Author's response to Reviewer 1

General comments:
This paper presents an analysis of the factors that affect the occurrence of marine heatwaves in the North Sea. A correlation-based K-means clustering approach was used to divide the North Sea into two regions that have different variability in marine heatwave cumulative intensity, and detailed analysis carried out to determine the mechanisms that cause that variability. The paper is well written and presented, and the topic and results are of strong interest.

Response: Thank you very much. We carefully considered each of your comments and suggestions, and we would like to respond to them in the following content.

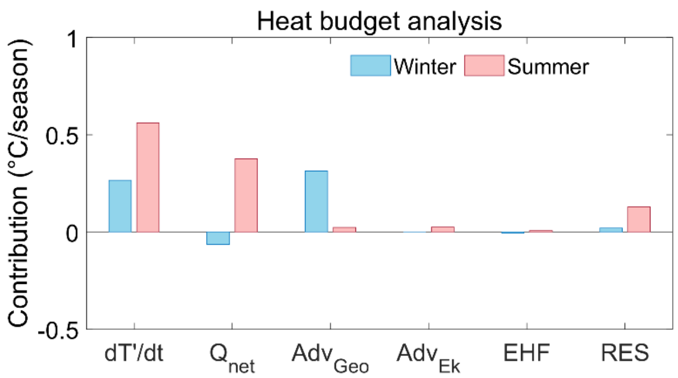
Specific comments:
Line 97 – should Worsfold et al. (2024; https://doi.org/10.3390/rs16183358) be referenced here?

Response: Thank you for noting this relevant paper. We have read it through and referenced it at appropriate places in the revised texts.

Line 157 – a minor comment, but why include November and May in the calculation of tendency but not March or September? Shouldn't it be calculated either November - March and May – September if including the months surrounding the season, or December – February and June – August if not?

Response: We agree that our description of the SST anomaly tendency window could be confusing. To ensure temporal consistency between the left-hand-side tendency and the seasonally averaged budget terms, we have revised the tendency calculation, so that it is computed within the core season: (Feb-Dec) for winter (DJF) and (Aug-Jun) for summer (JJA) and normalized by the corresponding time interval. All right-hand-side terms are now averaged over the same DJF/JJA periods. The manuscript and figure have been updated accordingly.

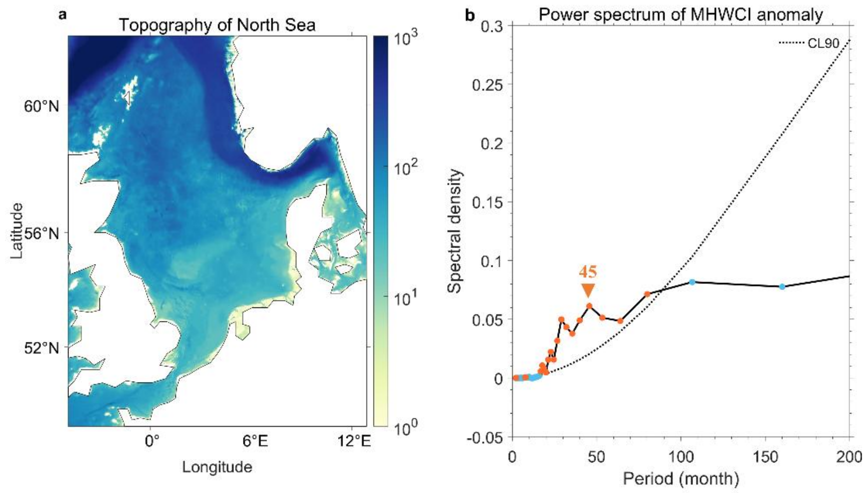
L231-L232: "We calculated this tendency as the temperature difference between February and December for winter and between August and June for summer, respectively. "



Updated Figure 8. Quantitative contribution (˚C/season) of atmospheric and oceanic processes to the upper ocean temperature anomaly tendency for two clusters identified by the K-means algorithm. The atmospheric and oceanic variables are shown as composite patterns during positive phases of the cluster-specific time series in winter (blue) and summer (red). The temperature tendency (*dT'/dt*) represents the difference in the sea surface temperature anomaly between February and December for winter and between August and June for summer, respectively. Contributions from the net heat flux anomaly (Q_{net}), geostrophic heat advection (Adv_{Geo}), Ekman heat advection (Adv_{Ek}), entrainment heat flux (*EHF*), and residual term (*RES*), averaged over the same periods, are also shown.

