

Response to the Editor and Reviewer

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“The 2025 Mediterranean marine heatwaves throughout sea surface temperature analogues”

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Dear Prof. Lionello, dear Reviewer,

We thank you for the positive assessment of our revised manuscript and for the careful and constructive list of minor comments. We have implemented essentially all of the suggested changes. Below we reproduce each comment in italics and give our reply, indicating where the text has been modified. A marked-up version of the manuscript (Main_R2_markedup.docx) with tracked changes accompanies this letter, together with the clean revised version (Main_R2.docx).

The main changes in this round are: (i) a shortened title; (ii) editorial clarifications in the abstract and introduction; (iii) a new Figure 1 with larger fonts and a continuous intensity colour scale, and an extended caption; (iv) relocation of the climate-index sources from the Results to the Methods; (v) a substantially expanded and more cautious discussion of the interpretation of the patchy dynamic-field differences, with supporting references; and (vi) a rewritten comparison with CMIP-based attribution.

1. Reply to the Editor

“I thank the authors for the extensive work undertaken to revise the manuscript and for carefully addressing all the reviewers’ comments. Both reviewers are now very positive and recommend publication. However, one reviewer has provided a detailed list of minor comments that deserve careful consideration and should be checked again by the reviewer after revision.”

Reply: We are grateful for this positive decision and for the efficient handling of the manuscript. We have addressed every point raised by the reviewer, item by item, as detailed in Section 2 below. All changes are visible as tracked changes in the marked-up file, so that the reviewer can verify them quickly. We hope that the revised version can now be accepted.

2. Reply to the Reviewer

“The authors have made a substantial revision of the manuscript [...] which is now clearer and better structured. [...] Therefore, I recommend publication after some minor comments (below) are addressed.”

Reply: We thank the reviewer for this positive evaluation and for the detailed, constructive suggestions, which have improved the clarity of the text.

2.1 Title

“The current title is good but could also be shortened to: ‘The 2025 Mediterranean Marine heatwaves throughout sea surface temperature analogues’.”

Reply: We agree that a shorter title is preferable and have adopted the reviewer's proposal. The title is now "The 2025 Mediterranean marine heatwaves throughout sea surface temperature analogues".

2.2 Abstract

"...that differs from the more common, atmospheric (?) circulation-based analogue attribution approach"

Reply: Adopted. The sentence now reads "...an analogue framework that differs from the common atmospheric circulation-based analogue attribution approach".

"...the associated atmospheric and surface conditions in a past (1950 to 1986) and a present (1987 to 2024) period, using ERA5 daily fields over the Mediterranean between June to September."

Reply: Adopted. The sentence has been rewritten following the reviewer's wording.

"When you say 'atmospheric and surface conditions' do you mean atmospheric and ocean surface conditions or surface atmospheric conditions?"

Reply: Thank you for spotting this ambiguity. We mean both: the composites include an ocean surface field (SST), near-surface atmospheric fields (T2m, MSL, 10 m wind speed) and the air-sea exchange terms at the interface (net shortwave and longwave radiation, latent and sensible heat fluxes). To convey this without a long enumeration, we now write "the associated atmospheric and air-sea surface conditions", which is the terminology used consistently in the Methods and Results.

"They do not constitute a complete formal attribution on their own, sSince the analogue framework cannot fully separate externally forced trends from internal variability and it does not explicitly resolve ocean dynamical processes such as advection, mixing, and stratification changes, these results do not constitute a complete formal attribution on their own. Nevertheless.."

Reply: Adopted essentially verbatim. The sentence now reads: "Since the analogue framework cannot fully separate externally forced trends from internal variability and it does not explicitly resolve ocean dynamical processes, these results do not constitute a complete formal attribution on their own. Nevertheless, ...".

2.3 Introduction

"...with major impacts on local marine ecosystems and coastal environments (Coll et al. 2010..."

Reply: Adopted; "local" has been added.

"...conditions, whose frequency is itself increasing in recent years"

Reply: Adopted; the sentence now reads "..., conditions whose frequency is increasing in recent years (d'Andrea et al. 2024)."

“...complementary approach in extreme event attribution field (Vautard et al., 2016; ...”

Reply: Adopted; the text now reads “...an established complementary approach in the extreme event attribution field (Vautard et al., 2016; ...).”

