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Future projections of compound drought and heatwave events in the eastern part of the Baltic Sea region

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Abstract

Human-induced climate change is contributing to an increase in the frequency of weather extremes. Among these are compound drought and heatwave events (CDHEs), which occur when both phenomena are recorded simultaneously. This study aimed to assess projected changes in the recurrence, duration, and intensity of CDHEs during the warm season (April–September) by the end of the 21st century in the eastern part of the Baltic Sea region. Downscaled projections from five CMIP6 climate models representing the two Shared Socioeconomic Pathways (SSP2–4.5 and SSP5–8.5) scenarios were used for this analysis. Projections of CDHEs were generated for 2081–2100, with 1995–2014 selected as the baseline period. Droughts were identified using the Standardised Precipitation Index (SPI), while heatwaves were defined based on the 90th percentile of maximum air temperature. Although most models foresee an increase in the number of drought days in 2081–2100, the projected changes are mostly not statistically significant. In contrast, the number of heatwave days is expected to increase significantly across the entire study area by the end of the 21st century. As air temperatures rise and heatwaves become more frequent, the recurrence of CDHEs will increase. By the end of the 21st century, an additional 1–5 CDHE days (SSP2–4.5 scenario) and 6–18 days (SSP5–8.5 scenario) per year are projected. The duration and spatial extent of CDHEs will also rise with the magnitude of these changes determined by precipitation patterns.

1. Introduction

Since 1850, global land and ocean surface temperatures have risen 0.06°C per decade, with the rate of warming accelerating to about 0.20°C per decade since 1975 (Lindsey and Dahlman 2025). The rise in global air temperature associated with climate change has increased the frequency and intensity of various extreme weather events, including heatwaves, extreme precipitation, floods, and droughts (AghaKouchak et al. 2020; Di Capua and Rahmstorf 2023; Seneviratne et al. 2021). Until recently, it was common to study these extreme events separately. However, over the past decade, it has been observed that greater damage is caused when several processes, which may not be extreme individually, occur simultaneously (Seneviratne et al., 2012). Such events are called compound climate events. Currently, four types of compound climate events are distinguished (Zscheischler et al. 2020). Multivariate compound events are the most widely studied, representing about 75% of cases (Brett et al. 2025). These events occur when two or more hazards act simultaneously to cause negative impacts (Zscheischler et al. 2020). Multivariate events also include compound drought and heatwave events (CDHEs), which have recently received considerable attention (Brett et al. 2025).

Over the past decade, CDHEs have been widely studied on a global scale (Mukherjee and Mishra 2021; Ridder et al. 2020; Wang et al. 2023), in Europe (Bezak and Mikoš 2020; Ionita et al. 2021; Manning et al. 2019; Sutanto et al. 2020), and in individual countries, such as China (Wang et al. 2024b; Ye et al., 2019; Zhao et al. 2023). The number of such compound climate events has increased, particularly in mid-latitudes, with changes in the Northern Hemisphere greater than in the Southern Hemisphere due to faster temperature increases (Mukherjee and Mishra 2021; Ridder et al. 2020). In Europe, several

hotspots characterised by recurrent CDHE formation have been identified, especially in the southern part of the continent, including Italy and the Balkan Peninsula (Bezak and Mikoš 2020). However, the trend of increasing CDHEs recurrence is observed not only in arid or semi-arid areas, but also in areas with excess moisture (Wang et al. 2024a), such as Northern and Eastern Europe (Bezak and Mikoš 2020; Klimavičius and Rimkus 2024; Wibig and Jędruszkiewicz 2024).

CDHEs are considered among the most damaging climate-related stressors (Yin and Slater 2023). These compound climate events are associated with increased human mortality (Ducros et al. 2025; Rau et al. 2025; Yao et al. 2024) and negative effects on mental health (Sewell et al. 2024). They also negatively affect vegetation and crop yields (Gazol and Camarero 2022; Matusick et al. 2018; Tripathy and Mishra 2023). The concurrent occurrence of drought and extreme heat accelerates the depletion of soil and atmospheric moisture, leading to greater forest drying and increased wildfire risk (Shan et al. 2024). CDHEs also pose problems in the energy sector, as reduced water availability combined with elevated electricity demand can disrupt hydropower generation and raise energy prices (Ducros et al. 2025; Yin and Slater 2023).

