Review of Marine Heatwaves in the Red Sea and their Relationship to Different Climate Modes: A Case Study of the 2010 Events in the Northern Red Sea

Main comments

In this paper, the authors have run an extensive analysis of SST and MHW events in the Red Sea and also at a regional level (North and South RS). They have characterized SST anomaly and MHWs and also assessed long-term trends. Additionally, an attempt to relate atmospheric variables in the region with MHWs was run and a winter event on 2010 was analysed with higher detail.

The work presented in the manuscript is certainly of interest, especially in an area as unique as the Red Sea but some concerns arise from the text. Regarding the title of the manuscript, the case study of 2010 seems to be a main aim but the discussion in the corresponding section is not as extensive as the reader could expect. I suggest changing the title or deepening the case study analysis. Besides, I could not find a proper justification of the event studied. Was it a record event? The most intense? Which is the interest of studying this event?

We would like to express our gratitude to the Reviewer for his/her insightful comment and valuable feedback on our paper. We have carefully considered all the Reviewer suggestions in the revised Manuscript. Detailed point-by-point reply to all their questions are given below.

In response to the suggestion to change the title, we propose "Investigating the Long-term Variability of the Red Sea Marine Heatwaves and their Relationship to Different Climate Modes: Focus on 2010 Events in the Northern Basin" to emphasize the focus on the 2010 events.

Regarding the justification for studying this particular event, it was the most intense event of that year, longest winter event and occurred during the winter season, making it an interesting case to investigate its potential drivers. We have added new texts in the Introduction and Discussion Sections to provide further explanation for the selection of 2010 events as a case study.

Lines (119-121): "2010 was selected as a case study as it was one of the warmest years with highly frequent MHWs and had a different spatial distribution of SSTA and marine heatwave days (MHWDs) than the other warm years."

Lines (389-398): "The selection of 2010 as a case study for MHWs in the northern Red Sea is based on several reasons. Firstly, 2010 was one of the warmest years on record, with a high frequency of MHWs in the region. Secondly, the spatial distribution of SSTAs and MHWDs in 2010 was found to be different from that of other warm years. Thirdly, although the SRS is known to be warmer than the NRS through out the year (Fig. 2), in 2010 the SSTA of the NRS was higher by more than 1°C than the SRS (Supplementary Figures S2. d). Therefore, this section aims to provide a detailed description of the spatial and vertical extent as well as the potential atmospheric drivers of the intense MHW event that occurred in the NRS in 2010.

During both winter and summer of 2010, the NRS experienced ten MHW events (Fig. 12). These included one severe event in February and March (Category III), one strong event between October and December (Category II), and several moderate events (Category I). In this section, we will provide a detailed analysis of the most intense and longest winter MHW event that occurred in the NRS."

Another main concern is that the analysis of the relation between atmospheric variables and MHWs, or SSTA, seems too cursory despite the undoubted interest it may have. I recommend that the authors describe this analysis in more detail, as I assume that this is work that has already been done but it is not sufficiently highlighted in the text.

We thank the Reviewer for pointing this out, this helped us to improve the Methodology Section. A paragraph was added in the methodology to describe in detail the analysis of the relation between the climate modes and MHWs/SSTA, as follows:

"To gain a deeper understanding of the relationship between the different climate modes and the occurrence of MHWs over the last four decades in the RS, spatial correlations were examined. The climate modes considered in this study are the Oceanic Niño Index (ONI), the East Atlantic/West Russia Pattern (EATL/WRUS), the Atlantic Multidecadal Oscillation (AMO), the North Atlantic Oscillation (NAO) and the Indian Ocean Dipole (IOD). The correlation maps were calculated using the Pearson correlation coefficient (r), a widely used method for measuring linear correlations between two variables (Kirch, 2008; Patten and Newhart, 2017). The Pearson correlation coefficient ranges from -1 to 1, where -1 stands for a perfect negative correlation, 1 indicates a perfect positive correlation and 0 for no correlation. In this study, we calculated the correlation maps between the annual time series of each climate mode and the annual MHWs/SSTA in the RS. The MHWs were identified and characterized using a set of metrics, such as their duration, frequency, mean intensity, maximum intensity, cumulative intensity and total days (as described in the previous Section). We calculated the correlation between the different annual climate modes and annual MHW metrics, in particular frequency, duration and total days. The results showed a consistent spatial correlation pattern with MHW different metrics, while the correlation coefficients varied only slightly. For the sake of brevity, we present only the correlation results with MHW frequency and SSTA in our results. The MHW frequency was chosen for presentation due to its slightly higher correlation compared to MHW duration and total days. To test the significance of the correlations, a two-tailed t-test was used (Patten and Newhart, 2017). The t-test is a statistical hypothesis test that compares the means of two samples and determines whether they differ significantly from each other. Finally, we also compared the time series between different climate modes and the frequency of MHWs in the RS and its sub-basins. By analyzing the correlation maps and the significance of the correlations, we can gain insights into the potential co-variability between MHWs in the RS and larger-scale climate variability."