Line 184 – I struggle to relate the text here, which says two distinct temporal patterns, to Figure 1b, which does not seem to show a strong peak at ~6 month period. Perhaps a log scale on the y axis might help?

Response: Thank you for this important and constructive comment. We apologize for not clearly describing the preprocessing applied prior to the spectral analysis. The power spectrum shown in Figure 1b was computed from a 12-month running-mean MHWCI anomaly, which acts as a low-pass filter and was intended to emphasize interannual variability. As a result, seasonal variability is strongly dampened and is therefore not expected to appear as a pronounced spectral peak in this figure. To avoid confusion, we have revised this figure (see below) and corresponding texts in the manuscript.



Updated Figure 1. (a) The research domain of the North Sea. The bathymetry (m) is shown on a logarithmic scale. (b) Power spectrum analysis of 12-month running-mean marine heatwave cumulative intensity (MHWCI) anomalies in the North Sea derived from OSTIA. Orange dots indicate periods exceeding the 90% confidence level (black dashed line), while blue dots represent periods below this threshold. The 90% confidence level is calculated using a χ^2 test against a red-noise (AR(1)) background spectrum based on the lag-1 autocorrelation.

L261-L266: Power spectrum analysis of the detrended monthly MHWCI (Fig. 1b), constructed as a continuous time series by summing the cumulative intensity of all MHW events occurring within each month (and set to zero when no events occur), shows that, after removing the dominant seasonal pattern, substantial variability remains at interannual timescales. Several spectral peaks exceed the 90% confidence level, suggesting that MHWCI variability in the North Sea is organized on multi-year timescales. This provides a basis for exploring whether such variability exhibits coherent spatial and seasonal structures across the region.

Equation 3 – Is the left brace notation intended? The equivalent equation in the referenced paper uses square braces. Also, I'm not clear why the stationary version of the equation is used rather than the full one?

Response: You are correct regarding the notation. We have revised Eq. (3) to use square brackets for consistency with the original presentation in Takaya and Nakamura (2001). The wave activity flux formulation adopted here follows the stationary Rossby wave activity flux as defined by Takaya and Nakamura (2001), which is widely used to diagnose the propagation of quasi-stationary Rossby wave energy in seasonal-mean and large-scale circulation patterns. Since our analysis focuses on seasonally averaged atmospheric teleconnections rather than transient wave evolution, we argue that the stationary version of formulation is appropriate for the purpose of this study.

Updated Eq.3: $$WAF = \frac{p\cos\varphi}{2|U|}\begin{bmatrix} \frac{U}{a^2\cos^2\varphi}\left[\left(\frac{\partial\psi'}{\partial\lambda}\right)^2 - \psi'\frac{\partial^2\psi'}{\partial\lambda^2}\right] + \frac{V}{a^2\cos\phi}\left(\frac{\partial\psi'}{\partial\lambda}\frac{\partial\psi'}{\partial\varphi} - \psi'\frac{\partial^2\psi'}{\partial\lambda\partial\varphi}\right) \\ \frac{U}{a^2\cos\varphi}\left(\frac{\partial\psi'}{\partial\lambda}\frac{\partial\psi'}{\partial\varphi} - \psi'\frac{\partial^2\psi'}{\partial\lambda\partial\varphi}\right) + \frac{V}{a^2}\left[\left(\frac{\partial\psi'}{\partial\varphi}\right)^2 - \psi'\frac{\partial^2\psi'}{\partial\varphi^2}\right] \end{bmatrix}$$

