



Spatiotemporal patterns of surface marine heatwaves in the northeastern North Atlantic

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Abstract. Marine heatwaves (MHWs) are increasing globally, yet their long-term variability and trends remain poorly characterized across the high-latitude northeastern North Atlantic. We analysed daily sea surface temperature from the TOPAZ reanalysis during 1991–2025 to quantify the spatial characteristics, temporal trends and dominant modes of surface MHW variability across the North Sea, Norwegian Sea and Barents Sea and assessed associations with large-scale climate variability. We also examined MHW exposure within Norwegian particularly valuable and vulnerable areas (SVOs). MHWs occurred at an average frequency of 1.7 events yr⁻¹ and lasted 22.6 ± 6.6 days, with southern and coastal regions experiencing more frequent and intense events, whereas northern and sea ice-influenced regions experienced fewer but generally longer events. MHW frequency, cumulative intensity and annual MHW days increased over the study period, while trends in mean and maximum intensity were weaker and more spatially heterogeneous. The fraction of open water affected by MHWs increased by 21.7% per decade, reaching 99% in 2025. The two leading modes of detrended annual MHW day variability explained 53.5% of the total variance and represented a coherent basin-scale pattern and a north–south dipole. Statistical associations with the East Atlantic pattern, previous summer North Atlantic Oscillation and previous year Atlantic thermal conditions suggest contributions from both atmospheric circulation and oceanic preconditioning. These lagged atmospheric and oceanic relationships suggest potential for improving MHW early-warning frameworks. MHW exposure was substantial within ecologically important SVOs. This increase in MHW frequency, persistence and extent across the region, has the potential to reduce thermal refugia and increase risks to fisheries, aquaculture and high-latitude marine ecosystems. These findings provide a regional baseline for ecological impact assessment and long-term monitoring, supporting ecosystem-based management and adaptation strategies in a rapidly changing subarctic region.



1 Introduction

30 Marine heatwaves (MHWs), defined as discrete, prolonged periods (≥ 5 days) of anomalously high sea temperatures (Hobday et al., 2016), have emerged as key indicators of oceanic change in a warming climate. These extreme events can have major ecological and socioeconomic impacts, including shifts in species ranges, mass die-offs, ecosystem reconfigurations, declines in fishery catch rates, and increased mortality or reduced performance of farmed aquaculture species (Smale et al., 2019; Smith et al., 2021; 2023). The frequency, duration, extension, and severity of these events have increased globally in the last decades and are projected to further increase due to global warming (Frölicher et al., 2018; Oliver et al., 2019; Gou et al., 2025).

35 High-latitude regions are experiencing amplified warming, with surface MHWs becoming a recurrent feature (Oliver et al., 2018). In Norwegian seas, MHWs have been associated with declines in kelp forests (Filbee-Dexter et al., 2020), which are key habitat forming species and important carbon sinks, and have posed increasing challenges for aquaculture, including intensified salmon lice outbreaks (Gonzalez et al., 2025). Despite these ecological and socioeconomic impacts, a comprehensive understanding of the long-term patterns of MHWs in this region remains limited.

40 Although recent studies have advanced our understanding of MHWs in Norwegian waters, they have primarily focused on individual extreme events (e.g. Gonzalez et al., 2025; in press) or on particular subregions (e.g. Mohamed et al., 2022; 2025; Lien et al., 2024; Williams-Kerslake et al., 2026). These efforts do not capture the full spatial heterogeneity or long-term temporal trends of MHWs across the northeastern (NE) North Atlantic. A comprehensive, region-wide analysis based on a consistent dataset is needed to establish a robust baseline, reveal persistent patterns and trends in MHW frequency, duration, and intensity, and assess the main drivers of these patterns.

45 Here, we analyze a 35-year record (1991–2025) of sea surface temperatures across the NE North Atlantic to (1) quantify the mean characteristics and long-term trends of surface MHWs, (2) identify the dominant spatiotemporal modes of variability in MHW occurrence and examine their association with large-scale climate variability, and (3) document past MHW events at selected areas of ecological or economic importance where understanding MHW occurrence is particularly relevant for marine ecosystems and human activities. This region-wide assessment provides a baseline for understanding MHW occurrence and variability and their potential ecological and socioeconomic impacts, informing ecosystem-based management and adaptation strategies in a rapidly changing subarctic region.

55 2 Methods

2.1 Study area

The study area encompasses the NE North Atlantic around Norway, including the North Sea, Norwegian Sea and Barents Sea management regions (Fig. 1). This region spans strong latitudinal, bathymetric, and hydrographic gradients and is influenced by the interaction between warm Atlantic inflow, coastal waters, and cold polar water masses (e.g. Emeis et al., 2015; Oziel et



60 al., 2016; Mork et al., 2025). The North Sea is a relatively shallow shelf sea with strong tidal mixing and high nutrient input from rivers and the Atlantic inflow. Seasonal stratification develops in summer, supporting high primary production, particularly in coastal and fjord regions. The North Sea is influenced by saline Atlantic water and less saline waters from the Skagerrak and Baltic outflows (Ducrotoy et al., 2000). The Norwegian Sea is a deep, open-ocean basin influenced by the Norwegian Atlantic Current, which carries warm, saline Atlantic water northward along the continental slope. The region
65 exhibits strong horizontal and vertical gradients in temperature and salinity, with persistent mesoscale features such as frontal zones and upwelling areas that enhance local productivity (Loeng and Drinkwater 2007). The Barents Sea is a high-latitude shelf sea characterized by a mixture of warm Atlantic water in the southwest and cold Arctic water in the northeast, separated by the Arctic Front (Loeng and Drinkwater 2007). Seasonal sea ice coverage strongly affects light availability, stratification, and primary production, while shallow productive shelves and frontal zones support key fish spawning, feeding grounds, and
70 hotspots for marine mammals and seabirds (Hunt et al., 2013). The Norwegian Coastal Current transports relatively fresh, nutrient-rich waters northward along the Norwegian coast and continental shelf influencing stratification and nutrient availability along the shelf and fjord regions (Sætre et al., 2003). These regions support highly productive marine ecosystems, host economically important fisheries and one of the world's largest aquaculture industries.

In addition, MHW characteristics were examined at selected areas corresponding to the particularly valuable and vulnerable
75 areas (SVO, Norwegian Ministry of Climate and Environment 2024). SVOs are marine areas identified through national integrated ocean management plans based on their high environmental value and the presence of important ecological processes and habitats, including fish spawning and nursery grounds, migratory corridors, and regions of high biological productivity (Eriksen et al., 2021). They therefore require special consideration in management and planning. SVOs include areas in the North Sea, Norwegian Sea, Barents Sea, and coastal and shelf regions of Norway (Fig. 1, Table 1), encompassing
80 55 % of the Norwegian exclusive economic zone and a wide range of oceanographic conditions, ecosystem types, and climate influences.

2.2 Data

MHWs were detected and characterized using daily sea surface temperature (SST) from the TOPAZ reanalysis, which provides gridded oceanographic fields for the North Atlantic and Arctic regions at a horizontal resolution of 12.5×12.5 km (Copernicus
85 Marine Service 2024). We analysed the period 1991–2025. The dataset is based on the latest version of the TOPAZ4 coupled ocean–sea ice reanalysis system, which employs an ensemble-based data assimilation framework. Previous evaluation of TOPAZ4 against observational datasets showed good performance for near-surface ocean variables, with relatively small SST biases and errors (Xie et al., 2017). Sea ice concentration from TOPAZ was used to identify regions where MHW metrics may be influenced by seasonal sea ice cover. Grid cells were classified as influenced by sea ice if sea ice concentration exceeded
90 15% on more than 1% of the days in the study period. Study-domain statistics and time series were also calculated after excluding these sea ice-influenced grid cells to assess the sensitivity of MHW trends to sea ice.



To investigate the influence of large-scale climate variability on MHW occurrence, time series of climate indices representing major modes of atmospheric circulation and ocean temperature variability in the North Atlantic and Arctic were obtained from publicly available datasets. These indices were selected to represent large-scale atmospheric circulation patterns that can influence regional winds, air-sea heat exchange, ocean circulation, and basin-scale Atlantic temperature variability that may contribute to MHWs preconditioning. These included the North Atlantic Oscillation (NAO; <https://www.ncei.noaa.gov/access/monitoring/nao/>) and Arctic Oscillation (AO; <https://www.ncei.noaa.gov/access/monitoring/ao/>) indices from the NOAA National Centers for Environmental Information (NCEI), the East Atlantic (EA) index from the NOAA Climate Prediction Center (CPC; <https://www.cpc.ncep.noaa.gov/data/teledoc/ea.shtml>), the Scandinavian (SCAND) teleconnection index from the NOAA Physical Sciences Laboratory (PSL; <https://psl.noaa.gov/data/timeseries/month/SCAND/>), and the Atlantic Multidecadal Oscillation (AMO) index from Colorado State University (https://tropical.colostate.edu/archive_amo.html). Climate index values were aggregated into annual and seasonal (DJF, MAM, JJA, and SON) means. In addition, the Atlantic Ridge (AR), one of the four recurrent Euro-Atlantic weather regimes and a circulation linked to North Atlantic jet stream variability and the EA pattern (Fabiano et al., 2020), was examined as a complementary measure of large-scale atmospheric circulation. Annual and winter (DJF) frequencies were calculated from the 3-hourly ERA5-based North Atlantic–European weather regime attribution data (Grams 2025) as the percentage of time steps classified as AR.

2.3 MHW metric definitions.

MHW events were defined following Hobday et al. (2016) as periods of ≥ 5 consecutive days during which sea surface temperature exceeds the 90th percentile of its daily climatology. Events separated by ≤ 2 days were considered a single event. Daily SSTs from TOPAZ were used to construct a seasonally varying climatology (1991–2020). Both the climatology and 90th percentile threshold were computed for each grid point and day of the year using an 11-day centered window, followed by a 31-day running mean, as recommended by Hobday et al. (2016).

MHW characteristics were quantified using standard metrics: frequency (number of events per year), duration (days between event start and end), maximum and mean intensity (maximum and mean SST anomalies relative to climatology), cumulative intensity (sum of SST anomalies during the event), and total MHW days (sum of all MHW days per year). Metrics were calculated at each grid point using the marineHeatWaves Python module (<https://github.com/ecjoliver/marineHeatWaves>). Following the intensity-based MHW categorization proposed by Hobday et al. (2018), events were classified into four categories: moderate ($1-2 \times \Delta$), strong ($2-3 \times \Delta$), severe ($3-4 \times \Delta$), and extreme ($>4 \times \Delta$), where Δ is the difference between the threshold and the climatology at the event peak.

For each SVO, two complementary analyses were performed. First, local MHWs were detected independently at each grid cell. All MHW metrics were computed for each grid cell and then averaged across cells, providing a measure of typical local MHW exposure within each SVO. Second, regional SVO MHWs were detected from a single daily SST time series calculated as the mean across all grid cells within each SVO. Because spatial averaging reduces the influence of localized anomalies, this



125 approach emphasizes MHWs that are spatially coherent across the SVO. For each regional event, spatial coverage was
calculated as the daily percentage of grid cells within the SVO that simultaneously experienced locally detected MHW
conditions. Maximum spatial coverage, coverage at peak regional intensity, and the number of days on which coverage
exceeded 25%, 50%, and 75% were recorded. The number of grid cells and the proportion influenced by seasonal sea ice were
also reported for each SVO.

130 **2.4 Statistical analyses.**

Long-term trends in MHW metrics were quantified using linear regression. Statistical significance was evaluated with the
Mann-Kendall test. Spatial trends were calculated independently for all grid cells and for the full study domain (Fig. 1). To
assess sensitivity to seasonal sea ice influence, study-domain time series and trend estimates were additionally calculated after
excluding grid cells affected by seasonal sea ice.

135 To characterize the dominant spatial patterns of interannual MHW exposure, EOF analysis was applied to annual MHW days.
Annual MHW days were calculated as the number of days in each year experiencing MHW conditions at each grid cell. Prior
to EOF analysis, a linear trend was removed from the annual MHW days time series at each grid cell to separate interannual
and decadal variability from the long-term trend. The analysis was restricted to open water grid cells, excluding locations
influenced by seasonal sea ice. EOF analysis was performed using the pyEOF Python package (Zheng 2021). The first three
140 EOF modes were retained for analysis.

