Response to reviewer

Manuscript title: Marine heatwave amplifies extreme multi-hazards of extratropical cyclone Babet

Journal: Natural Hazards and Earth System Sciences (NHESS)

Reviewer 2:

General remarks

This is a well-structured, clearly written, and overall good manuscript. The methodology is coherent, and the results are interesting, particularly given the growing importance of understanding the role of MHWs in modulating atmospheric extremes. The study addresses a timely question.

While the paper is strong overall, I provide below several suggestions that could improve clarity, precision, and interpretation. The explanation of boundary-layer processes in Section 4.1 is particularly strong and one of the highlights of the manuscript.

Response: *We thank the reviewer for the careful reading of the manuscript and for the constructive and helpful comments. We will revise the manuscript to improve clarity and interpretation in response to the points raised below.*

Structure and Methods

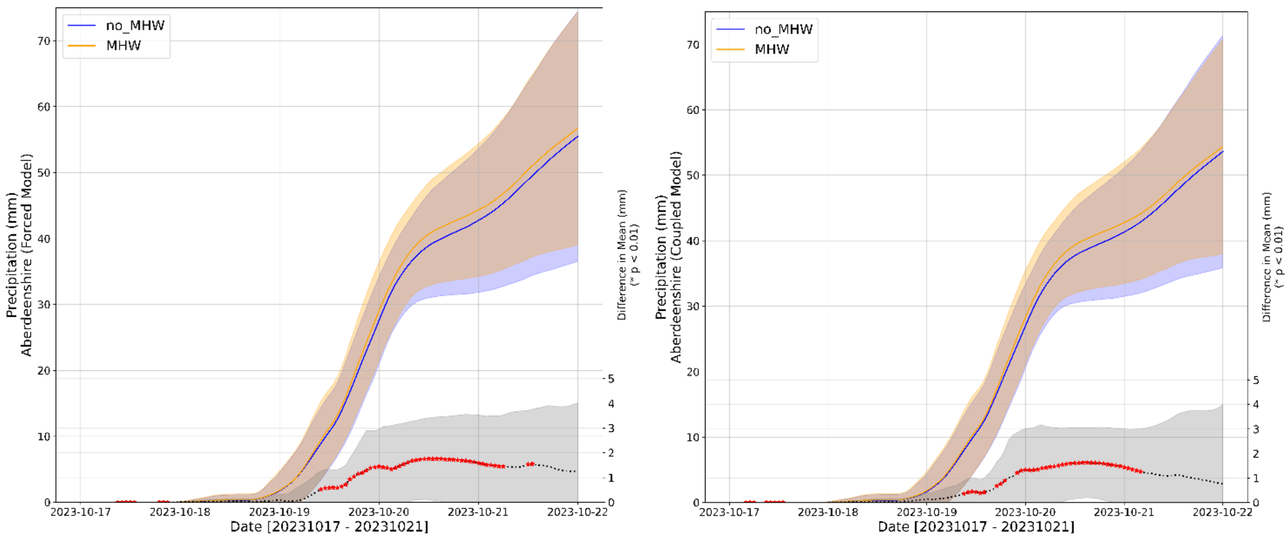
The manuscript is generally well organized. However, the Methods section could likely be improved, particularly in the detailed description of model components and coupling strategy. While transparency is appreciated, some of this information may be better summarized or moved to supplementary material to improve readability.

Response: *We thank the reviewer for this suggestion. We will revise the Methods section to improve clarity and readability. Indeed, the configuration paper is now available online from Geoscientific Model Development so we will considerably reduce the size of the model description where possible, while retaining the information needed to understand the modelling framework and experimental design.*

In addition, in the methodology, I wonder why a daily climatological SST (e.g., 1982–2011) was not prescribed in the forecast model as a reference baseline (with a call back at the daily step). Including such a reference could help better isolate the role of the MHW relative to climatological conditions and clarify the interpretation of anomalies.

