Response to the comments from reviewer 1

We thank the reviewer for carefully going through the manuscript and offering insightful and constructive suggestions. The manuscript has been revised, taking all comments of the reviewer into account. Detailed replied to each of the comments are given below. Reviewer's comments are marked in **BOLD** font and the responses are in normal text.

The authors of this manuscript apply a commonly used marine heatwave detection code to NOAA OISST satellite data to investigate marine heatwave (MHW) statistics in the Arabian Sea during 1982-2019. Furthermore they investigate the impact of a mean background warming trend vs. surface temperature variability in the region and also assess the role of dominant climate modes for the generation of marine heatwaves in the region. To further understand the physical drivers of the detected MHWs, a regional ocean model used to derive a mixed layer budget.

Studying MHWs in the Arabian Sea is very likely important given their potential impacts on ecosystems and economies and the regions dense population. While I am not an expert in this region's oceanography, in my opinion, just presenting MHW statistics does not provide significant new insight. Many of the described sea surface temperature patterns and connections to climate modes are already well know in the literature. The definition of MHWs is a very useful construct to convey temperature changes/extremes, however, inherently no new insight is gained by calling something a marine heatwave. The focus of future MHW studies should lay on the depth-extent of these events and or biological/economical impacts as well as a more detailed discussion of the regional circulation and its variability (oceanic and atmospheric).

I believe it is acceptable to repeat certain analyses that have been only published in a global context, to set the scene for a regional study, however I encourage the authers to change the focus of the study (more details below). While the motivation of the study is relevant, I am not convinced that the results presented here provide enough new relevant insight. Therefore, I recommend reconsidering publishing the manuscript after major revision.

Response: We thank the reviewer for pointing the overall issue with the manuscript. The manuscript has been revised to incorporate more regional flavour while discussing the results. The known results are given the due citations.

While the definition of the MHW is inherently linked to the changes in the ocean temperature (in this case SST), but not necessarily correlate with maximum warming. For example, we have shown the strongest heatwaves in the Arabian Sea is usually appear in the northern part of the basin when the SST is in general lower than the warm pool region of the southern Arabian sea. Hence, in that sense, the definition of MHW is useful in identifying extremes rather than absolute change in the SST. In the revised manuscript, we tried to highlight these regional contexts in more detail. In doing so, we have now modified the "Dynamical mechanisms" section by including a detailed discussion on the heatwave observed during the year 2010 as a case study. The event was the longest and one of the most intense heatwaves observed since the availability of the satellite observation. We have shown its spatio-temporal evolution and discussed the dynamics behind its generation, peak and decay using a mixed layer heat budget. Also, relate these processes to the known climate responses whenever possible.

As the reviewer mentioned, the detailed discussion of the regional statistics, using a method that is already applied on a global scale, adds value in setting up the regional context of the problem. In this manuscript, we have discussed heatwaves trends, their spatial patterns and some of the associated dynamics in detail. These discussions are often ignored in global studies. Hence, we expect that the results presented here will contribute significantly to the existing literature on the regional marine heatwaves, particularly it will encourage further studies in this region.

The studies on subsurface heatwave characteristics for this basin is now underway. Considering the details involved, it is not possible to include them here and will be submitted as a sequel to this manuscript.

General Comments from the reviewer

Papers like Oliver 2019 show already, using the same dataset and detection algorithm, regions where mean warming vs. variability change is dominant globally (see their figure 4), which even picks up the stronger warming in the northeastern Arabian Sea with the chosen colormap. Furthermore the Indian Ocean SST variability and response to climate modes such as ENSO, IOD etc, I believe has been well studied over the last decade. I understand that it can be important to compile these results with a truly regional focus. I wonder if the authors could present the first part of the paper more like a review and then include more discussion about actual impacts or regional details e.g.:

- **Discuss absolute temperatures during MHWs and how that can impact the development and genesis of cyclones, which is done here only briefly.**
- **Discuss the observed patterns and variability in terms of the regional ocean circulation.**
- **I guess one main point to highlight is that the complex coupling with climate modes can can either dampen or exacerbate the impacts of a mean warming trend, thus significantly contributing to the observed interannual variability of MHW characteristics.**
- **What role does freshening in eastern Arabian Sea play for stratification change and ultimately SST?**

Response: As we mentioned in our earlier response, this manuscript aimed to describe the observed MHW characteristics in detail for the Arabian Sea. Given that it uses a similar technique that was used earlier in a global context, some of the presented features were shown earlier. We have cited the associated papers wherever appropriate.