To investigate potential large-scale climatic drivers of MHW variability, the first three principal components (PCs) of annual
MHW days were compared with annual and seasonal climate indices using Pearson correlation. Both same-year and selected
lagged relationships were examined. To account for temporal autocorrelation, correlation significance was calculated using an
effective sample size based on the lag-1 autocorrelations of the PC and climate index time series following Pyper and Peterman
145 (1998). The false discovery rate (FDR) was controlled within each explicitly defined family of correlation tests using the
Benjamini–Hochberg procedure (Benjamini and Hochberg 1995). The primary family comprised the 15 same-year annual
comparisons among three PCs and five climate indices, whereas targeted seasonal, lagged, and Atlantic Ridge analyses were
treated as separate test families.

All correlation analyses were repeated using linearly detrended climate indices as a sensitivity test. Selected associations were
150 subsequently evaluated using standardized linear regression models. These included a single-predictor model relating PC1 to
detrended annual EA and a two-predictor model relating PC2 to the previous summer's NAO and previous year's annual
AMO. Additional sensitivity models compared associations with annual and spring AMO under same-year and one-year-
lagged conditions. Regression uncertainty was estimated using Newey–West heteroskedasticity and autocorrelation-consistent
(HAC) standard errors with a maximum lag of one year (Newey and West 1987). Variance inflation factors (VIF) were
155 calculated to assess predictor collinearity (Belsley et al., 1980; O'Brien 2007). The robustness of the selected climate–PC
correlations was further evaluated by recalculating the correlation coefficient after removing each year.

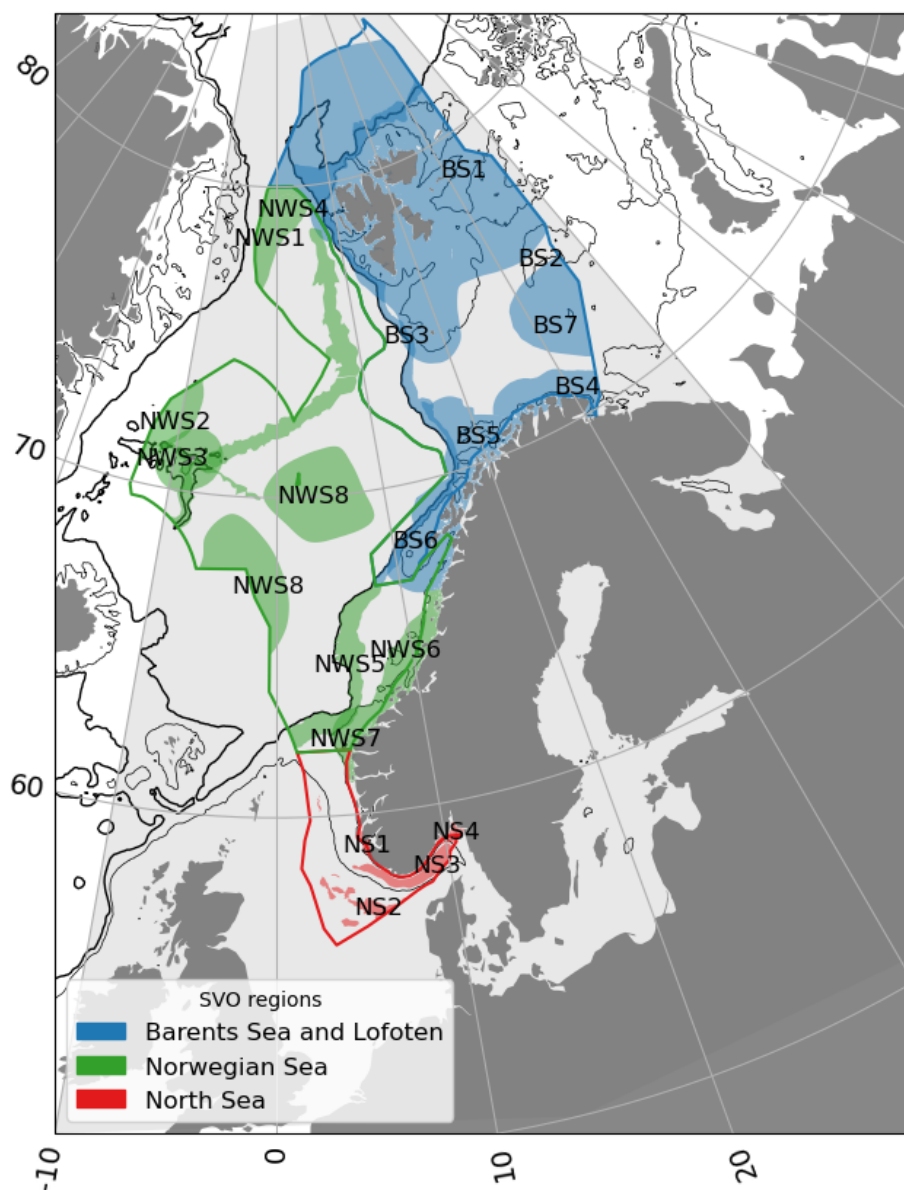


Figure 1: Study area showing the Norwegian particularly valuable and vulnerable areas (SVOs) spanning the three management regions: Barents Sea and Lofoten (BS), Norwegian Sea (NWS), and North Sea (NS). The geographic extent used for the calculations (10°W–40°E and 50°N–85°N) is highlighted in light gray. The 200 and 1000 m isobaths are shown.

160



3 Results

3.1 Spatial patterns of long-term mean MHW characteristics

Mean MHW characteristics exhibited clear spatial gradients across the study area (Fig. 2). Across most of the study area, MHW frequency averaged $1.7 \text{ events yr}^{-1}$, with the highest frequencies ($\sim 3 \text{ events yr}^{-1}$) occurring along the Norwegian coast, in the North Sea and around the UK (Fig. 2a). Lower frequencies were generally observed toward the northern Barents Sea and the seasonal sea ice zone (Fig. 2a).

MHW duration averaged 22.6 ± 6.6 days (median 21.3 days), ranging from 11 to 73 days across the full study region and from 11 to 64 days when seasonally ice-covered regions were excluded (Fig. 2b). Regions with lower MHW frequency generally experienced longer-lasting events, resulting in a strong negative spatial correlation between mean frequency and mean duration ($r = -0.96$). The longest events (> 25 days) occurred in the Barents Sea and in areas influenced by seasonal sea ice (Fig. 2b). Mean, maximum, and cumulative intensity were highest along the ice edge, around Svalbard, and in the Barents Sea (Fig. 2c–e). High mean and maximum intensities ($> 3 \text{ }^{\circ}\text{C}$) were also observed in the North Sea, off the coast of western Norway, and in the Baltic Sea (Fig. 2c–d).

Annual MHW days averaged 36.5 ± 6.6 days, with some regions experiencing up to 74 MHW days per year (Fig. 2f). The highest values occurred around Svalbard, the Barents Sea, along the seasonal sea ice margin, and in the Greenland Sea/Norwegian Sea. This pattern more closely followed the spatial distribution of event duration rather than frequency, indicating that regional differences in annual exposure to MHW conditions are driven primarily by event persistence rather than by the number of events.

The spatial distribution of MHW characteristics was broadly consistent across seasons (Fig. A1), although their magnitude varied. MHW frequency and intensity generally peaked during summer, whereas the longest events occurred during spring, particularly in the sea ice edge regions.

Moderate MHWs occurred throughout almost the entire study area and accounted for the majority of MHW events (Fig. 3a). Strong and severe events were less frequent with strong events remaining widespread across the Norwegian seas (Fig. 3b–c).

In contrast, extreme events were largely confined to the seasonal sea ice margin, indicating that the strongest thermal anomalies are concentrated in high latitude Arctic transition zones (Fig. 3d).

MHWs were observed year-round across the study area (Fig. 4). The fraction of event starts was generally highest during summer, which accounted for more than 30% of all MHW event starts, with the largest monthly fraction occurring in July. A secondary peak in January was evident in the full study area but was much less pronounced after grid cells influenced by seasonal sea ice were excluded. In contrast, the summer peak remained largely unchanged, indicating that high winter MHW occurrence was primarily associated with seasonally ice-covered regions.

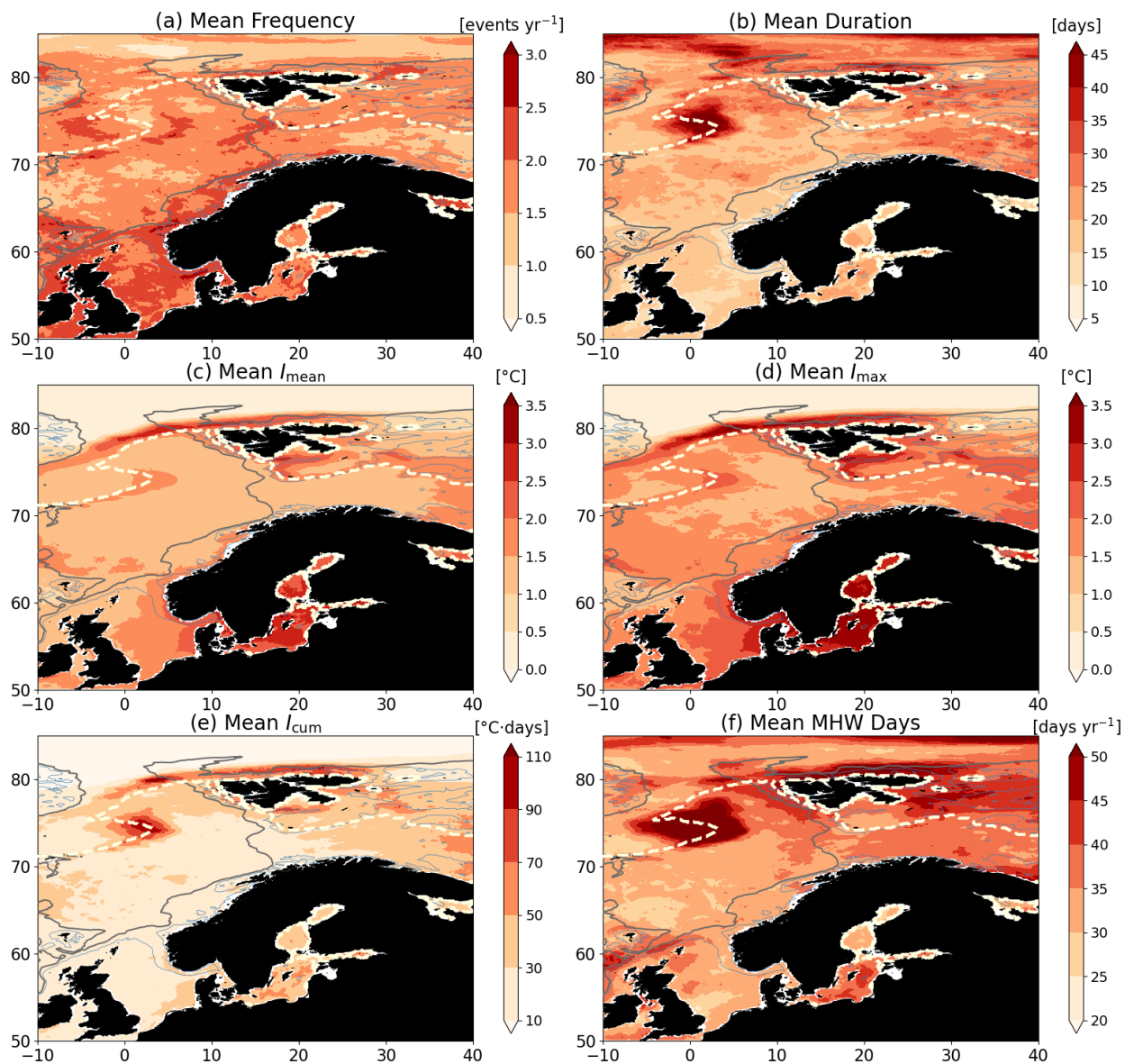
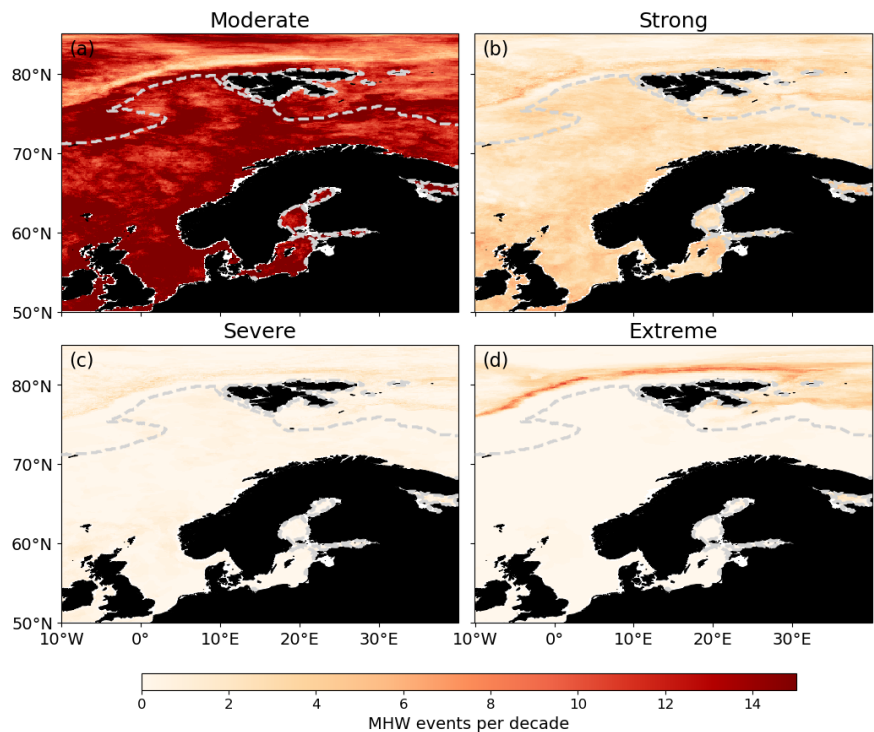
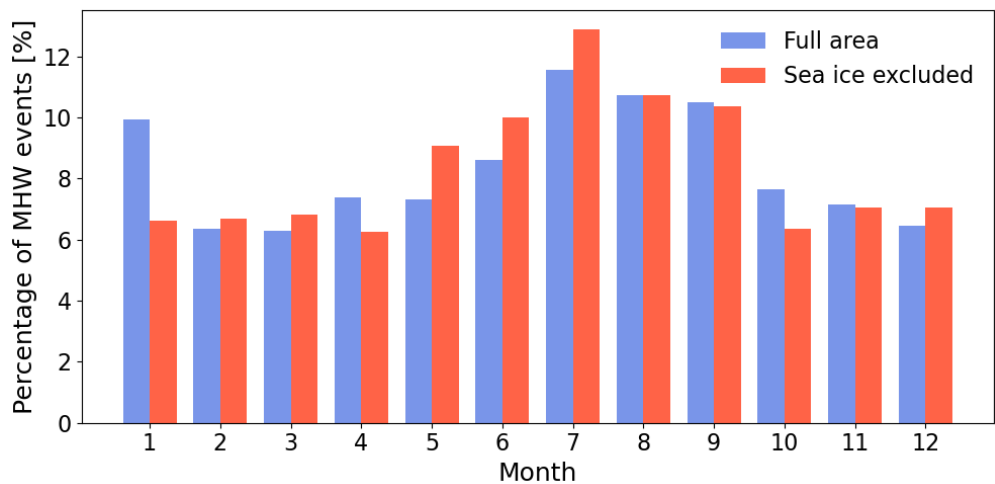