Response: *We thank the reviewer for this suggestion. A prescribed daily climatological SST experiment would indeed represent an alternative baseline, but it would also constitute a different experimental design from the initialized coupled forecasts used here. In the coupled framework, we require a* *physically coherent three-dimensional ocean state for initialization, and we do not have a corresponding long-term climatological ocean state available for this purpose. For this reason, the no_MHW experiment was instead constructed using the 17 October 2020 ocean state, which provides a near-climatological (2003-2022) and dynamically coherent reference within the operational coupled system. We will add the sentence in section 2.4 : "….available (2018-now). **A prescribed daily climatological SST baseline would represent a different experimental design and was not used here because the coupled forecast system requires a physically coherent three-dimensional ocean initial state, which is not available from a climatological reference.** The MHW is…"*

As an additional check, we ran an atmosphere-only sensitivity experiment using daily SSTs relative to a climatological reference, and it produced a very similar precipitation response (+5%), giving us confidence that the main thermodynamic signal identified in our coupled experiment represents the main MHW signal.



Although 2020 exhibits values close to climatology in some respects, it lies within the 2003–2022 period, which already includes a substantial contribution from human induced warming, aerosol forcing, and multidecadal internal variability.

For this reason, I am not fully convinced that the term "counterfactual" is appropriate. The experimental setup does not represent a pre-industrial or no-anthropogenic-forcing world, but rather a world without the specific MHW anomaly superimposed on an already warmed background state.

It may therefore be more accurate to refer to this as:

- a "no-MHW experiment",

- a "climatological SST experiment",

Response: *We thank the reviewer for this comment. Regarding the use of the term 'counterfactual', we use it in the causal-inference sense, which is more general than the way the reviewer describes,* *and answers a "what if things had been different" question (e.g. Pearl and Mackenzie, The Book of Why). In this study, it refers to a paired experiment without the specific marine heatwave anomaly, rather than to a pre-industrial or no-anthropogenic-forcing world. We will clarify this briefly in the manuscript by adding a sentence: "….characteristics of Storm Babet.* ***We use the term 'counterfactual' here in the causal-inference sense, to refer to a paired experiment without the specific marine heatwave anomaly****. Section 2 describes…."*

Finally, the manuscript (L426) refers to "attributing" the event. This is not strictly an attribution study in the formal D&A framework. This word could be changed to avoid confusion.

Response: *We thank the reviewer for this comment. We use "attribution" here in a broader sense than the formal D&A framework referred to by the reviewer. Attribution is used more widely within the prediction and causal-inference literature, including conditional attribution to internal properties of the climate system (see discussion in Lloyd and Shepherd, 2023), whereas the formal D&A framework is more commonly used for unconditional attribution to anthropogenic climate change. We will clarify this in the manuscript : "…This framework provides a structure for attributing observed responses* ***to specific drivers within a causal explanatory framework,*** *and* ***for*** *testing whether similar connections appear in other cases.* ***In the conditional framework used here, the counterfactual experiments indicate that the pre-existing MHW amplified the hazards under the observed broad storm setup****. With a larger.."*

Interpretation of the MHW Signal

The manuscript sometimes attributes increased hazards directly to the MHW itself, whereas in practice the impacts likely arise from:

- the thermodynamic background SST anomaly,

- modification of air–sea fluxes,

- boundary layer preconditioning,

- or the interaction between internal variability and anthropogenic warming.

- can we disentangle the role of pre-moistened air parcels (L309 mentions already humid air masses)?

