Reply to Reviewer 1

Dear Reviewer,

We want to thank you for your dedicated time to review our manuscript. Your input has helped improve the clarity and robustness of the document. The changes are marked in the manuscript, as well as the reply to your comments below (in blue).

This study uses a combination of satellite observations and ocean reanalysis data to research the characteristics and trends of marine heatwaves on the northwest European Shelf. Spatial variations of the marine heatwave metrics and their trends are emphasized. The author further looked into the relationship between the marine heatwaves and water column stratification on the shelf and they have found a decreasing trend of the stratification despite the increasing surface marine heatwaves. It is an interesting study, however, some further analyses are necessary to support the conclusion from the study, so I would suggest major revisions before a publication can be considered.

Below, we present a point-to-point reply to all comments.

The authors use two datasets but there is a lack of cross-validation of the two. Also, for the ocean model data, some validation for the research region is necessary.

The two datasets mentioned by the reviewer are the CMEMS reanalysis data, covering the period 1993-2022, and the ESA CCI SST data, spanning the years 1982-1992. In the manuscript we provided references to them. As stated in both the 'quality information document' and the 'user manual' of the CMEMS product (refer to Table 1 in the manuscript), the latter dataset, specifically the ESA CCI SST L3 satellite observations, is utilized for assimilating ocean model data and generating the L4 CMEMS reanalysis data, which constitutes the former dataset. Regarding the validation of the model's temperature and salinity, the data are compared with in-situ observations from the World Ocean Database, mooring data, and the multi-model ensemble of multi-year products, an internal CMEMS product (see the 'quality information document', Table 1). In this reply, we provided references to them:

QUID: https://catalogue.marine.copernicus.eu/documents/QUID/CMEMS-NWS-QUID-004-009.pdf

PUM: https://catalogue.marine.copernicus.eu/documents/PUM/CMEMS-NWS-PUM-004-009-011.pdf

In the revised manuscript, we have incorporated the above information in the first and second paragraph of section 2 ‘Material and Methods’ as follows: "The modelled temperature and salinity are validated through comparisons with in-situ observations from the World Ocean Database, mooring data, and the multi-model ensemble of multi-year products, an internal CMEMS product.", and “The ESA dataset is also employed as observational data for assimilating CMEMS data (see QUID and PUM of the product, Table 1).

The authors propose some subsurface warming causes the opposite trends between marine heatwaves and stratification. However, the subsurface data is now shown in the study, which is necessary to confirm the conclusion.

In our study, we did not present subsurface temperature data; instead, we showcased the Potential Energy Anomaly (PEA) resulting from temperature alone (Figure 5). This was computed based on temperatures at various layers of the water column, serving as a parameter to quantify the temperature heterogeneity of the water column. Typically, temperatures in deep water columns are lower than those at the surface. The reduction in PEA indicates a diminishing temperature difference between the surface and the subsurface. As stated in the discussion, the annual mean Sea Surface Temperature (SST) trends in the NWES over the past three decades have shown an increase. Consequently, the declining trend in PEA, attributed solely to temperature, can be linked to the warming of the subsurface water. This subsurface warming is predominantly influenced by robust winter warming (Mathis and Pohlmann, 2014). The lower water column retains the memory of winter warming for a more extended period compared to the surface (Chen et al., 2022).

Reference

Mathis, M., & Pohlmann, T.: Projection of physical conditions in the North Sea for the 21st century, Clim. Res., 61, 1-17, https://doi.org/10.3354/cr01232, 2014.

Chen, W., Staneva, J., Grayek, S., Schulz-Stellenfleth, J., & Greinert, J.: The role of heat wave events in the occurrence and persistence of thermal stratification in the southern North Sea, Nat. Hazards Earth Syst. Sci., 22, 1683-1698, https://doi.org/10.5194/nhess-22-1683-2022, 2022.

To clarify this point, we revised the discussion text as follows: “As this parameter quantifies the temperature heterogeneity of the water column, the decrease in PEA suggests a reduction in the temperature difference between the surface and the subsurface. With the observed increasing trend of NWES SST in response to a warming climate, the decline in PEA due to temperature can be solely attributed to the warming of the subsurface water. This warming is primarily driven by strong winter warming, leading to a weakening of thermal stratification (Mathis and Pohlmann, 2014). Additionally, the lower water column retains the memory of winter warming for a longer duration compared to the surface (Chen et al., 2022).