Figure 2: Long-term mean MHW characteristics in the NE North Atlantic around Norway during the 1991–2025 study period, (a) MHW frequency, (b) MHW duration, (c) MHW intensity I_{mean} , (d) maximum MHW intensity I_{max} , (e) MHW cumulative intensity I_{cum} , and (f) MHW total days. Blue contours indicate the 200 m isobath and grey contours (thicker line) indicate the 1000 m isobath. The dashed contour delineates regions influenced by sea ice, defined as grid cells experiencing sea ice concentration $\geq 15\%$ during more than 1% of the days over the study period.

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200 **Figure 3: Frequency of MHWs (number of events per decade) in four intensity categories in the NE North Atlantic around Norway during the 1991–2025 study period: moderate (a), strong (b), severe (c), and extreme (d). The dashed contour delineates regions influenced by seasonal sea ice.**



205 **Figure 4: Monthly distribution of detected MHW event start dates in the NE North Atlantic around Norway during 1991–2025. Bars show the percentage of all MHW event start dates occurring in each month, aggregated across ocean grid cells, for the full study area (blue) and after excluding grid cells influenced by seasonal sea ice.**

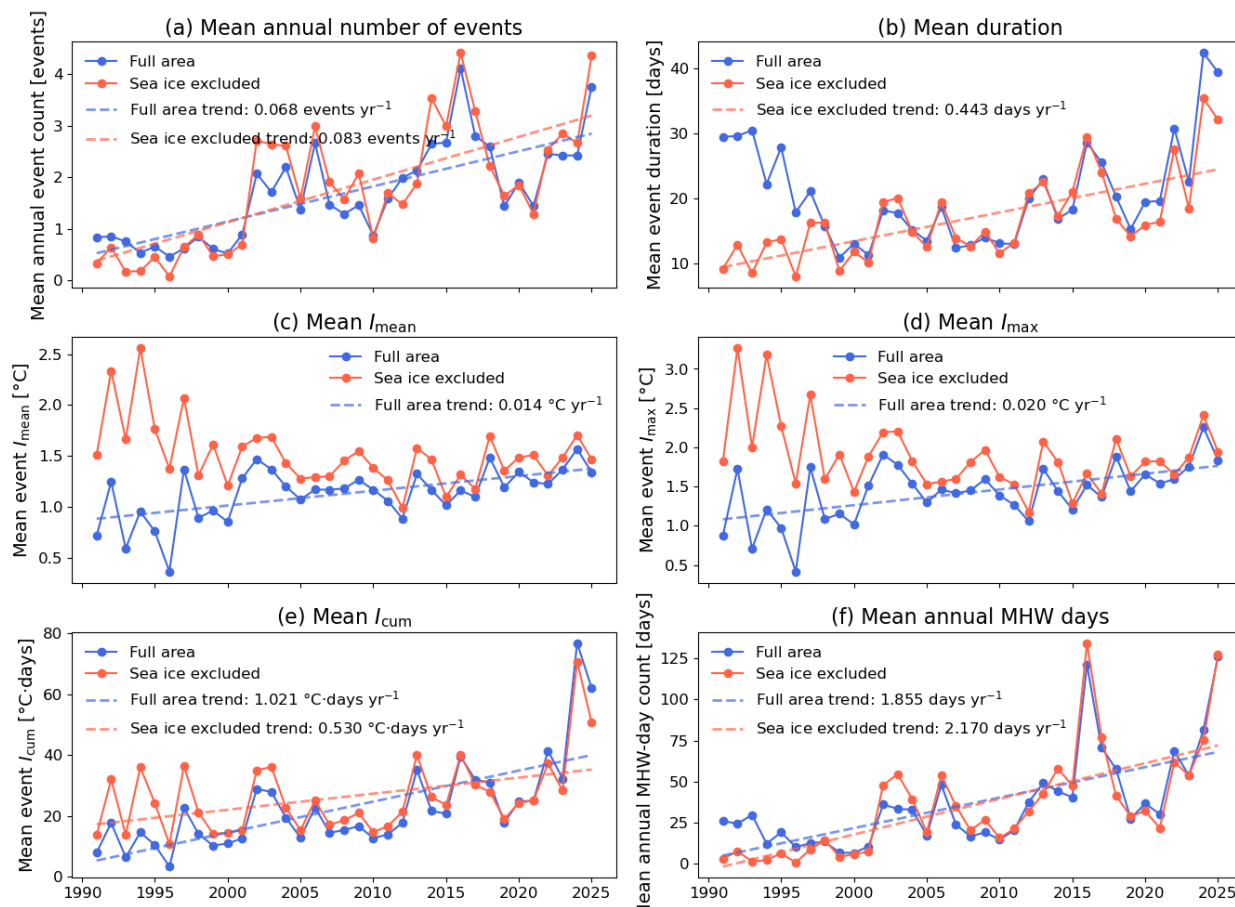


3.2 Long-term trends in MHW characteristics

210 Overall, MHW frequency, cumulative intensity, and annual MHW days increased over the study period, with similar long-term trends obtained when seasonally sea ice-influenced regions were excluded (Fig. 5). Excluding seasonally sea ice-influenced grid cells strengthened the increasing trend in MHW duration, whereas trends in mean and maximum intensity became weaker (Fig. 5). The divergence between the full area and sea ice excluded time series was most pronounced during the early 1990s. These trends were broadly consistent across seasons with strongest trends found in summer and autumn (Fig. 215 A2).

Two pronounced periods of high MHW occurrence were evident during 2002–2006 and 2013–2018, followed by another marked increase beginning in 2022 and continuing through 2025. This most recent period was characterized by high MHW frequency, duration, cumulative intensity and annual MHW days (Fig. 5a–b,e–f).

220 Positive trends in MHW frequency and annual MHW days were spatially widespread across most of the study region (Fig. 6a,f). In contrast, increases in duration and intensity were more heterogeneous, with the strongest positive trends concentrated around the seasonal sea ice margin and in the northern Barents Sea (Fig. 6b–e). Spatial patterns in MHW trends were broadly consistent across seasons (Fig. A3)



225 **Figure 5: Temporal evolution of study-domain mean MHW characteristics in the NE North Atlantic around Norway during the 1991–2025 study period. Results are shown for the full area (blue) and after sea ice-influenced grid cells were excluded (red). (a) Mean annual number of MHW events, (b) mean duration, (c) mean event-mean intensity I_{mean} , (d) mean event-maximum intensity I_{max} , (e) mean event cumulative intensity I_{cum} , and (f) mean annual number of MHW days. Dashed lines indicate significant linear regression fits ($p < 0.05$).**

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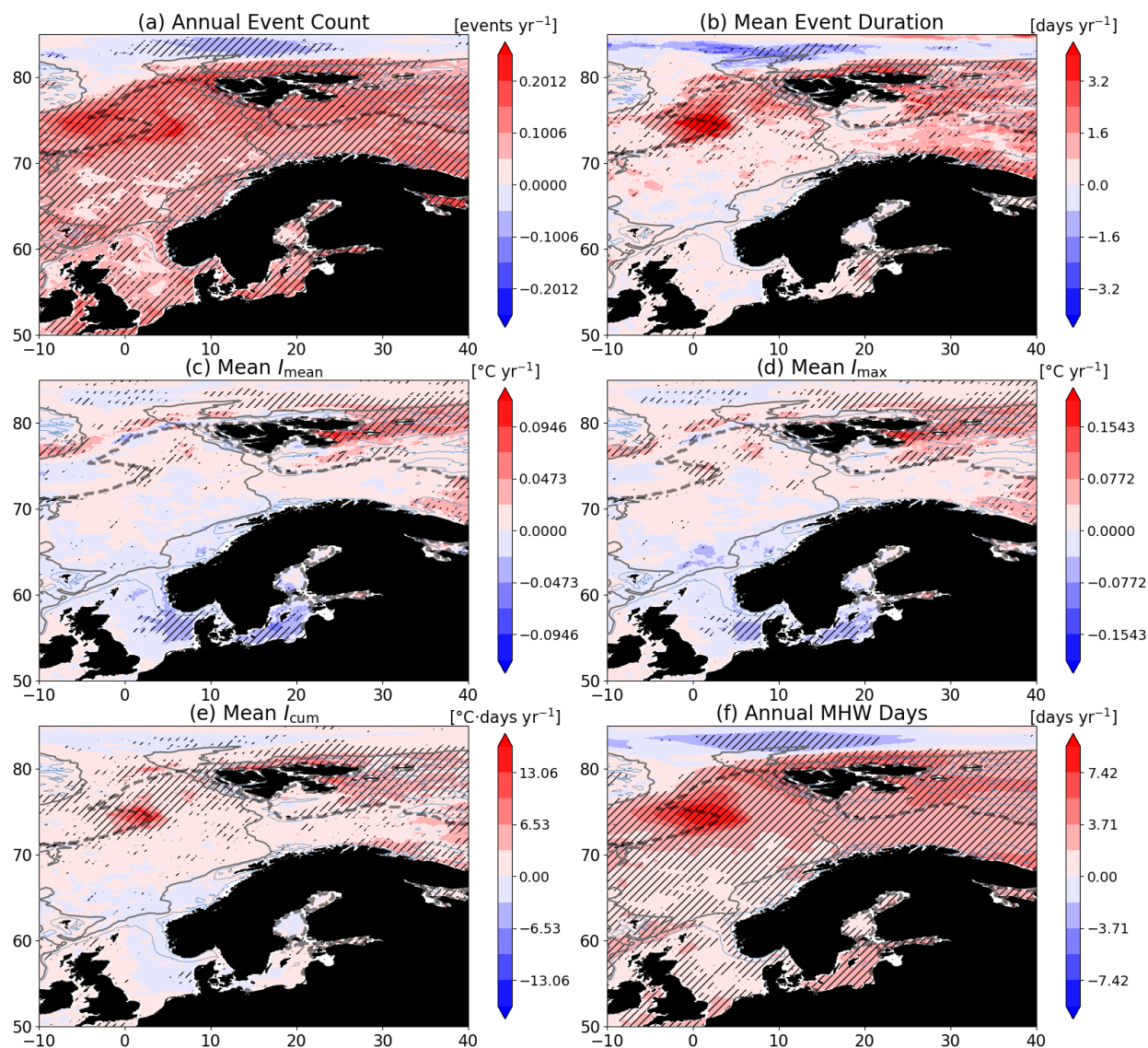
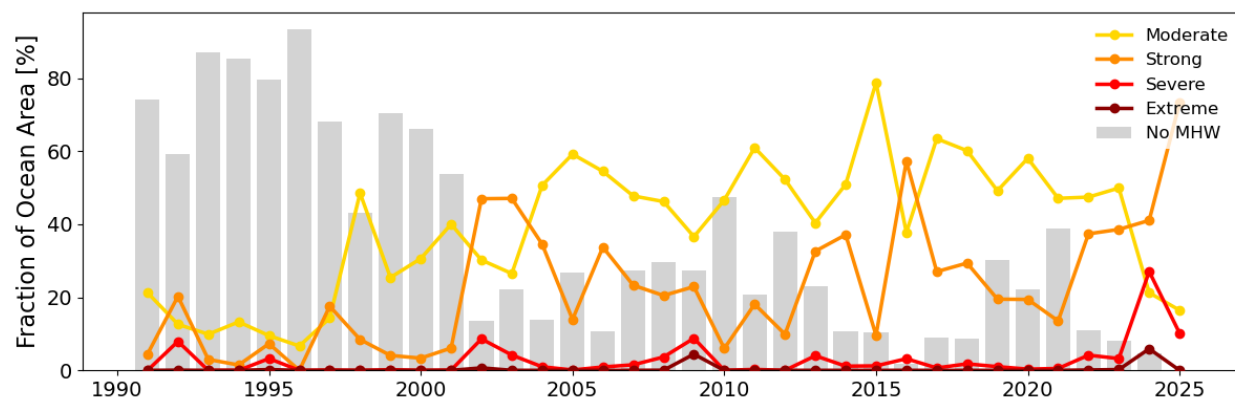