Given the observed increases in the frequency and intensity of CDHEs under ongoing climate change and their substantial socio-economic and environmental impacts, growing attention has been paid to future changes in such compound climate events. These projections are crucial for developing climate change adaptation strategies (Rastogi et al. 2024; Yao et al. 2024). Future changes in CDHE characteristics by the end of the 21st century have been assessed in the United States (Rastogi et al. 2024), Australia (Chapman et al. 2025), Europe (Dosio et al. 2023; Felsche et al. 2024; Lhotka et al. 2023; Sedlmeier et al. 2018; Sutanto et al. 2025), China (Liu et al. 2024; Xu et al. 2024; Yao et al. 2024), and other regions. It has been estimated that by the end of the 21st century, 93–95% of the world's population will experience more than double the number of CDHEs compared to the period 1980–2014 (Ridder et al. 2022), with a more substantial negative impact predicted in low-income and rural areas (Yin et al. 2023). This could lead to increased mortality, especially among people over 65 (Yao et al. 2024). Significant attention has also been given to CDHE projections to assess their effects on the economy (Yin and Slater 2023; Zhang et al. 2024), agriculture (Wang et al. 2023), and other sectors.

Although the Baltic Sea region has experienced a more rapid increase in mean air temperature in recent decades compared with Europe and the global average (HELCOM 2024; Kalvāns et al. 2023), future changes in CDHE characteristics in this region have been little studied to date. However, it has been noted that CDHEs, currently observed in Eastern Europe, are likely to spread along much of the Baltic Sea coast in the future (Felsche et al. 2024). Limited attention has been paid to past changes in the recurrence, spatial distribution, and intensity of CDHEs in the region. It has been found that CDHEs have become more frequent and intense in Poland (Wibig and Jędruszkiewicz 2024), and their occurrence has also increased in the eastern part of the Baltic Sea region between 1950 and 2022 (Klimavičius and Rimkus 2024).

The main aim of this study is to assess changes in the recurrence, duration, and intensity of compound drought and heatwave events in the eastern part of the Baltic Sea region through the end of the 21st century using CMIP6 model data. The first part of this article focuses on projected trends in drought recurrence and duration, while the second part discusses changes in the characteristics of heatwaves. The third and final part is devoted to assessing CDHE changes by the end of the 21st century.

2. Data and methodology

2.1. Study area

This study examines CDHEs in the eastern part of the Baltic Sea region, covering the area from 53.5° to 59.5° N and from 20° to 28.5° E (Fig. 1).

The eastern part of the Baltic Sea region is classified as *Dfb* according to the Köppen–Geiger classification (Peel et al. 2007). During the warm season, the study area receives approximately 305–465 mm of precipitation. The wettest months are July and August, with mean monthly totals ranging from 79 to 84 mm. Most precipitation during the warm season falls in the central part of the study area, and the least in the north-western part, while precipitation in the region exceeds evaporation (Meilutytė–Lukauskienė et al. 2024). The maximum daily air temperature in April–September averages 17.8°C, with the highest value occurring in July (22.2°C). The spatial distribution of maximum air temperature in the eastern part of the Baltic Sea region depends on latitude, with higher values observed in the southern part of the study area and lower values in the northern part.

2.2. Data

CDHEs were first determined for the period 1995–2014. This was done using daily precipitation and maximum daily air temperature (t_{max}) data from the Global Meteorological Forcing Dataset (GMFD) for Land Surface Modeling, developed by the Terrestrial Hydrology Research Group at Princeton University (Sheffield et al. 2006). The spatial resolution of the dataset is 0.25° × 0.25°. CDHEs were analysed only in grid cells with more than 50% land area. These compound climate events were investigated during the warm season (April–September).

To assess future changes in CDHE characteristics, daily precipitation and t_{max} data from the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) database were used. This database was compiled using the Bias Correction Spatial Diaggregation (BCSD) method for 35 Coupled Model Intercomparison Project Phase 6 (CMIP6) global circulation models (GCMs) (Thrasher et al. 2022). The BCSD approach incorporates GMFD data and assumes that relative spatial patterns identified during the historical reference period remain consistent under future climate conditions, thereby preserving information on extremes. The NEX-GDDP-CMIP6 dataset was selected due to its relatively high spatial and temporal resolution, which is suitable for regional studies (Thrasher et al. 2022).