Response: *We thank the reviewer for this comment. Our interpretation is that the MHW influence is causal in the conditional framework used here: under the same broad storm setup, the pre-existing warm North Sea led to systematically larger hazards than in the no_MHW case. At the same time, we will clarify this interpretation by describing it more explicitly as a physical chain, through enhanced air-sea fluxes, boundary-layer moisture supply, and their interaction with the evolving storm. We will also revise the discussion to state more explicitly that the effect was weaker when incoming air was already humid and stronger when drier air crossed the warm North Sea. We will modify section 5.2 as:*

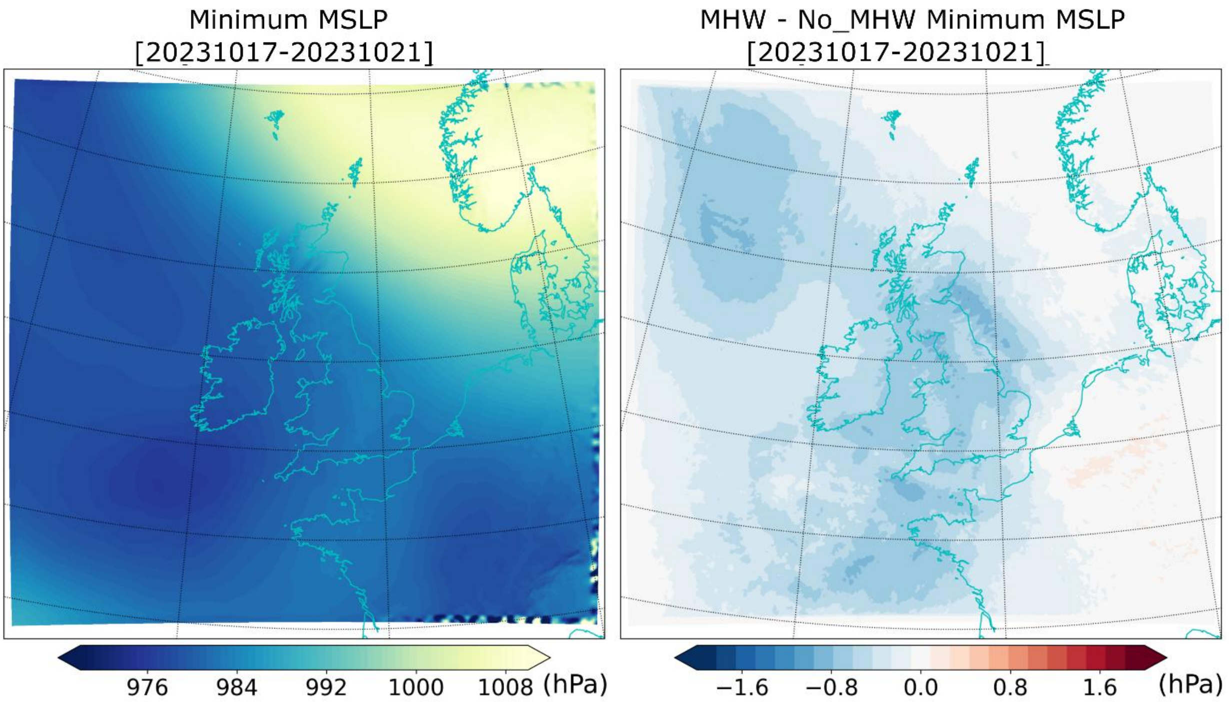
"…air-sea coupling. ***In this sense, the MHW influence should be understood as a causal amplifier operating through enhanced air-sea fluxes, boundary-layer moisture supply, and their interaction with the evolving storm dynamics, rather than as a uniform direct effect on all hazards****.*

We can formalise these pathways, in a causal network that ***links the pre-existing warm shelf-sea state and*** *anomalous ocean heat content to surface fluxes, storm intensity, and downstream hazards (Figure 10). This framework provides a structure for attributing observed responses* ***to specific drivers within a causal explanatory framework, and for*** *testing whether similar connections appear in other cases.* ***In the conditional framework used here, the counterfactual experiments indicate that the pre-existing MHW amplified the hazards under the observed broad storm setup****. With a larger…"*

- L346–347: Could the MSLP gradient play a role? Is it possible that the MHW modifies the pressure gradient and thus influences wind intensification dynamically, beyond purely thermodynamic effects?