Figure 6: Linear trends in MHW characteristics in the NE North Atlantic around Norway during the 1991–2025 study period. (a) Annual number of events, (b) mean event duration, (c) mean event-mean intensity I_{mean} , (d) mean event-maximum MHW intensity I_{max} , (e) mean event cumulative intensity I_{cum} , and (f) annual MHW days. Hatching indicates significant trends ($p < 0.05$). Blue and grey (thick line) contours show the 200 and 1000 m isobaths, respectively, and the dashed contour delineates sea ice-influenced grid cells.

Over the 1991–2025 period, the fraction of the open water study area affected by MHWs increased significantly (+21.7% per decade, $p < 0.05$), with increasing fractions of the area experiencing moderate (+10% per decade, $p < 0.05$), strong (+10% per decade, $p < 0.05$), and severe (+1.6% per decade, $p < 0.05$) events (Fig. 7). Since 2002, more than half of the open water study area has experienced MHW conditions each year, with the greatest spatial extent observed in 2025 (99%), 2016 (98%) and 2024 (95%). Strong MHWs reached their largest spatial coverage in 2025 (73%), followed by 2016 (57%), 2002 and 2003



(47% each), and 2024 (41%), whereas severe and extreme MHWs reached their maximum extent in 2024, affecting 27% and 6% of the study area, respectively, particularly within the Barents Sea region (Fig. 7; Fig. A4).



245 **Figure 7: Annual fraction of the open water study area affected by no, moderate, strong, severe, or extreme MHW conditions during the 1991–2025 period. Sea ice-influenced grid cells were excluded from the analysis.**

3.3 Dominant spatiotemporal modes of MHW variability and relationships with large-scale climate variability

EOF analysis of detrended annual MHW days identified two leading modes of interannual variability that together explained 250 53.5% of the total variance (Fig. 8). The leading mode (EOF1) explained 35.1% of the variance and exhibited predominantly positive loadings across most of the study region, indicating coherent interannual variability in MHW days throughout the Norwegian region (Fig. 8b). The strongest positive loadings occurred in the Norwegian and Barents seas, whereas weak negative loadings were confined to the Baltic Sea and a limited area near the seasonal sea ice margin. The corresponding principal component (PC1) showed alternating positive and negative phases, with positive phases during 2002–2006, 2013–255 2017, and 2024–2025 (Fig. 8a). The largest positive amplitudes occurred in 2016 and 2025, indicating years when the basin-wide spatial pattern represented by EOF1 was most strongly expressed.

The second mode (EOF2) explained 18.4% of the variance and represented a north–south dipole across the study region (Fig. 8d). Positive loadings characterized the North Sea, Norwegian coast, and southern Norwegian Sea, whereas negative loadings characterized the northern Norwegian Sea and Barents Sea. Positive PC2 values therefore correspond to years with relatively 260 more MHW days in the southern part of the study region and fewer in the north, while negative values indicate the opposite spatial pattern. PC2 exhibited positive phases during 2002–2009, 2014, and 2025, and negative phases during 2012–2013 and 2015–2017 (Fig. 8c). The largest absolute PC2 amplitudes occurred in 2003, 2006, 2016, and 2025, indicating that the north–south dipole was most strongly expressed in those years. A third EOF mode, explaining 9.9% of the total variance, was also retained and is included in Fig. A5.

265 The two leading modes showed distinct relationships with large-scale climate variability (Table S1). A moderate positive association was observed between PC1 and detrended annual EA ($r = 0.47$, autocorrelation-adjusted $p = 0.006$, FDR-adjusted



q = 0.093; Fig. 8a; Fig. A6a; Table S1). The association remained positive when individual years were removed, with leave-one-year-out correlations ranging from 0.41 to 0.50 (Table S1). In a standardized regression, detrended annual EA was positively associated with PC1 ($\beta = 0.47$, 95% CI: 0.10–0.84, Newey-West HAC $p = 0.014$), and the model accounted for 22.3% of PC1 variance (Table S2). Neither annual nor winter Atlantic Ridge regime frequency was meaningfully associated with PC1 ($r = -0.15$ and -0.13 , respectively; Table S1), suggesting that simple changes in Atlantic Ridge occurrence frequency did not capture the variability associated with PC1.

PC2 showed clearer associations with previous atmospheric and oceanic conditions. PC2 was positively correlated with previous summer's NAO ($r = 0.46$, autocorrelation-adjusted $p = 0.006$, $q = 0.077$ within the broader exploratory family; Fig. 8c; A6b; Table S1) and with the previous year's annual AMO ($r = 0.43$, autocorrelation-adjusted $p = 0.038$, $q = 0.231$; Fig. 8c; Fig. A6c; Table S1). Both correlations remained largely unchanged after the climate indices were detrended. The association with the previous summer's NAO also remained positive in all leave-one-year-out analyses, with correlation coefficients ranging from 0.41 to 0.53 (Table S1).

When the previous summer's NAO and the previous year's annual AMO were included jointly in a standardized regression model, both retained positive associations with PC2. The standardized coefficient was 0.53 for the previous summer's NAO (95% CI: 0.20–0.86, HAC $p = 0.003$) and 0.50 for previous year's annual AMO (95% CI: 0.20–0.86, HAC $p = 0.001$; Table S2). The predictors were weakly correlated ($r = -0.14$) and showed low multicollinearity ($VIF = 1.02$). Together, they accounted for 45.7% of the variance in PC2 (adjusted $R^2 = 0.42$, overall model HAC $p < 0.001$). Nearly identical results were obtained after detrending both climate indices (Table S2).

Seasonal sensitivity analysis indicated that the association between AMO and PC2 was strongest for conditions during the previous spring ($r = 0.52$, autocorrelation-adjusted $p = 0.009$, $q = 0.043$ within the AMO tests; Table S1). Positive associations were also observed for the previous winter ($r = 0.47$), the previous year ($r = 0.43$), and the previous autumn ($r = 0.41$), whereas previous summer's AMO showed little association with PC2 ($r = 0.12$). The consistency of the positive associations across annual, winter, spring, and autumn averages supports the interpretation of a broader prior Atlantic thermal anomaly signal rather than an exclusively spring-specific relationship.

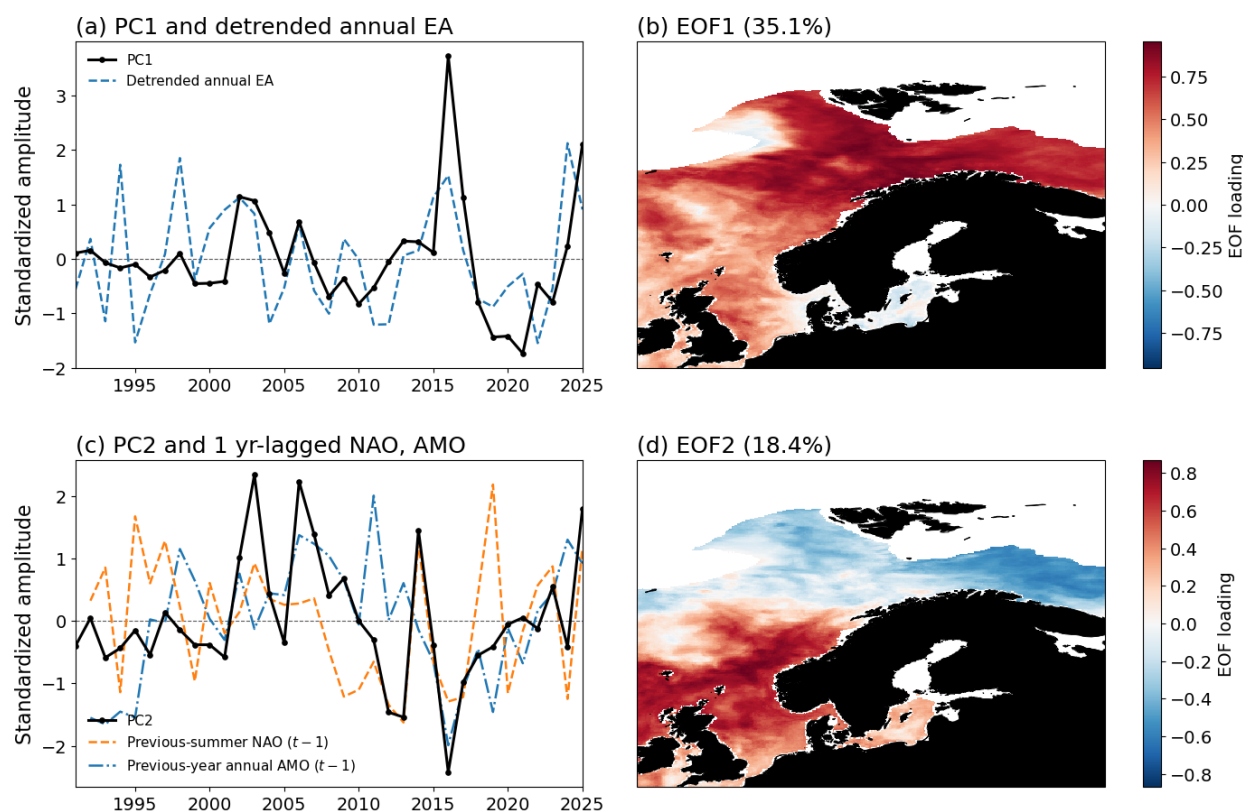


Figure 8: EOF analysis of detrended annual MHW days in the NE North Atlantic around Norway during 1991–2025, excluding seasonally ice-covered regions. The two leading modes are shown with their corresponding standardized principal component time series and associated climate index: (a) PC1 together with detrended annual East Atlantic (EA) index, (b) EOF1, explaining 35.1% of the total variance, (c) PC2 together with previous summer's NAO and previous year's annual AMO, (d) EOF2, explaining 18.4% of the total variance.

