<u>Response to reviewer 1:</u>
Manuscript number: egusphere-2024-2210
Manuscript title: Subsurface manifestation of Marine Heatwaves in the South West Indian Ocean

Dear reviewer,

We sincerely thank Reviewer 1 for your valuable feedback and constructive suggestions, which have significantly improved the quality and clarity of our manuscript. We have carefully addressed all comments, including the addition of quantitative analyses to strengthen the link between EKE, SST variability, and MHW metrics, as well as clarifications on MHW metrics, time periods, and data selection. Additionally, we have incorporated minor text edits and updates to figure captions and titles to enhance readability and precision. We believe these revisions address all concerns raised and contribute to a more robust and comprehensive study on the characterization and impacts of MHWs in the SWIO. We appreciate your thorough review and are confident that the revised manuscript now provides a clearer and stronger contribution to the field.

To make the responses easier to follow, we have colour coded our responses as well as reviewer comments using the key below:

- **In bold black: Reviewer 1**
- In plain blue: our responses

General comments:

The paper focuses on the characterization of Marine Heat Waves (MHW) at the surface and subsurface in the Southwest Indian Ocean region and the role that mesoscale eddies might play in their generation. The results are relevant in terms of addressing knowledge gaps on the vertical extent of temperature extremes and for regional impacts on biodiversity and fisheries. The paper is well-written, and the methods are sound overall. However, the link between EKE, SST and MHW metrics present in Fig 3 is quite qualitative. Adding a spatial correlation analysis, for example, would strengthen the suggested links between eddies and MHW activity.

Thank you for your insightful feedback and for recognizing the value of our work in addressing knowledge gaps regarding the vertical extent of MHWs in the Southwest Indian Ocean and their potential links to mesoscale eddies.

We agree that the relationship between Eddy Kinetic Energy (EKE), Sea Surface Temperature (SST), and MHW metrics in Figure 3 could be further quantified. To further statistically quantify these relationships a scatterplot was generated with MHW intensity plotted against SST standard deviation, and a regression line was fitted to the data. The results reveal a statistically significant positive correlation ($r = 0.75$, $p < 0.001$), indicating that regions with higher SST variability are associated with increased MHW intensity. To further strengthen the link between these variables, a colour bar representing EKE was overlaid on the scatterplot. The results demonstrate that regions with higher EKE values tend to cluster in areas with lower MHW intensity and SST variability, whereas lower EKE values tend to cluster ins areas with higher MHW intensity and variability. This supports the hypothesis that mesoscale eddies play a significant role in modulating both SST variability and MHW activity. We have incorporated this new analysis and updated the manuscript to include the scatterplot and its interpretation (see revised Fig. 3 and Section 3.1). This additional analysis provides quantitative evidence to support the relationship between EKE, SST variability, and MHW metrics.

It is also unclear why MHW total days (annual total of extreme days) and maximum intensity metrics were omitted from the analysis.

In Figure 2, we show the annual mean MHW frequency (average no. of events per year), annual mean MHW duration (average no. of days per year), annual mean MHW intensity (°C) and annual mean MHW cumulative intensity (°C days) and these figure panels are discussed in the results section (lines 147-171). For consistency, we chose to show only the annual mean metrics. We computed both the suggested metrics of MHW total number of extreme days and the maximum intensity and found they did not provide any additional insight to the MHW characteristics and so for simplicity chose to omit them.

Finally, the analysis time periods of SST, subsurface temperature and SLA, currents data are not consistent without a clear justification (see details in specific comments below). The authors need to address these points and the specific comments below.

Thank you for bringing this to our attention. We have responded to the specific comments below and edited the manuscript accordingly. We hope this provides sufficient clarification and justification of the time periods selected.

Specific comments:

Line 16: Explain what is meant by moderate MHW. Are they moderate in intensity or have moderate occurrences, ...?

Moderate MHWs are considered abrupt, yet intense, which is typical of MHWs that occur in western boundary currents (Marin et al. 2022). Since this is not a generally accepted metric to describe MHWs, we have changed it to ‘abrupt and intense’.