Response:

We thank the reviewer for this helpful question. A modest dynamical contribution through changes in mean sea-level pressure and its gradient is possible. The MHW case shows a slight deepening of the low on the UK side of the North Sea, which would tend to strengthen the cross-basin pressure gradient and could therefore contribute to the wind increase. We cannot cleanly separate this effect from the thermodynamic contribution, but it is likely that both the strengthened pressure gradient and the boundary-layer response to enhanced air-sea fluxes play a role. We will discuss this in the revised manuscript and add this figure in the supplementary materials: "Storm MSLP deepening, ***and the associated strengthening of the cross-basin pressure gradient (Figure S5),*** *may also have contributed to stronger wind speeds." We will also add an additional arrow from deepening of pressure to wave increase in the causal diagram.*



This raises a key conceptual question: Are the hazards driven by the MHW as a discrete event, or by the elevated background SSTs and associated thermodynamic state?

We thank the reviewer for raising this conceptual point. In our framework, the MHW influence should be understood as the effect of the pre-existing anomalously warm shelf-sea state associated with the MHW, rather than the threshold label itself. The counterfactual experiments are therefore designed to test how the storm and its hazards respond to that warm ocean background under the same broad initial atmospheric state.

Moreover, it seems that the Clausius-Clapeyron is not valid over UK (at least for the summer months):

De Leeuw, J., Methven, J. and Blackburn, M. (2017) Physical factors influencing regional precipitation variability attributed using an airmass trajectory method. Journal of Climate, 30 (18). pp. 7359-7378. ISSN 1520-0442 doi: https://doi.org/10.1175/JCLI-D-16-0547.1

The manuscript would benefit from explicitly discussing whether it is possible to disentangle the MHW contribution from seasonal and thermodynamic effects on the atmosphere.

Response: *We thank the reviewer for highlighting de Leeuw et al. (2017). We agree that precipitation over the UK cannot be interpreted through simple Clausius-Clapeyron scaling alone, and that circulation and air-mass pathways are essential controls. This is consistent with our interpretation. In the case of Storm Babet, the heavy-precipitation event was primarily set up by the storm dynamics, while the pre-existing MHW acted as an amplifier by enhancing the heat and moisture uptake along that pathway. Our trajectory analysis shows that the strongest effect occurred when relatively dry air crossed the anomalously warm North Sea and acquired substantial additional moisture, rather than as a uniform thermodynamic response.*

Regarding the disentangling of the MHW contribution from broader seasonal and thermodynamic effects, the coupled factual (MHW) and counterfactual (No_MHW) experiments are run for the same October event and therefore share the same seasonal background and large-scale synoptic setup, while differing in the ocean initial state. In that sense, the experiment allows us to isolate the conditional contribution of the pre-existing MHW within the observed Storm Babet setup, rather than a general seasonal or thermodynamic effect.

To make this clearer, we will revise Section 4.1 to emphasise the conditionality of the Clausius-Clapeyron scaling and the pathway-dependent nature of the moisture increase, and we will revise Section 5.2 to state more explicitly that the response reflects the combined influence of the anomalously warm North Sea and the evolving air-mass pathway.

Section 4.1: "The magnitude of ***the moisture increase aligns with Clausius-Clapeyron expectations for the observed SST anomaly (7% more moisture per degree of warming), but*** *its manifestation* *depended on the interplay between the* ***MHW and the evolving*** *air-mass origin.* ***This is consistent with De Leeuw et al. (2017) who emphasise that air-mass pathways and origin humidity, rather than background SST alone, are key controls on precipitation over the UK. For Storm Babet, amplification of the precipitation was confined to periods when dry continental air masses crossed the warm basin under strong winds."***

Section 5.2: "…acted together. ***While De Leeuw et al. (2017) show that background SST alone does not explain precipitation variability over the UK, our results illustrate that, for this event, the anomalously warm North Sea provided locally significant additional moisture when initially dry air crossed the basin.*** *The model experiments…"*

Furthermore, a previous MHW occurred in June. Could accumulated heat or persistence effects have contributed to the atmospheric response later in the season? The cumulative aspect is not discussed and could be relevant.