3.4 MHWs at particularly vulnerable areas

Annual MHW exposure, calculated from locally detected MHW days and averaged across grid cells, varied strongly among years, with particularly high values in 2016 and 2025 (Fig. 9). Across the six selected SVOs, mean annual exposure ranged from 31.8 MHW days in NS4 to 39.2 days in BS1 (Table 1). Regional event counts ranged from 43 in BS1 to 82 in NWS7. Median regional event duration increased from approximately 10 days in the North Sea and southern Norwegian Sea to 13–14 days in BS5, BS6 and BS1, whereas median mean intensity declined from 2.45°C in NS4 to 0.78°C in BS1. In the five selected SVOs without sea ice-influenced grid cells, the median event-specific maximum grid cell coverage ranged from 70.1% in BS6 to 100% in NS4. The corresponding median was 37.0% in BS1, where 90.6% of cells were classified as sea ice-influenced. Results for NS4 should be interpreted cautiously because it was represented by only six grid cells.



MHW characteristics in all SVOs are shown in Fig. A7 and Table A1. Local grid cell event counts, durations and intensities were generally similar to those obtained from the SVO-mean SST analysis, indicating relatively coherent MHW conditions within most SVOs (Table A1). Differences were greater in large, spatially heterogeneous and sea ice-influenced SVOs. The highest-category regional event selected for each SVO was concentrated in recent years in the Barents Sea, including extreme events in BS4 and BS7 during 2024 and prolonged severe events in BS1–BS3 during 2024–2025 (Table A2). These events lasted 125–208 days and reached maximum grid cell coverage of 80.6–100%.

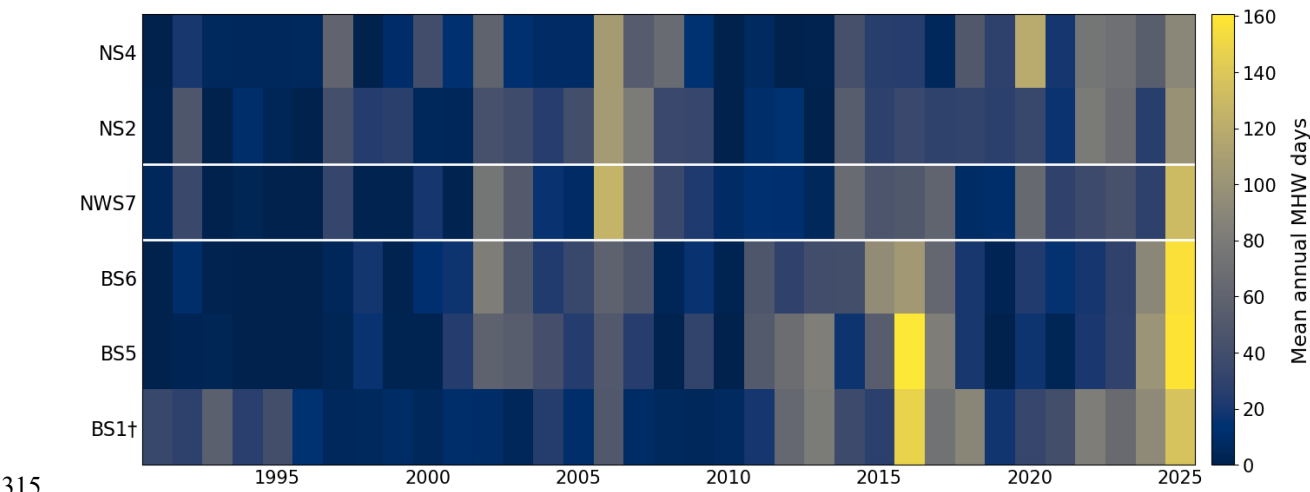


Figure 9: Annual MHW exposure in selected particularly valuable and vulnerable areas (SVOs) during 1991–2025. Colours show the mean number of MHW days per year across grid cells within each SVO. The selected regions represent contrasting ecological functions across the North Sea (NS), Norwegian Sea (NWS) and Barents Sea (BS). SVO names and ecological relevance are provided in Table 1 and their locations are shown in Figure 1. † indicates an SVO containing seasonally ice-influenced grid cells.

Table 1. MHW characteristics of selected particularly valuable and vulnerable areas (SVOs) during 1991–2025. Mean annual MHW days were calculated across grid cells within each SVO. MHW events, median duration and mean intensity refer to events detected from the daily SVO-mean SST time series. Duration and intensity are reported as median [interquartile range] across events. Maximum grid cell coverage is the median [interquartile range] of the largest fraction of cells experiencing local MHW conditions during each regional event. Ice-influenced cells are the percentage of cells where sea ice concentration exceeded 15% on more than 1% of days.

SVO	Ecological relevance	Cells	Mean annual local MHW days	Regional MHW events	Regional median duration [IQR] (days)	Regional event-mean intensity [IQR] (°C)	Median maximum grid cell coverage [IQR] (%)	Ice-influenced cells (%)
NS4 – Outer Oslofjord	Important winter feeding and staging area for seabirds.	6	31.8	77	10.0 [6.0–16.0]	2.45 [2.15–2.86]	100.0 [83.3–100.0]	0
NS2 – Sandeel Fields	Specialized sandy habitat supporting sandeel, a key prey species for fish, seabirds and marine mammals.	90	32.1	77	10.0 [7.0–17.0]	1.47 [0.99–2.28]	87.8 [60.0–100.0]	0
NWS7 – Coastal Zone Norwegian Sea South	Coastal shelf and bank habitats supporting fish spawning and larval development, seabird foraging and diverse benthic communities.	193	32.1	82	10.0 [7.0–18.0]	1.44 [1.02–2.20]	80.8 [58.2–95.7]	0
BS6 – Coastal Zone Lofoten	Major spawning and nursery area for cod and haddock, larval transport corridor, and important seabird and cold water coral habitat.	652	33.2	70	13.5 [6.0–21.0]	1.10 [0.63–1.81]	70.1 [50.3–95.4]	0
BS5 – Tromsøflaket	Fish spawning and larval transport area with rich sponge and coral communities and important seabird and marine mammal feeding grounds.	719	34.6	65	13.0 [6.0–22.0]	1.02 [0.67–1.60]	85.0 [57.0–98.2]	0
BS1 – Sea Areas Around Svalbard	Productive ice-associated ecosystem supporting polar cod, capelin, seabirds and Arctic marine mammals, including polynya and glacier-front feeding habitats.	14233	39.2	43	14.0 [6.5–47.0]	0.78 [0.57–1.06]	37.0 [31.3–47.2]	90.6





4 Discussion

4.1 MHW characteristics and trends

Surface MHWs were recurrent across the North Sea, Norwegian Sea and Barents Sea, with frequencies broadly comparable to those reported from other high-latitude regions (Fernández-Barba et al., 2024; Huang et al., 2021). Southern and coastal Norwegian waters generally experienced more frequent events, whereas northern and sea ice-influenced regions were characterized by fewer but more persistent events. Annual MHW exposure consequently followed event duration more closely than frequency in the northern Norwegian and Barents seas, indicating that persistence may be a more important determinant of accumulated thermal stress than the number of events. The persistence of MHWs in the northern part of the study domain is consistent with Williams-Kerslake et al. (2026), who identified prolonged events west of Svalbard that were predominantly driven by anomalous ocean heat transport rather than surface heat fluxes. Comparable differences between event occurrence and persistence have also been reported for the Patagonian Shelf (Delgado et al., 2026).

The main long-term changes were increases in event occurrence, cumulative intensity and annual MHW days, whereas trends in mean and maximum intensity were weaker and less spatially consistent. This suggests that MHW change in the region appears primarily through more frequent, persistent and geographically widespread exposure rather than through uniform intensification of individual events. The declining fraction of the open water domain remaining MHW-free can lead to reduced availability of potential thermal refugia for organisms.

High-latitude patterns were strongly influenced by seasonal sea ice conditions. Long and high severity category events were concentrated around Svalbard, the northern Barents Sea and the seasonal ice margin, consistent with previous evidence of increasing Arctic MHW duration and spatial coverage. Huang et al. (2021) linked the lengthening of the Arctic MHW season to atmospheric warming, declining sea ice and delayed event termination. In our analysis, the secondary winter peak in MHW event starts was substantially weaker after sea ice-influenced grid cells were excluded, suggesting that winter MHW occurrence at high latitudes is partly associated with changes in ice cover and freeze-up timing.

MHW metrics near the seasonal ice margin should therefore be interpreted together with sea ice concentration and open water fraction. Under ice-covered conditions, weak SST variability can result in only a small difference between the climatological mean and percentile threshold, allowing small absolute temperature changes to exceed percentile-based MHW criteria. Ice retreat and the transition to open water conditions expose the surface ocean to atmospheric and radiative forcing, producing abrupt changes in SST variability and potentially large anomalies relative to an ice-constrained climatology (Richaud et al., 2024; Zhang et al., 2025; Athanase et al., 2026). Positive trends in event frequency and annual MHW days across the study domain persisted after sea ice-influenced cells were excluded, indicating that these increases were not only a result of changing ice conditions. However, duration and intensity metrics were more sensitive to ice exclusion.



4.2 Large-scale variability and climate associations

The EOF analysis indicates that interannual MHW variability is organized into both a broadly coherent basin-scale pattern and a north–south dipole pattern. This structure suggests that MHW occurrence across the region reflects a combination of atmospheric forcing and oceanic memory rather than a single dominant driver. This is consistent with Eisbrenner et al. (2024), who found that summer marine extremes in the southeastern Barents Sea reflected an interplay between atmospheric pressure patterns and ocean heat convergence on interannual timescales, while individual MHWs could be dominated by either advective preconditioning or local atmospheric forcing.

The association between the leading mode and the East Atlantic pattern is consistent with an influence of Euro-Atlantic atmospheric circulation. PC1 showed its largest positive amplitudes in 2016 and 2025, when the EA index was also positive. This is consistent with Mohamed et al. (2022), who linked the strong 2016 MHW in the Barents Sea to a strong positive phase of the EA pattern, associated with southwesterly winds, anomalously high pressure and enhanced atmospheric heating. However, the EA association explained only part of PC1 variability, suggesting that interactions among circulation patterns, jet-stream position, atmospheric blocking and regional ocean–atmosphere processes are not fully represented by a single climate index (Fabiano et al., 2020).

The lagged associations of the second mode with previous summer NAO and previous autumn, winter and spring Atlantic thermal conditions suggest that both atmospheric preconditioning and persistent ocean anomalies may influence the subsequent geographical distribution of MHW days. The weak association with previous summer AMO may partly reflect seasonal shoaling of the mixed layer, which makes summer SST more indicative of short-term surface forcing rather than persistent subsurface thermal anomalies. Thermohaline anomalies can propagate northward along the Atlantic Water pathway and retain a thermal signal from the subpolar North Atlantic into the Norwegian and Barents seas (Langehaug et al., 2019; Passos et al., 2024). Their evolution is modified by air–sea exchange, eddies and interactions between Atlantic and Arctic water masses (Asbjørnsen et al., 2019), potentially contributing to the observed north–south pattern.

The years 2016 and 2025 illustrate how the two leading modes can combine to produce different spatial patterns of MHW exposure. In 2016, strongly positive PC1 and negative PC2 indicate widespread positive MHW day anomalies with a stronger expression in the northern Norwegian and Barents seas, consistent with the enhanced MHW conditions documented in the Barents Sea that year (Mohamed et al., 2022). In 2025, both PC1 and PC2 were strongly positive, indicating widespread positive MHW day anomalies across the study domain, with an enhanced expression along the Norwegian coast and in the southern part of the study domain. This pattern extended broadly along the Atlantic Water pathway (see Fig. A4) and is consistent with record-high summer MHW conditions documented in western Norway in 2025 (Gonzalez et al., in press).

4.3 Ecological and management implications

MHW exposure occurred within SVOs important for fish spawning and recruitment, seabirds, marine mammals, benthic habitats and high biological production. Regional events generally affected large fractions of the selected SVOs, indicating



that exposure was often spatially coherent rather than limited to isolated locations. This widespread exposure is particularly important in spawning and nursery areas, where several life stages can be affected and nearby suitable habitats may be limited. The lower spatial coherence around Svalbard likely reflects the large extent of the SVO, its hydrographic heterogeneity and its strong seasonal sea ice influence.

Long-term warming gradually shifts thermal baselines and suitable habitat, whereas MHWs represent short-lived extremes on this changing background. MHWs may therefore accelerate ecological effects by pushing organisms beyond the thermal ranges they are adapted to. MHW impacts will depend on season, absolute temperature and the sensitivity of individual species, stocks and life stages (Sandø et al., 2024). The summer predominance of MHW frequency and intensity is important across Norwegian waters, where biological production is strongly seasonal and concentrated in spring and summer. In southern and coastal waters, summer MHWs may pose higher ecological risk because they also coincide with the highest temperatures of the year. Summer anomalies may push some cold-temperate North Sea populations towards or beyond their thermal limits (Sandø et al., 2024), and extreme summer temperatures have been linked to mortality of habitat-forming kelp in southern Norway (Filbee-Dexter et al., 2020). In contrast, mobile boreal species may benefit from expanding suitable habitat farther north (Sandø et al., 2024).

