

Author's response to Reviewer 3

The manuscript examines the spatio-temporal variability of marine heatwaves (MHWs) in the North Sea and explores how different large-scale climate variabilities interact to shape their occurrence and characteristics. The authors use long-term SST observations, identify two main regional patterns of MHW variability, and relate these patterns to different atmospheric and oceanic climate modes, with a primary focus on seasonal differences.

Overall, the topic is important and highly relevant, especially given the increasing frequency and impacts of marine heatwaves in shelf seas. The focus on the North Sea is well chosen, and the approach of examining the combined influence of climate modes, rather than treating them independently, is interesting. The study appears scientifically sound, and the results are clearly relevant to the community.

However, I believe the manuscript still requires major revisions. My main concern is the lack of several methodological details and the presentation, particularly in the results section, which makes it difficult to follow the main results and understand them. With significant improvements in clarity and structure, the paper could be much stronger.

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.

Introduction

1. The introduction provides useful background, but the aim of the study is not clearly stated. I strongly recommend rewriting the objectives part of the introduction to clearly state the goal(s) of the work and the main research questions.

Response: We agree that the original Introduction does not sufficiently highlight the specific aims of the study. We have revised the Introduction to clearly state the aim of the study and to explicitly formulate the main objectives, including the identification of seasonally distinct spatial domains of MHW variability and the investigation of their associated physical mechanisms.

L81-L91: “In this study, we address the knowledge gap in understanding synergistic impacts of climate modes on MHWs in shelf seas. We focus on the greater North Sea region, which is projected to warm as fast as global levels (Hobday & Pecl, 2014) but exhibits large climate variability caused by interactions between the Arctic and subtropical zones (Quante & Colijn, 2016). This makes it an ideal regional example for understanding how climate modes synergistically influence MHWs in complex shelf sea settings. Specifically, this study aims to (1) identify coherent spatial domains in the North Sea based on the seasonal patterns of interannual marine heatwave cumulative intensity (MHWCI) variability, (2) quantify how the frequency, intensity, and duration of MHWs differ between these domains during their seasonally dominant periods, and (3) examine the associated atmospheric and oceanic processes that modulate the observed regional contrasts. A correlation-based k-means clustering approach is used to characterize MHWCI variability, followed by an examination of the associated large-scale climate variability, air-sea heat fluxes, and oceanic heat transport.”

2. Additionally, since the analysis relies heavily on different climate modes, it would be helpful to define these climate modes early on, either in the introduction or in the data/methodology section. And add a brief explanation of how the positive and negative phases of these modes could affect SST variability in the North Sea.

Response: We agree that a clear definition of the climate modes and their relevance to North Sea SST variability should be provided early in the manuscript. We have revised the manuscript to explicitly define all climate modes used in this study and to clarify their physical relevance. Specifically, a new subsection (Sect. 2.4) has been added to the Methods section, which details the definitions, data sources, and calculation methods of the NAO, EAP, and AMV indices. In addition, the section has included a brief explanation of how the positive and negative phases of these climate modes can influence SST variability and marine heatwaves in the North Sea.

L149-L164:

“2.1.3 Climate modes

The influence of large-scale climate modes is investigated using indices of the NAO, the EAP, and the AMV, which are known to modulate atmospheric circulation over the North Atlantic and adjacent shelf seas. The NAO and EAP indices are obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center and are derived from the first and second modes of a rotated empirical orthogonal function (EOF) analysis of monthly mean 500-hPa geopotential height anomalies over the North Atlantic.

The AMV index is derived from basin-averaged SST anomalies over the North Atlantic. To isolate internal multidecadal variability, the AMV index is calculated by removing the global-mean SST anomaly from the North Atlantic mean SST anomaly (Trenberth & Shea, 2006). Positive and negative phases of each climate mode are defined using a fixed threshold at zero, with values greater (less) than zero indicating positive (negative) phases. Seasonal indices are computed by averaging the corresponding monthly values over the relevant seasons.

Previous studies have shown that positive phases of the AMV and EAP are associated with increased annual MHW cumulative intensity in the North Sea, whereas positive NAO phases primarily enhance wintertime MHW occurrence in the southern North Sea (Mohamed et al., 2023; Mohamed et al., 2025).”

3. One minor point: the manuscript sometimes refers to the Atlantic Multidecadal Oscillation as AMO and sometimes as AMV. Please use only one term throughout the manuscript, as switching between them is confusing.