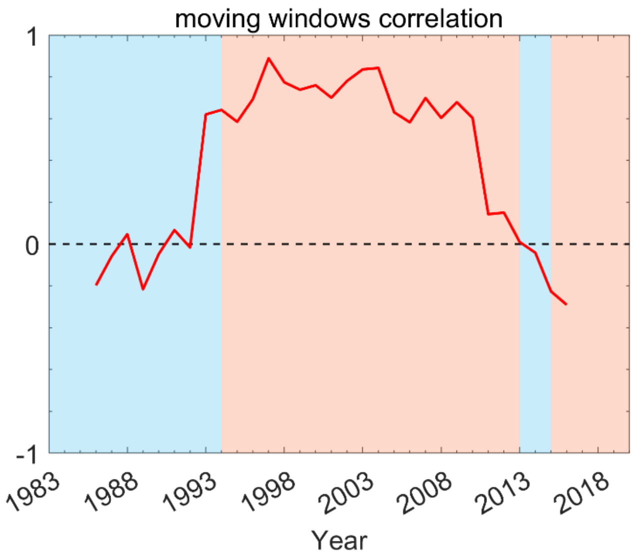
Line 185 – How was the 90% confidence interval calculated?

Response: The 90% confidence level in Fig. 1b was estimated using a chi-square significance test against a stochastic noise background. Specifically, we computed the power spectrum from the detrended monthly MHWCI anomalies, estimated the effective degrees of freedom, and then derived the 90% confidence threshold from the χ^2 distribution. When the lag-1 autocorrelation is positive (and larger than lag-2), we adopt a red-noise (AR(1)) background spectrum following the standard formulation; otherwise a white-noise background is used. Spectral peaks exceeding this 90% threshold are marked as significant in the figure. We have clarified this procedure in the updated caption of Figure 1.

L95-L99: "Figure 1. (a) The research domain of the North Sea. The bathymetry (m) is shown on a logarithmic scale. (b) Power spectrum analysis of 12-month running-mean marine heatwave cumulative intensity (MHWCI) anomalies in the North Sea derived from OSTIA. Orange dots indicate periods exceeding the 90% confidence level (black dashed line), while blue dots represent periods below this threshold. The 90% confidence level is calculated using a χ^2 test against a red-noise (AR(1)) background spectrum based on the lag-1 autocorrelation."

Line 211 – 2013 onwards seems a short period to calculate the correlation, even though it is statistically significant. Do any other similar length periods in the record have low correlation?

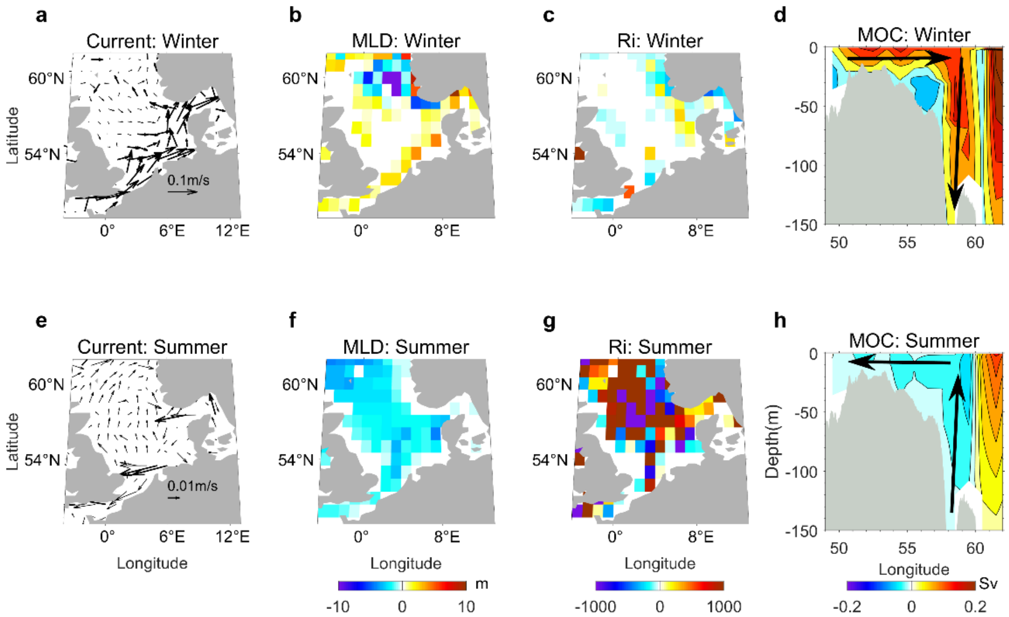
Response: To address this concern, we calculated correlations using moving windows of the same length as the 2013-2022 period across the full time series record. The sliding-window analysis shows that correlations remain consistently high during positive AMV phase (1994-2013), even when the same short window length is applied. In contrast, correlations are weak as those observed after 2013 (Fig. S2). This indicates that the 2013-2022 reduction is not a feature of short windows but instead reflects a distinct weakening of the relationship. We have added this figure as Supplementary Figure S2 in the revised manuscript.