NASA NEX-GDDP-CMIP6 data have been widely used to study precipitation and air temperature extremes (Baogang et al. 2024; Chervenkov and Malcheva 2023; Jiang et al. 2023) and to make projections of CDHE characteristics throughout the 21st century (Wen et al. 2024; Xu et al. 2024; Zhang et al. 2024). The results obtained are in good agreement with data from various reanalyses, supporting the suitability of the NASA NEX-GDDP-CMIP6 dataset for assessing such compound climate events (Wen et al. 2024; Xu et al. 2024).

Five CMIP6 global climate models (GCMs) were selected for this study: CanESM5, ACCESS-CM2, GFDL-CM4, MPI-ESM1-2-LR, and NorESM2-MM (Table 1). The models were intentionally selected to represent a wide range of Equilibrium Climate Sensitivity (ECS) values, a metric describing the increase in global mean surface temperature following a doubling of atmospheric CO_2 concentrations relative to pre-industrial levels (Meehl et al. 2020). This selection captures differences in model sensitivity to greenhouse gas forcing. Selected models have also been applied in other regional CDHE studies (Chapman et al. 2025; Niu et al. 2024; Sutanto et al. 2025; Yang et al. 2024).

Table 1
CMIP6 models used in the study and their Equilibrium Climate Sensitivity (ECS) values (°C) (Meehl et al. 2020).

Model name	**Modelling center**	**ECS (°C)**
CanESM5	Canadian Centre for Climate Modelling and Analysis	5.6
ACCESS-CM2	CSIRO-BOM	4.7
GFDL-CM4	Geophysical Fluid Dynamics Laboratory of the National Oceanic and Atmospheric Administration	3.9
MPI-ESM1-2-LR	Max Planck Institute for Meteorology	3.0
NorESM2-MM	Norwegian Climate Center	2.5

This study uses projections from two Shared Socioeconomic Pathways (SSP) scenarios: SSP2–4.5 and SSP5–8.5. The SSP2–4.5 scenario represents a "medium" trajectory, in which CO_2 levels stabilize and gradually decrease, leading to an estimated global mean surface air temperature increase of about 2.1–3.5°C by the end of the 21st century relative to 1850–1900 (Chen et al. 2021; IPCC 2021). Currently, models predict temperature rises of 1.9–3.7°C by 2100, making SSP2–4.5 a credible pathway (Hausfather, 2025). Meanwhile, SSP5–8.5 represents a high-emissions scenario with limited mitigation efforts, resulting in a projected global temperature increase of 3.3–5.7°C by the end of the 21st century relative to the pre-industrial period (Chen et al. 2021; IPCC 2021).

Future changes in CDHE characteristics were assessed from 2081 to 2100, with 1995–2014 as the baseline period. These 20-year periods were used in the IPCC AR6 report and are long enough to capture robust climate signals while remaining short enough to evaluate temporal differences within the 21st

century (Chen et al. 2021). In addition, these periods have also been used in other CDHE studies (Chapman et al. 2025; Feng et al. 2023; Wang et al. 2023).

2.3. Identification and assessment of droughts, heatwaves, and CDHEs

To identify CDHEs in the study area and assess their future changes, droughts were identified using the Standardised Precipitation Index (SPI), developed by McKee et al. (1993). The SPI uses a single input parameter (precipitation) and is widely applied for the identification of meteorological drought (Svoboda et al. 2012). It has also been used in various drought studies across Eastern and Northern Europe (Kalbarczyk and Kalbarczyk 2022; Łabędzki and Bąk 2015; Rimkus et al. 2020; Wałęga et al. 2024). In this study, daily SPI values at each grid point in the study area were calculated from precipitation sums over the previous 30 days. This index was calculated using the SPEI package in the R programming language (Beguería and Vicente-Serrano 2023). A drought at a particular grid point was identified when SPI values were below − 1 for at least five consecutive days. The SPI threshold of − 1 is widely used in other CDHE studies as well (Chapman et al. 2025; de Luca and Donat 2023; Dosio et al. 2023; Wang et al. 2024a).

