General comments

This paper investigates the long-term impact of climate warming on the occurrence of marine heatwaves in the North Sea—a topic well within the scope of Ocean Science. The manuscript is well-written and clearly structured. The authors address the main research question appropriately and present interesting results that contribute to the scientific community. Overall, I believe the study meets the journal's standards and could be published after moderate revision. Detailed comments and suggestions for improvement are provided below.

A: The authors would like to thank the reviewer for his/her very careful reading, positive feedback, valuable comments, and suggestions that helped us improve the manuscript. And for finding that our manuscript is well-written, structured, and has clear objectives. We have addressed all the comments below.

Specific comments

P2_L50:

The authors state that "the variability of MHW in the southern North Sea has been attributed to changes in stratification…". I believe this is a misinterpretation of Chen et al. (2022). That study does not attribute MHW variability to stratification; rather, it argues the opposite—that the presence and persistence of stratification in the southern North Sea are attributed to the occurrence of MHWs.

A: Thank you for pointing this out. We acknowledge the misinterpretation of Chen et al. (2022). In the revised manuscript, we have rewritten the sentence as follows.

- **The presence and persistence of thermal stratification in the southern North Sea have been attributed to the occurrence of MHW, indicating the important role of MHW in the vertical structure of the water column (Chen et al., 2022).**

P2_L71:

Throughout the Introduction, there is no mention of chlorophyll-a, yet the final sentence abruptly introduces it as a focus question regarding its response to MHWs. Even earlier in the paragraph, the stated goal of the study is to quantify the role of climate change, specifically increasing SST, in MHWs. This sudden shift lacks coherence. I recommend that the authors either omit this focus (along with Section 3.5) and reserve it for a future study (which may already form a complete narrative), or revise the introduction to systematically incorporate this aspect.

A: Thank you for your insightful comment and your suggestion to reserve this section for a future narrative study. In the revised version of the manuscript, we added more detail about the CHL-a studies in the North Sea and the role of the MHW on the CHL-a from previous studies in other regions. We have highlighted these in the introduction and the methodology 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). 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). MHW has also been found to contribute to oxygen depletion in the northern North Sea (Jacobs et al., 2024) and the Elbe estuary (Fan et al., 2025). 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.**

- **<u>In the methodology</u>, we have added more details as follows: 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.**

P5_L155–160:

I would not describe 2012/13 as indicating a "second regime shift." A regime shift is not instantaneous; it marks a transition that may unfold over months or years. Figures 1a and 2 clearly illustrate such a transition. The regime shift appears to begin around 2000 and conclude in 2012. Rather than defining 2012/13 as a second regime shift, this study might more accurately be described as the first to delineate the full span of regime shift—from 2000 to 2012. Clarifying this timeframe provides greater scientific value than introducing an arguably redundant second shift.

A: We fully agree with you that the regime shift is not instantaneous, and it could take a longer period. For this reason, we considered a robust statistical technique to detect a single (e.g., Pettitt test, Fig. 1A) or multiple (e.g., cumulative deviation test, Fig. 1B) abrupt change points of mean SST. In addition, we consider the period between the two shifts as a transition period, where the SSTA fluctuated between negative and positive anomalies. We also used the LOWESS regression (black line in Fig. 2), which confirms the second shift and the accelerated trend in the post-2013 period compared to the previous period.

P5_L173–175:

According to the domain-averaged SSTA (the thick black line in Figure 2), 2000 seems to be the transition point between the cold and transitional periods, as it is when the averaged SSTA reaches 0°C. Moreover, Figure 1 shows that, based on the Pettitt test, 70% of the North Sea experienced the transition after 2000, while only 30% (mainly the southern North Sea) transitioned between 1996 and 1998. If 1997 is used as the transition year, the affected area would be less than 10%.

A: Thank you for this useful comment. Although we emphasized that this transition took place between 1996 and 2001 (vertical yellow shading in Figure 1B), your suggestion is better to consider the transition after 2000, as it covers a larger area. Therefore, we have changed the sentence as follows.

- **There was a strong temporal evolution of the average SSTA, dividing our study period into three distinct periods. The cold period (1982–2000), in which negative SSTA and a marine cold spell (MCS) are predominant. This was followed by a transition period (2001–2012), in which both positive/negative SSTA and MHW/MCS can be observed. In the period after 2013, the North Sea warmed dramatically and transitioned to a warmer state, with a strong increase in SSTA and MHW (Fig. 1C and Fig. 2).**

P6_L187–189:
The authors state that "SST in the North Sea experienced two significant regime shifts in the late 1990s and after 2013." In my view, the North Sea underwent a single regime shift between 2000 and 2012, transitioning from MCS dominance to MHW dominance.

A: We identified two statistically significant shifts in SST based on changepoint detection methods: the first occurred between 1996 and 2001, the second after 2013 (Fig. 1B). However, we acknowledge that these shifts can also be interpreted as part of a broader, more gradual transition that occurred between 2001 and 2012, as you suggest. Therefore, we consider the period between 2001 and 2012 as a transition period between the two shifts. In this transition period, both positive/negative SSTA and MHW/MCS were observed, while in the post-2013 period, only positive SSTA and MHW were dominant.

P7:
Following my previous comment, I suggest that the authors indicate the regime shift period (2000–2012) in Figure 2.

A: In the revised version, we consider this period as the transition period between the two shifts.

P9_L251–252:
The authors state: "The increase in internal variability of SST leads to a broadening of the PDF of temperature, making the occurrence of MHW more likely." However, Figure 4A–B shows a decrease in variance from the pre-2013 to post-2013 period. Does this imply that MHWs became less likely after 2013? This needs clarification.