Response: Thank you for pointing this out. We have revised the manuscript with a consistent use of AMV.

Data and Methods

This section requires the most attention, primarily because important details are missing or not clearly described.

1. The data section is not sufficiently clear. I suggest rewriting it in a more straightforward manner, listing the datasets used, their sources, temporal and spatial resolution, and how they are used in the analysis. Currently, it is difficult to understand exactly which products are used and why.

Response: We have rewritten and reorganized the Data section to improve clarity and transparency following your suggestion. The revised version now explicitly lists all datasets used in the study, including their sources, temporal and spatial resolutions, and their specific roles in the analysis.

Specifically, the Data section has been restructured into separate subsections (listed below) for (i) SST data and MHW identification, (ii) atmospheric and oceanic reanalysis data, and (iii) climate mode indices. This reorganization provides a clear description about which data products are used at each stage of the analysis and for what purpose.

L100-L164:

“2 Data and Methods

2.1 Data

2.1.1 SST and MHW Identification

Our analysis of MHWs in the North Sea (Fig. 2a) is based on high-resolution SST data ($0.05^\circ \times 0.05^\circ$, daily) obtained from the Copernicus Marine Environment Monitoring Service (CMEMS). This product is generated by the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) , which integrates multiple satellite observations and in situ measurements, and covers the period 1982-2021. An independent observation-based SST dataset from the FerryBox system (Macovei et al., 2021), developed by Helmholtz-Zentrum Hereon, is used for validation purposes (Fig. S1).

MHWs, which are defined as individual thermal events during which their associated temperature is larger than the 90th percentile threshold for at least 5 days (Hobday et al., 2016), are detected by using the MATLAB Marine Heatwaves (M_MHW) toolbox (Zhao & Marin, 2019). The climatological mean and percentile-based threshold used to detect MHW events are computed over the period 1982-2021, which corresponds to the full temporal coverage of the SST dataset used in this study. To ensure internal consistency across all analyses, a unified climatological baseline and detrending strategy is applied throughout this study. All anomalies are computed relative to the same reference period, and long-term trends are removed before analyses that focus on variability and climate-mode relationships.

The long-term warming trend was subtracted to better estimate the effects of climate modes (Liu et al., 2022). To isolate variability relative to the long-term warming background, SST was detrended before MHW detection. The detrending was performed by identifying a linear trend estimated from the global-mean SST time series over 1982-2021 and subtracting this common trend from the SST time series at each grid point. This procedure reduces the influence of externally forced warming on the identification of marine heatwaves and subsequent analyses.

Characteristics of MHWs, including frequency, duration, mean intensity, and cumulative intensity, were derived following event detection. Among these metrics, cumulative intensity integrates the effects of event duration and mean intensity and provides an effective measure of the overall impact of MHWs (Marin et al., 2021). In this study, the cumulative intensity was summed to derive the monthly MHWCI, representing the combined impact of all MHW events occurring within a given month (Gröger et al., 2024; Mohamed et al., 2023). Specifically, the cumulative intensity of all MHW events whose onset date falls within a given month was summed to form the monthly MHWCI, while months without any MHW events were assigned a value of zero. This results in a continuous monthly MHWCI time series, which was subsequently expressed as anomalies relative to its long-term mean to characterize interannual variability

2.1.2 Atmospheric and oceanic reanalysis data

Atmospheric conditions were characterized using the ERA5 reanalysis dataset (Hersbach et al., 2020) produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5 provides monthly variables at a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$. The variables used in this study include 10-m wind components, 500-hPa geopotential height, precipitation, and surface heat fluxes. Although ERA5 is available from 1940 onward, only data from 1982-2021 were used in this study to ensure consistency with the satellite-based SST record used for marine heatwave detection.

Oceanic conditions were analyzed using monthly data from the ECMWF Ocean Reanalysis System 5 (ORAS5) (Zuo et al., 2019), which provides global ocean reanalysis data at a horizontal resolution of 0.25° . Variables of interest include potential temperature and ocean current velocity, which were used to examine subsurface thermal structure and oceanic heat transport associated with MHW variability. Our analysis focuses on seasonal to interannual variability, for which monthly-mean fields are commonly used in existing studies (Liu et al., 2022; Mohamed et al., 2023).