The section on the “Role of dominant climate mode” is now expanded significantly by relating known climate mode impacts to the observed correlations between MHW events and the climate signals. Further discussion is presented in the “Dynamical mechanisms” section where the dynamical mechanisms responsible for the genesis and evolution of the heatwave event of the year 2010 are examined. In doing so, we also presented more results on cyclogenesis and its impact on persistent heatwave events. Also, in the discussion section, we have added an extra figure to discuss the changes in the cyclone frequency over the last two decades. Overall, we have provided three test cases when a tropical cyclone is involved in terminating long heatwave events. This suggested that persistent heatwaves (in other words very warm conditions over a longer period) are likely linked to the increased cyclogenesis in the Arabian Sea. However, a detailed analysis of the associated air-sea interactions and the genesis of cyclones are beyond the scope of this study.

The freshwater from the Bay of Bengal gets advected to the Arabian Sea by the coastal currents and can even reach the northern part by February/March (Chatterjee et al., 2012). In our earlier papers, we have shown that these advected freshwater alter the mixed layer depths there which has a severe consequence on the primary productivity of this region (Shankar et al., 2015; Vijith et al., 2016). Further, climate variability modulates the advection intensity and thereby, adds to the complexity. We agree with the reviewer that these processes should also be important in the genesis of heatwaves, but it would require a separate manuscript to look at these processes. This manuscript is expected to provide a base for such future work on these lines.

In the second part of the study the model mixed layer budget part can be extended and discussed in more detail with respect to the actual physical mechanisms driving the individual terms. Part of this is done in the discussion at the end but it could be more detailed. Furthermore the model could be used to investigate some of the discussion points above.

Response: We thank the reviewer for providing this suggestion. We have expanded the "Dynamical mechanisms" section by including a detailed discussion on the heatwave observed during the year 2010 as a case study. The event was the longest and one of the most intense heatwaves observed since the availability of the satellite observation. We have shown its spatio-temporal evolution and discussed the dynamics behind its generation, peak and decay using a mixed layer heat budget. Also, relate these processes to the known climate responses whenever possible.

In multiple passages the fact that patterns of MHWs coincide with warming SST patterns is presented as novel, however per MHW definition (using a fixed baseline) this is not surprising at all.

Response: We agree with the reviewer. We have now explicitly mentioned this fact in Section 4 of the revised manuscript and now read as follows:

"Notably, the regions of strongest warming trend also experience an increasing trend of MHWs (see Figure 1), indicating that the warming of the mean SST contributes to the increasing trend of heatwave days in the Arabian Sea. This is in agreement with Oliver et al. (2019) who suggest that during the satellite period about 2/3rd of the global ocean experiences an increasing trend of heatwave days due to the rising mean temperature of the ocean. However, this observation is not very surprising partly due to the fact that we have used a fixed climatological baseline and therefore, the rapid warming in the recent decade shifted the mean SST towards the threshold."

I think the manuscript would greatly benefit from a little more discussion when results are presented; e.g. L161-172 would be much more comprehensive if discussed in the light of already know SST responses to climate modes (see linebased comments below for more detail)

Response: We have included more discussions on the known climate responses on the Indian Ocean SST at many parts of the revised manuscript.

It is not clear to me why it makes sense to separate the pre-monsoon and summer monsoon season. It is mentioned that the SST trend is strongest during this time, however, I would appreciate a discussion with respect to e.g. different dynamics during these seasons.

Response: We thank the reviewer for this suggestion. Yes, both the seasons are very different in terms of overall oceanic and air-sea interaction processes. Detailed discussions on the processes at play are discussed in our recent review paper by Phillips et al. (2021). However, to benefit the readers we have now included a brief discussion on these two seasons in Section 3 of the revised manuscript.

I wish physical processes that could explain the described correlations between MHWs/SST and the climate modes would be discussed better.

