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To cite this article: Shakti Singh *et al* 2026 *Environ. Res.: Climate* **5** 015001

IOP Publishing Environ. Res.: Climate 5 (2026) 015001 https://doi.org/10.1088/2752-5295/ae249b

ENVIRONMENTAL RESEARCH
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OPEN ACCESS

RECEIVED
29 August 2025

REVISED
20 November 2025

ACCEPTED FOR PUBLICATION
26 November 2025

PUBLISHED
9 December 2025

PAPER

Marine cold spells in the Baltic sea

Shakti Singh*, Ilja Maljutenko and Rivo Uiboupin

Department of Marine Systems, Tallinn University of Technology, Tallinn, Estonia
* Author to whom any correspondence should be addressed.

E-mail: shakti.singh@taltech.ee

Keywords: marine cold spells, baltic sea, ocean extremes

Supplementary material for this article is available online

Abstract

Marine cold spells, characterized by anomalously low sea surface temperatures (SSTs), play a crucial role in shaping marine ecosystems and have significant socioeconomic implications. Unlike the extensively studied marine heatwaves, research on marine cold spells (MCSs) remains limited, particularly in the Baltic Sea, one of the fastest-warming seas globally. Its semi-enclosed nature, strong seasonal variations, and sensitivity to atmospheric–oceanic changes make it an ideal case study region for examining the occurrence and impacts of cold spells under ongoing climate change. This study analyzes MCS characteristics in the Baltic Sea from 1982 to 2023 during the extended summer–autumn season (June–November). The Cold spell occurrences declined, with coastal events being more intense (≈4 °C) than offshore (≈3 °C). The MCS event duration has decreased, especially in the western Baltic Sea. The decline is mainly driven by a sustained SST warming trend of ≈0.05 °C per year, with interannual variability being secondary. Cold spell parameters derived from detrended SST data remove long-term warming and were used to assess cold spell variability. In recent years, coastal regions, especially upwelling zones, have experienced fewer and shorter cold spells, consistent with other regions, but their intensity has significantly increased (0.047 °C per year since 2006). These intensifications may be linked to large-scale atmospheric circulation patterns such as the North Atlantic oscillation, Scandinavian pattern, and East Atlantic pattern.

1. Introduction

Numerous studies have shown that rising ocean temperatures caused by global warming are leading to more frequent extreme events, causing major ecological and socioeconomic consequences (Frölicher *et al* 2018, Oliver *et al* 2018, Smale *et al* 2019).

Marine heatwaves (MHWs) are characterized by anomalously high ocean temperatures (Hobday *et al* 2016, 2018) and have shown an increasing trend in frequency, duration, and intensity over recent periods (Frölicher *et al* 2018, Oliver *et al* 2018, Plecha and Soares 2020). This trend is projected to continue, with MHWs becoming more frequent and intense globally in the future (Oliver *et al* 2019).

The Arctic and Baltic Sea have warmed much faster than other regions in the past four decades, increasing the risk of marine heatwaves (MHWs) (Meier *et al* 2022, Rantanen *et al* 2022). Several studies have examined MHWs in the Baltic Sea (Suursaar 2020, Bashiri *et al* 2024, Travkin *et al* 2024). Summer MHWs in the Baltic Sea are primarily driven by local meteorological conditions (caused by dominant Scandinavian (SCAND) blocking), while winter MHWs are associated with the advection of warm, moist air from the North Atlantic (Gröger *et al* 2024).

Marine cold spells (MCSs), on the other hand, are events characterized by anomalously low ocean temperatures (Schlegel *et al* 2021). As ocean temperatures increase, MCSs decrease (Schlegel *et al* 2021) and are projected to keep decreasing in the future (Yao *et al* 2022). Nevertheless, MCSs have significant impacts on marine ecosystems, often leading to socioeconomic consequences. These events can drive shifts in species distributions, alter the composition of communities, and even trigger evolutionary changes (Parmesan 2006, Campbell-Staton *et al* 2017). For instance, the 2008 Taiwan Strait MCS caused mass die-offs of cultured fish but increased migratory species catches by ≈230% (Lee *et al* 2014).

Despite their importance, MCS events remain inadequately addressed in global research (Schlegel *et al* 2021, Wang *et al* 2022, Yao *et al* 2022).

Schlegel *et al* (2021) conducted a comprehensive review of notable MCSs, highlighting key driving factors. Often anomalous winds were primary factors, causing wind-driven cooling of shallow waters and wind-driven upwelling. Additional influences included severe winter air and ocean temperatures from Arctic spells, Arctic air intrusions, and reduced ocean heat transport, etc. (Schlegel *et al* 2021).

The Baltic Sea is distinguished by its unique hydrological and ecological characteristics, which are affected by both continental and marine influences. Seasonal and interannual temperature variability in the Baltic Sea is particularly significant, driven by complex interactions between atmospheric and oceanographic forces. MCSs are an essential part of this variability, often reflecting broader shifts in climate patterns and atmospheric anomalies (BACC 2008, Kahru *et al* 2016). Several possible atmospheric drivers of MCS events in the Baltic Sea include the North Atlantic oscillation (NAO), SCAND and East Atlantic (EA) patterns, and wind-driven mixing, alongside other factors such as cold-water advection, reduced solar radiation, and ice cover. However, only upwelling events, which contribute to coastal cold spells, have been examined in the literature (Lehmann and Myrberg 2008, Uiboupin and Laanemets 2009, Zhang *et al* 2022, Skudra *et al* 2023).

In the Baltic Sea, lengthened ice-free periods and altered seasonal temperature patterns have been observed, with a notable increase in warm spells over the past few decades (Kahru *et al* 2016, Singh *et al* 2025). With rising ocean temperatures, a decline in cold spell events is anticipated over time. However, it is crucial to investigate the contributions of long-term warming and interannual-to-decadal variability to this observed decrease in MCSs, as well as to determine which factor predominates in different regions of the Baltic Sea. Detrending the sea surface temperature (SST) data allows us to isolate interannual variability and assess its contribution separately from the long-term SST trend in marine cold spell (MCS) characteristics (Simon *et al* 2023a). No studies have employed such an approach to assess the relative impacts of long-term warming and SST variability on MCSs in the Baltic Sea. This approach is comparable to that used by Simon *et al* (2023a) to investigate MHW events in the Mediterranean Sea.

Given the ecological and economic significance of cold spells in the Baltic Sea, their role as key indicators of climate variability, and the existing gap in the literature, this study aims to provide a comprehensive analysis of cold spell events, focusing on their frequency, duration, intensity, and spatial extent from 1982 to 2023. These characteristics of MCSs are critical for developing adaptation strategies that can mitigate the ecological and socio-economic impacts of changing cold spell dynamics, thereby contributing to the resilience of the Baltic Sea region in a warming climate.

Objectives: The specific objective of the study are (1) to analyze MCS statistics using satellite SST data over the Baltic Sea during the extended summer–autumn season (June–November) from 1982 to 2023, as well as calculating MCS statistics for the detrended SST data to isolate variability by removing the long-term warming signal; (2) to determine the spatial distribution of trends and temporal trends of MCS metrics; (3) to compute the MCS activity index and decompose it into contributions from long-term warming and SST variability; (4) to identify coastal regions experiencing the most intense cold spell events during the study period.

2. Data and methods

2.1. Satellite data

The Copernicus Marine SST dataset from the reprocessed level 4 (L4) product has been used for the study. The Copernicus Marine SST reprocessed L4 product, known as SST_BAL_SST_L4_REP_OBSERVATIONS_010_016 (Høyer and Karagali 2016) has been developed at the Danish Meteorological Institute and offers comprehensive, gap–free maps of SST for the Baltic Sea region. The L4 product is made at a spatial resolution of 2.4 × 1.44 km (0.02° × 0.02°) using satellite data from ESA's SST CCI and Copernicus C3S projects. It combines data from multiple satellite sensors, including NOAA AVHRRs, MetOp, ATSR1, ATSR2, AATSR, and SLSTR, with *in situ* measurements from the HadIOD dataset. The dataset is available from 1 January 1982 to 31 December 2023. The product's quality has been assessed in its quality information document, and the overall validation metrics for the L4 SST product indicate that the mean differences with drifting buoys fall well within the target thresholds set for satellite SST products (Høyer and Karagali 2016, O'Carroll *et al* 2019).