2.1.3 Climate modes

The influence of large-scale climate modes is investigated using indices of the NAO, the EAP, and the AMV, which are known to modulate atmospheric circulation over the North Atlantic and adjacent shelf seas. The NAO and EAP indices are obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center and are derived from the first and second modes of a rotated empirical orthogonal function (EOF) analysis of monthly mean 500-hPa geopotential height anomalies over the North Atlantic.

The AMV index is derived from basin-averaged SST anomalies over the North Atlantic. To isolate internal multidecadal variability, the AMV index is calculated by removing the global-mean SST anomaly from the North Atlantic mean SST anomaly (Trenberth & Shea, 2006). Positive and negative phases of each climate mode are defined using a fixed threshold at zero, with values greater (less) than zero indicating positive (negative) phases. Seasonal indices are computed by averaging the corresponding monthly values over the relevant seasons.

Previous studies have shown that positive phases of the AMV and EAP are associated with increased annual MHW cumulative intensity in the North Sea, whereas positive NAO phases

primarily enhance wintertime MHW occurrence in the southern North Sea (Mohamed et al., 2023; Mohamed et al., 2025).”

2. The SST analysis is limited to 2021, but high-resolution SST products are available at least until the end of 2024. It is unclear why the study stops at 2021. If this limitation is due to other variables or datasets, it should be clearly stated. Otherwise, extending the analysis to include the most recent years would strengthen the study, especially since recent years include strong extremes that could affect the statistics.

Response: Thank you for noting the temporal coverage of the SST analysis. The original manuscript used the CMEMS OSTIA reprocessed analysis product, which is a long-term, homogeneous dataset specifically designed for climate studies and marine heatwave statistics. The reprocessed OSTIA product is generated retrospectively using the OSTIA system with re-processed satellite observations (including ESA SST CCI and C3S products, as well as EUMETSAT and REMSS data) and in situ measurements from the HadIOD dataset, all processed using a consistent system and algorithms. This ensures temporal homogeneity and provides a climate-quality estimate of foundation SST, which is free of diurnal variability.

At the time when the data were processed and the manuscript was prepared, this reprocessed dataset was available only up to 2021, which explains the end year of the original analysis. We note that near-real-time (NRT) OSTIA SST products extend to the present day. However, the NRT-ANALYSIS is a near-real-time hindcast produced with less optimal observational coverage and quality compared to the reprocessed best-analysis product, and may involve temporal inhomogeneities. For this reason, we did not merge the NRT product with the reprocessed dataset for long-term climatological and marine heatwave analyses.

3. Regarding the marine heatwave definition, the authors use the standard Hobday et al. method, but the climatology period used to define the MHW threshold is not mentioned. It must be included in the methodology. Also, please clarify whether the same climatology baseline period is used when computing other anomalies in the study, as this is not currently clear.

Response: The MHWs are identified using the standard Hobday et al. methodology, with the climatological mean and threshold computed over the 1982-2021 period, consistent with the temporal coverage of the SST dataset. In addition, all other anomalies analyzed in this study are calculated relative to the same 1982-2021 climatological baseline. We have clarified these points in the Methods section.

L110-L116: “MHWs, which are defined as individual thermal events during which their associated temperature is larger than the 90th percentile threshold for at least 5 days (Hobday et al., 2016), are detected by using the MATLAB Marine Heatwaves (M_MHW) toolbox (Zhao & Marin, 2019). The climatological mean and percentile-based threshold used to detect MHW events are computed over the period 1982-2021, which corresponds to the full temporal coverage of the SST dataset used in this study. To ensure internal consistency across all analyses, a unified climatological baseline and detrending strategy is applied throughout this study. All anomalies are computed relative to the same

reference period, and long-term trends are removed before analyses that focus on variability and climate-mode relationships.”

L118-L122: “The long-term warming trend was subtracted to better estimate the effects of climate modes (Liu et al., 2022). To isolate variability relative to the long-term warming background, SST was detrended before MHW detection. The detrending was performed by identifying a linear trend estimated from the global-mean SST time series over 1982-2021 and subtracting this common trend from the SST time series at each grid point. This procedure reduces the influence of externally forced warming on the identification of marine heatwaves and subsequent analyses.”