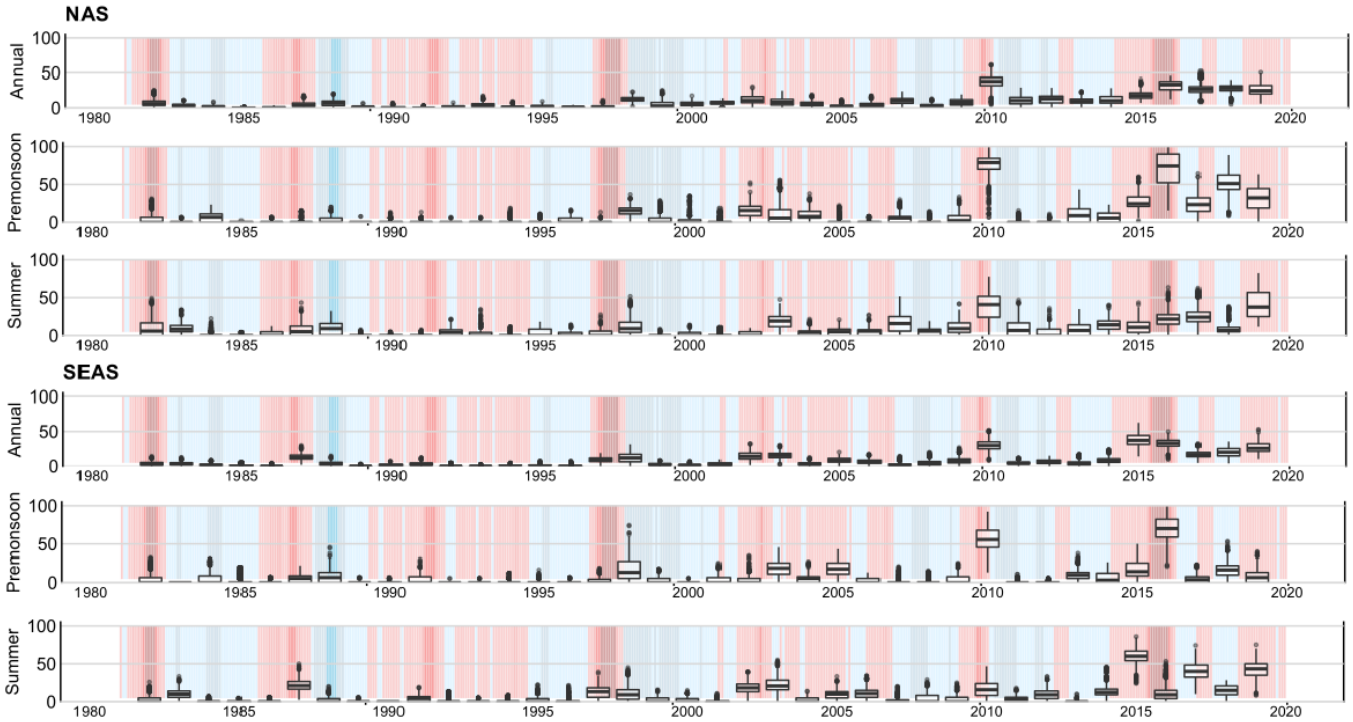
Response: We have included such general climate features only briefly in this manuscript. However, a detailed discussion is now provided for the heatwave event of the year 2010.

Figures

Figure 2: It should be stated in the caption that the y-axis presents percentages. Would it be possible to rearrange the figure? Here the red/blue Nino index, which is repeated in each panel, dominates the figure while the actual MHW data is very small. I would suggest to make the panels larger at least and maybe apply some kind of transparency to the red and blue to take the focus away a little. Could the boxplots of NAS and SEAS for annual and each season be combined in one panel, thus having three instead of 6 subpanels? That way it would also be easier to compare NAS and SEAS. This should be possible since the panels can be stretched across the whole pagewidth, allowing two boxplots per year next to each other.

Response: We tried multiple ways, including as suggested by the reviewer, to make these figures more readable. Finally, we decided not to club the seasons in one panel as it looks very busy with too many details to follow. So we kept it simple, but re-arranged the panels and modified the way the Nino3 index was shown in the background. We believe this modification will help the readers to follow the text in the revised manuscript.