2.2. NAO Climate Prediction Center (CPC) data

The NAO index used in this study is obtained from NOAA's CPC and is calculated using rotated principal component analysis following Barnston and Livezey (1987). The method is applied to monthly standardized 500 hPa geopotential height anomalies over the 20°N–90°N region, using data from 1950 to 2000, to isolate dominant teleconnection patterns. More details available on the project page www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/history/method.shtml. Monthly NAO index values from May to November were averaged for each year from 1982 to 2023 to produce a seasonal index. The resulting time series was standardized, and years with values greater than +1 or less than −1 were classified as positive and negative NAO phases, respectively. These thresholds identify years that deviate by more than one standard deviation from the mean, indicating notable changes in atmospheric circulation.

2.3. ERA5 data

In the current study, we used ERA5 monthly-mean single-level reanalysis data from the Copernicus climate data store for the period 1982–2023 to analyze large-scale atmospheric conditions associated with MCSs in the Baltic Sea. ERA5 provides monthly averages of surface variables, including 2 m air temperature and 10 m wind components, produced by the European center for medium-range weather forecasts at a spatial resolution of 0.25° × 0.25°. A detailed description and evaluation of the ERA5 reanalysis is provided by Hersbach *et al* (2020).

2.4. Definition of MCSs

The current study focuses on cold spell events in the Baltic Sea for the period 1982–2023, and the whole 42 year period is used to define climatology, which is in accordance with the standard set by the World Meteorological Organization. Near-ice regions (the polar and subpolar seas) can be problematic for accurate detection of cold-spell events from satellite observations because the presence of sea ice alters the 10th-percentile threshold (Schlegel *et al* 2021). The Baltic Sea experiences minimal to no sea-ice formation until the end of November, with ice typically remaining until May of the following year (Singh *et al* 2025). Hence, the main analysis is limited to the extended summer–autumn (June–November) ice-free period. Detailed analysis of year-round statistics is given in the appendix section. Criteria defined by Schlegel *et al* (2021) is used for defining MCSs. A MCS is defined as a discrete, prolonged anomalously cold-water event at a particular location, and as the inverse of the MHW definition (Hobday *et al* 2016, 2018). The definition uses a seasonally varying climatological baseline to determine whether the atmospheric or oceanic temperature on a given day is anomalously low. Because of longer memory of seawater than air, the MCS definition applies a period of five or more days below the 10th percentile threshold (rather than three days for the atmosphere), with no more than a 2 d rise above that threshold (Schlegel *et al* 2021).

Using the definition for MCSs, the following grid cell-based metrics were used in the study: number of events during a time period, duration (D), mean intensity (i_{mean}), maximum intensity ($i_{\max}$), and cumulative intensity (i_{cum}). These metrics are thoroughly defined in Schlegel *et al* (2021) and are based on a similar criterion to heat waves (Hobday *et al* 2016, 2018). For cold spells, the signs for intensity metrics are negative by definition.

2.5. MCS activity index

The activity index from Simon *et al* (2023a and 2023b) is applied in the current study. The activity index is based on a similar concept to the cumulative intensity; which combines the duration and intensity of an event (Hobday *et al* 2016). The activity index is calculated at each gridpoint (x,y) for a time period (for each extended summer–autumn season separately between 1982–2023) and is given by below formula:

$$\mathrm{Activity}\ (x,y) = \sum_{\mathrm{Period}} [I_{\mathrm{mean}}(x,y)]_E . [D(x,y)]_E . [\mathrm{gridarea}(x,y)]_E \tag{1}$$

where E are the discrete cold spell events, within each extended summer–autumn season between 1982–2023. $[D\ (x,y)]_E$ denotes the number of days each discrete event lasts at each gridpoint. $[I_{\mathrm{mean}}\ (x,y)]_E$ is the mean of the SST anomaly from the climatology during each event at each gridpoint. $[\mathrm{gridarea}\ (x,y)]_E$ is the area of each gridpoint (x,y) affected by each event.

The total activity is the horizontal sum of activity value over all the grid points for each extended summer–autumn season between 1982–2023.

2.6. Decomposition of MCS trends: long-term warming vs interannual variability

The cold spells trends are decomposed into contributions from long-term SST warming trend and interannual variability, like Simon *et al* (2023a), for MHWs in Mediterranean Sea. For each gridpoint (x,y), the SST data is decomposed into these two components:

$$\mathrm{SST}\ (x,\ y,\ t) = \mathrm{SST_L}(x,\ y)\,.t + \mathrm{SST_A}(x,\ y,\ t) \tag{2}$$

where SST_L (x, y) is long term SST warming trend which is multiplied by the number of years analyzed (t) and SST_A (x, y, t) is the detrended SST data (anomaly from the long-term SST trend), which represents the short term (interannual to decadal) variability.

Using SST data, overall MCS activity (equation (1)) trends are calculated. MCS activity (equation (1)) trends derived from detrended SST data (SST_A) represent the contribution of interannual variability. Subtracting this contribution from the overall MCS activity trends isolates the influence of the long-term SST trend on MCS activity.

2.7. K-means clustering

To group the different regions, K-means clustering is used in this study. The algorithm assigns each data point to the nearest cluster center, aiming to minimize the distance between each point and its assigned cluster center (MacQueen 1967, Lemenkova 2019). The Elbow method and the Silhouette method are both used to assess clustering quality. The Elbow method evaluates clustering performance by analyzing the explained variance across different cluster numbers, identifying the optimal cluster count at the 'elbow point' where adding more clusters provides little improvement (Thorndike 1953, Ketchen and Shook 1996). The Silhouette method measures how similar each point is to its own cluster compared to others, with a higher Silhouette score indicating better-defined clusters (Rousseeuw 1987). Using both approaches ensures that the selected number of clusters balances explained variance and cluster cohesion.

The geographical boundaries of the sub-basins used in the current study are based on the PLC–6 project, obtained from Helsinki Commission (HELCOM 2018), shown in figure 1(a).

3. Results

3.1. MCS activity

The Baltic Sea exhibits spatial variations in SST and MCS characteristics. To support regional analysis, the sub-basins boundaries based on the PLC–6 project (obtained from the Helsinki Commission 2018) are utilized (figure 1(a)). The warming trend of the Baltic Sea's area-weighted horizontally averaged surface temperature is shown in figure 1(b), with an average increase of about 0.049 °C per year with uncertainty range of 0.013 °C per year at 95% significance level. The regional trends vary between approximately 0.04–0.07 °C per year in the extended summer–autumn season (figure 1(d)). The MCS activity (equation (1), in methods section) and the MCS extent (defined as the daily total area affected by MCSs over the Baltic Sea in the extended summer–autumn season from 1982 to 2023) are much lower in the latter half of the study period (figures 1(b) and (c)). Spatially, the decreasing MCS activity trends are significantly higher over the offshore regions (figure 1(e)).

Given the significant warming trend in the Baltic Sea, its influence on the decreasing activity trend is analyzed along with the contribution of short-term variability. To better understand this, the spatial trend in the activity parameter is decomposed into contributions from long-term warming and short-term (interannual to decadal) variability (figures 1(f) and (g)).

The decomposition (detailed in the methods section) reveals that the primary driver of the decreasing MCS activity trends is long-term SST warming. While interannual variability also contributes to the decline in MCS activity, its impact is less pronounced. A slight exception is observed in the southeast Baltic Proper subbasin, where interannual variability plays a larger role in the decrease of MCS activity trends. Additionally, interannual variability causes an increase in MCS activity along the west coast of the Baltic Sea (figures 1(f) and (g)).

The MCS metrics are discussed in detail in a subsequent subsection. To assess the variability of these parameters, an analysis of the MCS metrics based on detrended SST data (removing the long-term warming signal) is also conducted.

3.2. Number, duration and intensity of MCS

The spatial distribution of overall statistics for the MCS metrics is highlighted (figure 2) during the extended summer–autumn season of the study period. Over the 42 year study period, between 20 and 45 events were recorded across the spatial domain of the Baltic Sea (figure 2(a)). The Gulf of Riga (GoR) and Gulf of Finland (GoF) sub-basins (in general the eastern part of the Baltic Sea) had considerably fewer cold spell events. The mean duration of MCS for these sub-basins is also shorter (table 1).

In terms of event duration, cold spells in offshore regions tend to persist slightly longer (figure 2(c)). However, coastal cold spells are more intense, with mean intensity reaching approximately 4 °C, while offshore cold spells are milder, with a mean intensity of around 3 °C (figure 2(e)).