4. Another confusing aspect is the detrending or trend removal. In lines 109–110, the manuscript refers to trended and detrended data, but it is not clearly explained: how the detrending is performed? and how it affects the results? This needs a clearer explanation, as detrending choices can influence both clustering and correlations with climate modes.

Response: The detrending procedure has been clarified in the revised manuscript. Specifically, long-term warming is identified by estimating a linear trend of the global-mean SST over the study period (1982-2021). This global trend is then subtracted from the original SST field prior to marine heatwave detection. This approach follows common practice in MHW studies and is intended to remove the externally forced warming signal while retaining internal variability. As a result, the clustering and the relationships with climate modes reflect variability relative to the evolving background state, rather than being dominated by the long-term warming trend. We have added a description of this procedure and its rationale in the Methods section.

L118-L122: “The long-term warming trend was subtracted to better estimate the effects of climate modes (Liu et al., 2022). To isolate variability relative to the long-term warming background, SST was detrended before MHW detection. The detrending was performed by identifying a linear trend estimated from the global-mean SST time series over 1982-2021 and subtracting this common trend from the SST time series at each grid point. This procedure reduces the influence of externally forced warming on the identification of marine heatwaves and subsequent analyses.”

5. I also recommend a minor change in the subsection title in the methods (line 106). The subtitle is “Cumulative Intensity of Marine Heatwaves,” but the section actually describes the overall MHW calculation and detection method and includes multiple metrics. A title such as “Marine Heatwave Calculation” would be more accurate and clearer.

Response: We agree that the scope of the original subsection title was too narrow. The subsection title has been updated to more accurately reflect the content of the section.

6. I was confused by the calculation of the “cumulative intensity anomaly.” Since MHWs are already defined as anomalous events, it is not clear why an additional anomaly is needed. If the authors choose to keep this variable, they need to clearly explain its importance and what additional information it provides.

Response: Thank you for raising this point. The MHWCI anomaly is introduced for the purpose of our study. In this study, the cumulative intensity is used to quantify the overall impact of all MHW events occurring within a given year or season. The anomaly of this metric is then calculated to identify interannual variability, allowing a direct comparison of how active or inactive different years are relative to the long-term mean. We acknowledge that this distinction was not sufficiently explained in the current manuscript. In the revised version, we have clarified the rationale for using cumulative intensity anomalies and explained the additional information they provide beyond the event-based MHW definition.

L126-L132: “In this study, the cumulative intensity was summed to derive the monthly MHWCI, representing the combined impact of all MHW events occurring within a given month (Gröger et al., 2024; Mohamed et al., 2023). Specifically, the cumulative intensity of all MHW events whose onset date falls within a given month was summed to form the monthly MHWCI, while months without any MHW events were assigned a value of zero. This results in a continuous monthly MHWCI time series, which was subsequently expressed as anomalies relative to its long-term mean to characterize interannual variability.”

7. Since the analysis relies heavily on seasons, the seasonal divisions should be clearly stated and justified. Currently, there is no clear explanation of why these particular seasonal divisions are chosen or what they represent physically for the North Sea.

Response: Thank you for this comment. We agree that although the seasonal divisions (DJF, MAM, JJA, SON) are explicitly defined in the Methods section, their physical relevance to the North Sea was not sufficiently explained.

These seasonal divisions correspond to well-established physical regimes in the North Sea, including weakening of the winter thermal stratification and summer stratification with shallow mixed layers. Similar seasonal divisions have been adopted in previous studies on North Sea MHWs, which highlight pronounced contrasts between winter and summer mechanisms (Chen & Staneva, 2024; Mohamed et al., 2023). We have clarified this in the revision.

L182-L186: “The four seasons are defined as winter (December of the previous year and January-February of the current year, DJF), spring (March-May, MAM), summer (June-August, JJA), and autumn (September-November, SON), which correspond to well-established physical regimes in the North Sea (Chen & Staneva, 2024; Mohamed et al., 2023), including wintertime deep mixing and weak stratification, and summertime strong stratification with shallow mixed layers.”

Results

For me, the Results section is currently difficult to follow, not because the figures are unclear, but because the text does not clearly describe the results shown in the figures. In many paragraphs, the text moves directly to interpretation and discussion without first explaining what is actually being observed. As a result, the reader must go back and forth between the figures and the text to understand what is being claimed.