Supplementary Figure S2. Sliding-window correlation between domain-averaged MHWCI for Cluster 2 during summer and Interdecadal Pacific Oscillation (IPO) index using a 9-yr window. blue and red shading indicate negative and positive phases of Atlantic Multidecadal Variability (AMV), respectively. The blue bar from 2013-2015 indicates the Atlantic "cold blob" event.

Figures using arrow vectors (particularly Figure 7) – Is it possible to make the arrows clearer as their direction is not easy to see?

Response: We have improved Figure 7 (see below) by increasing the arrow size to make the flow direction more easily discernible. In addition, we have simplified the vector representation by using arrow length to indicate current speed and a uniform color for all vectors.



Updated Figure 7. Composite anomalies of oceanic variables during positive phases of the cluster-specific time series in winter (a-d) and summer (e-h). (a), (e) Oceanic current (vectors, m/s), (b), (f) mixed layer depth (MLD, m), (c), (g) Richardson number (Ri), (d), (h) meridional overturning circulations (MOC, Sv). The MOC is domain-integrated overturning circulations, obtained by integrating the velocity field over the entire zonal and meridional extent of the study domain, respectively. Negative stream function values correspond to clockwise circulation, while positive values indicate counterclockwise circulation. Black arrow-headed lines in (d) and (h) indicate the direction of the overturning circulation.

Figure 7 – Colour bar for panels a and f uses a diverging colour scale and it would be better to use a non-diverging scale as the scale goes from 0 to 0.02.

Response: Thank you for this helpful suggestion. In the revised Figure 7 (see above), we have further simplified the presentation of the velocity fields. For panels (a) and (f), the flow speed is no longer represented using a color scale. Instead, all vectors are plotted in black, and the current speed is indicated solely by arrow length.

Figure 7 – Are the MOC and ZOC calculated at a particular latitude / longitude?

Response: The MOC shown in Figure 7 are not calculated at a single fixed latitude or longitude. Instead, they are obtained by integrating the velocity field across the entire zonal or meridional extent of the study domain, respectively. Therefore, the resulting MOC represents basin-integrated overturning circulations rather than transports along a particular section. We have clarified this in the revised figure caption (see above).

Figure 7 convergence and overturning circulation colour scales - What direction do negative or positive numbers indicate?

Response: We apologize for not clearly stating this in the original caption. In Figure 7, “Negative stream function values correspond to clockwise circulation, while positive values indicate counterclockwise circulation.”. This information has been added to the figure caption for clarity.

Technical comments:

Line 400 – Should it say AMV instead of AMO?

Response: You are right. We have revised the manuscript and consistently use AMV.

Fig 2c and d – Series is misspelt in the titles.

Response: Thank you. The spelling errors have been corrected in the revised figure.

Figure 7d, e, i, j – Suggest adding Latitude or Longitude labels on the x axis.

Response: Thank you for this helpful suggestion. Latitude/longitude labels have been added to the x axis.

Figure 8 – budget is spelt wrong in the title.

Response: The spelling error has been corrected in the revised figure.

Figure 9 – Colour bar should be labelled

Response: The colour bar in Figure 9 is now labelled with the unit (m^2/s^2).