The revised figure is given below:



Caption: Boxplots of the percentages of heatwave days using OISST experienced during annual, pre-monsoon and summer monsoon season for the north Arabian Sea (NAS) and the southeastern Arabian Sea (SEAS). The shading represents the Niño3.4 index.

The caption is also corrected now as noted by the reviewer.

Figure 5: Add to caption what numbers in over bars mean

Response: We have now modified the "Dynamical mechanisms" section where these numbers were discussed in the original submission. In the revised manuscript we have removed such discussion to focus mainly on the event of the year 2010. So, these numbers are now removed from the figure.

Figure 6: A correlation between MHW days and climate modes to my thinking just reflects the correlation between SST and climate modes. Again these patterns are fairly established in the region, e.g. Roxy et al. 2014 show SST composites for El Nino and La Nina

Response: We agree with the reviewer that, as the construct of MHW is based on SST, the correlation is in general show the relation between SST and climate modes. However, these correlations are calculated considering all the seasons in this manuscript. Roxy et al. (2014) discussed only the summer months.

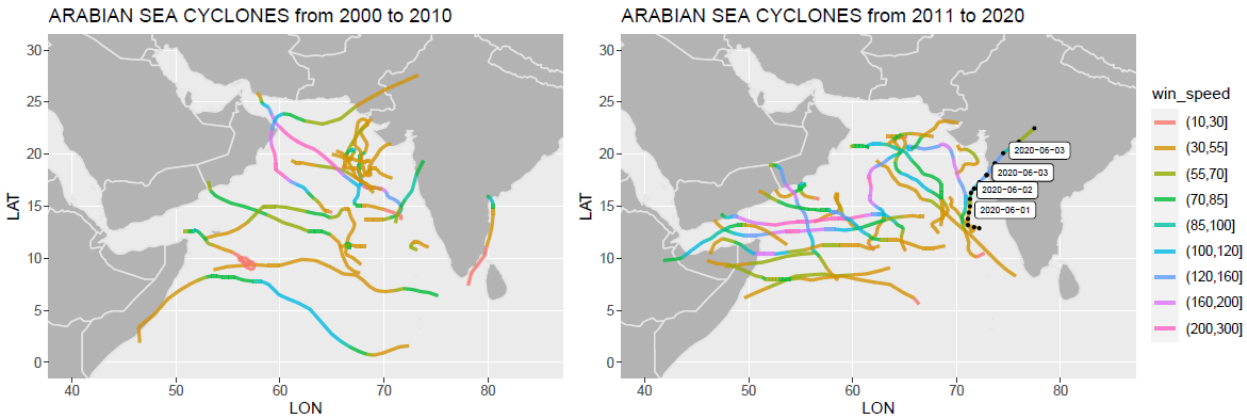
Figure 7: Abbreviations on captions should be consistent with panels, e.g. Q_v is SFX in a?

Response: This figure is now removed from the revised manuscript.

Figure 9: Would it be possible to plot two panels, one with previous and one with more recent cyclone tracks?

Response: We have now modified this figure to show the contrast in tracks between 2000-2010 and 2011-2020 period (Figure 1 of the revised manuscript). We have also expanded the discussion on the relation between cyclones and heatwaves.

The revised figure is given below. Note that the event line plot for the cyclone Nisagra is shown as a separate plot (Figure 14 of the revised manuscript).



Caption: Cyclones tracks during 2000-2010 (left) and 2011-2020 (right). The cyclone track of Nisagra which made landfall off Mumbai in 2020 is marked with the dates.

Line-based comments

L8: '…events that can cause a destructive…'

Response: Corrected.

L9: change 'are' to 'is'?

Response: Corrected.

L55: delete 'even'

Response: Corrected.

L57: shows

Response: Corrected.

L60/61: add citation?

Response: We have now included appropriate citations in the revised manuscript and it reads as follows:

"Moreover, the frequency of cyclogenesis in the Arabian Sea has also increased over the last few decades largely believed to be driven by this rapid rise in the SST (Murakami et al., 2020; Deshpande et al., 2021)."

L61/62: Impacts of increasing SST should be the same as MHW impacts since they are essentially the same thing

Response: Here, we intend to refer to such short bursts of SST extremes and not the trend.

L64-66: Is there any data which implies changes in the catches over the recent warming decade?