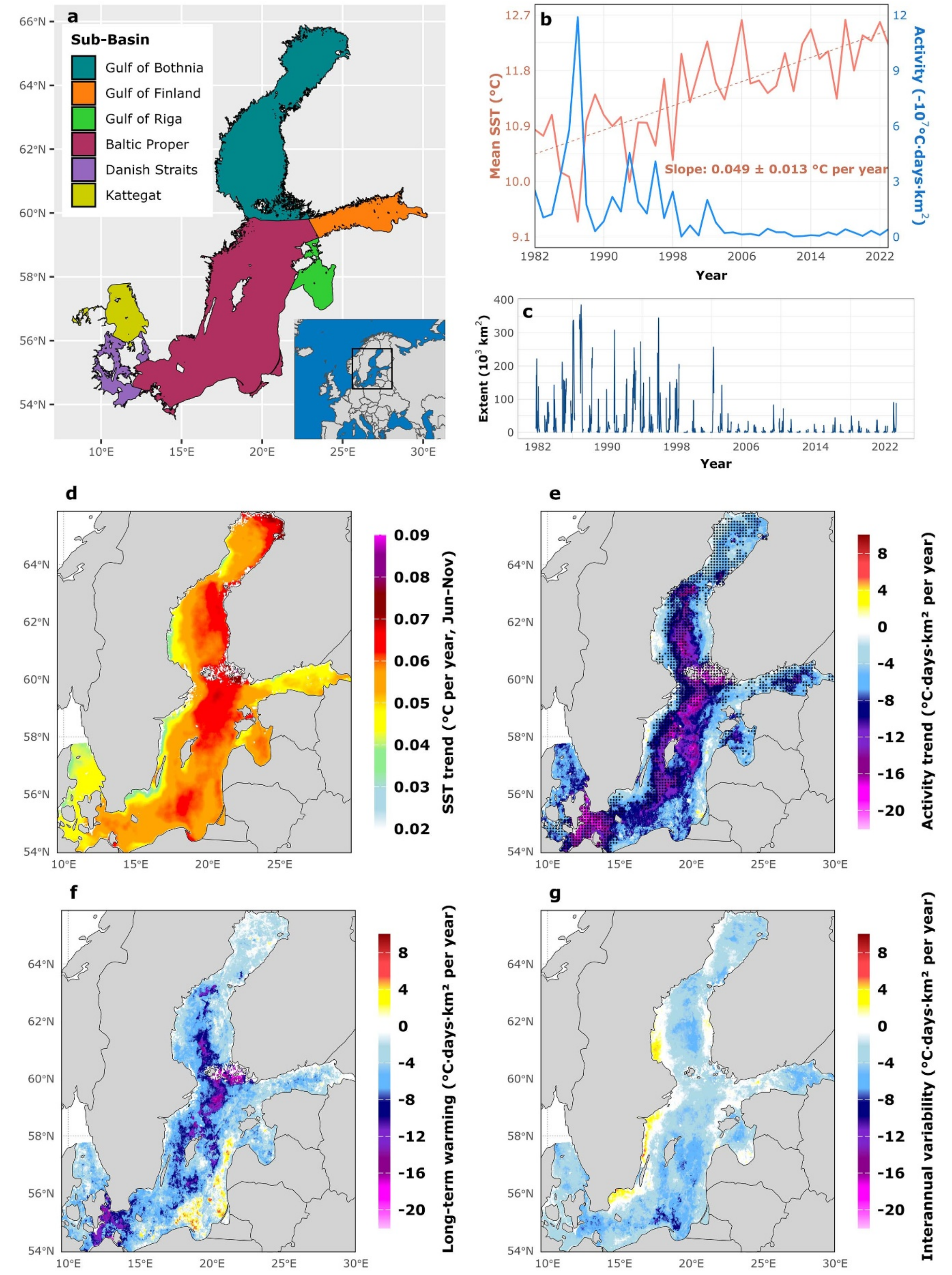

Figure 1. (a) Spatial distribution of the Baltic Sea sub-basins based on the PLC–6 project, obtained from the Helsinki Commission (HELCOM 2018); (b) Yearly averaged time series of sea surface temperature (orange) with an average increase of about 0.5 °C per decade (95% significance level), total cold spell activity (blue); and (c) extent of MCS over the Baltic Sea for the extended summer–autumn period. The SST values are area weighted average over the Baltic Sea, while the total cold spell activity reflects the annual aggregated Activity (equation (1)) of MCS for the same period. The spatial maps are (d) Mean sea surface temperature trend; and (e) marine cold spell activity (equation (1)) trend (where black dots represent 95% significance level), decomposed into contributions of (f) long-term warming and (g) interannual variability for extended summer–autumn period from 1982 to 2023.

The MCS characteristics show clear differences when comparing raw SST data with detrended SST data (figure 2). Using detrended SST data for MCS detection resulted in a larger number of events overall. This increase is primarily due to the inclusion of more events in the latter part of the study period,

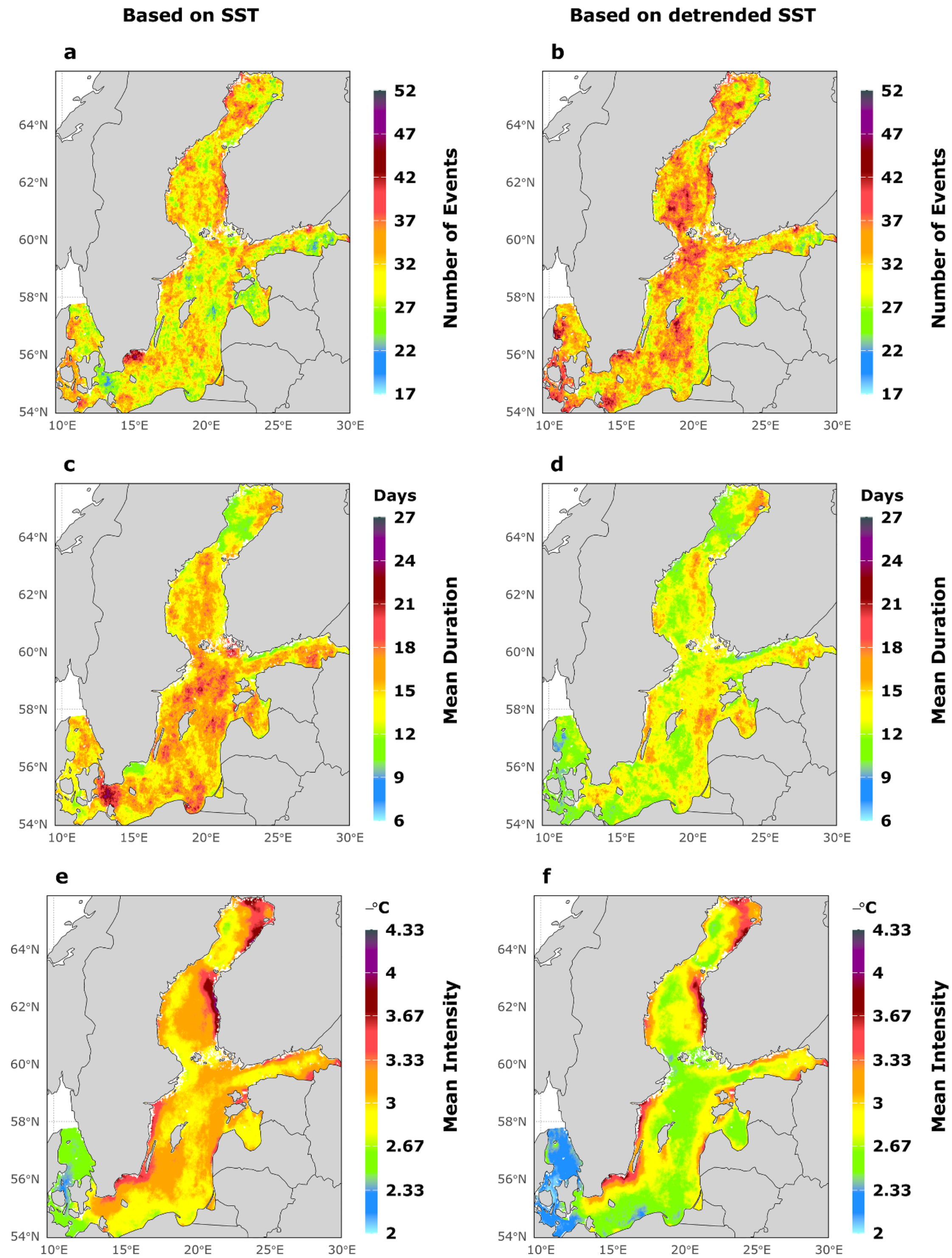

Figure 2. Marine cold spells characteristics: number of events (a), (b), mean duration of each event (c), (d), mean intensity of each event (e), (f) for period 1982–2023 during extended summer–autumn period (June–November) based on SST (left) and long term detrended SST data (right).

as warming trends in raw SST data led to significantly fewer events being detected in recent years. The mean duration of cold spell events decreases as shorter events from the second half of the study period are incorporated in the statistics. Detrended SST data also highlights a stronger contrast between coastal and offshore areas for mean intensity, with coastal areas continuing to display higher-intensity cold spells. Overall, detrending SST data helps to remove the long-term warming impact, allowing for a better understanding of the variability in cold spell events.