“...and magnitude of the 2025 event with from an independent observational perspective.”

Reply: Adopted; “with” has been deleted (Section 2.1).

2.4 Data and Methods

“The Data and Methods are also more clearly described and better presented than before. No comments.”

Reply: We thank the reviewer. One addition has been made to this section in response to the comment on Lines 249–253 (see Section 2.6 below): the sources of the six climate variability indices have been moved from the Results into Section 2.5, where they now follow the list of indices.

2.5 Section 3 – The June 2025 Mediterranean marine heatwave

“This section reads as Results. Maybe it could be moved in that section??”

Reply: We agree that this section is descriptive and observational in nature. We have chosen to keep it as a separate section rather than merging it into Section 4, for two reasons: (i) it is based on a different dataset (the Copernicus MED-REP-L4 observational product) than the analogue analysis (ERA5), and merging the two would blur that distinction; and (ii) it defines the target event used by the analogue protocol, and therefore logically precedes the analogue results. To make its status explicit, we have retitled it “3. Event characterisation: the June 2025 Mediterranean marine heatwave” and added the missing section number.

“Figure 1a). It would be better to increase the fontsize of both the x axis and y axis ticklabels and the legends to improve readability.”

Reply: Done. Figure 1 has been entirely redrawn. In panel a the axis tick labels, axis labels, title and both legends have been substantially enlarged and the line widths increased.

“Figure 1b) What is the white area over the Aegean Sea? Do this correspond to an areas not touched by the MHW? If so, this has to be mentioned in the caption of the figure.”

Reply: The reviewer’s interpretation is correct: the white areas over the sea are grid points where the MHW criterion of Hobday et al. (2016) was not met during the 25 June–09 July 2025 window, so that a mean MHW intensity is not defined there. These points are now labelled “Not evaluated” in the colour bar of panel b, and this is stated explicitly in the caption of Figure 1.

“Also, the colorbar of this figure looks odd. Could you perhaps plot a discrete colorbar with coherent colours? Otherwise, explain in the caption of the figures, what do the squares illustrate exactly.”

Reply: Thank you for pointing this out. The odd appearance came from the fact that panel b was drawn with a colour scheme that suggested a categorical variable. MHW intensity is in fact a continuous quantity (in °C), unlike the MHW categories shaded in panel a, and the “squares” noted by the reviewer were an artefact of that scheme. Panel b has therefore been redrawn with a continuous colour scale and a single horizontal colour bar labelled in °C. The caption now states explicitly what panel b shows (the temperature anomaly above the 1991–2020 climatology), that the colour scale is continuous, and that the white areas over the sea are grid points where no MHW was detected during this period.

“Line 178: The first sentence of the Abstract states that the event occurred between 20 and 30 June, whereas this section indicates that it persisted until mid-July. For consistency, the corresponding sentence in the Abstract could perhaps be revised?”

Reply: Thank you for catching this inconsistency. The first sentence of the Abstract now reads: “The Mediterranean Sea experienced an exceptional marine heatwave in early summer 2025, which developed through June, reached its peak between late June and early July, and persisted until mid-July.” The 20–30 June window is now introduced later in the Abstract explicitly as the build-up and peak phase used as the analogue target, which removes the apparent contradiction.

“Lines 184–187: These two sentence I sense they express a similar concept or are well connected, so maybe they could be merged?”

Reply: Agreed and merged. The two sentences now read: “The spatial distribution of MHW intensity therefore qualifies the event as a western Mediterranean-centred one (Fig. 1b): although it affected much of the basin, its most exceptional expression was clearly located in the western Mediterranean, which motivates focusing the following sections on this sub-basin.”

2.6 Results

“Lines 249–253: The information on the source of the large scale climate indices may be better moved in the relevant Methods section [...] Currently, it is a bit disruptive for the Results description.”

Reply: Agreed. The list of index sources (ERSSTv5, SWFSC, ICPC, ERSST_TS, CPC) has been removed from Section 4.5 and moved to Section 2.5, immediately after the enumeration of the six indices. Section 4.5 now flows directly from the statistical test to the description of the shifts.

2.7 Discussion

“Lines 289–290: Replace the lines with commas instead.”