Response: There are few scattered studies available. However, to our knowledge, to date, no organized consolidated data is available publicly.

L66: change 'is' to 'are'

Response: Corrected.

L129/130: This seems to be an important point regarding impacts on cyclones?

Response: This is the primary reason for the premonsoon cyclones in the northern Arabian Sea among other effects on monsoon.

L131-133: Since MHWs are detected using a seasonal climatology, this reasoning is not plausible. The following sentence (L133/134) would be a better reasoning for focusing on the two chosen regions.

Response: We have modified this discussion extensively in the revised manuscript.

L135: I assume there would be significant circulation changes in these two seasons? How do these relate to the described spatial patterns? E.g. seasonal changes in the Somalia Current and the Northeast/Southwest Monsoon current?

Response: We agree with the reviewer. We have highlighted the impact of upwelling along the western boundary of the Arabin Sea while discussing the evolution and dynamics of the 2010 heatwave in Section 6.

L151-153: Complicated sentence. Instead just say something like: "This means that the duration of MHWs has increased rather than their frequency".

Response: We have now modified this statement and now reads as follows:

"This indicates that the duration of heatwaves turned much prolonged in the recent decade than that of the early 80s' and 90s'."

L161: This can be due to both, a stronger warming from 2000 onward, as well as the choice of the baseline, which just means that mean temperatures get closer to the threshold.

Response: As mentioned earlier, we have now already discussed the impact of the shift in the mean SST in the recent decade in our analysis in Section 4. Further, we have added a disclaimer on the adopted methodology in the discussion section of the revised manuscript and that reads as follows:

"It is noteworthy that the heatwaves extremes are defined here using a fixed baseline of 1982-2011. Hence, considering that the recent decades have experienced a rapid rise in SST, the overall SST running mean is shifted more towards the heatwave threshold in the recent past. Therefore, if one were to use a moving baseline, warming SSTs would not necessarily lead to a trend in MHW days. The construct of MHW definition should take into account the ultimate impact that one would like to address. The fixed baseline is possibly better suited when the impact on marine biology or atmospheric phenomenon like cyclones are considered. Whereas, the moving baseline may be a better choice if the impact of the warming trend is to be avoided. The implication of various such heatwave definitions is discussed in Oliver et al. (2021)."

L162/163: It would be helpful to just mention that these SST responses are well known, i.e. higher SST with +IOB and El Nino decay.

Response: We have expanded these discussions with appropriate citations.

L174/175: Per MHW definition this is causation and should not be presented as a novelty.

Response: As the variability of the SST driven by the climate modes can also contribute to the trend in the MHW, the statement is not very obvious. However, it is true that any change in such natural variability is also influenced by the warming trend.

On the other hand, the construct of MHW definition should take into account the ultimate impact we would like to address. The fixed baseline is possibly better suited when the impact on marine biology or atmospheric phenomenon like cyclones are considered. Whereas, the moving baseline may be a better choice if the impact of the warming trend is to be avoided. Notably, many real-world applications like seasonal monsoon forecasts by most operational agencies generally use fixed baseline. So, we preferred to use this methodology over a rolling mean.

L177/178: Not surprising due to known SST response to modes.

Response: We agree with the reviewer.

L181: change 'is' to 'has been'

Response: Corrected.

L189/190: See comment to line 174/175. Furthermore, you can see this in Fig 6 in Oliver 2019, looking at the Arabian Sea.

Response: Please see our earlier responses.

L201-203: Rewrite these sentences as they are not clear. I suggest to delete the sentences or add something like " It should be noted that the detection of MHWs is relative to a fixed baseline. If one were to use a moving baseline, warming SSTs would not necessarily lead a trend in MHW days. "

Response: We have modified this sentence as suggested by the reviewer in the revised manuscript.

L208-211: Can this be explained by different forcing mechanisms associated with the monsoon?

Response: As mentioned in the original submission, event-wise analysis is needed for a detailed understanding of the dominant processes. Hence, in Section 6 of the revised manuscript, we have provided a detailed discussion on the heatwave observed during the year 2010 as a case study. The event was the longest and one of the most intense heatwaves observed since the availability of the satellite observation. We have shown its spatio-temporal evolution and discussed the dynamics behind its generation, peak and decay using a mixed layer heat budget. Also, relate these processes to the known climate responses whenever possible.