Heatwave days were identified using a percentile-based approach. The 90th percentile of t_{max} was calculated separately for each grid cell using all warm season (April–September) values from the baseline period (1995–2014). The percentile values were derived individually for each model. The calculated 90th percentile values showed a clear spatial pattern with the highest values obtained in the southeastern part of the study area (27.8–28.2°C) and the lowest in the northwestern part (21.6–22.2°C). A heatwave was identified in a particular grid cell when t_{max} exceeded the 90th percentile threshold for at least five consecutive days. The percentile-based method is widely applied in various studies to identify heatwaves due to its flexibility across regions and seasons (Perkins 2015). Different percentile thresholds are used, but the 90th percentile is among the most widely adopted for both standalone heatwave analyses and CDHE assessments at global (Bevacqua et al. 2022; Yin et al. 2023) and European (Bezak and Mikoš 2020; Sutanto et al. 2020; Wibig and Jędruszkiewicz 2024) scales. Finally, the 90th percentile threshold ensures sufficient data for adequate statistical analysis.

A CDHE was identified when drought and a heatwave occurred simultaneously. Changes in the recurrence of drought, heatwave, and CDHE days at the end of the 21st century were assessed relative to the 1995–2014 baseline period. The statistical significance of changes in drought and heatwave days was evaluated using a Student's t-test ($p < 0.05$). Meanwhile, for CDHE days, the Mann–Whitney–Wilcoxon test ($p < 0.05$) was applied. This test was used because CDHEs occur considerably less frequently than droughts or heatwaves, leading to sparse annual observations at individual grid cells.

Periods of droughts, heatwaves, and CDHE were also identified. Events were identified when the phenomenon covered at least one-third of the study area at its maximum extent. The start date of a drought, heatwave, or CDHE was defined as the day when the phenomenon was recorded in more than a

tenth of the study area, and the end date was identified as the day when this condition was no longer met for at least three consecutive days.

To evaluate changes in the duration of droughts and heatwaves, the ten longest events for each model SSP2–4.5 and SSP5–8.5 scenario for the period 2081–2100 were selected. In terms of intensity, the ten most severe droughts or heatwaves were chosen based on the SPI and t_{max} deviation from the 90th percentile value, respectively. The results were compared with the values of these characteristics obtained for the period 1995–2014 using GMFD data. Finally, the duration of each CDHE and the percentage of the study area covered at its maximum extent were determined, and projected changes in these characteristics were assessed.

3. Results

3.1. Droughts

Most of the CMIP6 models used in this study predict an increase in the number of drought days in the eastern part of the Baltic Sea region by the end of the 21st century (Fig. 2). Under the SSP2–4.5 scenario, the ACCESS-CM2, MPI-ESM1-2-LR, and NorESM2-MM models indicate an average increase of 5–12 drought days per year compared to the 1995–2014 period. Depending on the model, the changes are statistically significant in up to 34% of grid cells (Fig. 2b–e). Under the SSP5–8.5 scenario, four models project an increase in drought days, with an average rise of 10–25 days per year by 2081–2100 compared with the baseline period (Fig. 2g–j).

The largest and statistically significant change in the number of drought days is predicted by the NorESM2-MM model, which has the lowest ECS value (Fig. 2e, j). In contrast, the CanESM5 model, which has the highest ECS value, projects a decrease in drought days across almost the entire study area. According to this model data, the number of drought days in 2081–2100 is expected to decline by an average of 13 days per year under the SSP2–4.5 scenario and by 6 days per year under the SSP5–8.5 scenario (Fig. 2a, f). Such a pattern is primarily associated with the substantial increase in precipitation projected by this model. According to CanESM5 simulations, precipitation is projected to increase by an average of 42 mm under SSP2–4.5 and 72 mm under SSP5–8.5 compared with the baseline period.

Despite the projected increase in the number of drought days by the end of the 21st century, no significant change in their duration is expected (Fig. 3a). During the baseline period, the longest drought event lasted 75 days, with an average duration of 47 days. In the future, the longest droughts are projected by the ACCESS-CM2 model (Fig. 3a). However, even in this case, the difference is not significant – the average duration of droughts is expected to be 54 days (SSP2–4.5 scenario) and 58 days (SSP5–8.5 scenario).

According to most model projections, droughts will become more severe by the end of the 21st century. In 2081–2100, the 3-day averages of SPI median values of the ten most severe droughts are expected to range from − 2.26 to − 2.47 under the SSP2–4.5 scenario and from − 2.40 to − 2.95 under the SSP5–8.5

scenario. During the baseline period, this value was − 2.21. As with the assessment of changes in the number and duration of drought days, only the CanESM5 model shows opposite trends for the SSP2–4.5 scenario (Fig. 3b).