The spatial trend distribution maps for the MCS metrics reveal a decrease in all metrics across nearly all regions (figure 3(a), (c) and (e)). On average, the western part of the Baltic Sea shows significant

Table 1. Basin wise statistics of MCS metrics for the extended summer–autumn season from 1982 to 2023. Statistics include MCS metrics (mean intensity and mean duration) values for the Gulf of Bothnia (GoB), Gulf of Finland (GoF), Gulf of Riga (GoR) and Baltic Proper (BP) sub-basins.

Parameters	Basin	Mean	SD	Min—Max
Mean intensity (°C)	GoB	3.06	0.395	2.29–3.72
	GoF	3.07	0.346	2.46–4.01
	GoR	2.91	0.597	1.67–4.03
	BP	2.83	0.496	2.05–3.75
Mean duration (days)	GoB	11.1	6.00	5–35.1
	GoF	10.3	7.41	5–35.4
	GoR	10.3	7.52	5–35.5
	BP	11.9	7.64	5.37–45.4

decreasing trends in MCS duration (significant at the 95% confidence interval), with a decrease of up to 1 d per year (figure 3(c)). The mean intensity of MCS events shows a significant increasing trend along the coastal regions, reaching up to 0.03 °C per year, while offshore areas exhibit a significant decreasing trend of up to 0.06 °C per year (figure 3(e)). The increasing mean intensity trends contribute to much milder overall decreases in MCS activity along the coastal regions (figure 1(e)). MCS trends derived from detrended SST data also display similar decreasing patterns, though notably weaker (figures 3(b), (d) and (f)), emphasizing that the observed declines in cold spell metrics are primarily driven by the overall long-term warming of the Baltic Sea.

3.3. Clustering the MCS regions

As previously discussed, the coastal regions experienced high mean intensity MCS events during the study period (figure 2(f)). To analyze MCS characteristics in the coastal and offshore regions, K-means clustering is applied to mean intensity values (based on detrended SST data) and distance from the coast (figure 4), which allows grouping of regions with similar MCS intensity patterns. The mean intensity of cold spells, based on detrended SST data removing the effect of long-term warming trends, is useful for a more consistent assessment of short-term anomalies such as upwelling events.

The optimal number of clusters, determined through the Elbow and Silhouette methods (figure S1), is 3. This clustering approach helps identify coastal areas with intense cold spell events during the study period, allowing for more detailed analysis of these specific regions. Within the identified clusters, *Cluster 2* corresponds to coastal regions characterized by high mean intensity cold spells ($i_{\text{mean}} = 3.16$, $D = 11.2$ d), while *Cluster 3* represents coastal areas with low mean intensity cold spells ($i_{\text{mean}} = 2.81$, $D = 11$ d). *Cluster 1* consists of offshore areas with low cold spell intensity values ($i_{\text{mean}} = 2.78$, $D = 11.8$ d).

In the high-intensity coastal MCS regions, despite the overall warming trend in the Baltic Sea, the intensity of MCS has shown an increasing trend (figures 2(e) and 3(e)). These regions are grouped in *Cluster 2*, where the overall increase is less pronounced but has been statistically significant in recent years, from 2006 to 2023 (figure 5(a)). The NAO index has been negative during recent extended summer–autumn seasons (figure 5(b)), suggesting it may be a contributing driver. However, in the study's later period, the area covered by MCS is much smaller and fewer events are detected, so these trends should be interpreted with caution (figure 1(e)).

The MCS activity (equation (1)) within the three clusters with corresponding seasonal Baltic SST averages (during the extended summer–autumn season) revealed varying correlations (−0.72, −0.65 and −0.77 respectively). *Cluster 2*, representing high-intensity coastal MCS regions, shows a slightly weaker correlation with SST, suggesting that these regions are less affected by overall seasonal SST conditions compared to other clusters.

4. Discussion

This study provides a comprehensive analysis of MCS characteristics for the Baltic Sea, which are crucial for marine ecosystems (highlighted in several studies such as Santos *et al* 2016, Smale *et al* 2019, Feng *et al* 2021). These events can have varying impacts on marine ecosystems. For example, the 2010 MCS in South Florida caused mass fish mortalities, especially among recreationally important species in the

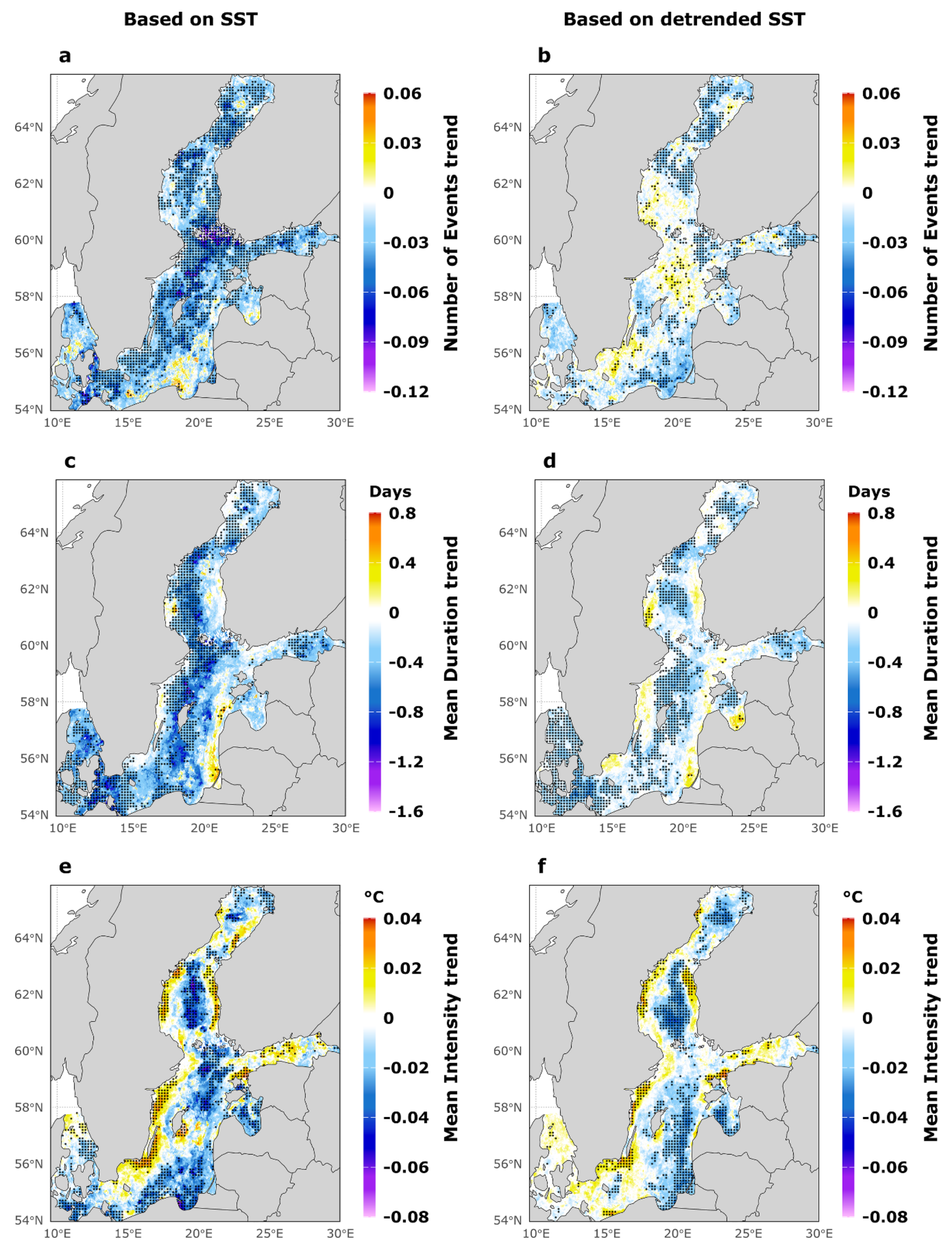

Figure 3. Trends (per year) in marine cold spells characteristics: number of events (a), (b), mean duration of the events (c), (d), mean intensity of the events (e), (f) for period 1982–2023 during extended summer–autumn period (June–November) based on SST (left) and long term detrended SST data (right), stipples show 95% significance level.

