Review: An Atlantic wide assessment of marine heatwaves beyond the surface in an eddy-rich ocean model

This study uses two model configurations with eddy permitting and eddy-rich horizontal resolution to assess the influence of the representation of mesoscale dynamics on surface and deep MHWs in the Atlantic ocean. The effect of the model drift and the baseline, against which MHWs are detected, are investigated with respect to the events' characteristics. Finally the study examines the physical processes that seem to control the heat content in the Cape Archipelago, in an attempt to explain what controls the development of MHWs in that region. Although I find this study useful and quite novel, in some aspects, for the MHW community, the current structure and writing of the paper does not help the reader to follow key results with a coherent flow and meaning. Given the considerable length of the paper and the often unstructured arguments and experiment description the reader is often lost on where they should look and focus. Therefore, although I believe this study has a potential for publication, it needs a major re-structuring and re-writing of its content. Below I provide detailed major and minor comments that could help the writers improve the clarity of their paper. I advice for publication but only after major revision is performed.

Major Comments:
1. Although generally well-written, the paper could profit from a native English speaker to further improve the language and syntax throughout the manuscript. This would improve the clarity of the paper for the benefit of the reader.

2. The heat budget formulation used in the paper, aims at representing advection fluxes throughout partial interfaces of the selected region (Equations 2 & 3). However, the way that is currently mathematically formulated is rather ambiguous, according to Lee et al., (2004) and Kim et al., (2006), mostly representing internal processes redistributing heat within the domain under investigation. Unless this is the overall goal of the writers, I would advise reading those two works and reformulating the mixed layer heat budget to represent the external processes that control the domain's heat content and then estimate the effect of the heat contribution through each of the region's boundaries, following the proposed mathematical formulation. Alternatively, the writers can use the traditional mathematical formulation of the heat budget, but assessing the heat contribution of the to total (horizontal and vertical) advection instead.

References:
Lee, T., Fukumori, I., & Tang, B. (2004). Temperature advection: Internal versus external processes. *Journal of Physical Oceanography*, *34*(8), 1936-1944.
Kim, S. B., Fukumori, I., & Lee, T. (2006). The closure of the ocean mixed layer temperature budget using level-coordinate model fields. *Journal of Atmospheric and Oceanic Technology*,*23*(6), 840-853.

3. The description of the results is often ambiguous due to the lack of clear references to the corresponding figures, which may lead to reader confusion. I strongly recommend that the authors improve the numbering of their figures and carefully review the manuscript to ensure that each figure and its subplots are cited appropriately within the relevant text. Please refer to my comments below for specific suggestions.

4. Some methodological choices in the study, such as the selection of the 1st and 6th cycle of the simulation, are not clearly justified at the beginning of the paper but are introduced later. To enhance clarity and avoid potential confusion for the reader, I recommend that the authors provide a clear and explicit justification for all methodological decisions early in the manuscript. Please refer to my comments below for specific suggestions.

5. The description of the results is often intermingled with elements that belong in the discussion, which detracts from the clarity of the paper. I recommend that the authors more clearly separate these two sections, while also enhancing the structure and clarity of the methods section.

Minor – Detailed Comments:

Line 104: Could you clarify the specific rationale behind selecting the 1st and 6th cycle of the model for analysis? This section is where you should define the key characteristics of the simulations and justify your choices, ensuring that readers understand the reasoning behind them. Providing this information early on will help familiarize readers with the terminology and framework, allowing for a clearer interpretation of the results later in the paper.

Lines 125 – 130: I recommend that the authors present a more structured and clearly organized overview of the different simulations/experiments conducted, along with their key characteristics. This could be achieved through a matrix or bullet points, explicitly highlighting the distinctions between the two experiments. A clearer presentation of these details will enhance the readability of the manuscript and provide readers with a solid understanding of the analysis that will follow.

Line 134: Does that mean that the results will be the same with other baseline approaches (e.g. Smith et al., 2025)?Clarify.