3.2. Heatwaves

By the end of the 21st century, a substantial increase in the number of heatwave days is expected in the eastern part of the Baltic Sea region. According to the projections of both SSP scenarios and all models, the number of such days will rise across the entire study area (Fig. 4). Under SSP2–4.5, heatwave days increase by 23–44 days per year in 2081–2100 relative to 1995–2014. While under the SSP5–8.5 scenario, the changes are considerably larger, averaging 28–84 days per year. In nearly all cases, these changes are statistically significant ($p < 0.05$) across almost all grid cells. The largest changes are expected when using data from the CanESM5 and ACCESS-CM2 models (Fig. 4a, b, f, g).

Heatwaves are projected to increase not only in frequency but also in duration and intensity. Based on GMFD data, the ten longest heatwaves during the baseline period (1995–2014) had an average duration of 17 days. In contrast, during 2081–2100, the mean duration of the longest heatwaves is projected to reach 26–56 days under SSP2–4.5 and 58–112 days under SSP5–8.5, depending on the model (Fig. 5a).

The 3-day average of median t_{max} deviations from the 90th percentile threshold is also projected to increase significantly by the end of the 21st century. During the baseline period, the mean value of this indicator was 2.4°C, while in 2081–2100 it will increase to 6.3–10.2°C (SSP2–4.5 scenario) and 9.3–14.7°C (SSP5–8.5 scenario). The most intense heatwaves are predicted by the CanESM5 and ACCESS-CM2 models (Fig. 5b), which have the highest ECS values and therefore project stronger warming signals. For both droughts and heatwaves, more pronounced changes in duration and intensity are obtained using the SSP5–8.5 scenario.

3.3. Compound drought and heatwave events (CDHEs)

CDHEs were initially evaluated for each grid cell across the study area. Across models and emission scenarios, a rise in the number of CDHE days is expected in 86–100% of grid cells by 2081–2100 (Fig. 6).

Under the SSP2–4.5 scenario, the number of CDHE days in 2081–2100 is projected to increase by 1–5 days per year on average relative to 1995–2014 (Fig. 6a–e), while under SSP5–8.5 this change may reach 6–18 days per year (Fig. 6f–j). For SSP5–8.5, the projected rise in CDHE days is statistically significant ($p < 0.05$) across almost the entire eastern part of the Baltic Sea region (Fig. 6f–j). The greatest changes are predicted by the ACCESS-CM2 and NorESM2-MM models. This pattern reflects the fact that NorESM2-MM projects the largest increase in drought days, whereas ACCESS-CM2 simulates the strongest rise in heatwave days.

Between 1995 and 2014, four CDHEs that at their maximum extent covered more than one-third of the study area, were identified in the eastern part of the Baltic Sea region: 17–23 August 1996, 1–8 August

1999, 24–31 August 2002, and 3–13 July 2006. From 2015 to 2100, the number of these compound climate events in the study area is projected to increase. This trend is particularly pronounced at the end of the century. For the period 2081–2100, the CanESM5 and GFDL-CM4 models predict 2 and 4 CDHEs, respectively, under the SSP2–4.5 scenario (Fig. 7a, c). However, the remaining models project 11–19 events during these twenty years (Fig. 7b, d, e). Even higher recurrence of CDHEs is predicted under the SSP5–8.5 scenario, with 13–29 CDHEs expected during 2081–2100, depending on the model (Fig. 7f–j).

In addition to increased frequency, CDHE duration is projected to lengthen. During the baseline period, CDHEs lasted an average of 9 days. By the end of the 21st century, the duration of these compound climate events is expected to increase to 10–20 days under the SSP2–4.5 scenario and to 15–33 days under the SSP5–8.5 scenario. The spatial extent of CDHEs is also projected to expand. While CDHEs covered, on average, 58% of the study area at their maximum extent during 1995–2014, this proportion is expected to rise to 59–71% (SSP2–4.5 scenario) and to 58–77% (SSP5–8.5 scenario) in 2081–2100. An analysis indicates a seasonal shift in CDHE occurrence, with events increasingly concentrated in the second half of the warm period of the year. By 2081–2100, depending on the model and scenario, approximately 33.3–79.4% of CDHEs are projected to occur during August–September (Fig. 7).