Edited text: Line 17 ‘abrupt and intense MHWs’

Line 53: add ‘the’ before focus

Edited text: Line 65 ‘the’ added before focus

Line 53-54: Can also add that the SWIO is one of the main 6 hotspots of global marine biodiversity (Ramirez et al. 2017; https://www.science.org/doi/10.1126/sciadv.1601198), which makes assessing MHW in this region even more crucial and urgent.

Thank you for this recommendation. This is a useful and impactful addition to the paper.

Edited text: Line 65 – 69

‘Here, the focus is on the South West Indian Ocean (SWIO), which is part of the greater western Indian Ocean global warming hotspot (Roxy et al., 2014), and is host to a highly unique, complex and variable WBC current system that supports one of the six primary global marine biodiversity hotspots (Ramirez et al., 2017). This makes assessing MHWs in this region even more crucial and urgent, yet, to date, MHW characterization in the SWIO is sparse and remains limited to the surface (Mawren et al., 2022 a).'

Line 96 section 2.1: Why the study time period was restricted to 1993-2022 when the satellite SST record extend from 1982 to 2023 (as full years)?

While satellite SST data is available from 1982 – 2023, the XBT IX21-HR transect only has data available from 1993 – 2022. Thus we used the overlapping period 1993-2022 for both the SST and HR-XBT data sets. A 30 year climatological period (1993-2022) is a generally acceptable time period to reliably compute robust MHW metrics (Hobday et al., 2016; Smith et al., 2025)

Edited text: **Line 127 - 129**

'For consistency with previous studies, a fixed climatological baseline, 1993 – 2022, and a 31 day smoothing window was used to identify surface MHWs (Smith et al., 2025).'

Line 102-103: What's the exact climatological period used in from what year to what year. Please specify.

The climatological period used to detect MHWs was from 01/01/1993 – 31/12/2022. This is previously stipulated at line 97. To make it clearer, we have added the years from which the fixed climatological baseline was calculated at lines 101 and 109.

Edited text: **Line 119 - 120**

'High resolution gridded (0.25°) NOAA optimally interpolated sea surface temperature (OI SST) V2 data was used to explore SST conditions and identify surface MHWs in the SWIO region from 01/01/1993 – 31/12/2022'

Line 127 - 129

'For consistency with previous studies, a fixed climatological baseline, 1993 – 2022, and a 31 day smoothing window was used to identify surface MHWs (Smith et al., 2025).'

Line 104-106: Why Total Days (annual total of extreme days) and maximum intensity metrics were omitted? Is there a specific reason?

As noted above, we primarily considered only the mean annual frequency, intensity, cumulative intensity, and duration as MHW metrics in our analysis. We examined the total days and total maximum intensity metrics for the entire period and they show similar MHW characteristics and spatial distributions as the selected metrics, and so we do not think that the addition of these figures add any vital or unique insights for the purpose of this paper.

Lines 128-129: Why just 20 years period only from 1993-2012. Please explain the choice of not using an SLA time period that extends to the end of the subsurface or surface temperature data (2022) when the aim is to examine the influence of eddies on MHWs?

Thank you for bringing this to our attention. The sea level anomaly and geostrophic currents data was downloaded for the full period from 1993 – 2022, however the SLA data downloaded from AVISO altimeter data has already been computed with respect to a twenty-year (1993 – 2012) mean. To make this distinction and provide clarity, the manuscript has been edited accordingly.

Edited text: **Line 159 – 162:**

'To investigate the influence of mesoscale eddies on the properties of surface-identified MHWs, high resolution (0.25°), optimally integrated, gridded daily sea level anomalies (SLA) and geostrophic currents, over a thirty-year period (01/01/1993 – 31/12/2022), were extracted from altimeter satellite data distributed by AVISO (Archiving, Validation, and Interpretation of Satellite Oceanographic data). Altimeter satellite gridded SLA are computed with respect to a twenty-year [1993, 2012] mean.'