Ecological sensitivity is not necessarily lower at high latitudes simply because absolute temperatures remain cool. Even small SST anomalies may be important for cold-adapted organisms with narrow thermal ranges. Around Svalbard and in the northern Barents Sea, polar cod spawning and larval nursery habitats depend on the seasonal and spatial coupling of sea ice, under-ice production and *Calanus glacialis* prey (Huserbråten and Vikebø 2026). Warming and sea ice retreat may displace these habitats and increase the risk of mismatches between larval first feeding and prey availability (Huserbråten and Vikebø 2026). Climate-impact assessments also suggest negative responses for some cold-adapted stocks, including North Sea cod, polar cod and capelin (Sandø et al., 2024).

Responses at the base of the food web may occur rapidly and propagate to higher trophic levels. Following the 2003 North Atlantic MHW and subsequent warm period, changes in plankton were associated with altered pelagic fish condition in the Norwegian Sea and benthic communities in the Fram Strait (Werner et al., 2026). Such responses may arise through changes in stratification, nutrient supply, bloom timing and prey availability. These effects may be especially important in high latitude spring bloom systems, where consumers are adapted to short and predictable seasonal production windows and may be vulnerable to mismatches even when total annual production does not decline.

Beyond their direct thermal effects, MHWs can interact with other environmental and anthropogenic pressures. In coastal waters, warmer and more strongly stratified conditions may favor some harmful algal blooms, although responses depend on species, season, nutrient supply and circulation (Lim et al., 2021; Silva et al., 2025). MHW effects may also interact with fishing pressure and population structure, as demonstrated by the combined demographic and climatic influences on the poleward shift of Norwegian spring-spawning herring (Slotte et al., 2025).



The diversity of ecological characteristics and vulnerabilities among the SVOs indicates that monitoring and management should be tailored to each SVO, with priorities including spawning phenology and prey availability, coastal habitat condition, fisheries interactions and sea ice-associated food webs.

4.4 Limitations and future work

425 This analysis describes surface conditions only and may not represent thermal extremes at depth, particularly in stratified, deep or benthic habitats. The ecological impact of an event will depend on its vertical extent and on the habitat depth and mobility of the organisms considered. In addition, the 12.5-km TOPAZ grid cannot fully resolve fjords, narrow coastal currents or small nearshore SVOs, while uncertainty is greater near the seasonal ice margin, where SST and sea ice conditions are closely coupled.

430 The fixed 1991–2020 climatological baseline means that the trends reported here reflect both long-term background warming and shorter-term temperature variability. This is appropriate for assessing ecological exposure relative to recent historical conditions or for organisms that cannot adapt or relocate rapidly (Smith et al., 2025). Fixed and moving climatologies address different questions and can produce substantially different estimates of MHW frequency and duration. Therefore, baseline choice should reflect the study objective (Rosselló et al., 2023; Smith et al., 2025; Delgado et al., 2026). Future ecological risk
435 assessments could also apply adaptation-adjusted baselines tailored to specific species or populations within each SVO, informed by thermal tolerances and estimated adaptation rates (Smith et al., 2025).

Despite these limitations, the lagged atmospheric and oceanic associations suggest potential for improved MHW early-warning frameworks. Thermohaline anomalies propagating along the Atlantic Water pathway may provide an early indication of future MHW conditions, although current prediction systems show lower and less consistent SST skill in the Norwegian Sea than in
440 the subpolar North Atlantic because of difficulties representing fronts, eddies, bathymetry and intense air–sea exchange (Passos et al., 2023). Future work should also examine upper-ocean heat content, mixed-layer depth and ocean circulation, which may provide more direct measures of MHW preconditioning than climate indices alone. Combining these ocean-state variables with atmospheric-circulation forecasts, surface heat fluxes and sea ice conditions may therefore be more informative than relying on a single climate index.

445 Continued monitoring of surface and subsurface temperature together with ecological observations will be important for identifying where MHWs pose the greatest risks to ecosystems and marine activities. Including this monitoring and prediction within the SVO framework could support ecosystem-based management in ecologically important areas.

5 Conclusions

450 Surface MHWs became more frequent, persistent and spatially extensive across the NE North Atlantic and adjacent Arctic seas during 1991–2025, although trends in event intensity were weaker and less spatially consistent. Southern and coastal



regions generally experienced more frequent and intense events, whereas northern and sea ice-influenced regions were characterized by fewer but longer events. Interannual MHW day variability was characterized by a coherent basin-scale mode and a north–south dipole. Associations with atmospheric circulation and prior Atlantic thermal conditions suggest
455 contributions from both atmospheric and oceanic preconditioning. High MHW exposure and broad spatial coverage within ecologically important SVOs highlight potential risks to spawning and nursery habitats, benthic communities, seabirds and ice-associated food webs. This has implications for fisheries, aquaculture and ecosystem resilience, particularly where thermal extremes interact with sea ice loss and other environmental pressures. This study provides a regional assessment of surface MHW characteristics and exposure across Norwegian waters and ecologically important SVOs, which can inform ecological
460 impact assessments, long-term monitoring and the development of MHW early-warning systems to support ecosystem-based management and climate adaptation.

Code and data availability

Fixed station in situ temperature and salinity data are available from the Institute of Marine Research
465 (<https://www.imr.no/forskning/forskningsdata/stasjoner>). ERA5 atmospheric reanalysis data are available from the Copernicus Climate Change Service (<https://climate.copernicus.eu>). The code to calculate MHW characteristics is available at <https://github.com/ecjoliver/marineHeatWaves/blob/master/build/lib/marineHeatWaves.py>

Author contributions

S.G. led the study, performed the formal analyses, prepared the visualizations, and wrote the original manuscript. R.B.I.,
470 H.R.L., A.B.S., S.S.H., F.V., and M.W-K. contributed to interpretation, discussion, and scientific guidance. All authors reviewed and edited the manuscript and approved the final version.

Competing interests

The authors declare no competing interests.



475 Acknowledgements

S.G. postdoctoral position is funded by the Bjerknes Centre for Climate Research and the Institute of Marine Research. A.B.S. and S.S.H acknowledge the financial support from the Norwegian research project no. 309562 - Climate Futures and its funding partners. In addition, the research leading to these results has received funding from RCN through the Nansen Center institutional basic funding (RCN grant 342624).

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Annex

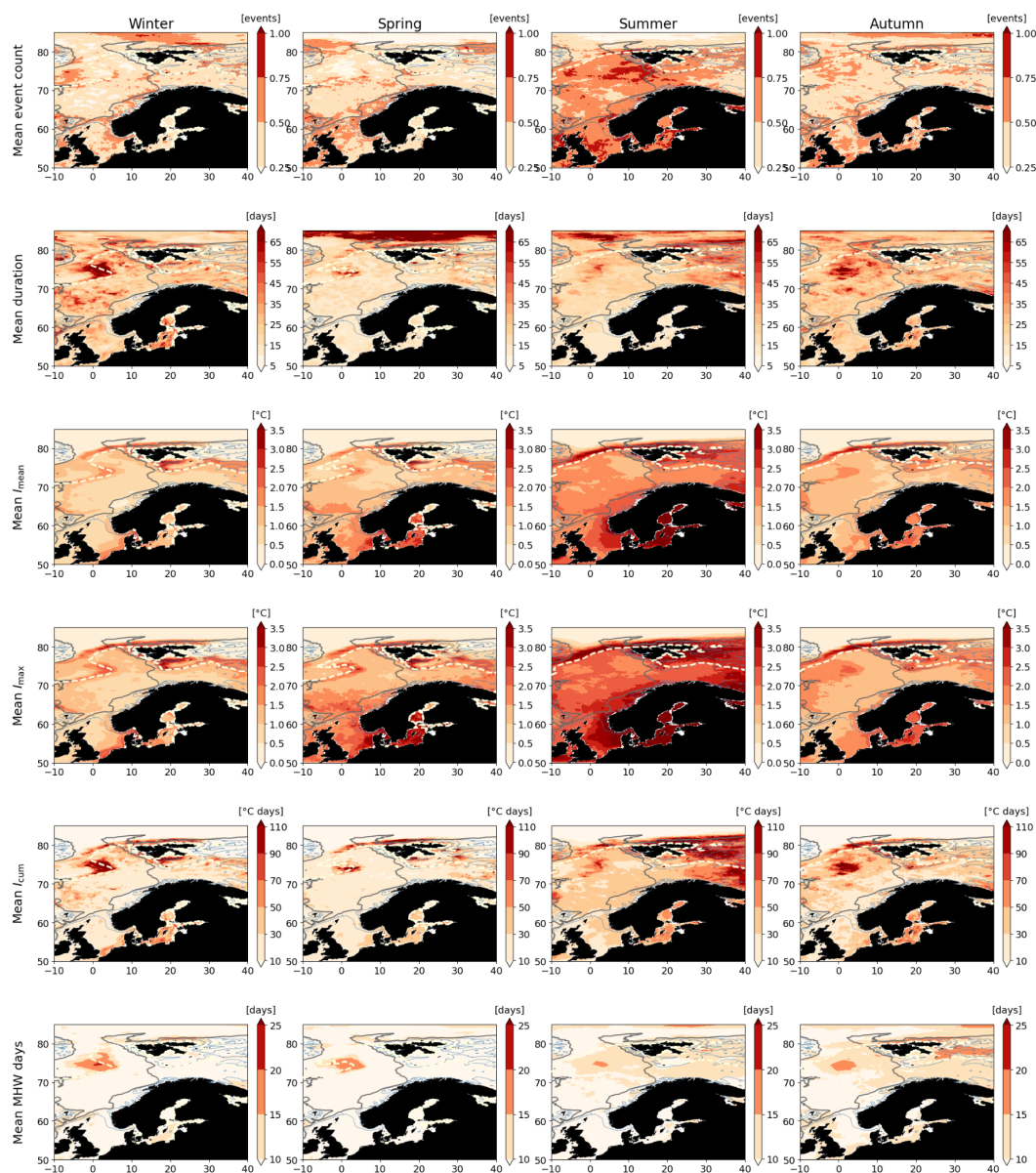


Figure A1: Seasonal mean characteristics of MHWs in the NE North Atlantic around Norway during the 1991–2025 study period. Columns correspond to winter, spring, summer, and autumn, while rows show mean number of MHW events, MHW duration, mean MHW intensity, maximum MHW intensity, MHW cumulative intensity, and mean MHW total days. Blue contours indicate the 200 m isobath and grey contours (thicker line) indicate the 1000 m isobath. The dashed contour delineates regions influenced by sea ice for each season, defined as grid cells experiencing sea ice concentration $\geq 15\%$ during more than 1% of the days within that season over the study period.



Figure A2: Seasonal trends in MHW characteristics in the NE North Atlantic around Norway during the 1991–2025 study period, (a) number of MHW events, (b) mean MHW duration, (c) mean MHW intensity, (d) mean MHW maximum intensity, (e) mean MHW cumulative intensity, and (f) mean MHW total days. Regional averages were calculated after excluding grid cells influenced by sea ice, defined as locations experiencing sea ice concentration $\geq 15\%$ during more than 1% of the days within a given season over the study period. Dashed lines indicate statistically significant trends.