1. I strongly recommend rewriting the Results section to be more descriptive: each figure should be clearly explained first (what pattern is shown, what changes occur, what differences appear), and only after that should the interpretation be introduced. This would make the manuscript much easier to read.

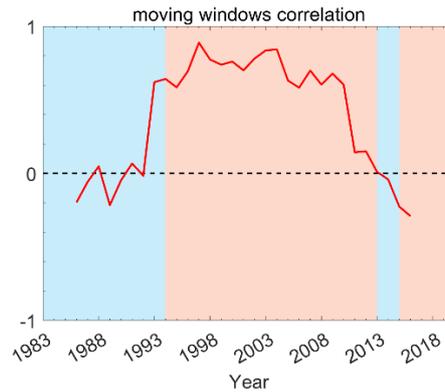
Response: Thank you for this constructive suggestion. Following this recommendation, we have substantially revised the entire Results section to adopt a more descriptive, step-by-step presentation. Specifically, we rewrote Sections 3.2 and 3.3 so that each figure is now introduced and described explicitly before further interpretation is provided. For each figure, we first describe the dominant spatial patterns, the sign and magnitude of anomalies, and the key differences between regions or phases. After explaining the basic elements of each figure, we introduce physical interpretations and linkages to MHW characteristics. In addition, we reorganized the Results to ensure a clear top-down progression from large-scale atmospheric circulation to surface forcing, upper-ocean structure (e.g., mixed layer depth and Richardson number), ocean circulation diagnostics (e.g., overturning), and finally MHW characteristics. This restructuring ensures that interpretations are based on clearly described observational evidence, improving readability and logical flow throughout the Results section.

2. Additionally, in lines 355-361, the manuscript separates the analysis into periods before and after 2013, but it is not clear why 2013 was chosen as a breakpoint. Where is this significant in the results? What evidence supports this split? This section needs more explanation.

Response: Thank you for raising this point. We would like to clarify that this choice is not arbitrary but is supported by both our results and independent evidence from existing literature.

First, our moving-window correlation analysis (Fig. S1, shown below) reveals a clear change in the relationship between summer MHWCI in Cluster 2 and the IPO around 2013, indicating a shift in the teleconnection structure at that time. We have added this figure as supplementary of revised manuscript to support this.

Second, previous studies have documented an abrupt cooling in the subpolar North Atlantic during 2013-2014, often referred to as the development of the “cold anomaly” or “cold blob,” which coincides with a weakening of the AMV signal during the early 2010s (Frajka-Williams et al., 2017; Josey & Sinha, 2022; Moat et al., 2020). In the revised manuscript, we have clarified this by explicitly linking the period separation to the moving-window correlation results and by citing relevant studies documenting the North Atlantic cooling and the contemporaneous weakening of the AMV.



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.

L309-L315: “In Cluster 2, the summer-averaged MHWCI displays pronounced decadal modulation (Fig. 2d). During the negative AMV phase (1982-1994, blue shading in Fig. 2d), MHWCI exhibits relatively weak intensity. In contrast, during the positive AMV phase (1994-2013, red shading in Fig. 2d), MHWCI shows notable enhancement, with its interannual variability strongly correlated with both ENSO and the Interdecadal Pacific Oscillation (IPO) ($r = 0.69$ and 0.70 , respectively). However, this teleconnection substantially weakens after 2013 (Fig. S2), with correlations becoming statistically insignificant ($p > 0.1$), indicating a substantial reduction in Pacific influence on North Sea MHWs.”

L516-L523: “After 2013, previous studies have documented an abrupt cooling in the subpolar North Atlantic (Mooney, 2015), often referred to as the development of the “cold anomaly” or “cold blob,” which coincides with a weakening of the AMV signal during the early 2010s (Frajka-Williams et al., 2017; Josey & Sinha, 2022; Moat et al., 2020). During this period, the tropical and subtropical Pacific exhibit markedly diminished atmospheric responses (Fig. 10d-f). Tropical Pacific SST anomalies weaken substantially compared to 1994-2012, accompanied by the reductions in precipitation. Moreover, the geopotential anomalies in the North Pacific weaken significantly (Fig. 9b), and the dipole circulation pattern between the subpolar and subtropical Pacific substantially weakens. WAF analysis reveals a marked disruption of Rossby wave energy propagation from the Pacific to the Atlantic (Fig. 9b).”

Minor Comments

L26–27: The sentence is long and somewhat difficult to understand; consider splitting it for clarity.