4. Discussion

By the end of the 21st century, the number of drought days in the eastern part of the Baltic Sea region is projected to increase by most models used relative to 1995–2014. However, in most cases, changes are minor and not statistically significant. Since droughts were identified in the study using the SPI, which is based solely on precipitation, projected changes in drought occurrence are closely linked to simulated precipitation trends. Similar to this study, drought recurrence projections for Eastern and Northern Europe are characterised by high uncertainty and limited robustness (Seneviratne et al. 2021). In Poland, droughts are expected to become less frequent by the mid-21st century, but their number will increase during 2071–2100 (Ghazi et al. 2025; Rutkowska et al. 2025). More frequent droughts are also projected south of 59° N in the Baltic Sea region (Rutgersson et al. 2022). During summer in 2081–2100, a similar trend is projected in the Nemunas River basin, particularly in its southern and central parts (Stonevičius et al. 2018).

Drought intensity is projected to increase in the eastern part of the Baltic Sea region, although the changes are minor. An intensification of droughts is also predicted in Poland (Ghazi et al. 2025) and in most of Europe (Spinoni et al. 2018; Vicente-Serrano et al. 2022). More pronounced changes are expected under the high-emission SSP5–8.5 scenario, indicating that climate change will affect precipitation and, consequently, the formation of droughts. With a global temperature increase of 3°C, the area affected by droughts in Europe is projected to increase by 40% by the end of the century, exposing 42% more of the population (Samaniego et al. 2018).

Rising air temperatures are expected to increase the frequency of heatwaves across many regions, with the greatest change in intensity projected in mid-latitudes and semi-arid regions (Seneviratne et al.

2021). It is predicted that without effective adaptation and mitigation measures, the impacts of heatwaves in Europe could increase nearly fivefold by 2060 relative to 1981–2010 (García-León et al. 2021). Although southern Europe is expected to remain the hotspot for this phenomenon in Europe (Sutanto et al. 2025), more frequent and intense heatwaves are also projected for Central and Eastern Europe by the end of the century (Lau and Nath 2014; Lhotka et al. 2018).

The number of heatwave days will also increase in the eastern part of the Baltic Sea region. Such a tendency is expected at the end of the 21st century according to the projections of all models used in the study. Heatwave duration and intensity are likewise projected to increase markedly. A rapid increase in heat extremes is also expected in other parts of the Baltic Sea region (Rutgersson et al. 2022), and events that previously occurred once every 20 years may recur every five years by the end of the century (HELCOM, 2024). Additionally, heatwave days are predicted to be more common in major Lithuanian cities (Ramanauskas et al. 2024), while in Poland, the number of these extremes is found to double or even triple by the end of the 21st century compared to 1971–2000 (Jędruszkiewicz and Wibig 2019). However, it should be emphasised that the heatwaves analysed in this study were assessed using a 90th percentile of t_{max} calculated for 1995–2014. In the context of a changing climate and rising air temperatures, these 90th percentile thresholds are likely to represent typical conditions in the future and may no longer be considered extreme.

An increase in CDHE duration and intensity is expected in the study area throughout the 21st century. The projected changes are particularly pronounced under SSP5–8.5. An increase in the number and intensity of CDHEs is predicted in other regions, including the United States (Rastogi et al. 2024), Australia (Chapman et al. 2025), and China (Feng et al. 2023; Liu et al. 2024; Zhang et al. 2024). In Europe, even under a low-emission scenario, the area affected by these compound climate events is projected to increase by 60% (Dosio et al. 2023). The intensification of CDHEs is primarily attributed to rising air temperature (Manning et al. 2019) and increasing heatwave frequency (Dosio et al. 2023). A 1°C increase in global air temperature is expected to lengthen CDHEs by ten days between 2020 and 2100 (Zhang et al. 2022). However, heatwaves may become so frequent and prolonged that almost all droughts occurring by the end of the 21st century will coincide with this phenomenon (Bevacqua et al. 2022). This tendency was also observed in our study: a larger projected increase in the number of CDHE days occurred in areas where the number of drought days is expected to increase the most.

Several sources of uncertainty must be considered when interpreting projections of droughts, heatwaves, and CDHEs. The recurrence of CDHEs is highly dependent on the index chosen to identify droughts (de Luca and Donat 2023; Rastogi et al. 2024). Droughts are often distinguished using the Standardised Precipitation Evapotranspiration Index (SPEI). This index considers not only precipitation, as in the case of SPI, but also air temperature and potential evapotranspiration. Therefore, using SPEI leads to a larger increase in the number of CDHE days (Chapman et al. 2025; Rastogi et al. 2024). However, SPI is better suited for determining meteorological droughts and is more appropriate for use in areas where precipitation is the main factor limiting drought occurrence (Wang et al. 2025). In Lithuania,

summer soil moisture variability is more strongly controlled by precipitation than by temperature (Rimkus et al. 2020), so SPI is suitable for identifying droughts in the region.