Figure 2e title and caption: Do you mean "mean intensity"? If so, please update accordingly.

Thank you for bringing this to our attention. Figure 2e represents the annual mean intensity. To provide clarity, we have updated the figure caption.

Edited text: **Line 180**

'Surface mean annual MHW (c) frequency, (d) duration (days), (e) mean intensity (ºC) and (f) cumulative intensity (ºCdays)'

Figure 2 panels titles: To avoid confusion between SST and MHW metrics, please update the title as follows: b) SST standard deviation, c) MHW Frequency, d) MHW Duration, e) MHW Mean Intensity, f) MHW Cumulative Intensity

Thank you for bringing this to our attention. We have updated Figure 2 panel titles to distinguish between SST and MHW metrics as per your recommendation. The updated titles are as follows: b) SST standard deviation c) MHW Frequency d) MHW Duration, e) MHW Mean Intensity, f) MHW Cumulative Intensity.

Line 144-145: How were the seasonal MHW derived?

MHW events over the 30 year climatological period were grouped according to the season in which they occurred to construct Seasonal MHWs - seasons were considered as: Summer: December, January and February; Autumn: March, April and May; Winter: June, July and August and Spring: September, October and November. The mean annual cumulative intensity MHW metric was considered for the seasonal metrics as it best describes the severity of the events. We have updated the manuscript to include a short description of how seasonal MHWs were derived in the methods section.

Edited text: **Line 132 -135**

'Seasonal MHW patterns were also investigated using the metric cumulative intensity, which provides a good description of the severity of MHW events (Mawren et al., 2021). Detected MHW events over the entire climatological mean were grouped by season (Summer -

December, January and February; Autumn - March, April and May; Winter - June, July and August and Spring - September, October and November).’

Line 163: true but excluding MHW frequency.

Agreed, however we discuss frequency separately in lines 227 - 229.

Lines 191-195: This fits better in Discussion.

Thank you for this suggestion. We agree and have moved these lines to the discussion.

Line 191 - 195 moved to discussion, now line 460 - 463.

Line 204-205: The dates in Figure 4 captions do not always match those in panels titles. Correct accordingly.

Thank you for pointing this out. We have carefully reviewed the dates in this figure’s captions and the corresponding panel titles. The necessary corrections have been made to ensure consistency between the dates in both the captions and the panel titles. The corrected dates are as follows: **(a, d, g, j)** 9 January 2020, **(b, e, h, k)** 14 July 2012, **(c, f, i, l)** 20 October 2007. Please note that, based on the request from the second reviewer to include additional statistical analyses, two additional figures have been added to the results under a new section 3.2. The case studies mentioned here, that were previously found in Figure 4 have been moved to section 3.3 and are now found in Figure 6.

Response to reviewer 2:
Manuscript number: egusphere-2024-2210

Manuscript title: Subsurface manifestation of Marine Heatwaves in the South West Indian Ocean

Dear Reviewer,

We would like to express our sincerest gratitude to the reviewer for the constructive feedback and suggestions. We appreciate the recognition of our study's value, particularly regarding the regional focus and the clarity of our figures. We also acknowledge the suggestion to strengthen our statistical analysis, and agree with the reviewer that further statistical analysis is critical for the strength of the paper (as also highlighted by the other reviewer). In response to this valuable suggestion, we have now included section 3.2 in the results section for the statistical analysis of subsurface warm anomalies associated with surface MHWs based on the full ensemble of XBT data.

We believe these enhancements significantly improve the manuscript's robustness and hope that the reviewer finds our revisions satisfactory. By incorporating the requested statistical analyses, clarifying our figures, and expanding the discussion to include recent literature, we have addressed the major and minor concerns raised. We are confident that these revisions have enhanced the scientific rigor, clarity, and overall quality of our work. We sincerely hope the reviewer finds the updated manuscript satisfactory.