Everglades (Santos *et al* 2016). On the other hand, some MCSs, like those following the Ningaloo Niño 2011 MHW of Western Australia, have facilitated fisheries recovery by enhancing primary production (Feng *et al* 2021).

Current study highlights that regionally fewer MCS events occurred in the shallow sub-basins of the Baltic Sea, such as the GoR and the GoF (table 1). Coastal zone events are generally more intense, where cold air outbreaks over shallow waters can cause rapid chilling, while extremely strong winds can induce unusual upwelling, leading to the MCS events (Schlegel *et al* 2021). The importance of upwelling has

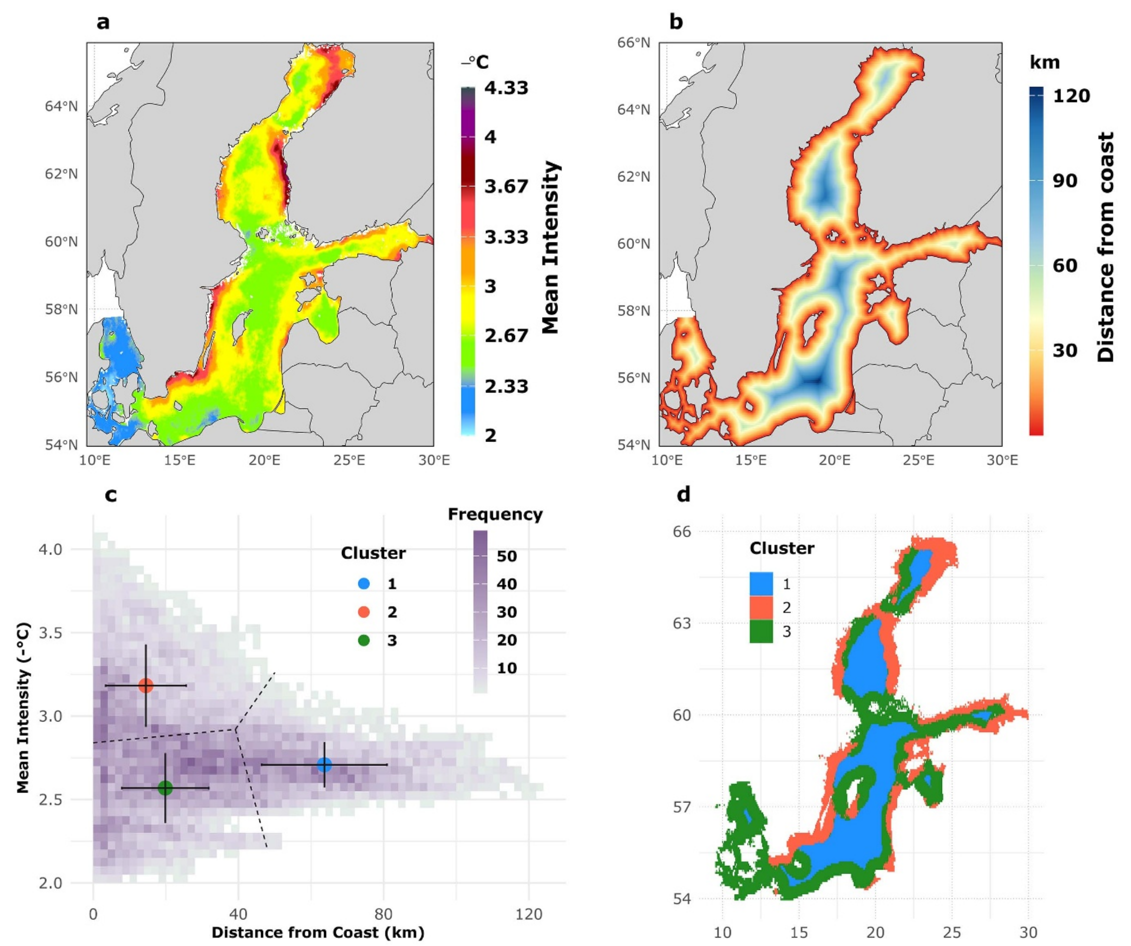

Figure 4. (a) Mean intensity of cold spell events across the Baltic Sea, calculated based on detrended sea surface temperature for the extended summer–autumn season from 1982 to 2023; (b) distance of grid points from the coast (in kilometers); (c) 2D hist plot (bin width is 2 km by 0.05 °C) between mean intensity of cold spells and distance from the coast, with data grouped into three clusters using K-means clustering, along with the corresponding centroids (Centroid 1 at 64.15 km and 2.71 °C, Centroid 2 at 15.64 km and 3.18 °C, and Centroid 3 at 20.66 km and 2.57 °C) and standard deviations for both parameters; (d) spatial distribution of the identified clusters across the Baltic Sea.

been widely recognized in the Baltic Sea, as it plays a crucial role in shaping the physical and biogeochemical dynamics of the Baltic Sea, influencing nutrient distribution, primary productivity, and even coastal temperature regimes (Lehmann and Myrberg 2008).

4.1. Effect of long-term warming on MCS statistics

Consistent with previous studies, the long-term warming trend in SST emerges as the dominant factor shaping MCS statistics (Oliver *et al* 2018, Simon *et al* 2023a and 2023b). Assessing the contributions of long-term warming versus SST variability to MCS trends is essential. The long-term SST trend plays a dominant role in decreasing MCS activity, particularly in offshore regions. MCS events in the Baltic Sea are becoming less frequent, covering smaller areas, and lasting for a shorter duration. As SSTs in the Baltic Sea are projected to rise further, a continued decline in MCSs is anticipated. This highlights the importance of studying their impacts, particularly on marine ecosystems.

The long-term warming trend in the Baltic Sea has led to higher values of the MCS metrics during the first half of the 42 year study period when SST was generally colder. Consequently, fewer MCS events are detected in the later half, as highlighted in this study. This creates a detection bias, with MCS identification skewed toward the first half, while significant but weaker cold SST anomalies in the later half are not classified as cold spells. Detrending SST prior to MCS detection helps reduce this bias and enables a more accurate assessment of cold spell variability (like the approach used for MHW in earlier studies such as Xu *et al* 2022). After detrending, previously undetected cold spells in the later period are accounted for, while weaker events from the earlier, colder period are filtered out. This leads to an overall increase in the number of detected MCS events, though their mean duration decreases, as shorter