In lines 118-119, the authors suggest that there is a periodicity of 7-10 years in regard to the MHWs occurrences. This is not obvious in Fig. 1. There needs to be more statistical analysis on that statement.

Thank you. We removed this statement in the revised manuscript.

Line 134-136: This is an interesting finding. Is there a climate driver or dynamic process that drives this spatial variation?

We are thankful to the reviewer for initiating this insightful discussion. Following this sentence, we extended the subsequent paragraph with additional content: “The occurrence of Marine Heatwaves (MHWs) can be primarily attributed to two drivers: local air-sea heat exchange resulting from abnormally high air temperatures and nonlocal heat transport via ocean advection (Gupta et al., 2020; Schlegel et al., 2021). The atmospheric factor emerges as the predominant driver of MHWs in the southern to middle North Sea (Chen et al., 2022; Mohamed et al., 2023). Nonlocal heat fluxes, such as the influx of warm Atlantic water into NWES, may be responsible for the development of MHWs.

Compared to the long-term average, higher seawater temperatures will result in more heat fluxes into the NWES by the North Atlantic shelf current, particularly in the English Channel and the Shetland-Irish Shelf (zones 4 and 6 of Figure 1a). The heightened seawater makes these areas more prone to experiencing MHW compared to regions less affected by the North Atlantic current, such as the Norwegian Trench (zone 5, Fig. 1a). This may explain why these regions have more days with MHW. Furthermore, the mean intensity of MHW in these two regions is notably lower than in the Norwegian Trench (Figure 2d), supporting the assertion. The lowest mean intensity is observed in the Irish Sea and the English Channel. The MHW intensifies towards the east coast of the NWES. Along the coast of Denmark and Norway, the mean intensity reaches approximately 2.5 ^{o}C to 3 ^{o}C. However, compared to the southern NWES, the shorter durations and higher frequencies of MHW in its northern region may be attributed to the distinct characteristics of climate drivers in their respective areas. This is because atmospheric influences, in contrast to oceanic influences, exhibit larger variability in affecting SST (Tinker and Howes, 2020). Other drivers, such as local wind (Mohamed et al., 2023), may introduce further uncertainties to the occurrence and persistence of MHWs. Identifying the dominant drivers of MHW features in NWES requires a systematic investigation of the relationship between air and sea temperatures in various regions. However, this detailed analysis is not elaborated in this paper due to space constraints.

References

Chen, W., Staneva, J., Grayek, S., Schulz-Stellenfleth, J., & Greinert, J.: The role of heat wave events in the occurrence and persistence of thermal stratification in the southern North Sea, Nat. Hazards Earth Syst. Sci., 22, 1683-1698, https://doi.org/10.5194/nhess-22-1683-2022, 2022.

Gupta A. S., Thomsen M., Benthuysen J. A., Hobday A. J., Oliver E., Alexander L. V., et al.: Drivers and impacts of the most extreme marine heatwaves events. Sci. Rep. 10, 19359. http://doi.org/10.1038/s41598-020-75445-3, 2020.

Mohamed, B., Barth, A. and Alvera-Azcarate, A.: Extreme marine heatwaves and cold spells events in the Southern North Sea: classification, patterns, and trends, Front. Mar. Sci., 19, https://doi.org/10.3389/fmars.2023.1258117, 2023.

Schlegel R. W., Oliver E. C. J., Chen K.: Drivers of marine heatwaves in the northwest atlantic: the role of air–sea interaction during onset and decline. Front. Mar. Sci. 8. http://doi.org/10.3389/FMARS.2021.627970/BIBTEX, 2021.

Tinker J., Howes E. L.: The impacts of climate change on temperature (air and sea), relevant to the coastal and marine environment around the UK, MCCIP Science Review. http://doi.org/10.14465/2020.arc01.tem, 2020.

line 158: Are all shelf regions present summer stratification?

Clear summer stratification is observed in the Shetland-Irish shelf region, as presented in Figure 3, with PEA (ø) ≥ 50 J m^{-3} during summer and ø < 50 J m^{-3} for the annual mean. The Celtic Sea area also exhibits summer stratification with a seasonal cycle, although not as pronounced as the Shetland-Irish Shelf. Its annual mean PEA hovers around 50 J m^{-3}. This difference is attributed to the southern location of the Celtic Sea, resulting in a longer warming period compared to the northern regions and stratified shelf waters during autumn. In the revision, we rephrase this sentence as follows: 'In the middle North Sea and the Shetland-Irish Shelf, ø≥50 J m^{-3} during summer and ø<50 J m^{-3} for the annual mean, indicating clear seasonal summer stratification (Figure 3). The Celtic Sea also exhibits seasonal cycles in PEA, with ø ranging from 110~120 J m^{-3} during the summer and around 50 J m^{-3} over the entire year. The large annual mean PEA is mainly attributed to the extended warming period and stratification during autumn.