Line 172- Equation 2: I understand that this is the conventional approach to formulating horizontal advection flux through each boundary of a given area or section. However, as demonstrated by Lee et al. (2004) and Kim et al. (2006), this formulation renders the conventional temperature flux through a partial boundary problematic. Their research highlights that temperature flux, when expressed in this manner, becomes ambiguous because mass is typically not conserved through a partial interface. Consequently, the advection flux, as derived from the Gauss/divergence theorem, cannot be meaningfully decomposed into western, eastern, southern, and other directional components as presented here. Instead, they propose an alternative formulation that ensures the temperature flux through a partial section remains meaningful by referencing it to the domain-averaged temperature. I advise the writer to carefully read the studies and modify their calculations according to what they would like to represent (total advection flux or advection through a partial boundary)

Line 180: Which depths does the integration happen?This needs to be clarified from the beginning to provide the readers with a solid understanding of the analysis that will follow.

Lines 200-202: Which figure do these results correspond to? Please provide a clear reference to the corresponding figures.

Line 209: Do you mean Figure 3a-d? The figure subplots should have a different numbering/letter in order to tell them apart more easily.

Lines 210-214: Please, provide a clear reference of the results described here to the corresponding figures.

Lines 214-215: Could you clarify further the connection between the MHW threshold behavior at 2200m and the mid-depth ocean warming observed in the 1980s compared to the 1990s? The relationship between these two aspects is not immediately clear.

Line 217: To ensure clarity and consistency for the reader, it is best to use a single term throughout the text. Either "detrending" or "linear increase in baseline" or even better find more intuitive names for the experiments and use throughout the text. This avoids potential confusion

Lines 218-219: "*Therefore, it is not possible to recover the MHW statistics from non-detrended temperatures in the 6th cycle by detrending the 1st cycle (e.g. 1st-linear does not match 6th-fixed/WMO)*". Could you clarify whether you mean that one should not expect similar MHW statistics when comparing non-detrended temperatures (which include both climate trends and model drift) to temperatures detrended using only the first cycle? What would be the rationale for such an approach? In the first case, strong model drift is present, whereas in the second, detrending removes real-world climate trends. It is unclear why one would expect comparable results under these conditions. Additionally, the distinction between the first

and sixth cycle temperatures should be more rigorously defined in the Methods section using precise scientific terminology

Line 222: Line 222: Did you mean Figure 3a, b? Additionally, the red lines in Figure 3a and 3b appear similar, could you clarify where the dissimilarities are?

Lines 224-225: Problem with the syntax of this sentence.

Lines 226-227: What do you mean disadvantages due to finite length of the timeseries. Could you elaborate this more so that the reader understands it better?

Figure 3d: The two regions should be highlighted in different colors and explicitly referenced in the text for clarity. Additionally, why are only the results of the WMO shown, while those of the linear 1st and linear 6th are omitted? Also, it would be helpful to include a brief description of what the 1st and 6th cycle represent in the caption of the figure, for the benefit of the reader.

Line 229: Could you clarify how the MHW statistics were calculated? Were events identified separately at each grid point and depth level across the entire Atlantic, followed by averaging over longitude and latitude? Or was the Atlantic first averaged at each latitude and longitude, reducing the dataset to only the vertical dimension, with the MHW detection algorithm then applied separately at each level? Or were MHWs first identified at the surface, with MHW days at depth determined based on the timing of surface MHW events? Please clarify the methodology used for constructing the vertical MHW dataset, preferably in methods section.

Additionally, what explains the minimal differences between the 1st linear and 6th linear experiments? Why are the differences in the number of MHW days between the first and last 10 years so small?Clarify. Also what about the differences between the 1st and 6th linear in FIgure 3d?why are they not mentioned anywhere?

Lines 236-240: This section leans more toward discussion rather than results, which should focus solely on reporting numbers, percentages, and observed changes. Any further interpretation or commentary should be reserved for the discussion section.

Line 241: m" in any case" is not an appropriate scientific expression. Rephrase

Lines 242-248: This section leand more towards conclusion than results.

Lines 246 - 247: What is the rationale behind selecting this specific type of simulation for your analysis? A clear explanation and objective justification for this choice are necessary, either early in the methodology, where all the steps of your methods should be clearly defined, or here.

Line 252: Why did you select maximum intensity as a metric for comparison instead of mean intensity? A clear and well-supported justification is needed. Also, while the model generally underestimates maximum intensity across most of the Atlantic, it appears to overestimate it in the Gulf Stream region. Therefore, this argument is not exactly correct.

