Review of "Amplified Warming and Marine Heatwaves in the North Sea Under a Warming Climate" by Bayoumy Mohamed et al

Overview

The manuscript uses a long-term dataset of sea surface temperature (SST) observations in the North Sea to study the impact of the warming climate on SSTs and marine heatwaves (MHWs). The authors use established statistical techniques to confirm a regime shift in the 1990s, identify a further change in 2013, and attribute much of the recent increase in MHW occurrence and severity to increases in SST. MHWs strongly impact the marine environment, particularly the ecosystem and this study, showing ocean warming to be a major driver, is important for understanding how MHWs may develop in the future.

In addition to the SST/MHW analysis, a case study of a strong MHW event in spring 2024 and the impact of hot and cold events on chlorophyll-a concentrations are also studied.

A: The authors would like to thank the reviewer for his/her time and effort in providing valuable comments and suggestions that helped us improve the manuscript. And for the very careful reading of the manuscript and the positive feedback. We have addressed all the comments below.

Main comments

The analysis of the spring 2024 event and chl-a concentrations are rather disconnected from the SST/MHW analysis (sections 3.1 – 3.3) and not related to the manuscript title. These sections should be better integrated in the manuscript. For instance, the 2024 event is attributed to anomalous atmospheric conditions; would the event still have happened without SST warming? Also, the description of changes in the timing of the chl-a cycle pre- and post-2009 is interesting but difficult to relate to the SST or MHW changes which are shown for different time periods (pre- and post-2013).

A: Thank you for this insightful comment. In the revised version of the manuscript, we have added and highlighted the following to improve the coherence of the manuscript and integrate these sections to clarify their relevance to the manuscript theme.

In the introduction:

- **Climate-related changes and extreme events in this region could have a profound impact on this rich marine ecosystem (Kirby et al., 2007; Smale et al., 2019). These extreme events can also lead to shifts in species distribution, changes in biodiversity and community structure, and increased vulnerability to invasive species (Smale et al., 2019). Smale et al. (2019) identified the North Sea as an area where many species live near the edge of their thermal** tolerance. MHWs in the North Sea in recent summers (2018-2022) have been associated with a collapse in dominant zooplankton populations, with physiological thermal limits exceeded for some species, indicating a significant impact of MHWs on zooplankton (Semmouri et al., 2023). MHWs are also likely to have an impact on chlorophyll-a concentration (CHL), which is a common indicator of phytoplankton biomass and essential for important biogeochemical processes (e.g., oceanic carbon sequestration and export). CHL in the North Sea is strongly influenced by sea surface temperature (SST), nutrient levels, and light conditions (Desmit et al., 2020). Recently, Alvera-Azcárate et al. (2021) pointed out the dominant role of SST on the timing of the spring bloom in the North Sea. They also observed a phenological shift, with the spring bloom occurring earlier each year, by about one month from 1998 to 2020. Generally, MHWs are associated with a decrease in CHL in the tropics and mid-latitudes, and an increase at high latitudes (Noh et al., 2022). However, the response of CHL to MHWs in the North Sea remains unclear.

In the methodology:

- For the CHL analysis, we first analyze the seasonal variation and spatial trend of CHL over the period (1998–2024). Then, to investigate the potential impact of MHWs and MCSs on the CHL concentration in the North Sea, we redetermined the characteristics of MHWs and MCSs based on the climatological baseline of the period overlapping with the CHL (1998–2024). Subsequently, the CHLA is correlated with the total number of MHW days and MCS days.

Regarding the question about the MHW event in spring 2024: That's a very good question. Thank you for bringing this to our attention. In the revised version, we have added the answer to this question at the end of section 3.4 and emphasized it as follows:

- **These results suggest that, in addition to long-term warming, which has contributed to the increase in the MHW occurrence in recent decades (Fig. 7), natural variability and atmospheric circulation may also play a role in modulating (i.e., either amplifying or attenuating) MHW characteristics (Chen and Staneva, 2024; Mohamed et al., 2023). Particularly in shallow water regions such as the North Sea, where atmospheric circulations over the North Atlantic and European region, including the North Sea, are likely to influence SST variability due to the rapid response of shallow water seas to atmospheric forcing (Atkins et al., 2024).**

Regarding the timing of chl-a and SST/MHW changes: To address this point, we reanalyzed the chl-a phenology using the same temporal breakpoint as the SST/MHW analysis. This alignment allows for a more direct comparison and

shows that the shift in Chl-a timing (e.g., earlier onset of bloom) is more pronounced in the post-2013 period and coincides with an increased frequency and intensity of MHWs. In addition, as mentioned above, we have added a more robust and in-depth analysis of the relationship between the CHL and the total days of MHW and MCS.

One of the metrics used is MHW frequency, which does not account for the duration of events. An increase in heatwave frequency does not necessarily mean more time under MHW conditions compared to longer, less frequent events. Number of heatwave days per year would be a better metric.