The Norwegian Trench is not shown in Fig. 1.

The Norwegian Trench is labeled with number 5 in Fig.1a).

Line 206 and 214: what is "SST intensification"?

We revise it to SST heightening.

Line 238-239: a scatter plot may show the relationship better.

We appreciate the reviewer's suggestion. This statement is concluded based on the comparison of the increasing SST and the decreasing PEA due to temperature (Figure 4 middle rows). We believe that this statement becomes clear in the revised manuscript after we rewrite lines 256~264. Nonetheless, using the Celtic Sea as an example, we present a scatter plot in this reply to illustrate the relationship between the rise in SST caused by Marine Heatwaves (MHW) (the mean intensity of MHW) and the PEA due to temperature for the periods 1993-2022. There is no obvious linear correlation between the two variables (with R^2=0.1). However, it is found that the PEAs in more recent years are lower than those in earlier periods. Moreover, the mean intensity in more recent years (1.6~1.8°C) is larger than in earlier periods (1.2~1.4°C). These are the same features one can observe from Figure 2h and Figure 4 (middle row) of the manuscript, which provides additional spatial distribution of the variables of Figure R1. Considering Figure R1 does not add much new insight regarding the relationship, and the restrictions of the figure numbers required by the Ocean State report, we decide not to include this figure in the updated manuscript.

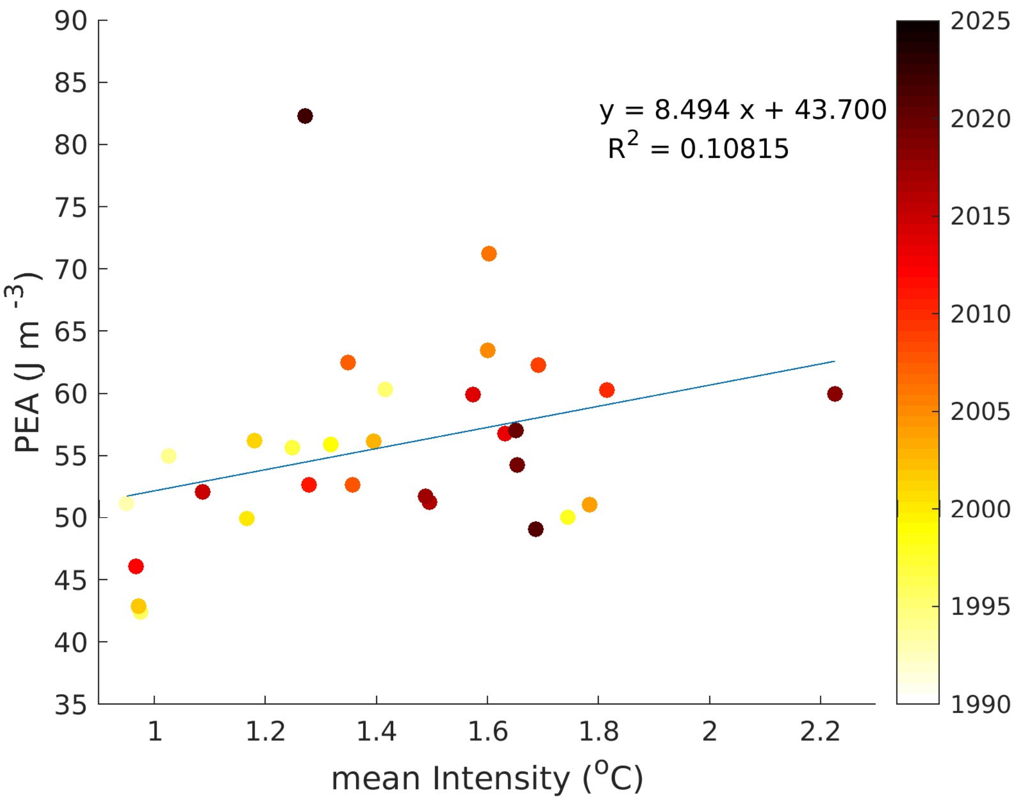

Figure R1. Scatter plot of the annual mean intensity due to MHW and annual mean PEA due to seawater temperatures at different years (in color scatter points).