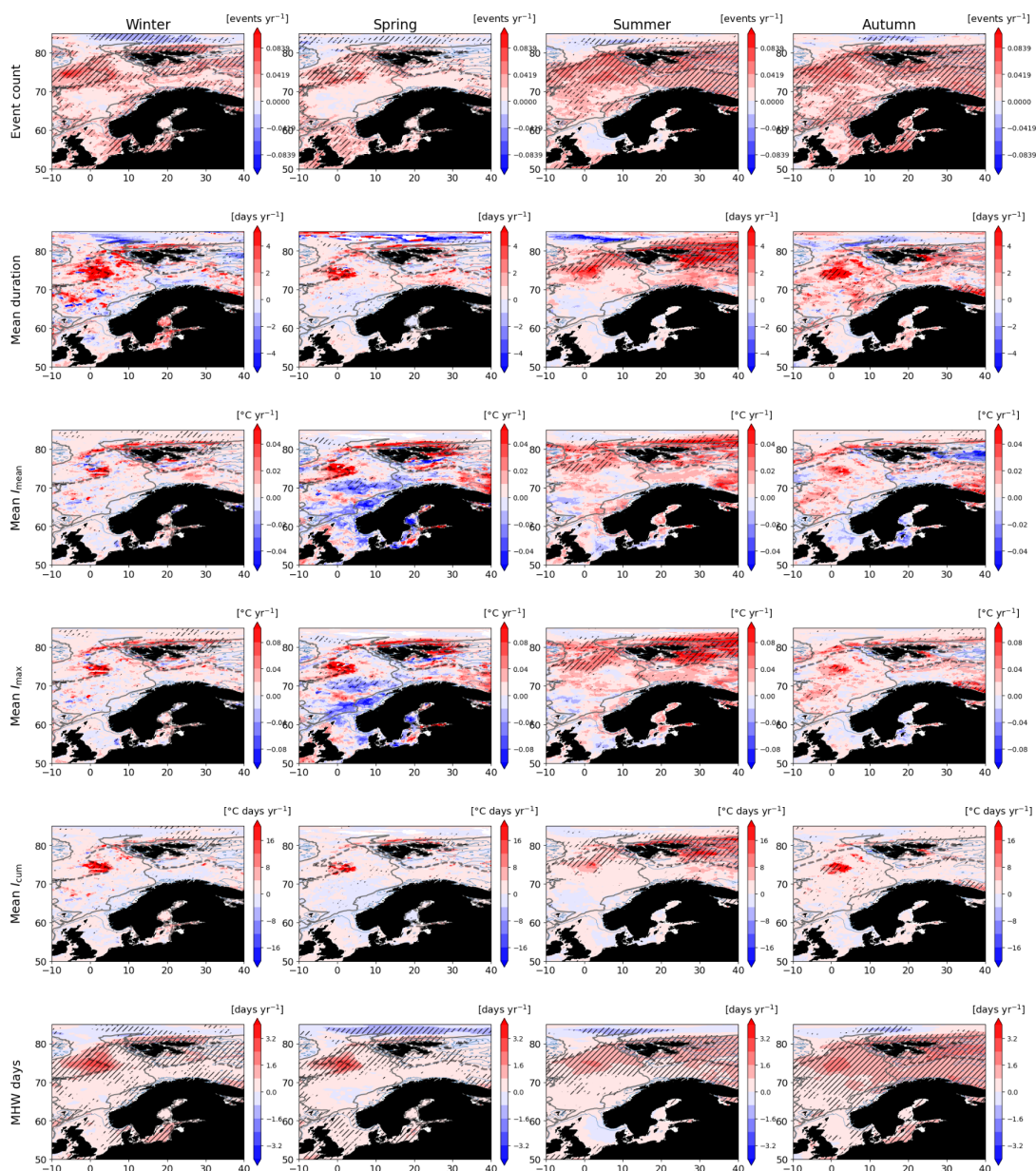


Figure A3: Seasonal trends in MHW characteristics in the NE North Atlantic around Norway during the 1991–2025 study period. Columns correspond to winter, spring, summer, and autumn, while rows show number of events, MHW duration, mean MHW intensity, maximum MHW intensity, MHW cumulative intensity, and MHW total days. Blue contours indicate the 200 m isobath and grey contours (thicker line) indicate the 1000 m isobath. The dashed contour delineates regions influenced by sea ice for each season, defined as grid cells experiencing sea ice concentration $\geq 15\%$ during more than 1% of the days within that season over the study period.

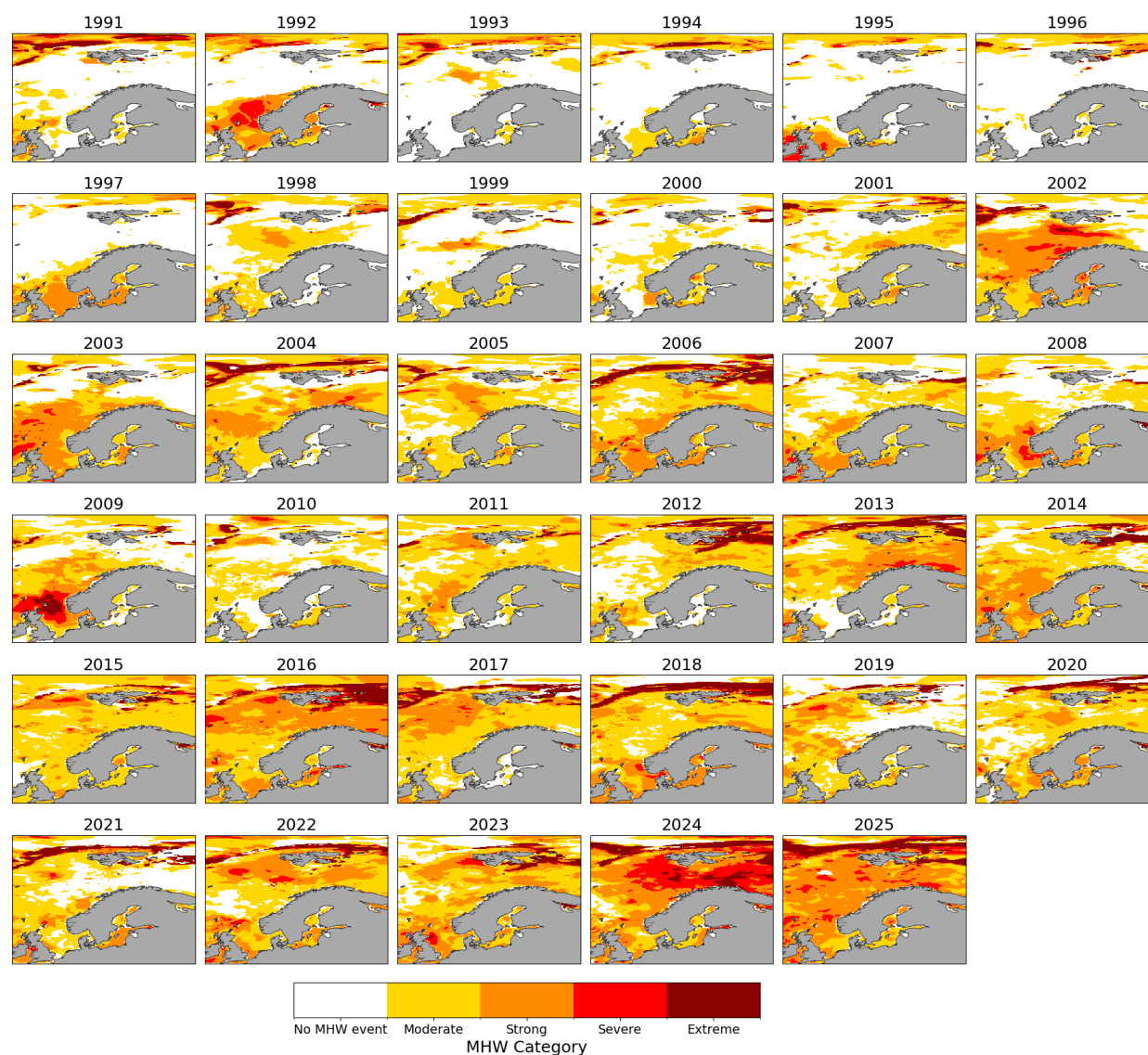
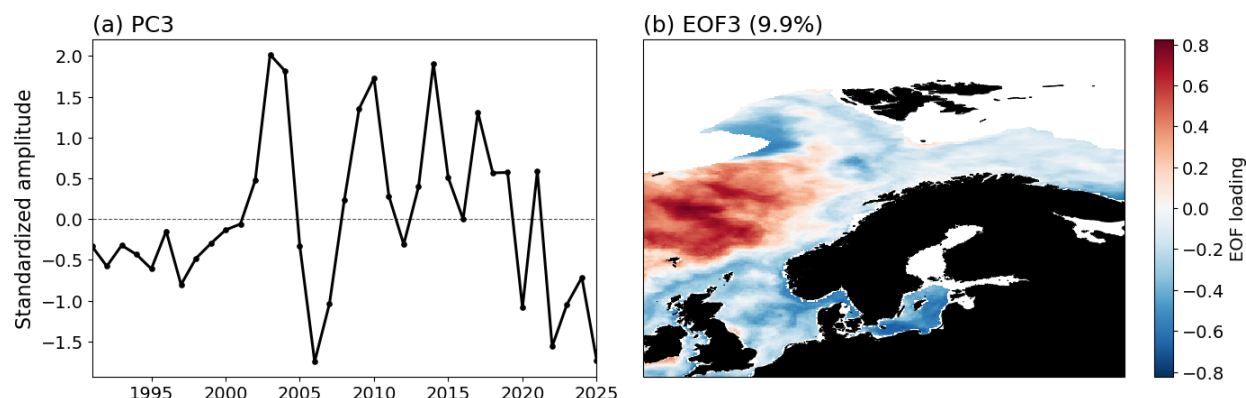
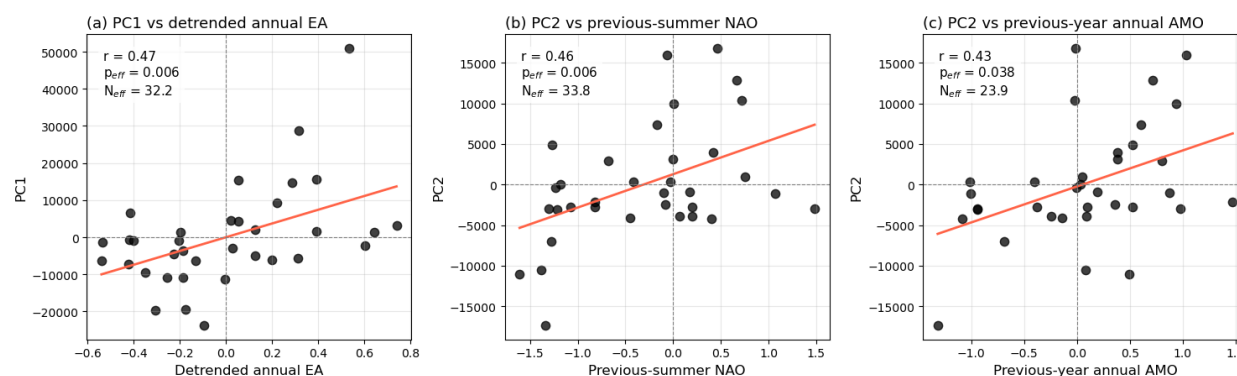


Figure A4: Annual highest MHW category per grid cell over the 1991–2025 study period in the NE North Atlantic around Norway.



655 **Figure A5: Third mode from the EOF analysis of detrended annual MHW days in the NE North Atlantic around Norway during 1991–2025, excluding seasonally ice-covered regions. (a) Standardized PC3 time series and (b) corresponding EOF3 spatial pattern, which explained 9.9% of the total variance.**



660 **Figure A6: Relationships between the two leading EOF principal components and selected large-scale climate indices. Scatterplots show (a) PC1 versus detrended annual East Atlantic (EA) index, (b) PC2 versus previous summer North Atlantic Oscillation (NAO) index, and (c) PC2 versus previous year annual Atlantic Multidecadal Oscillation (AMO) index. For lagged relationships, climate-index values from year $t-1$ are compared with the PC value in year t . Solid lines indicate least-squares linear fits. Pearson correlation coefficients and autocorrelation-adjusted p -values are shown in each panel.**

