code Availability, Page 26): The manuscript states that the code is available upon request to the corresponding author. Could the authors provide more details on the process for requesting the code? Are there any restrictions or conditions that potential users need to be aware of before requesting access to the code?

Please see the answer to question 1 on code availability.

4. Line 669-672 (Code Availability, Page 26): In terms of ensuring the reproducibility of results, could the authors discuss whether the code includes all necessary scripts and dependencies? How have the authors ensured that the code will produce consistent results across different computing environments?

Please see the answer to question 1 on code availability.

5. Line 669-672 (Code Availability, Page 26): The manuscript mentions that the code will be uploaded to public repositories. Could the authors specify which repositories they plan to use? How do they ensure that the repository chosen will provide long-term access and maintainability of the code?

Please see the answer to question 1 on code availability.

6. Line 669-672 (Code Availability, Page 26): To assist in the review process and to verify the findings, could the authors please provide the code and the associated data used for this study? Access to these resources will help ensure a thorough and accurate evaluation of the results presented.

All data used for this study are based on ERA5 reanalysis which is freely available for any researcher. For code availability please see the answer to the previous questions.

New references added

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