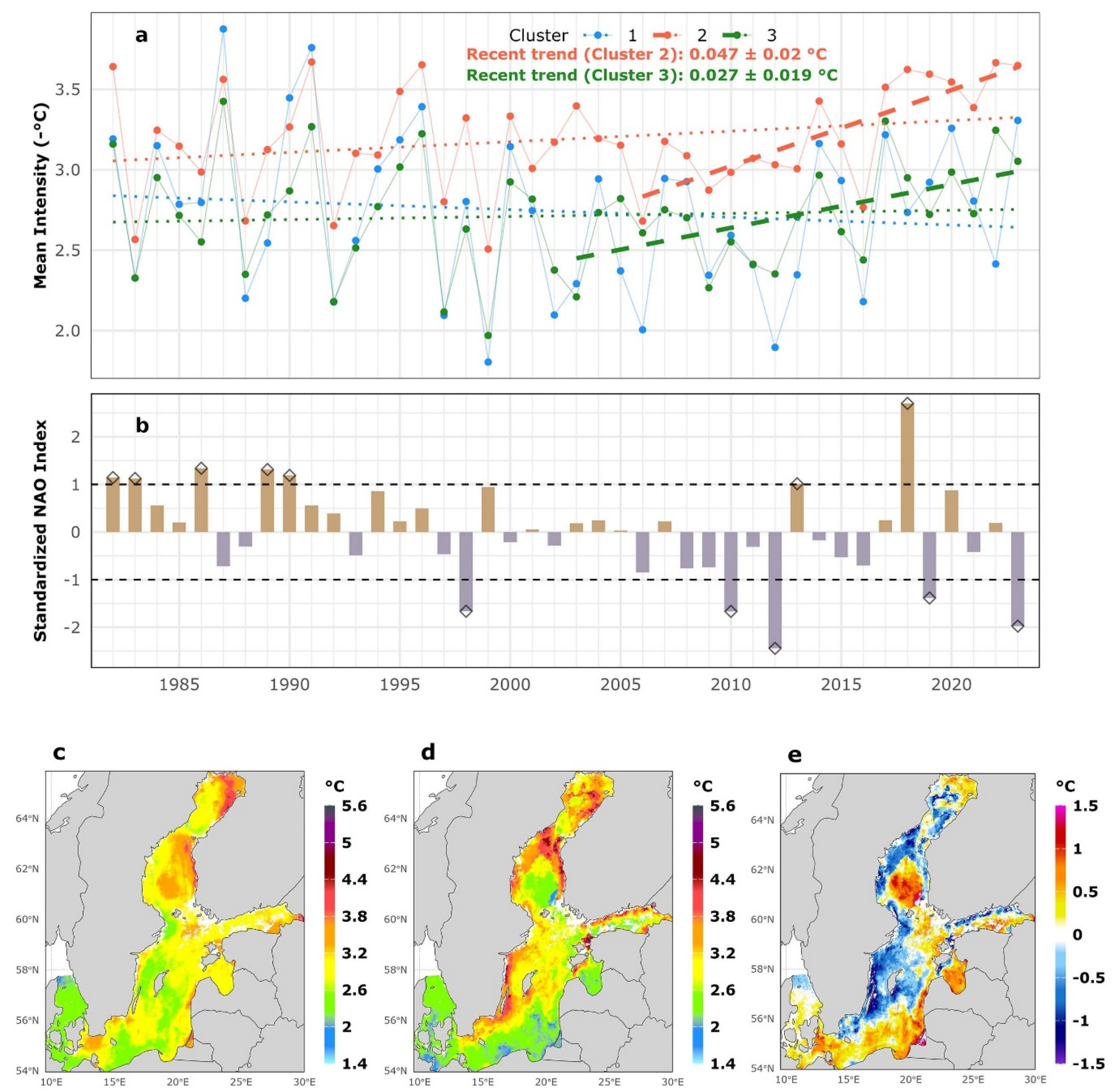

Figure 5. (a) Annually averaged mean intensity of MCSs over each cluster region for the extended summer–autumn season. The recent trends for *Cluster 2* and *Cluster 3* are statistically significant at the 95% significance level from 2006 and 2003 onwards respectively. (b) Standardized annually averaged North Atlantic Oscillation (NAO) Index for the extended summer–autumn season from 1982 to 2023 obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Centre (CPC) dataset (ftp://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/nao_index.tim). Dashed lines at 1 and—1 threshold to separate NAO-positive and NAO-negative years. Mean intensity of MCSs during (c) NAO-positive years (NAO index > standard deviation) and (d) NAO-negative years (NAO index < standard deviation). (e) Difference in mean intensity of MCSs from the NAO-positive years to the NAO-negative years during the extended summer–autumn season (1982–2023). NAO-positive years include 1982, 1983, 1986, 1989, 1990, 2013, and 2018; NAO-negative years include 1998, 2010, 2012, 2019, and 2023.

SST anomalies (specifically in the second half of the study period) are now classified as cold spells (figures 2(a) and (b)). Consequently, the decreasing trends for MCS metrics (number of events, mean duration, and mean intensity) are less pronounced when SST variability is accounted for by detrending (figure 3).

4.2. Drivers and reasons for changes in coastal MCS statistics

The Baltic Sea, a semi-enclosed basin with varied border orientations, experiences frequent coastal upwelling since almost any wind direction can trigger it along some part of the coast (Myrberg and Andrejev 2003, Lehmann and Myrberg 2008, Lehmann *et al* 2012). High-intensity coastal MCS regions were identified using *K*-means clustering, which correspond closely to known upwelling regions in the Baltic Sea (Lehmann and Myrberg 2008, Bednorz *et al* 2021, Zhang *et al* 2022), although the study periods do differ in those studies compared to ours. 15 out of 22 identified upwelling zones in Bychkova *et al* (1988) approximately coincide with high-intensity coastal MCS regions in our study. These high-intensity coastal MCS regions exhibit a statistically significant increasing trend in intensity during recent years.

Local bathymetry and upper-ocean structure also help explain the stronger coastal MCS intensities observed in this study. In the Baltic Sea, the coastal regions are generally shallow (Jakobsson *et al* 2019), and in many cases this limited depth supports a relatively shallow mixed layer depth (MLD), with the upper layer sometimes mixed down to the seabed when wind driven or convective turbulence is strong enough (Rak *et al* 2024). This allows surface cooling to affect the entire upper layer more quickly, leading to sharper and more intense cold anomalies than in deeper offshore areas, where a thicker mixed layer reduces the impact of short-term surface cooling. Similar processes have been demonstrated in recent studies of subsurface and bottom temperature extremes, which show that water depth and vertical structure strongly influence how thermal anomalies develop and persist (Amaya *et al* 2023, Cao *et al* 2024, Li *et al* 2025). Although our analysis focuses on surface events, these findings highlight that variations in MLD and bathymetry, closely reflected by our distance from coast metric, play an important role in shaping spatial differences in MCS characteristics.

The NAO, which is a key atmospheric circulation pattern, directly influences the climate over Europe and controls various regional climate dynamics. Although the correlation between the NAO index (during the summer–autumn seasons) and MCS intensity is weak, the index has generally remained low in recent years. This persistent negative phase could still be one of the contributing factors to the increasing MCS intensity in regions influenced by coastal upwelling. It has been highlighted by Lehmann *et al* (2002) how intensified westerly airflow during the NAO's positive phase influences upwelling and downwelling in various Baltic Sea regions. During NAO's positive phase, MCSs are more intense in eastern Baltic Proper, GoR and offshore Gulf of Bothnia (figure 5(c)). Whereas coastal MCSs in the western Baltic Proper, northern GoF and Gulf of Bothnia are generally more intense during the NAO-negative phase (figure 5(d)). Since the NAO index has been predominantly negative in recent years, the mean intensity of MCSs has consequently increased by approximately 1 °C in the western Baltic Proper, northern GoF, and coastal regions of the Gulf of Bothnia (figures 5(d) and (e)). These findings are consistent with those reported by Bednorz *et al* (2019) for the southern Baltic Sea. It is also important to note that several atmospheric patterns such as the NAO, the SCAND pattern, and the EA pattern etc., can influence coastal upwelling and consequently affect MCS intensity. While this study does not explicitly focus on atmospheric drivers, we examined the NAO as a potential contributing factor, given its established influence on upwelling and downwelling dynamics in the region (Lehmann *et al* 2002). Previous research has also shown that the SCAND and EA patterns, in addition to the NAO, impact summer upwelling in the southern Baltic Sea (Bednorz *et al* 2019).

To strengthen the mechanistic interpretation of the increasing coastal MCS intensity, we performed ERA5 composite analyses of 10 m wind and 2 m air-temperature fields for NAO-positive and NAO-negative years (figures 6 and 7). The influence of the NAO on atmospheric circulation over northern Europe and the Baltic Sea is well established. Bednorz *et al* (2019) demonstrated that NAO phases modify the regional pressure gradient and wind regime, thereby controlling the direction and strength of coastal upwelling and downwelling events. During NAO-positive years, a strengthened westerly circulation supports enhanced upwelling along the southeastern Baltic coast, while NAO-negative years feature weaker pressure gradients and a predominance of northeasterly to easterly winds, favoring upwelling along the southwestern Baltic and downwelling along the southeastern coast. These patterns in our ERA5 composites are consistent with the mechanisms outlined by Bednorz *et al* (2019), linking wind-driven circulation shifts to coastal upwelling and downwelling events in the southern Baltic Sea. It should be noted that the NAO index is only one of several atmospheric patterns along with SCAND and EA that have been shown to influence Baltic Sea coastal upwelling and downwelling events.

In addition, the 2 m air-temperature composites reveal pronounced cold anomalies during NAO-negative phases, reflecting the increased frequency of Arctic air intrusions into the Baltic basin. These intrusions are particularly effective over the shallow northern basins, the Gulf of Bothnia and the GoF, where the cold, continental air enhances surface heat loss and intensifies near-shore cooling.

Because NAO-positive and NAO-negative years are not evenly distributed through time, detrended temperature anomalies were used in figure 7 to minimize the influence of long-term warming and better isolate these dynamic atmospheric effects. Collectively, these findings indicate that the observed increase in coastal MCS intensity primarily reflects wind-driven upwelling and air–sea cooling processes (Schlegel *et al* 2021) during the different NAO phases.