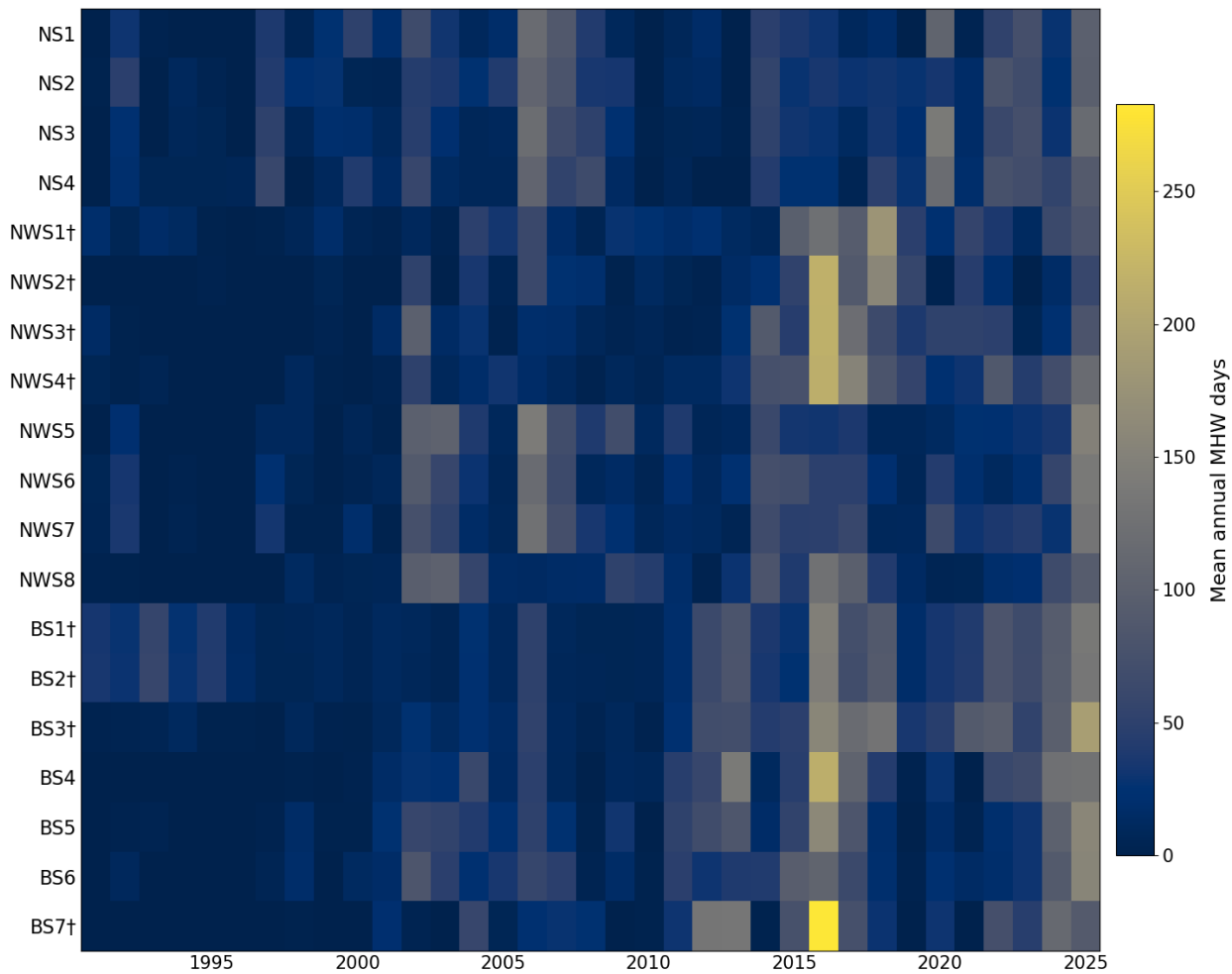


Figure A7: Annual MHW exposure in all particularly valuable and vulnerable areas (SVOs) during 1991–2025. Colours show the mean number of MHW days per year across grid cells within each SVO. The regions represent contrasting ecological functions across the North Sea (NS), Norwegian Sea (NWS) and Barents Sea (BS). SVO names and ecological relevance are provided in Table 1 and their locations are shown in Figure 1. † indicates an SVO containing seasonally ice influenced grid cells.



Table A1: Local and regional MHW characteristics for all particularly valuable and vulnerable areas (SVOs) during 1991–2025. Local metrics were calculated independently at each grid cell and then summarized across cells; local event frequency is the mean number of events per grid cell, while duration and mean intensity are reported as median [interquartile range] of cell-level median values. Regional metrics refer to MHWs detected from the daily SVO-mean SST series; event counts cover the full study period, and duration and mean intensity are reported as median [interquartile range] across regional events. Maximum grid cell coverage is the median [interquartile range] of the largest fraction of cells experiencing local MHW conditions during each regional event. Ice-influenced cells are the percentage of cells where sea ice concentration exceeded 15% on more than 1% of days. Location of the SVOs are shown in Figure 1 in the main text.

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SVO	Cells	Mean annual MHW days (days)	Mean local events per grid cell	Local		Regional		Maximum	
				median duration [IQR] (days)	median intensity [IQR] (°C)	median duration [IQR] (days)	median intensity [IQR] (°C)	grid cell coverage [IQR] (%)	Ice-influenced cells (%)
NS1 – Boknafjorden and Jærestrendene	2	31	67	10.5 [10.2–10.8]	1.79 [1.76–1.82]	10.0 [7.0–19.0]	1.77 [1.39–3.34]	100.0 [100.0–100.0]	0
NS2 – Sandeel Fields	90	32.1	77.6	10.0 [10.0–11.0]	1.60 [1.50–1.69]	10.0 [7.0–17.0]	1.47 [0.99–2.28]	87.8 [60.0–100.0]	0
NS3 – Norwegian Trench	108	32.1	78.2	10.0 [9.0–10.0]	1.89 [1.78–2.00]	10.0 [6.2–20.5]	1.73 [1.50–2.80]	88.4 [60.6–100.0]	0
NS4 – Outer Oslofjord	6	31.8	74	10.0 [9.6–10.8]	2.45 [2.44–2.53]	10.0 [6.0–16.0]	2.45 [2.15–2.86]	100.0 [83.3–100.0]	0
NWS1 – Sea Ice Fram Strait	820	34.4	52.9	13.0 [12.0–14.5]	1.62 [1.17–2.08]	15.0 [7.0–31.2]	1.24 [0.88–1.64]	47.0 [39.8–67.5]	93.9
NWS2 – Vesterisen	188	28.2	57.3	11.0 [10.0–11.5]	1.32 [1.19–1.39]	11.0 [6.0–19.0]	1.36 [0.99–1.63]	94.7 [73.4–100.0]	100
NWS3 – Jan Mayen	523	31.7	59.5	11.0 [10.0–12.0]	1.23 [1.14–1.31]	9.5 [7.0–21.8]	1.07 [0.86–1.50]	66.9 [51.0–84.1]	35.2
NWS4 – Mid-Atlantic Ridge	1639	36.2	59.8	11.0 [10.0–13.0]	1.20 [1.09–1.39]	9.5 [6.0–26.0]	0.98 [0.88–1.18]	44.1 [35.2–64.7]	10
NWS5 – Eggakanten South	511	32.8	73.5	11.0 [10.0–11.5]	1.23 [1.16–1.37]	12.0 [6.8–24.2]	1.31 [0.81–1.82]	73.3 [53.7–90.9]	0
NWS6 – Coastal Zone Norwegian Sea North	288	31.4	74.5	10.0 [9.0–11.0]	1.39 [1.34–1.46]	10.0 [6.0–21.0]	1.47 [1.02–2.14]	83.7 [59.7–99.3]	0



NWS7 – Coastal Zone Norwegian Sea South	193	32.1	81.5	10.0 [9.0–10.0]	1.55 [1.48–1.61]	82	10.0 [7.0–18.0]	1.44 [1.02–2.20]	80.8 [58.2–95.7]	0
NWS8 – Deep-sea Areas Norwegian Sea	2243	31.6	54.2	12.0 [11.0–13.0]	1.16 [1.05–1.27]	47	15.0 [6.0–27.0]	0.95 [0.71–1.21]	53.5 [45.2–78.9]	0
BS1 – Sea Areas Around Svalbard	14233	39.2	55.3	13.0 [12.0–14.5]	1.30 [0.07–1.69]	43	14.0 [6.5–47.0]	0.78 [0.57–1.06]	37.0 [31.3–47.2]	90.6
BS2 – Marginal Ice Zone	13761	39.3	54.8	13.0 [12.0–14.5]	1.31 [0.07–1.70]	46	13.5 [6.0–44.0]	0.73 [0.53–1.04]	36.2 [27.9–46.6]	95.7
BS3 – Eggakanten North	1910	42.2	63.6	12.5 [11.0–14.0]	1.49 [1.08–2.04]	49	16.0 [8.0–38.0]	1.01 [0.92–1.35]	51.6 [35.9–60.1]	54
BS4 – Coastal Zone Finnmark	554	37.2	61.2	11.0 [10.0–12.5]	1.08 [1.01–1.13]	57	12.0 [6.0–29.0]	0.98 [0.78–1.37]	81.2 [57.8–98.6]	0
BS5 – Tromsøflaket	719	34.6	65.3	11.0 [10.0–12.5]	1.10 [1.05–1.14]	65	13.0 [6.0–22.0]	1.02 [0.67–1.60]	85.0 [57.0–98.2]	0
BS6 – Coastal Zone Lofoten	652	33.2	71.4	11.0 [10.0–12.0]	1.20 [1.07–1.33]	70	13.5 [6.0–21.0]	1.10 [0.63–1.81]	70.1 [50.3–95.4]	0
BS7 – Central Barents Sea	1305	36.8	50.6	12.0 [11.0–13.0]	1.22 [1.16–1.32]	46	9.0 [7.0–23.2]	1.18 [0.98–1.49]	74.5 [59.2–100.0]	4.4



Table A2: Characteristics of the highest-category regional MHW identified in each particularly valuable and vulnerable area (SVO) during 1991–2025. Regional events were detected from daily SVO-mean SST. For each SVO, the event reaching the highest Hobday category was selected; where multiple events reached the same category, the event with the greatest cumulative intensity was retained. Maximum grid cell coverage is the largest fraction of cells experiencing local MHW conditions during the event, while coverage at peak intensity refers to the date of maximum regional intensity. For ice-influenced SVOs, mean and minimum open water grid cell fractions indicate the percentage of cells with daily sea ice concentration below 15% during the event.

SVO	Start date	End date	Peak date	Maximum category	Duration (days)	Mean intensity (°C)	Maximum intensity (°C)	Cumulative intensity (°C-days)	Maximum grid cell coverage (%)	Grid cell coverage at peak intensity (%)	Mean open water availability (%)	Minimum open water availability (%)
NS1 – Boknafjorden and Jærestrendene	2002-08-05	2002-09-17	2002-08-25	Strong	44	3.55	4.56	156.1	100	100		
NS2 – Sandeel Fields	2009-06-29	2009-07-10	2009-07-04	Severe	12	3.6	5.17	43.2	100	100		
NS3 – Norwegian Trench	2020-01-03	2020-03-24	2020-02-23	Strong	82	1.82	2.34	149.4	100	100		
NS4 – Outer Oslofjord	2018-05-20	2018-06-14	2018-06-03	Severe	26	4.89	7.47	127.2	100	100		
NWS1 – Sea Ice Fram Strait	2017-10-28	2018-02-27	2017-12-27	Strong	123	1.57	2.06	193.3	93.2	92	81.6	66
NWS2 – Vesterisen	2016-08-14	2016-12-24	2016-11-02	Severe	133	1.83	3.01	243.5	100	100	100	100
NWS3 – Jan Mayen	2016-08-12	2017-01-07	2016-11-02	Strong	149	1.66	2.71	247.1	100	100	100	100
NWS4 – Mid-Atlantic Ridge	2024-07-26	2024-10-01	2024-08-20	Severe	68	1.74	2.68	118.4	98.4	96.7	100	100
NWS5 – Eggakanten South	1992-05-28	1992-06-16	1992-06-12	Severe	20	2.97	4.7	59.3	100	100		
NWS6 – Coastal Zone Norwegian Sea North	2003-07-20	2003-08-28	2003-08-01	Strong	40	2.62	3.94	104.7	100	100		
NWS7 – Coastal Zone Norwegian Sea South	1992-05-26	1992-06-16	1992-06-10	Severe	22	3.42	4.78	75.2	100	100		
NWS8 – Deep-sea Areas Norwegian Sea	2002-05-27	2002-07-27	2002-07-07	Strong	62	1.8	2.6	111.7	100	100		
BS1 – Sea Areas Around Svalbard	2024-07-19	2024-11-30	2024-08-20	Severe	135	1.56	2.67	210.2	81.3	75.3	72	58.6
BS2 – Marginal Ice Zone	2024-07-19	2024-12-01	2024-08-20	Severe	136	1.55	2.64	211.3	80.6	74.3	70.9	57.1
BS3 – Eggakanten North	2025-06-06	2025-12-30	2025-07-21	Severe	208	1.99	3.39	414.2	99.7	80.7	93.4	58.7
BS4 – Coastal Zone Finnmark	2024-07-22	2024-11-28	2024-08-24	Extreme	130	2.2	3.78	285.5	100	98.7		
BS5 – Tromsøflaket	2025-07-24	2025-11-17	2025-08-12	Severe	117	1.8	3.25	210.3	100	100		
BS6 – Coastal Zone Lofoten	2024-07-18	2024-08-26	2024-08-06	Strong	40	3.03	4.69	121.4	100	100		



BS7 – Central Barents Sea 2024-07-28 2024-11-29 2024-08-25 Extreme 125 2.26 4.45 282.8 100 100 100 100