Response: *We thank the reviewer for this comment. A previous MHW did occur in June 2023, but available evidence suggests that much of the associated excess heat content was removed during the very stormy conditions of July 2023 (Berthou et al., 2024, Fig. S12). We therefore do not have clear evidence that the June event directly contributed to the atmospheric response examined here. Nonetheless, we agree that seasonal persistence and subsurface memory could still be relevant, and we will note this more explicitly in the discussion as a question for future work: "…fully represented.* ***Regarding the seasonal context, a previous NWES MHW also occurred in June 2023, raising the question of whether cumulative seasonal heat storage may have contributed to the autumn event. However, Berthou et al. (2024) suggest that much of the excess heat content associated with the June event was removed during the very stormy conditions of July 2023. We therefore do not have clear evidence that the June event directly contributed to the atmospheric response examined here, although possible seasonal persistence or subsurface memory effects remain an open question for future work****."*

River Discharge

The relationship between rainfall and river discharge may not be linear, especially under saturated soil conditions. Rapid saturation due to both intensity and high cumulative rainfall can lead to enhanced runoff. Therefore, the link between MHW influence and river discharge is not direct over the full length of the event.

Response: *We agree with the reviewer. The relationship between rainfall and river discharge is not expected to be linear. We will revise the text (section 4.2) to clarify that the influence on river discharge is mediated by catchment hydrological response rather than being interpreted as a simple linear consequence of increased rainfall*: **"…**basin response times. **This response is not expected to scale linearly with rainfall, because runoff also depends on antecedent soil moisture, rainfall intensity, and catchment saturation.** Importantly,…"

Discussion about large-scale dynamics and climate change

- The discussion could be strengthened by addressing the influence of climate change on baroclinity, jet stream variability, and North Atlantic internal variability.

Response: *We agree that broader changes in large-scale circulation, including baroclinicity, jet variability, and North Atlantic internal variability, may influence the background state in which events such as Storm Babet occur. However, a detailed treatment of these wider-scale drivers would be beyond the scope of the present event-based study, which focuses on the conditional influence of the pre-existing MHW within the observed large-scale setup. We will add a few sentences in the discussion (section 5.3) to acknowledge this more clearly.*

- The concept of preconditioning could be emphasized more clearly.

Response: *We agree. In the revised manuscript, we will emphasize more clearly the role of preconditioning by clarifying that the MHW influence operates through the pre-existing warm shelf-sea state and its effects on air-sea fluxes and boundary-layer moisture supply prior to the main hazard impacts.*

- In Section 5.3, it should also be discussed that in future experiments, internal variability patterns may remain structurally similar even if thermodynamic conditions shift. This assumption deserves explicit acknowledgment.

Response: *We agree. We will state more explicitly that the storyline approach used here isolates the effect of the MHW under a broadly similar large-scale atmospheric situation, and therefore assumes, to first approximation, that internal variability remains structurally similar while thermodynamic conditions are modified.*

We will address these points in the discussion as: "…temperatures rise. ***A key part of this amplification is the preconditioning of the shallow North Sea, with excess heat stored before the storm maintaining a warm shelf-sea state that supported enhanced air-sea fluxes during the event****. When such warming becomes the baseline rather than an extreme, the amplification observed here would apply to a much larger set of storms****. This interpretation assumes, to a first approximation, that the relevant internal variability and circulation patterns remain structurally similar, even as the thermodynamic background shifts in a warmer climate. At the same time, the large-scale background in which such events occur may also be influenced by changes in baroclinicity, jet variability, and North Atlantic internal variability. Assessing the role of these wider-scale drivers is beyond the scope of the present event-based study, which focuses on the conditional influence of the pre-existing MHW within the observed Storm Babet setup."***

Minor comments

- Marine heatwaves are sometimes abbreviated (MHWs) and sometimes written in full.