L217: Again this shift around 2000 is likely determined by the used baseline.

Response: Yes, in other words, due to the recent warming. We have clearly stated the same in the subsequent lines.

L244/245: This is to be expected given the well know impacts of these modes on SST

Response: Yes. It shows that these climate modes can exacerbate the ongoing warming condition and therefore, cause extreme conditions such as MHWs.

L247/248: What physical processes can explain that pattern?

Response: We have not done a detailed analysis of such processes here. We agree that they are important problems for a better understanding of these extreme events and in general SST patterns. However, they are beyond the scope of this manuscript. Nevertheless, we have included discussions based on known facts and cited suitable references to improve the readability of these observations.

L266-268: This is no surprise since correlation maps for SST show that exact pattern with much weaker correlation in the northern Arabian Sea, e.g. Fig3a in Roxy et al., 2014

Response: As mentioned earlier, Roxy et al. (2014) have shown the correlation only for the summer monsoon season. In this manuscript, we have computed the correlation across the seasons and therefore, not specific to the summer months. However, we have now cited Roxy et al. (2014) at several places in the revised manuscript.

L276: Holbrook

Response: Corrected.

L277: I would speak of surface MHWs here since more and more studies also investigate MHWs at depth which would not necessarily depend on mixed layer processes.

Response: Corrected.

L290: Fig7 does not really show the maximum number of heatwave days?

Response: The original figure 7 is removed in the revised manuscript.

L294: contributes

Response: Texts are removed in the revised manuscript.

L294/295: Here it would be great to add a discussion sentence as to which physical processes are behind the describe terms.

Response: We have removed these texts from the revised manuscript. Instead, provided a detailed discussion on the heatwave observed during the year 2010 as a case study. The event was the longest and one of the most intense heatwaves observed since the availability of the satellite observation. We have shown its spatio-temporal evolution and discussed the dynamics behind its generation, peak and decay using a mixed layer heat budget. Also, relate these processes to the known climate responses whenever possible.

L296 & 301: I am not sure I understand what is meant by 'persistent background warm conditions' or ' very warm precondition'. Aren't the warm SSTs a direct results of e.g. strong surface heat flux? In order to speak of background conditions or preconditioning I would expect to see all terms at different times, where one process drives warm SSTs and another one on top then drives a MHW.

Response: These texts are removed from the revised version.

L310/311: This connects to the previous comments and furthermore I don't think it is plausible to say that MHWs are driven by warm SST since one is defined by the other.

Response: These texts are removed from the revised version.

L338/339: I would make a point here that in these two years, on top of the mean warming trend, strong El Nino's lead to particular large and persistent SSTs.

Response: This sentence is modified in the revised manuscript and now reads as follows:

"Notebly, across the last four decades, the years 2010 and 2016 show the longest heatwave days as the strong El Nino, on top of the mean warming trend, caused large and persistent warm SST across the Arabian Sea."

L339-342: Both sentences seem to say the same thing.

Response: We deleted the redundant statement in the revised texts.

L342: discuss with respect to fixed baseline and how this would change if a moving baseline was used.

Response: We have added a disclaimer on the methodology in the discussion section of the revised manuscript and reads as follows:

"It is noteworthy that the heatwaves extremes are defined here using a fixed baseline of 1982-2011. Hence, considering that the recent decades have experienced a rapid rise in SST, the overall SST running mean is shifted more towards the heatwave threshold in the recent past. Therefore, if one were to use a moving baseline, warming SSTs would not necessarily lead to a trend in MHW days. The construct of

MHW definition should take into account the ultimate impact we would like to address. The fixed baseline is possibly better suited when the impact on marine biology or atmospheric phenomenon like cyclones are considered. Whereas, the moving baseline may be a better choice if the impact of the warming trend is to be avoided. The implication of various such heatwave definitions is discussed in Oliver et al. (2021)."

L369-371: Is it really the heatwaves or the absolute temperature increase that cause the blooms?

Response: We are not very sure if the extreme or the absolute increase in temperature is responsible for such blooms. Maybe both are needed for such blooms. We believe the existing studies are very primitive in nature and need further studies with focused observations to answer some of these questions with certainty.