Below, we provide point-by-point responses to the major and minor concerns raised, outlining the changes made to the manuscript accordingly. To make the responses easier to follow, we have colour coded our responses as well as reviewer comments using the key below:

- **In bold black: Reviewer 2**
- In plain blue: our responses

Major Concern: Need for Statistical Analysis of Subsurface Warm Anomalies associated with surface-identified MHWs

The paper presents a study of subsurface characterization of MHWs, which in the past have received more attention in terms of surface properties. The study is performed in the South West Indian Ocean, whose choice is well motivated both in terms of available datasets (a dense and recurrent array of XBTs), regional dynamics, and potential impacts of subsurface warm anomalies. The paper has two main claims: that MHWs have strong subsurface warm anomalies below the mixed layer and that these are mainly associated to the presence of eddies. In general, I found the paper well written, with pertinent bibliographic references, clear figures, and solid structure. Together with some very minor issues listed at the end, there is however in my view a critical issue that prevents the paper to be acceptable in the present form.

A statistical, robust identification of subsurface warm anomalies associated to surface MHWs is the key result that the reader waits for, and the pillar over which the entire paper could stand or fall. Nevertheless, this part is developed only in terms of a visual inspection of four case studies (Fig. 4). These case studies are well described and useful,

because they show concretely the type of events encountered and the datasets. However, a consolidation of this part by a statistical analysis is necessary. This in fact is somehow announced, as the authors write "For each day where subsurface data was available and a MHW signal was present over the XBT transect, the surface MHW intensity was compared to daily subsurface temperature and anomaly profiles." (L199-200). For some reasons, the result of this comparison beyond the case studies is not shown (the Result Section ends with the case study analysis). The paper has largely the space for an in-depth extra analysis, having at the moment only 4 figures, with 2 of them serving for the context.

In conclusion, the paper should provide a statistically robust analysis based on the ensemble of the XBT dataset presented, if the authors want to support quantitatively the two main claims namely, (i) the presence of subsurface warm anomalies associated to surface MHWs, and (ii) the association of these anomalies to the presence of mesoscale eddies. Without this additional analyses (i.e., at least two extra figures) in my view the paper is not strong enough for publication.

We fully agree with the reviewer's suggestion that a statistical analysis is required to strengthen our claims regarding the presence of subsurface warm anomalies and their association with mesoscale eddies. In response, we have conducted a comprehensive statistical assessment using the full dataset of 65 MHW occurrences identified along the IX21 XBT transect. The method used to conduct the statistical analyses has also been included in the methods section of the revised manuscript. This can be found at 'Section 2.3 Investigation of subsurface anomaly signals associated with surface MHWs' and includes two additional figures which aim to statistically support our two main claims, namely (i) the presence of subsurface warm anomalies associated with surface MHWs, and (ii) the association of these anomalies to the presence of mesoscale eddies.

The following modifications have been made and added to the manuscript in the results section 3.2:

1. The association of surface MHWs with subsurface warm anomalies:

Figure 4 represents the statistical analyses we conducted to quantitatively support our first main claim that surface MHWs are associated with subsurface warm anomalies. Figure 5a shows the scatterplot of surface anomaly temperatures compared to the maximum warm subsurface anomaly temperature, and a regression line was fitted to the data. From this plot, we statistically compare surface and subsurface anomalies, demonstrating 'a significant relationship between the two ($r = 0.70$, p-value < 0.0001) (Figure 4a)'. This supports the claim that stronger surface anomalies generally correspond to more intense subsurface anomalies.

To further strengthen our claim that MHWs intensify below the surface, we compared the distribution of surface anomaly temperatures to the maximum subsurface temperature anomalies (below 20m). This is shown in Figure 4b, by means of boxplots comparing surface and subsurface warm anomalies and a two-sample t-test was conducted to determine whether there is a significant difference between surface and subsurface warm anomalies. These statistics confirm that 'subsurface anomalies are significantly warmer than surface anomalies, with a mean difference of 1.04°C (p-value < 0.001) (Figure 4b)'.

We hope that these additional results directly address the reviewer's request for a robust identification of subsurface warm anomalies associated with surface MHWs.