A: This sentence is a general conclusion from Xu et al. (2022). For this reason, we follow it with another clarifying sentence, "To verify this in our study region, we compared………" (please see lines 153).

P10_L266–268:
The authors write: "The frequency of MHW occurrence is higher in all months post-2013 than pre-2013, except for February and March…" In my view, a more outstanding difference is post-2013, the mean MHW frequency is considerably higher (almost doubled) than pre-2013 from June to December. This implies that climate warming mainly affects the appearance of MHW in the second half of the year. While this is mentioned in lines 272–273, the earlier description (lines 266–271) does not clearly highlight it.

A: That's a very good point. In the revised version, we have highlighted this as follows.

- **To further investigate the MHW occurrences between the two periods, we calculated the frequency of MHW occurrences for each month based on the original (Fig. 4C) and detrended SST data (Fig. 4D). The comparison of the monthly MHW frequency between the pre- and post-2013 periods (blue and red bars in Fig. 4c) reveals a clear seasonal asymmetry. While most months post-2013 show an increase in MHW frequency, the most pronounced increase is observed from June to December, where the MHW frequency almost doubled (i.e., increases from an average of 1 event in the pre-2013 period to 2 events in the post-2013 period). This suggests that climate warming has a strong impact on MHWs in the second half of the year, which has also led to increased summer stratification and reduced vertical mixing in recent decades (Chen et al, 2022, 2025). In contrast, the changes in MHW frequency in the winter and early spring months (February and March) are less pronounced, indicating a weaker influence of warming during this period.**

P11_L285–287:
The statement "To date, no study has evaluated the relative role of the long-term trend and internal variability on the MHW in the North Sea" is not true. Chen and Staneva (2024) have addressed this very question, using similar data (1982–2022) and methodology (Hobday et al., 2016; MATLAB toolbox by Zhao & Marin, 2019). They also identified different MHW patterns over the last 30 years (1993–2002, 2003–2012, 2013–2022). To my knowledge, their study is the first of its kind in the North Sea. The authors should revise this claim and properly credit prior research, especially work so closely aligned with theirs.

Chen, W., & Staneva, J. (2024): Characteristics and trends of marine heatwaves in the northwest European Shelf and the impacts on density stratification: In: von Schuckmann, K., Moreira, L., Grégoire, M., Marcos, M., Staneva, J., Brasseur, P., Garric, G., Lionello, P., Karstensen, J., and Neukermans, G. (eds.): 8th edition of the Copernicus Ocean State Report (OSR8). Copernicus Publications, State Planet, 4-osr8, 7, doi:10.5194/sp-4-osr8-7-2024

A: Thank you for providing us with this very valuable study. In the revised version, we have included it with emphasis on their main findings. We would like to draw your attention to the fact that this study did not consider removing the SST trend before the MHW detection to evaluate the relative role of the long-term trend and internal variability.

P14_L356:
Why were specific years selected rather than showing long-term trends? While Figure 8 provides spatial maps of annual mean MHW days, selecting individual years only highlights temporal variability within the same region (i.e., the North Sea). For instance, although 2022 and 2023 had similar total MHW days, the southern North Sea experienced different MHW durations. Presenting trends instead, like in Figure 2e–h of Chen and Staneva (2024), would better illustrate spatial variability.

A: Thank you for this valuable suggestion. In the revised version, we have removed this figure and show the spatial trends instead. In this new figure, we calculate the trend of MHW frequency, total days, and cumulative intensity. And discuss these results with those of Chen and Staneva (2024).

P14_L365–367:
The statement that "SST variability and thus MHW in the North Sea are largely influenced by atmospheric rather than oceanic forcing, which is consistent with Tinker and Howes (2020)" is misleading. Tinker and Howes (2020) found that marine air temperature is the main driver of SST rise—not necessarily the dominant influence on MHWs.

A: Based on your above comment, we have removed this paragraph and replaced this figure and related text with the trend of the MHW frequency, total days, and cumulative intensity.

P15_L379–381:
Why focus only on frequency and intensity? I would expect a discussion of trends in MHW duration and total days, or at least an exploration of the drivers behind MHW characteristics.

A: 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).

P15_L387:
What exactly is meant by "internal variability"? Do the authors refer to hydrodynamics?

A: Here, internal variability refers to the change in the SSTA Variance due to the Baltic Sea inflow. We have clarified this point as follows.

The possible explanation is that the changes in internal variability due to the Baltic Sea inflow, which can influence the stability of the water column, contribute to a decrease in the trend of MHW intensity in these regions (Chen and Staneva, 2024).

P18_L440:
It's not only reduced wind mixing; stable stratification also suppresses vertical water mass exchange, thereby limiting heat transfer to deeper layers. As a result, heat accumulates in the surface layers.

A: We have rewritten the sentence as follows:

- **This decrease in wind speed could enhance the thermal stratification of the water column, inhibit vertical mixing, and thus reduce downward heat transfer and lead to heat accumulation in the surface layers.**

P19_Section 3.5:
As previously mentioned, I do not see a clear connection between this section and the overall focus of the paper (nor is it reflected in the title). Either develop the introduction and methodology to properly integrate this topic, or consider removing it and addressing it in a future study.

A: Thank you for this insightful comment. In the revised version of the manuscript, we have added and highlighted more details about CHL in the introduction and methodology to improve the coherence of the manuscript and integrate this section to clarify its relevance to the manuscript theme.

P22_Conclusions:

The conclusion section is overly long and verbose. Please revise to make it more concise and focused.

A: We have revised the conclusion section to make it more concise and focused.

Technical Corrections

P4_L125: Add a comma after the equation.

A: done.

P4_L126: Change “Where” to lowercase: “where”.

A: done

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