Line 254: What do these statistics represent?an average over the Atlantic? This should be mentioned in the text. not only in the figure caption.

Lines 263-265: How can model and observations agree on regions with longer and shorter durations but at the same time the differences between high and low durations be more pronounced in the model?That sentence is confusing. Clarify

Line 268: How does the vertical resolution of the model play a role when talking about differences in surface MHW characteristics?Unless the writers mean something else. Please clarify.

Line 270: The term "broken section" is not scientific. Please, rephrase.

Also, it is unclear how the black lines in Figure 5 correspond to the regions mentioned. Are they representing a simple vertical section along specific points across the Atlantic? If so, the exact latitude and longitude coordinates defining the start and end of these sections should be clearly documented in a table rather than solely in the figure maps, ensuring reproducibility. Alternatively, do these lines represent a spatially averaged area around the sections? This distinction needs to be clarified. Furthermore, the rationale behind selecting these specific regions should be explicitly stated. What criteria were used to define these areas, and why were they chosen for analysis? A clear justification is necessary.

Lined 271 - 272: Syntax error in the sentence.

Line 275: Which area does this sentence refer to?

Lines 277–278: It is unclear whether this statement is directly related to the preceding sentence or introduces a separate result. Additionally, the specific section to which this sentence refers is not clearly defined. Clarification is needed to ensure coherence and precision.

Line 290: does Labrador Sea correspond to Canada section in FIgure 5? Not clear. It is better to keep a consistent name of your areas both in the text and in the figures.

Line 295: For clarity and to benefit the reader, it is essential to use the same regional names in the text as those used in the figure. Additionally, please refer to the corresponding subplot in Figure 5 to further enhance clarity.

Line 300-302: It is important to reference specific subplots of Figure 5 and use consistent terminology for the regions throughout the text. Additionally, the explanation provided here appears to be more suited for the discussion section. Please ensure that the results section remains focused strictly on presenting the findings, without further interpretation.Also the MLD does not increase. Instead it gets shallower.

Figure 5: The subplots of this figure need to be named separately for clarity purposes and ease of reading in the text.

Lines 212-213: Can you provide evidence to support this, or is this a claim based on theoretical assumptions? It is important to substantiate this statement with relevant data, references, or a clear rationale to strengthen the argument.

Lines 316,320,323: You need to reference the relevant figure here, as it is unclear which one the reader should be looking at. Including a specific figure reference will enhance clarity and guide the reader effectively.

Lines 317-318: I do not understand this sentence. Do you mean that the interior and near coastal regions of the ocean, have similar sea-floor, depths? This sounds strange. Also, what does it mean" *even if the sea floor is located in similar depths*"? What would happen if the sea-floor was located in different depths (which it does not, at least comparing the coastal and interior areas of the ocean).

Line 326: It is unclear what is meant by "linear trend" in this context. Does it refer to a trend in temperatures or a trend applied to identified MHWs? Please clarify the specific variable or process being referenced by the term "linear trend."

Lines 327-329: These sentences require improved grammatical flow and syntax, in addition to clear references to the appropriate subplots of Figure 6 for enhanced clarity. What specific trends are being referred to? Are these linear trends in temperature, or do they pertain to trends in MHW duration or intensity? The current phrasing is unclear and needs further specification.

Lines 339 - 340: Please provide a justification for your choice of the WMO baseline over the linear one. Additionally, clarify where you demonstrate that the conclusions are independent of the baseline selection.

Lines 348-349: The statement regarding the mean frequency being similar, yet higher in VIKING20X, is contradictory. Please clarify how these two observations can be reconciled.

Lines 350-351: These sentences belong to discussion

Lines 355-357: In addition to the fact that this sentence belongs in the discussion section, how can the entire Northeast Atlantic MHW features be attributed solely to the Mediterranean outflow, rather than interactions between the North Atlantic Current and waters of (sub)polar origin? Please provide evidence to support this claim.

Lines 358-370: These sentences belong to the discussion.

Lines 376: Have you shown that somewhere?supplementary material perhaps?not clear.