Reply: Done; the em-dashes have been replaced by commas: “...lie in the thermodynamic fields, SST itself, near-surface air temperature over surrounding land, and incoming shortwave radiation, rather than in the dynamic fields.”

“Lines 292–294: [...] Is there previous work that supports this statement and specifically the part about atmospheric circulation remaining constrained by internal variability? If so, it should be

cited here. I am also wondering whether the patchy present-past differences of SLP, windspeed, latent and sensible heat fluxes, can only reflect that ‘the atmospheric circulation remains constrained by internal variability’ [...] could these heterogeneous patterns also mean that the atmospheric response is spatially complex or that atmospheric circulation changes could be weaker than internal variability, or that regional processes could also dominate?”

Reply: This is an important point and we agree that our original formulation was too categorical. We have (i) added supporting references for the general statement that forced circulation changes are small relative to internal variability and difficult to detect over the observational record (Deser et al., 2012; Shepherd, 2014; Faranda et al., 2023 — the first two are new entries in the reference list); and (ii) explicitly listed the alternative interpretations suggested by the reviewer. The passage now reads:

“...whereas forced changes in the large-scale atmospheric circulation are smaller and harder to detect against internal variability over the observational record (Deser et al., 2012; Shepherd, 2014; Faranda et al., 2023). We stress, however, that internal variability is only one of several plausible readings of the patchy present-minus-past differences in sea level pressure, wind speed, and latent and sensible heat fluxes. These heterogeneous patterns may equally reflect a spatially complex atmospheric response, forced circulation changes whose amplitude is simply weaker than the internal variability sampled by 42 analogue dates per period, or the influence of regional processes such as land-sea thermal contrasts, orographic channelling of the regional wind systems, and coastal upwelling, which are not well captured by basin-scale composites. Discriminating between these explanations would require large initial-condition model ensembles rather than the observational analogue framework used here.”

Reply: We believe this makes clear that our evidence constrains the magnitude of the dynamic signal, not its physical origin.

“Line 335: ‘..of the order of a few..’”

Reply: Done; the text now reads “are of the order of a few W m^{-2} ”.

“Lines 350–352: I feel this sentence is a bit too strong [...] The issue is not that CMIP models cannot produce these diagnostics. [...] The distinctive feature of the analogue method [...] is that the diagnostics are conditioned on observed analogues of a specific event, rather than derived from model simulations or attribution ensembles. That is the real methodological distinction.”

Reply: We fully agree, and we thank the reviewer for this precise reformulation of the methodological distinction. The sentence has been rewritten accordingly: “Model ensembles can of course also deliver variable-by-variable, grid-point-resolved diagnostics. The distinctive feature of the present framework is rather that these diagnostics are conditioned on observed analogues of one specific event and are therefore derived directly from the observational record, instead of being obtained from model simulations or attribution ensembles.”

“Line 374: ‘differing primarily in the background state’?”

Reply: Adopted; “differing primarily in background changes” has been replaced by “differing primarily in the background state”.

“Line 376: ‘..., making this assumption plausible’”

Reply: Adopted; the sentence has been corrected to “...constrain the broad spatial organization of anomalies, making this assumption plausible.”

2.8 Conclusions

“Line 393: Maybe revise it to: ‘This distinguishes the study from the more commonly used circulation-based analogue approach.’”

Reply: Adopted; the sentence now reads “This distinguishes the study from the more commonly used circulation-based analogue approach and is better aligned with the marine nature of the event.”

3. Additional changes made by the authors

While addressing the above comments we also made the following minor corrections:

- Hobday et al. (2018), which was cited in the text and in the caption of Figure 1 but missing from the reference list, has been added.
- Deser et al. (2012) and Shepherd (2014) have been added to the reference list in support of the revised Discussion passage.
- Two citations that had no corresponding entry in the reference list, Simon et al. (2023) in the Introduction and Atkins et al. (2025) in the Discussion, have been removed; in the latter case the clause on UNSEEN methods that it supported has been deleted as well.
- Section 3 has been given its missing section number and a more explicit heading.
- A few typographical corrections (spacing before punctuation, a missing full stop at the end of the Introduction paragraph on concurrent atmospheric extremes).

We thank the Editor and the Reviewer once again for their time and for comments that have clearly improved the manuscript. We hope that the revised version is now suitable for publication.

On behalf of all co-authors,

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