With this more detailed analysis and the other Reviewers' suggestions I would like to see a newly revised conclusions section to give some potentially interesting findings in the field of MHWs.

I would like to congratulate the authors on their work and encourage them to further develop it according to the indications received in this review process, prior to publication. My final decision is to review again after major revision but not because of problems in the methodology or conclusions but to clarify and deepen some of the analysis to improve the final result.

The Authors once again would like to thank the Reviewers for their kind comments on this paper and their very valuable evaluation. We have taken all suggested comments into account and answered all question

Minor comments

About Red Sea subregions, I could not find a justification for the spatial division between NRS and SRS. Please, indicate the spatial division criteria in the text.

We agree with the Reviewer and a paragraph was added in the Methodology Section to explain the choices of the subregions, as follow:

"To provide a more comprehensive and detailed description of MHWs in the RS, we have divided the RS into two regions: the Northern Red Sea (NRS) and the Southern Red Sea (SRS). The NRS extends from 22°N to 30°N, while the SRS extends from 22°N to 12.5°N. This division was based on the north-south spatial thermal gradient in the RS, which shows different characteristics of SST and MHWs between the regions."

Why do you consider winter months Jan-Feb-Mar? And summer months? It seems a little bit artificial division. Please better justify the Reviewer's selection or, better, consider different periods for winter and summer months.

We appreciate the Reviewer's feedback and the opportunity to clarify our methodology. The selection of winter and summer months was based on the seasonal cycle of SST, with the three months of the lowest SSTs representing the winter season, and the three months of the highest SSTs representing the summer season. Our focus on these two seasons was intentional, as we observed that the most intense Red Sea MHWs occurred predominantly during winters and summers.

For more clarity, we have added a paragraph in the Methodology Section explaining the method of selecting the winter and summer months as follows:

"The winter and summer SST in the RS was calculated and averaged over the study period (1982-2021) at each grid point. The winter season was represented by the months of January, February, and March, while the summer season was represented by the months of July, August, and September. The selection of winter and summer months was based on the seasonal cycle of SST, with the three months of the lowest SSTs representing the winter season and the three months of the highest SSTs representing the summer season. We focused on these two seasons as it was observed that the most intense RS MHWs occurred predominantly during winters and summers."

In your analysis, you mostly describe winter and summer months. What happens to SST and MHWs in spring and summer months? Sometimes you refer to annual frequencies, MHWDs… Please, be consistent with the periods selection and analysis or better indicate why and when such periods are being analysed.

As mentioned in our response to the Reviewer's previous comment, our focus on the winter and summer seasons was intentional, as we observed that the most intense Red Sea MHWs occurred predominantly during these seasons.

In light of the Reviewer's concerns regarding the clarity of the selected periods, analysis, and spatial divisions, we have thoroughly revised the manuscript. We have taken into account the Reviewers' valuable suggestions to enhance clarity and ensure consistency throughout the document. We trust that these revisions address the concerns raised and provide a clearer understanding of our research.

2010 event analysis it appears that is only for a winter event of the ten recorded during the year. Why?

We selected this event because it was the most intense and longest winter MHW event of that year. This combination of factors makes it an interesting case for investigating its potential drivers (Lines 225-226).

Please, do not use bold type fonts for the axis labels in the figures and don't use titles in plots if they can be explained in the caption.

We have improved all the figures as suggested.

Improve figure resolution for better readability. It's maybe because of the pdf conversion but carefully check all figures and use large enough fonts, especially if the text is placed inside plots.

Thank you for pointing this out, we have improved all the figures, as suggested.

Please, consistently use acronyms throughout the text. Take care especially when using MHW and "marine heat waves".

Thank you, we have revised the manuscript to ensure acronyms are consistently used.

Please, carefully review the text as there are some typos or misspellings.

We have made our effort to correct all the typos in the revised manuscript.

Line 172: an event can not be described by frequency, annual variability can.

Yes, that's right, thank you for catching this mistake. It was corrected as: "MHWs can be described with a number of metrics, such as ....."

Lines 172-173: Which is the difference between duration and total days. Maybe you are not referring to events but years?

In this study, the duration refers to the period between the start and the end of a specific MHW event, while the MHW total days is the sum of all the MHW days over a period of time for example a year. In order to make this clearer and avoid any misunderstanding, we now provide a detailed definition for each MHW metric in the Methodology Section, as follows:

"MHWs can be described with a number of metrics, such as their duration (in day), which refers to the period between the start and end dates of a MHW event. Frequency (in events) indicates the number of MHW events that have occurred within a given year or period. Mean intensity (°C) is the average value of the temperature anomaly during the duration of a MHW event, while maximum intensity (°C) is the highest value of the temperature anomaly recorded during a MHW event. Cumulative intensity (°C.day) is the integrated temperature anomaly over the entire duration of a MHW event and is a measure of the overall intensity of the event. Total MHW days (MHWDs, in day) refers

to the total number of MHW days that have occurred in a given year/period (Hobday et al., 2016, 2018)."

Lines 178-179: Is there any threshold for cold/warm years? Only the pos/neg sign of SSTA?