A: Thank you for this valuable suggestion. We agree with you that MHW frequency alone does not fully capture the temporal extent of MHW conditions. In the revised version, we have added the temporal evaluation and trend of the total number of MHW days (Fig. 7B) as well as their spatial trend (Fig. 8B). In addition, in the previous version we used the cumulative MHW intensity (°C. days) as the cumulative intensity can simultaneously reflect the frequency, duration, and mean intensity of MHW (Jin and Zhang, 2024), which is a more comprehensive metric for assessing the cumulative thermal stress.

Please include a description of what constitutes and impacts on “internal variability” which is the other main driver of MHW change along with SST increases.

A: In the revised version, we have added and highlighted this point as follows:

- **The long-term trends are most likely dominated by the external anthropogenic forcings, while the internal variability refers to natural fluctuations in the coupled ocean-atmosphere system, including hydrodynamic processes (e.g., currents, mixing, stratification) and atmospheric variability (e.g., wind and pressure patterns). These processes can play a role in SST variability, which can amplify or suppress MHW development on seasonal to interannual time scales. For example, Mohamed et al. (2023) found that the change in atmospheric circulation over the southern North Sea in April 2013 led to an extremely cold event, while in the same month of the following year (2014) it led to an extremely warm event.**

Detailed comments

Lines 15-16 there is no analysis shown relating SST to the AMO and EAP (only to MHW intensity PC1 and AMO/EAP) so the “crucial role” statement is not supported here.

A: In the revised version of the manuscript, we have added and highlighted the correlations between SST with both AMO and EAP, which support this statement.

- **We also examined the relationship between the PCs and the normalized indices of AMO and EAP (bars and green line in Fig. 6C). The first PC1 showed a significant correlation (r) with both AMO (r = 0.66, p<0.05) and EAP (r = 0.50, p<0.05). In addition, the SST of the North Sea showed significant correlations with the AMO (r = 0.79, p<0.05) and the EAP (r = 0.56, p<0.05).**

Line 16: the doubling of the SST trend is an important result, consider adding the rates in the abstract.
A: We have added the trend rates in the abstract as follows:

- **In particular, the SST trend has doubled in the post-2013 period (0.8°C/decade) compared to the pre-2013 period (0.4°C/decade), leading to longer and more frequent MHWs.**

Lines 25-27: please clarify the sentence on chl-a results, However the results were mostly not significant so probably not appropriate for the abstract.
A: In the revised version, we have rewritten the sentence as follows, based on the new analysis of the correlation between CHL and MHW days.

- **Finally, we also investigated how the chlorophyll-a concentration responded to the MHW, revealing a decrease in the deep and cold-water regions of the northern North Sea and an increase in the shallow and warm water areas of the southern North Sea.**

Line 47: since the AMO and EAP are used in the current analysis please include brief overviews of their major features and how they impact on SST/MHWs.
A: In the revised version, we have added and highlighted this point as follows.

- **These large-scale climate modes are associated with SST and atmospheric variability in the North Atlantic, ranging from interannual (e.g., NAO) to decadal or longer timescales (e.g., AMO and EAP), which can influence the likelihood of MHW in this region (Holbrook et al., 2019).**

Line 57-58: “Therefore, climate change …” does not follow from the previous sentence on the North Sea being a productive fishery. Please rephrase.

A: In the revised version, we have rephrased the sentence to be as follows.

- **Climate-related changes and extreme events in this region could have a profound impact on this rich marine ecosystem (Kirby et al., 2007; Smale et al., 2019).**

Lines 64-66: results should not be included in the introduction.
A: We briefly introduce the previous climate shift here to provide context, while the detailed findings are thoroughly presented in the 'Results' section.

Line 71: 2004 should be 2024.
A: Corrected, thanks for catching this typo mistake.

Line 75: Dataset -> Datasets.
A: Corrected.

Line 83: some of these products are not used in the analysis – remove those that aren't used from the list (eg latent heat etc).
A: In the revised version, we removed the unused data.

Line 110-112: sentence ending "to detect MHWs" does not make sense. Please clarify.
A: We have removed this end.

Lines134-140: definition of PR is not clear: how does the threshold for P1 change each year? Please clarify.

A: In the revised version, we have reworded the entire paragraph as follows to simplify the definition.

- **The PR is estimated as P1/P0, where P1 is the probability of MHW days in a specific year, defined as the total number of MHW days observed in that year divided by the total number of days in that year. P0 is the probability of MHW days during the entire study period (1982–2024), defined as the number of MHW days observed in all years divided by the total number of days in all years (43 years*365.25 days=15706 days). Thus, PR represents the relative strength of the MHW each year compared to the entire study period.**

Line 139 and line 142: what is the MHW "change" defined relative to?
A: Corrected>>> change in the MHW days.

Line 151: should be "top left".
A: Corrected.

Line 157: should be "top right".
A: Corrected.

Line 160: please define the abbreviation SSTA and state how it is calculated.

A: We have defined the abbreviation of SSTA and stated how it was calculated in the methodology section as follows.

- **The daily SSTA was calculated by subtracting the long-term average SST for a given day (i.e., the daily climatology) from the observed SST of the same day; the monthly and annual SSTA were then calculated using the daily SSTA.**

Line 160: in addition to the SST increase (0.8 deg C) please add the pre- and post-2013 mean temperatures.