Line 391: The phrase "are not in phase" is not the most appropriate syntax here. An alternative phrasing could be: "The surface MHW characteristics differ from those observed at depth." Additionally, you need to specify which subplot of Figure 9 you are referring to, as it is currently unclear where the reader should focus.

Line 392: Could you clarify what you mean by "explained variance"? Was a statistical test conducted to analyze the MHW characteristics?

Lines 393-394: How do the atmospheric heat fluxes relate to this figure, which focuses on MHW characteristics?

Lines 396-397: The decoupling of surface and deeper MHWs is generally not attributed to long-term trends. Instead, the distinct variability and decoupling of MHW characteristics are typically the result of differing oceanic processes at the surface (high-frequency variability) and at depth (low-frequency variability). Therefore, the physical relevance of this sentence is unclear.

Line 400: Again, what is explained variance here? Was there a statistical test performed here?

Lines 403-404: If this refers to a different dataset or data handling process, it is essential to provide a clear reference to the methods section for better context and understanding. Please ensure that the relevant details are adequately explained and linked to the methodology for clarity.

Line 406: Please ensure that the subplots in Figure 5 are clearly labeled and referenced in the text. This will help guide the reader to the correct location for the relevant information. The current lack of clarity makes it difficult to understand which specific subplot is being referred to.

Lines 406-407: The typical range of MHW variability is unclear in this context. Please ensure that you reference the appropriate figure or subplot to guide the reader. Without this reference, it is difficult to determine which data you are referring to.

Line 411: The statement that MHWs show no considerable trends at this depth appears contradictory. From Figures 9a-c, it is evident that there is a higher number of events at the beginning of the timeseries, with a decreasing trend toward the end. Please clarify this inconsistency.

Lines 412-413: These sentences belongs to methods. Also the phrase "MHWs vary in phase" everywhere in the text. This sentence is unclear and contains syntax errors. It is important to specify whether this refers to the relationship between surface and subsurface layers or if it applies to other layers. Please clarify the intended meaning, or consider rephrasing with a more precise expression for better clarity.

Figure 9: Depth ranges between Figures a-c is up to 3800m while in Figures d-f up to 1500m. This inconsistency should be addressed. Consistency across the figures is essential for clarity and accuracy in presenting the data.Also in the caption of this figure, a new simulation is mentioned "*WMO baseline but with the trend removed after calculating the annual mean MHW characteristics*". However, this simulation/experiment has not been mentioned previously in the Methods section, making it the first reference to it in the figure caption. It would be more appropriate to introduce and explain this simulation in the Methods section to adequately prepare the reader before mentioning it in the figure caption.

Line 420: It is not clear which specific subplot of Figure 10 is being referenced here, nor which experiment these results pertain to. It is essential to clearly specify the relevant subplot and provide context regarding the experiment to avoid confusion for the reader.\

Line 422: This sentence is unclear. What is meant by stating that the linear trend had a minor impact on the Cape Verde Archipelago? The linear trend can only affect the MHW characteristics in the Cape Verde region, not the region itself. Please clarify.

Line 423: The MHW coverage differs between the two simulations (Fig. 10a-b), particularly at depth, and is not similar at the surface.Clarify.

Lines 425-426: I do not understand how can you physically connect temperature anomalies (that are above the 90th percentile) and that have been identified at each layer separately. The application of the Hobday et al., 2016 at each layer does not guarantee spatial coherence of events at surface or at depth and so the events are not demonstrated to be connected from one layer to the other just because there is a temporal continuation of temperature anomalies. How can you know if the process that is responsible for the development of temperature anomaly at let's say 600m is physically and mechanistically related to the temperature anomaly identified at surface?This is an implicit assumption which can be made only by looking at the figures but it is not physically proven. Especially because these are anomalies above the 90th percentile at each layer. If an anomaly at a selected depth is below the90th percentile for some days but then comes back above the threshold, will it still be considered as a MHW?This is a problem inherent to the statistical MHW framework. Therefore assumptions of the vertical continuation of MHWs should not be made lightly.

Line 430-434: You need to reference the appropriate subplot of the figure for clarity. It is currently unclear which part of the figure these sentences refer to.