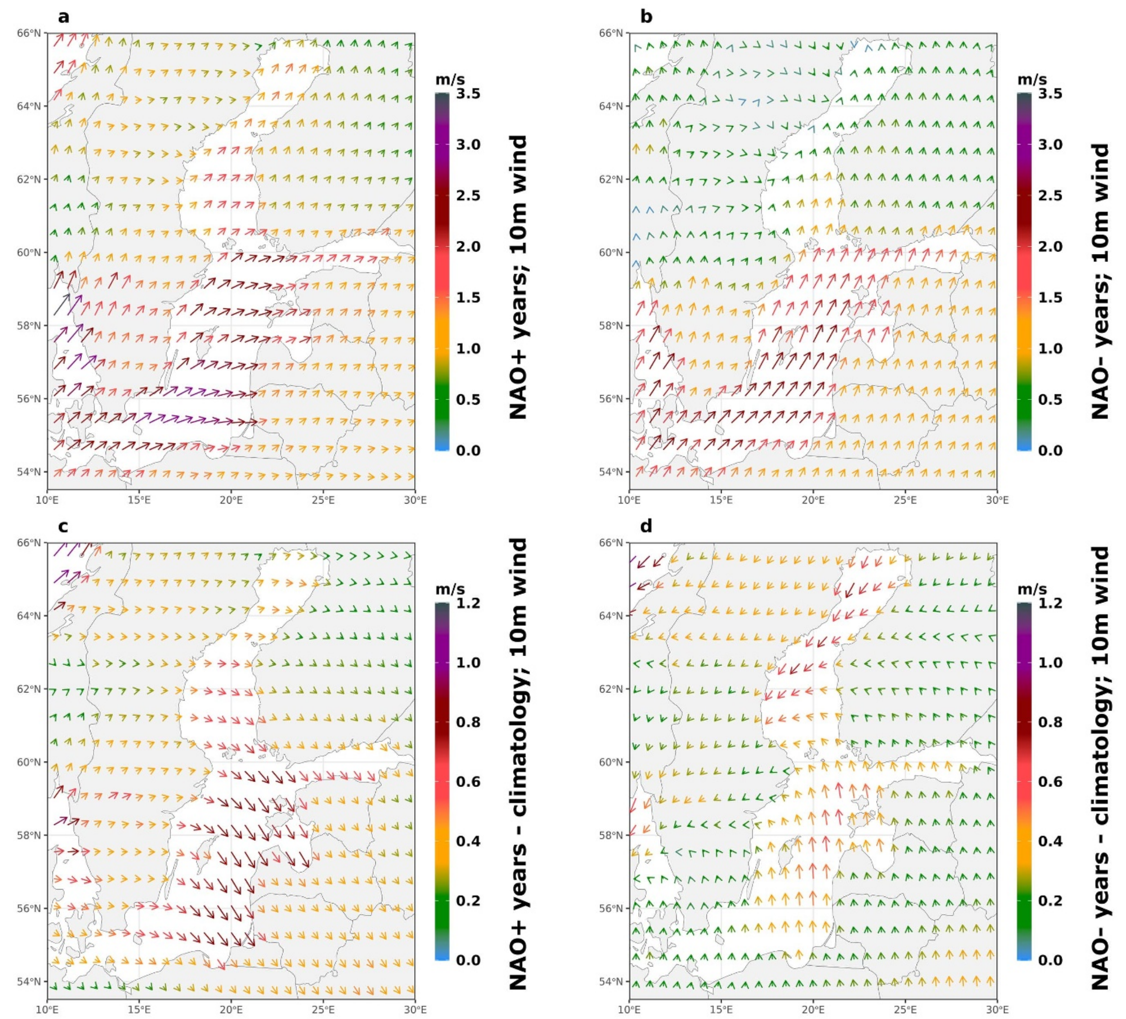

Figure 6. ERA5 10 m wind composite fields for the extended summer–autumn season (June–November). (a) NAO-positive and (b) NAO-negative composite wind vectors (annual means for the summer–autumn season over selected NAO+ and NAO-years). (c) NAO-positive and (d) NAO-negative, corresponding wind anomalies relative to the long-term climatology.

5. Conclusion

Over the 42 year study period (1982–2023), the Baltic Sea experienced approximately 20–45 MCS events, with fewer occurrences in the GoR and GoF. Coastal MCS events were more intense, with mean intensities reaching ≈4 °C, compared to just around ≈3 °C offshore.

The Baltic Sea surface temperature has exhibited a long-term warming trend, increasing by ≈0.05 °C per year during the extended summer–autumn season. This warming is the primary driver of the declining MCS activity, though interannual variability also plays a role.

Spatial trend analysis reveals a significant decrease in all MCS metrics across most regions. The western Baltic Sea shows a pronounced decline in MCS duration, while offshore areas exhibit a significant decrease in mean intensity, reaching up to 0.05 °C per year.

Despite the overall warming trend, high-intensity coastal MCSs have shown increasing intensity, particularly in regions associated with coastal upwelling (0.047 °C per year from 2006 onwards). While this increase is less pronounced overall, it has been statistically significant in recent years due to larger cold SST anomalies during the events. However, in the later study period, the spatial extent of MCSs has decreased, and fewer events have been detected, requiring cautious interpretation of these trends.

In the coastal regions, atmospheric circulation patterns such as the NAO, along with other large-scale patterns like the SCAND and EA patterns, could also contribute to MCS variability, particularly through their influence on coastal upwelling. While this study does not explicitly focus on these drivers, recent NAO behavior may be linked to the observed increase in coastal MCS intensity, and further investigation is needed.

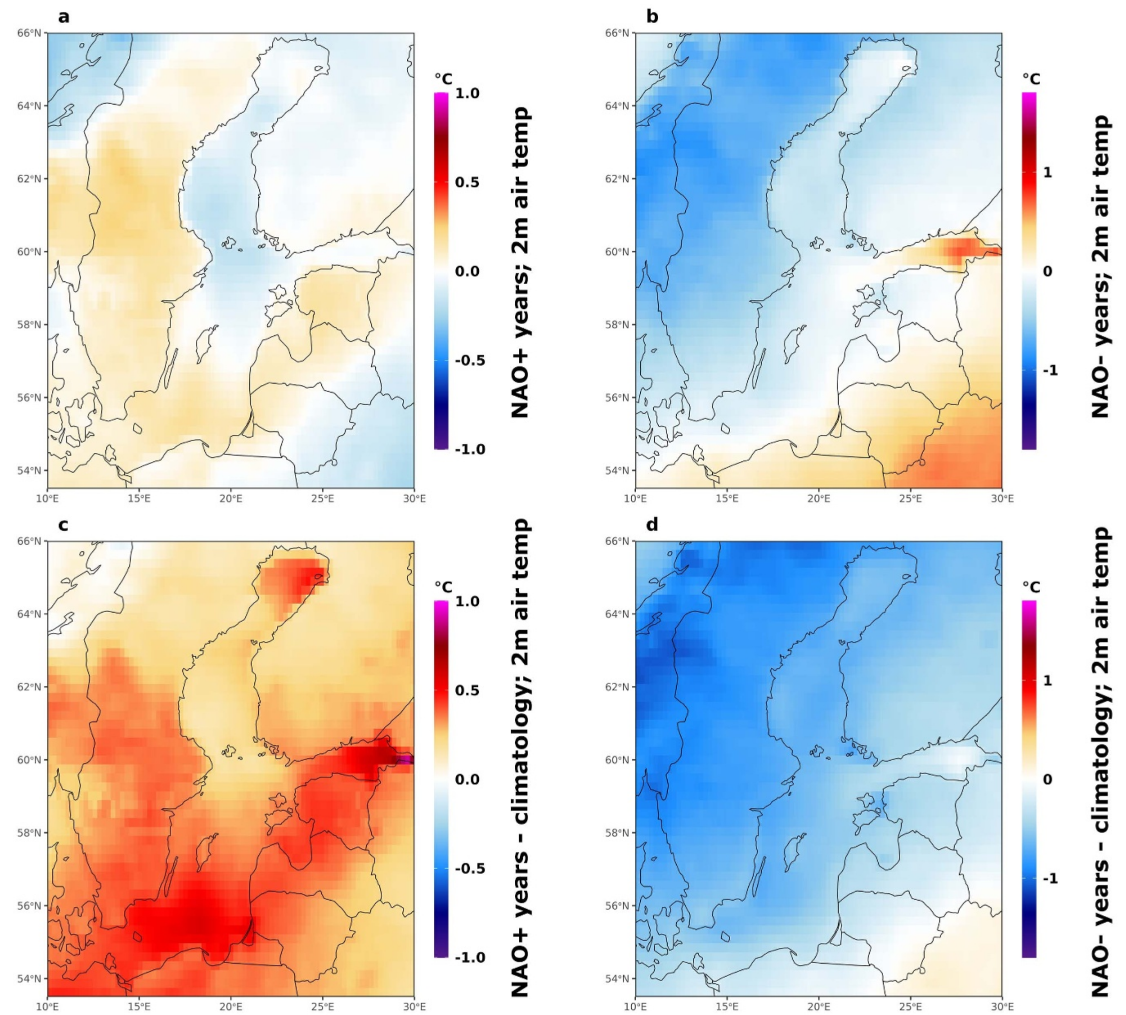

Figure 7. ERA5 2 m air temperature anomaly composites for the extended summer–autumn season (June–November). (a) NAO-positive and (b) NAO-negative composites relative to the climatology (annual mean anomalies from the climatologies for the summer–autumn season over selected NAO+ and NAO− years). (c) NAO-positive and (d) NAO-negative detrended air temperature composites relative to the climatology.