2. Influence of Mesoscale Eddies on Subsurface Anomalies:

To statistically support our other main claim that subsurface warm anomalies are associated with the presence of mesoscale eddies, we evaluate the relationship between maximum subsurface temperature anomalies and their depth in relation to sea level anomalies (SLA). This statistical analysis is present in Fig. 5. Fig. 5a is a scatterplot, with a regression line plotted to the data showing the relationship between maximum subsurface temperature anomalies (°C) and their corresponding depths (m), color-coded by Sea Level Anomalies (SLA, m). Positive SLA values (red) indicate anti-cyclonic eddies, while negative SLA values (blue) represent cyclonic eddies. 'A positive statistically significant relationship between maximum subsurface anomaly temperature is found, with a correlation of 0.5 (p-value < 0.0001), showing that the warmest subsurface temperatures are typically associated with greater depths (Fig. 5a). This highlights a positive association between the magnitude of the subsurface temperature anomaly and the depth at which it occurs.' The colour coded SLA further demonstrates that positive SLA anomalies (indicative of warm anti-cyclonic eddies) are associated with most of the data points, especially the warmest and deepest subsurface temperature anomalies, whereas subsurface anomalies associated with negative SLA are less common (indicative of cooler cyclonic eddies), and are not as warm or deep. This points to mesoscale eddies being the underlying physical mechanism that drives deeper and more intense subsurface maximum anomalies.

To further statistically quantify the association between mesoscale eddies and subsurface warm anomalies, the depth of maximum subsurface anomalies associated with cyclonic and anti-cyclonic eddies was compared. This statistical analysis is present in Fig 5b, which consists of boxplots comparing the depths of maximum subsurface anomalies between anti-cyclonic and cyclonic eddies. This analysis reveals that 'anti-cyclonic eddies (positive SLA) are associated with significantly deeper subsurface anomalies compared to cyclonic eddies (p-value < 0.0001), with mean maximum anomaly depths of 100 m and 51 m, respectively (Figure 5b).' This finding quantitatively supports our second main claim: that mesoscale eddies modulate the depth and intensity of subsurface warm anomalies.

By incorporating these new statistical analyses and visualizations (Figures 4 and 5), we have strengthened our argument with robust, ensemble-based evidence rather than relying solely on case studies. The case studies now follow after the statistical analyses, in section 3.3 and are presented in Fig 7. They provide visual, and specific examples of the typical surface MHW intensity and distribution, their associated subsurface warm anomalies and the influence of mesoscale eddies in this region. Furthermore, the results from the case studies further corroborate the statistics we present in section 3.2.

Minor Issues

"Fig. 2C: If I understand correctly, what is shown is the N of events/year. Please modify 'events' in 'events/year' to be consistent."
The y-axis label in Figure 2C has been updated to "events/year" to improve clarity and maintain consistency.

"I found just one more recent paper that also studied the subsurface signal of MHWs in the South Indian Ocean: Azarian et al. (2024). The authors may (or

may not) want to discuss their findings in its respect."
Thank you for this reference. We have now cited and briefly discussed Azarian et al. (2024) in the discussion section, comparing our findings with theirs. Their study similarly identifies subsurface intensification of MHWs in the Indian Ocean sector of the Southern Ocean, aligning with our results but differing in regional focus and dataset used. The reference list has also been updated accordingly.

Summary of Revisions

We have made substantial improvements in response to the reviewer's concerns, including:
1. Conducting a full statistical analysis of subsurface anomalies, confirming their prevalence and strength.

2. Establishing a strong correlation ($r = 0.70$) between surface and subsurface temperature anomalies.

3. Demonstrating the significant difference between surface and subsurface anomalies using a t-test ($p < 0.001$).

4. Quantifying the influence of mesoscale eddies on subsurface anomaly depths, with anti-cyclonic eddies driving deeper anomalies ($p < 0.0001$).

5. Revising Figure 2C for clarity and

6. Including a recent relevant study (Azarian et al., 2024) in the discussion.