Lines 437: The specific figure being referenced here is unclear, and the concept of "disconnection between the two depth layers" is not well-explained.

Lines 438- 439: Please provide a clearer explanation of this result, and ensure the appropriate figure is cited for better clarity.

Line 441-442: Has this long-term cooling trend seen anywhere?An appropriate figure (subplot) should be cited here.Otherwise this looks as a general statement without proof.

Lines 443-444: The similarity being discussed is between the simulations/experiments that identify MHWs using the WMO and linear baselines, not between the baselines themselves. This distinction needs to be clearly defined throughout the text. As it stands, the sentence is unclear and requires better clarification.

Lines 446- 455: This paragraph belongs to the discussion.

Lines 457-458: The phrase "hint on connection to the surface" is unclear. To improve clarity, the authors should specify what indicators or evidence suggest a connection between surface and subsurface events

Line 464: The base of the mixed layer should be clearly defined in the text or figure legend, as it is not evident from the figures. Additionally, it is essential to reference the specific figure or subplot to ensure the reader knows exactly where to look for the relevant information. For clarity, the layer's depth or definition should be described in relation to the figure presented.

Line 465: As previously mentioned, the MLHB format utilized in this study introduces ambiguity when representing temperature flux across a partial interface (x, y, z). It currently reflects the redistribution of heat within the domain rather than the change in heat content at the interface due to temperature variations. See my comment above

Line 468-472: This description probably refers to Figure 1? however, as no specific figure is cited, it is unclear where these results correspond to. Please clarify by referencing the appropriate figure (subplot) to ensure the reader knows where to look. Currently, this sentence is vague.

Line 474 - 475: This sentence is unclear. The sentence cites Figure 11b, discussing the impact of removing the linear trend, while the caption of Figure 11b describes the ocean heat content change based on the linear baseline. Please clarify the relationship between the two, as the current wording is contradictory.

Lines 475-476:Have you shown or read that before?Otherwise it is an arbitrary statement.

Lines 477-478: This sentence is confusing. Please clarify or rephrase.

Lines 478 - 483: Once again, the specific location of these results is unclear, and it is not evident which figures to refer to. Additionally, why is the description of the heat content provided for only one experiment/cycle used in the study, and not for both? Is there a notable difference between them? Please clarify.

Line 484: This statement requires proper citation of figures. Currently, it is unclear which figure is being referenced. Please ensure that the relevant figures are cited explicitly for clarity.

Lines 486-487: Could you please clarify the depth of the mixed layer base? Additionally, the colors used in Figure 11e are not distinct enough to clearly distinguish the different processes described. I recommend adjusting the color scheme for better clarity and differentiation of the processes.

Line 497: Could you clarify what you mean by "changing relative importance"? The expression is unclear. A rephrasing or further explanation would help ensure clarity.

Lines 501-511: This paragraph is more conclusion section and not results.

Figure 11: Could you specify the climatology period used to calculate the ocean heat content anomaly plot? This is currently unclear.

Line 546: Could you clarify what you mean by stating that the WMO and fixed baselines are not applicable below 100m? What specific application or context are you referring to?

Line 565: Could you clarify what you mean by "in the upper ocean, temperatures cover a large range"? Temperature is a fundamental and ubiquitous property of the ocean, so it would be helpful to specify what aspect of the temperature variability or range you are referring to.

Lines 585-586: Once again, I do not believe the influence of the Mediterranean Sea Outflow (MSO) has been adequately demonstrated here. It appears to be inferred based on unclear deductions. Please provide compelling evidence to support the claim that the variability described is indeed related to the MSO, or alternatively, clearly state it as a speculative observation. Additionally, which specific depth are you referring to? Given that the study examines multiple depths throughout the water column, this statement may not hold true across all depths analyzed. Please be more precise in your reference to the depth in question.

Line 588 - 591: For which of the experiments conducted here does this apply? Or are these observations valid for both experiments? Please clarify.

Line 593: A decrease in extreme positive temperatures? How is this observed? Which figures illustrate this? Please clarify.

Lines 614-615: Which publication. give examples.

Line 619: The word "pitfall" is not an appropriate word for a scientific paper. Use, limitation or challenge instead.