Response: *Thank you. We will use 'marine heatwave(s)' at first mention and 'MHW(s)' consistently thereafter throughout the manuscript.*

- MLD is inconsistently formatted.

Response: *We will check the manuscript and ensure consistent formatting of 'MLD' throughout.*

- can you specify if possible when you mention surface air temperature when considering surface temperature related to the atmosphere?

Response: *We will clarify the terminology where needed to avoid ambiguity between atmospheric and oceanic temperature variables.*

- L416: "the role of MHWs" → perhaps "the effects of MHWs" would be more precise.

Response: *We will make this change to improve precision.*

- L340: "stronger winds" → clarify whether this refers to mean wind speed, gusts, or both.

Response: *We thank the reviewer for this comment. Here, "stronger winds" refers to the mean 10-m wind speed shown in Figure 7c. We will revise the figure and the text in Section 4.1 to state this explicitly.*

- L338–339: It would be helpful to provide quantitative values (e.g., correlation coefficients, regression slopes) to support the stated relationships.

Response: *We thank the reviewer for this suggestion. In this case, a regression analysis is not very informative because all ensemble members follow the same event and do not sample a broad range of SST conditions. Our interpretation is therefore based on the paired experiment design together with the physical consistency of the response. In the manuscript, we will revise the sentence as: "**We hypothesise that the** warmer sea in the MHW experiment **contributed to** a higher boundary layer…"*

- Figures 5 and 6: The detailed description of air-mass trajectories is interesting, but these figures might potentially be moved to the Supplementary Information if space is needed.

Response: *We thank the reviewer for the suggestion. We prefer to retain these figures in the main text because they are central to the physical interpretation of the air-mass pathway and boundary-layer mechanism, and keeping them in the manuscript improves readability (the first reviewer asked for more figures of the synoptic situation of the storm).*

- L366: "atmospheric intensification" → specify which variables are concerned (rainfall rate, wind speed, pressure gradient, etc.).

Response: *We will revise this sentence as "The* ***increases in precipitation, near-surface wind speed, and cyclone deepening associated with*** *the North Sea MHW extended…"*

- OHC appears rather abruptly in L431–435 and L466. The link between OHC and the rest of the argument is not entirely clear. If OHC plays a mechanistic role (e.g., through enhanced flux persistence or deeper mixed-layer anomalies), this should be better integrated earlier in the discussion.

Response: *We thank the reviewer for this helpful comment. The role of ocean heat content in the argument was not expressed clearly enough. We will strengthen the mechanistic role of OHC throughout the paper. In Section 3.1, we will describe how the MHW anomaly deepened and stored heat below the surface, increasing the upper-ocean heat content available later in the season: "…it meant that the excess-heat anomaly deepened,* ***storing heat below the surface in*** *the North Sea* ***and increasing the upper-ocean heat content available later in the season.*** *This behaviour…"*

In the Discussion (Section 5.2), we will clarify that because the anomaly extended through the shallow water column, the enhanced air-sea fluxes were able to persist throughout the storm's duration rather than being mixed away: "…predictability and risk assessment. ***In this case, the anomaly was not confined to the surface but extended through much of the shallow water column helping to sustain warm surface conditions that supported enhanced air-sea fluxes to persist during the storm. Ocean*** *heat content…"*

- L438 It is not entirely clear that the experiment constitutes a true analogue in the dynamical sense. The term might overstate the methodological setup and could be clarified.

Response: *We agree and thank the reviewer for this helpful comment. Our intention was not to claim that the experiment represents a true dynamical analogue of future conditions, but rather that the North Sea SST anomaly during Storm Babet is of a magnitude comparable to warming levels that may become typical in future mean conditions. We will revise the wording in Section 5.3 as: "The observed North Sea anomaly can be viewed as* ***representative of warming levels that may become typical in future mean conditions. Indeed,*** *the North Sea…"*