Response: This sentence has been split to shorter sentences to improve clarity.

L24-L26: “In winter, the southern North Sea experiences increased MHW frequency, intensity, and duration. This enhancement is linked to a positive East Atlantic Pattern, which intensifies westerly winds and enhances warm Atlantic inflow through both atmospheric and oceanic pathways. ”

[L106–112: Please clarify the detrending approach and its spatial application.](#)

Response: The detrending is based on a linear trend estimated from the global-mean SST time series over 1982-2021, which represents the externally forced warming signal. This common trend is then subtracted from the SST time series at each grid point prior to marine heatwave detection. We have clarified this spatial application of the detrending procedure in the revised manuscript.

L118-L122: “The long-term warming trend was subtracted to better estimate the effects of climate modes (Liu et al., 2022). To isolate variability relative to the long-term warming background, SST was detrended before MHW detection. The detrending was performed by identifying a linear trend estimated from the global-mean SST time series over 1982-2021 and subtracting this common trend from the SST time series at each grid point. This procedure reduces the influence of externally forced warming on the identification of marine heatwaves and subsequent analyses.”

[L118–124: Seasonal definitions should be explicitly stated.](#)

Response: The seasonal definitions have been explicitly stated in the Methods section.

L182-L186: “The four seasons are defined as winter (December of the previous year and January-February of the current year, DJF), spring (March-May, MAM), summer (June-August, JJA), and autumn (September-November, SON), which correspond to well-established physical regimes in the North Sea (Chen & Staneva, 2024; Mohamed et al., 2023), including wintertime deep mixing and weak stratification, and summertime strong stratification with shallow mixed layers.”

[L194: The sentence structure is heavy; consider rephrasing.](#)

Response: We have rephrased this sentence to improve clarity and readability.

L274-L282: “Seasonal differences between the two clusters were quantified by calculating the relative contribution of each season, expressed as the percentage of its spatially averaged interannual variability intensity (VI) relative to all four seasons within each cluster. Positive values of VI indicate seasons that contribute more strongly to the total variability of that cluster, while negative values indicate weaker contributions. In Cluster 1, variability is dominated by winter (VI = 0.66) and autumn (VI = 0.41), with substantially weaker variability in summer (VI = -0.28) and spring (VI = 0.07) (Fig. 2b). Cluster 2, by contrast, shows its strongest variability in summer (VI = 0.57) and moderate variability in spring (VI = 0.24), while variability in autumn (VI = -0.08) and winter (VI = -0.30) is relatively weak. These results indicate a clear seasonal asymmetry between the central-southern and northern North Sea, implying that seasons with the most active MHW-related variability differ between the two regions.”

[Reference used in the response](#)

- Chen, W., & Staneva, J. (2024). Characteristics and trends of marine heatwaves in the northwest European Shelf and the impacts on density stratification. *8th edition of the Copernicus Ocean State Report (OSR8)*, 4-osr8, 7. <https://doi.org/10.5194/sp-4-osr8-7-2024>
- Frajka-Williams, E., Beaulieu, C., & Duchez, A. (2017). Emerging negative Atlantic Multidecadal Oscillation index in spite of warm subtropics. *Scientific Reports*, 7(1), 11224. <https://doi.org/10.1038/s41598-017-11046-x>
- Josey, S. A., & Sinha, B. (2022). Subpolar Atlantic Ocean mixed layer heat content variability is increasingly driven by an active ocean. *Communications Earth & Environment*, 3(1), 111. <https://doi.org/10.1038/s43247-022-00433-6>
- Moat, B. I., Smeed, D. A., Frajka-Williams, E., Desbruyères, D. G., Beaulieu, C., Johns, W. E., Rayner, D., Sanchez-Franks, A., Baringer, M. O., Volkov, D., Jackson, L. C., & Bryden, H. L. (2020). Pending recovery in the strength of the meridional overturning circulation at 26° N. *Ocean Sci.*, 16(4), 863-874. <https://doi.org/10.5194/os-16-863-2020>
- Mohamed, B., Barth, A., & Alvera-Azcárate, A. (2023). Extreme marine heatwaves and cold-spells events in the Southern North Sea: classifications, patterns, and trends. *Frontiers in Marine Science*, 10, Article 1258117. <https://doi.org/10.3389/fmars.2023.1258117>