The definition of "cold" and "warm" years is related to the SSTA variability and does not necessarily imply that the SSTA in those years was unusual or extreme. Specifically, warm (cold) years are identified as those that are warmer (colder) than the preceding or following years. In order to clarify this, we have added a paragraph in the Methodology Section about the cold/warm year definition, as follows:

"We further investigated the characteristics of MHWs during 'warm' or 'cold' periods. Specifically, we define warm periods as those that exhibit a pronounced positive SSTA compared to the long-term average, while cold periods are characterized by a pronounced negative SSTA. Warm years are identified as those that are warmer than the preceding and following year, and cold years as those that are colder than the year before and after. The definition of "cold" and "warm" years is relative to the SSTA variability and does not necessarily imply that the SSTA in those years was unusual or extreme."

Line 180: How do you define a MHWD? A single day exceeding 90 percentile or a day belonging to a MHW event?

The Total number of MHW days (MHWDs, in days) refers to the total number of MHW days that have occurred within a given year/period.

Line 231: What does "non consistent" trend mean? Statistically? Spatially?

We used the term "non consistent" to refer to events that were spatially different than those identified in other years. The sentence revised to enhance the clarity (line 277).

Lines 246-249: Can't get the relevance of indicating the relatively cold/warm years in each period. It's just variability.

You're correct that the definition of 'cold' and 'warm' years is relative to the sea SSTA variability and does not necessarily mean that the SSTA in those years was unusual or extreme. By examining the years that were warmer or colder than average, we aim to identify potential common spatial features in the MHW distribution.

Lines 275-282: The description of atmospheric variables in the case of MHW events deserve a more extensive and detailed analysis. I suggest the authors to properly rewrite this part.

We appreciate the Reviewer's suggestion. We have added a new paragraph in the Results and Discussion section to provide more details about the variability of atmospheric conditions before, during, and after a MHW event. We have also deepened our analysis by examining the temporal variability of SST in comparison with other atmospheric factors, including all heat flux components and relative humidity. A new figure has been also added to present these findings in the Supplementary Material (Fig. S8).

"To better understand how atmospheric forcings may have contributed to the development of this MHW event, the spatial averages of atmospheric variables before

(February 3 to 7), during and after (March 10 to 15) the event were calculated and presented in Figure 14. Additionally, the time series of atmospheric variables averaged over the NRS (24° - 28° N and 34° - 39° E) during the event are presented in Supplementary Figure S8. Prior to the MHW event, the average SSTA in the NRS was about 1°C above average, while it was negative in the SRS and in the Strait of Bab El-Mandab. During the MHW event, the SSTA increased in the NRS and reached a local maximum of 4°C above the climatological average (Figure 14a-c). The spatial distribution of the average air temperature (Tair) showed higher values in the west (over Egypt, Eritrea and Ethiopia) than in the east (over Saudi Arabia) (Figure 14d-f). Over the NRS, the Tair increased by approximately 8°C compared to before the event. After the MHW, the Tair decreased but did not return to pre-MHW values (Figure 14d-f and Figure S8b). The mean sea level pressure (MSLP) maps showed an opposite distribution to Tair, with areas of high Tair having low MSLP and vice versa (Figure 14j-l). In addition, the average MSLP over the NRS decreased during the MHW event compared to before the event (Figure S8c). Before the MHW event, the winds blew from the eastern region and mainly flowed towards the SRS. During this event, the winds blew from the south and shifted to the west before reaching the NRS region, which experienced very low winds (Figures 14m-o and Figure S8d). Furthermore, the relative humidity rose by 10% over the NRS during the MHW period (Figure S8e).

In the RS, the latent heat flux (LHF) shares a similar spatial and temporal distribution with the net heat flux (Qt) (Nagy et al., 2021). The majority of the net surface heat exchange variability in the NRS is known to depend on the turbulent components of the surface flux, primarily the latent heat flux (Papadopoulos et al., 2013). In our case study, before the MHW event, the LHF ranged from -140 to -60 W/m², and the Qt ranged from -150 to -20 W/m², indicating that the ocean was losing heat to the atmosphere (Figure 14g-i and Figure S8f).

During the MHW, the combined effect of increased Tair, humidity and reduced winds led to a strong decrease in the ocean latent heat loss, signifying reduced heat loss to the atmosphere. Particularly during the days of the MHW onset and peak, the LHF fluctuated between -20 and -10 W/m². This decrease coincided with a slight increase in net solar radiation from 180 W/m² before the MHW to more than 200 W/m² during the MHW (Figure S8f). Accordingly, the heat exchange between the air and ocean reversed, causing a prolonged ocean heat gain, with Qt reaching up to 100 W/m², ultimately driving the MHW (Figure 14g-i).

In summary, our findings indicate that the late winter MHW event in the NRS was primarily driven by atmospheric forcing, specifically an increase in Tair and humidity, possibly linked to reduced winds. These atmospheric conditions collectively resulted in reduced LHF and a strong ocean heat gain, creating favourable conditions for MHW occurrence."

Line 356: lake?

Thank you for catching this typo, it is corrected to "lack".