Data availability statement

All datasets used in this study are publicly available from the Copernicus Marine Service, NOAA Climate Prediction Center (CPC), and ERA5 (ECMWF) websites, and the results can be reproduced using the methodology described in the paper.

The data that support the findings of this study are openly available at the following URL/DOI: https://data.marine.copernicus.eu/product/SST_BAL_SST_L4_REP_OBSERVATIONS_010_016/description; www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml; https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels-monthly-means?tab=overview.

Supplementary figures available at http://doi.org/10.1088/2752-5295/ae249b/data1.

Code availability

The codes are available by request via e-mail at shakti.singh@taltech.ee.

Acknowledgments

This work was supported by (1) the European Union and Estonian Research Council via project TEM-TA38 (Digital Twin of Marine Renewable Energy) and (2) AdaptEST project (Implementation of national climate change adaptation activities in Estonia, VEU23019), funded by EU's LIFE programme. The authors are grateful to the Copernicus Marine Service for providing sea surface temperature data, to the National Oceanic and Atmospheric Administration's (NOAA) Climate Prediction Center (CPC) for providing the climate indices used in this study, and to the European Centre for Medium-Range Weather Forecasts (ECMWF) for providing the ERA5 monthly reanalysis data for 2 m air temperature and 10 m wind.

Conflict of interest

The authors declare that they have no conflict of interest.

Author contributions

Shakti Singh 0009-0008-8510-4496
Conceptualization (equal), Methodology (equal), Writing – original draft (lead), Writing – review & editing (equal)

Ilja Maljutenko
Conceptualization (equal), Funding acquisition (equal), Methodology (equal), Supervision (equal), Writing – review & editing (equal)

Rivo Uiboupin 0000-0002-6693-0441
Conceptualization (equal), Funding acquisition (equal), Methodology (equal), Supervision (equal), Writing – review & editing (equal)

Appendix

The spatial distributions of the number of MCS events detected for the summer–autumn (June–November) and winter-spring (December–May) periods are shown in appendix figure A1. To examine the impact of including the colder months, MCS statistics were additionally computed for both the winter-spring and full-year periods (appendix figure A2). These comparisons show that most December–May cold events are concentrated in regions with frequent sea-ice formation and melt, such as Gulf of Bothnia and GoF. The corresponding mean sea-ice-day distribution used for comparison is taken from our earlier Baltic Sea ice analysis (Singh *et al* 2025). The winter-spring detections primarily reflect mixed ice–water anomalies rather than open-water cold spells (Schlegel *et al* 2021).

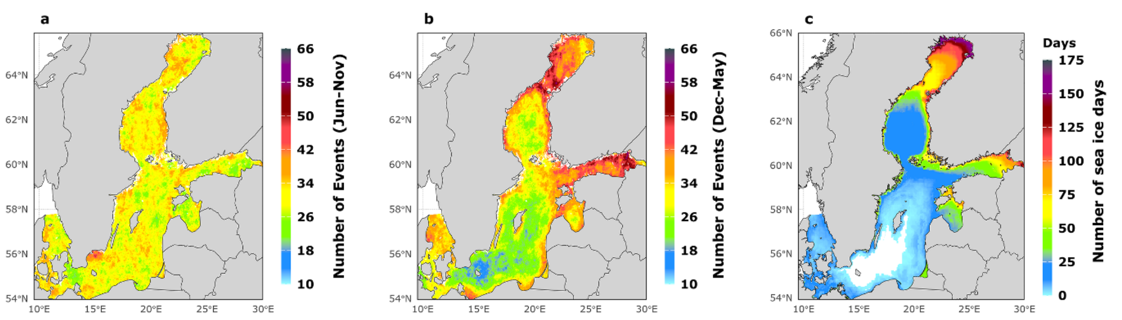

Figure A1. (a) Number of MCS events detected for the extended summer–autumn season (June–November) over 1982–2023, (b) Number of MCS events for the winter-spring season (December–May) over 1982–2023, and (c) mean sea-ice days (from the study Singh *et al* 2025).

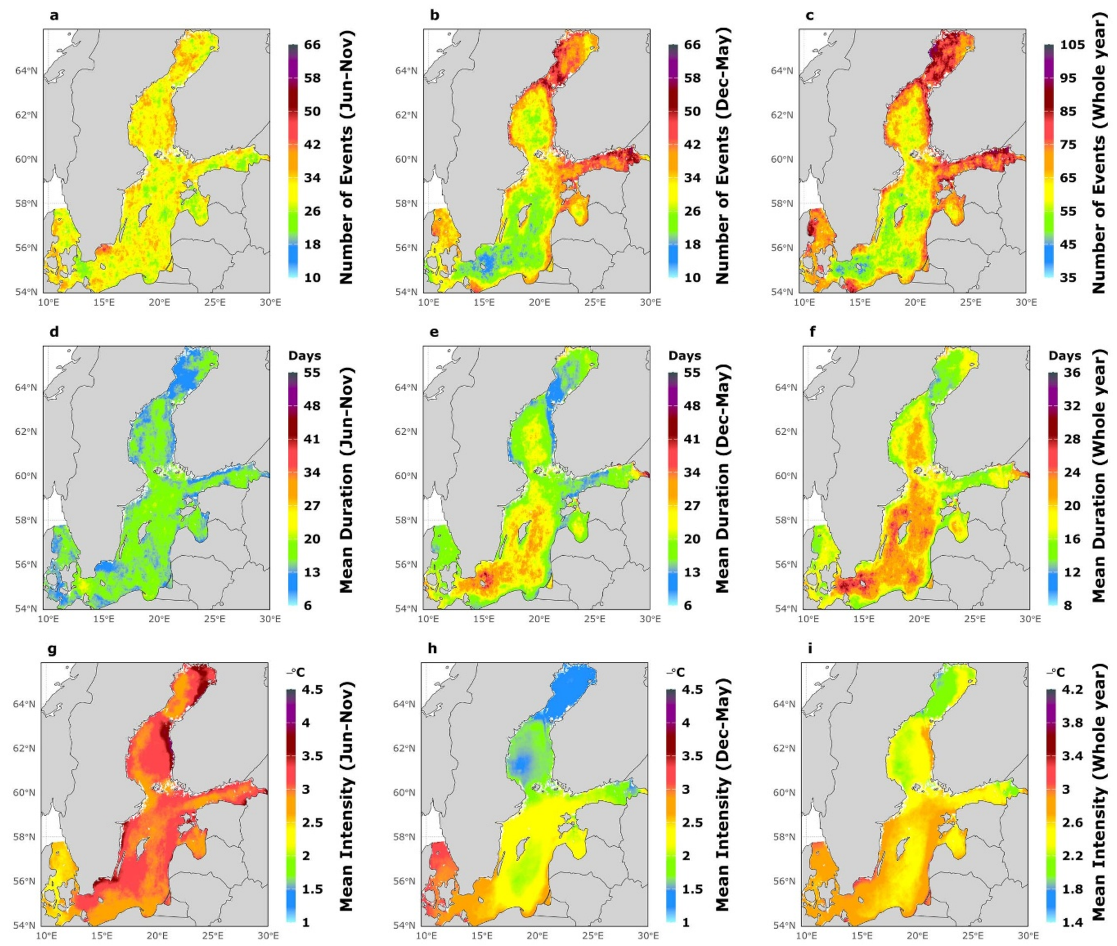

Figure A2. Comparison of MCS statistics computed for (a), (d), (g) summer–autumn (June–November), (b), (e), (h) winter-spring (December–May), and (c,f,i) full-year periods over 1982–2023.

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