A: In the revised version, we have added the mean values of the SST in the pre- and post-period as follows:

The annual SST has increased significantly by around 0.8°C in recent years (2013–2024: post-2013, hereafter) compared to the previous period (1982–2012: pre-2013, hereafter), with an average SST of 10.67°C and 11.46°C in the pre- and post-2013 periods, respectively.

Not sure that figure 1C is needed – figure 2 shows a clearer timeseries of SSTA and better supports the discussion (lines 172-174).

A: We think that Figure 1C is important and illustrative as it shows the temporal evolution of daily sea surface temperature anomalies.

Line 185: why use the LOWESS method and how are the weights calculated?
A: Here, we used LOWESS (a non-parametric regression technique) to confirm the climate shift and accelerated warming after 2013. The weights are calculated using a tricube weighting function. We have included the reference of Cheng et al. (2022) for more details on this technique.

- **The LOWESS trendline (thick black line in Fig. 2) also confirms the acceleration of SST warming after the crucial point of climate shift in the post-2013 period.**

Figure 3B: green line is not defined in the caption.
A: We have defined the green line, which refers to the SSTA.

Line 211: How do the SST increases in this study compare with estimates from literature?
A: We cannot make a comparison here as this value is the difference between the post- and pre-2013 periods, which is not documented in the literature.

Line 227: please clarify what are the cumulative trends and what do they signify.
A: The cumulative trend is the annual trend multiplied by the total number of years. However, we have removed this sentence to avoid confusion with the cumulative MHW. Especially, the trend of SST was illustrated in the previous part.

Lines 229-230: p>0.05 means that the correlations are not significant.
A: Thank you for spotting this error; the p-value is less than 0.05. We have corrected this in the revised version.

Line 232: brackets not needed (from 1.6 to 9.6).
A: Corrected.

Line 260: increase SSTA does not necessarily imply “an excessive trend in MHW”: MHWs are sustained increases (longer than 5 days) in temperature, please be careful of that point.
A: Corrected>>> leading to an increase in the MHW occurrence.

Line 312: use “maximum positive variability” instead of “opposite maximum variability”, which doesn’t make sense.
A: Corrected.

Line 314: there is no figure 6D.
A: Corrected to be Figure 6C.

Line 315: please clarify the statement “which corroborates a negative trend in variability intensity”.
A: Removed.

Line 351: typo in 0.1.98.
A: Corrected to be ± 1.98 (°C. days)/decade.

Line 367: please elaborate on how the results suggest that “SST variability and thus MHW in the North Sea are largely influenced by atmospheric rather than oceanic forcing”.
A: We have removed the whole section based on the reviewer # 1 suggestion.

Line 398 and elsewhere: end date of the spring 2024 event is given as July when it should be June.
A: Corrected.

Line 417: please elaborate or delete this statement on “atmospheric overheating”.
A: In the revised version, we rewrote the sentence as follows to define what we mean by overheating.

- **This suggests that atmospheric overheating (i.e., the increase in air temperatures compared to their climatological values at this time of year) and thus weather conditions could best explain this MHW event.**

Figure 11: Is the caption correct "all anomalies were calculated by subtracting the daily climatological SST"? The text on the subfigures is too small and blurry, labels A-C are difficult to read. The figure needs more explanation, e.g. how are the anomalies calculated – is the seasonal signal removed? The spring 2024 event was obviously severe, it is possible to say why it was so much more severe than others?

A: Thank you for recognising this mistake. We corrected to be: All anomalies were calculated relative to the daily climatological baseline (1982–2024). The resolution of the figure and labels is very clear in the Word file, perhaps only in the PDF file. If needed, we will provide the production section with a clearer copy (400 dpi). We have also described the calculation of the anomalies in more detail in the methodology section. This event was attributed to the anomalous anticyclonic circulation in addition to long-term warming.

Line 466: "smaller trend" denotes a comparison, but compared to what?
A: Corrected>>> small
Line 472: there is no blue line in figure 12.
A: Corrected to be green line.

Lines 473-475: figure 4C does not support this statement – it shows differences before and after 2013, not 2009.
A: We have rewritten the whole sentence and illustrated this statement based on 2013, not 2009.

Figure 12: yellow text is difficult to read and should be replaced. Please specify what the dots signify in B and C.
A: We have replaced the yellow text with the blue text. We also clarify that the dots indicate an insignificant trend or correlation (in Figure 13 in the revised MS).

Line 501: how is the chl-a anomaly calculated?
A: The CHL anomaly is estimated in the same way as the SSTA. We have added and highlighted this in the methodology section.

Figure 13D: white contour is not visible.
A: We have removed the figure and replaced it with another figure.

Lines 550-551: the response of chl-a to MHWs and MCSs was not so clear-cut as a north-south split, please clarify.
A: That's right, in the revised version, we rewrote it based on the new analysis of the correlation between CHLA and the total numbers of MHW and MCS days.

We hope these revisions and clarifications address your concerns. Thank you once again for your valuable feedback and constructive comments.