Future CDHE formation will also depend on changes in atmospheric circulation. In Europe, CDHEs are commonly associated with persistent high-pressure systems that weaken zonal flow, shift storm tracks southward, suppress upper-level circulation, and reduce moisture transport and precipitation (Ionita et al. 2021). In Poland, heatwaves and droughts are linked to blocking anticyclones and an elongated ridge extending from the Azores High (Jędruszkiewicz et al. 2024; Wałęga et al. 2024). Additionally, it has been observed that heatwaves in Western Europe and the Baltic countries are caused by the formation of a double jet stream (Rousi et al. 2022).

Uncertainties also arise from model selection and the number of models (Lhotka et al. 2023). The models used in this study reflect different parts of the ECS spectrum, but they do not necessarily represent the entire range of future climate variability (Ghazi et al. 2025). The magnitude of future CDHE changes also depends on the choice and duration of the baseline period (Ghazi et al., 2025). Finally, the NASA NEX-GDDP-CMIP6 database, used in this study, also has shortcomings. GMFD data were used both to compile the dataset and to correct biases in GCM outputs (Thrasher et al. 2022). However, this database is no longer updated and is therefore used less frequently in recent studies. Additionally, GMFD was created solely by combining data from meteorological stations. Consequently, data accuracy depends on station density (Hogan and Schlenker 2024). Uncertainties may also arise from model spatial resolution (Ghazi et al., 2025). Despite the relatively small size of the NASA NEX-GDDP-CMIP6 data grid (~ 28 km), warm-season precipitation can exhibit strong local variability. Despite these limitations, the results of this study consistently indicate that climate change will likely lead to more frequent, longer-lasting, and more spatially extensive CDHEs in the eastern part of the Baltic Sea region, underscoring the need for adaptation measures to reduce the negative impact of these phenomena.

5. Conclusions

This study used data from five CMIP6 models and SSP2–4.5 and SSP5–8.5 climate scenarios to assess changes in drought, heatwave, and CDHE characteristics in the eastern part of the Baltic Sea region during the warm season (April–September). Most models indicate that the number of drought days in 2081–2100 will increase relative to the 1995–2014 baseline period. However, the model projections show substantial variability, with relatively minor changes in most projections. Meanwhile, the number of heatwave days in the eastern part of the Baltic Sea region will increase under projections from all models and both SSP scenarios. Under the SSP2–4.5 scenario, the increase in such days at the end of the century is expected to average 23–44 days per year, whereas under the SSP5–8.5 scenario, it ranges from 28 to 84 days per year. In addition, all models project increases in heatwave duration and intensity in 2081–2100. The greatest changes in heatwave characteristics are projected using data from the CanESM5 and ACCESS-CM2 models, which have the highest ECS values.

The number of days with CDHEs is also projected to increase in the study area. Compared with the baseline period, approximately 1–5 (SSP2–4.5) or 6–18 (SSP5–8.5) additional CDHE days per year are expected for 2081–2100. Additionally, the duration of CDHEs and the maximum spatial extent of these events within the study area are projected to increase. The simulated intensification of CDHEs is primarily driven by rising air temperature and the increasing recurrence of heatwaves. However, the magnitude of these changes will largely depend on precipitation patterns. As a result, the largest increases in CDHE recurrence, duration, and maximum spatial extent are projected by the ACCESS-CM2 and NorESM2-MM models, which forecast the most rapid decline in precipitation during the warm season.

This study provides the first comprehensive future projections of CDHEs for the eastern part of the Baltic Sea region. These findings are important for improving climate change adaptation strategies and reducing the adverse impacts of compound climate events on human health, agriculture, the economy, and other vulnerable sectors.

Declarations

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

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Author Contribution

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by L. K. and E. R. The first draft of the manuscript was written by L. K. and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability

The downscaled CMIP6 models' projections from the NASA NEX-GDDP-CMIP6 database can be accessed on https:/www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp-cmip6 Global Meteorological Forcing Dataset (GMFD) is available at https://hydrology.soton.ac.uk/data/pgf/

The datasets generated during this study are available from the corresponding author upon reasonable request.

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Figures

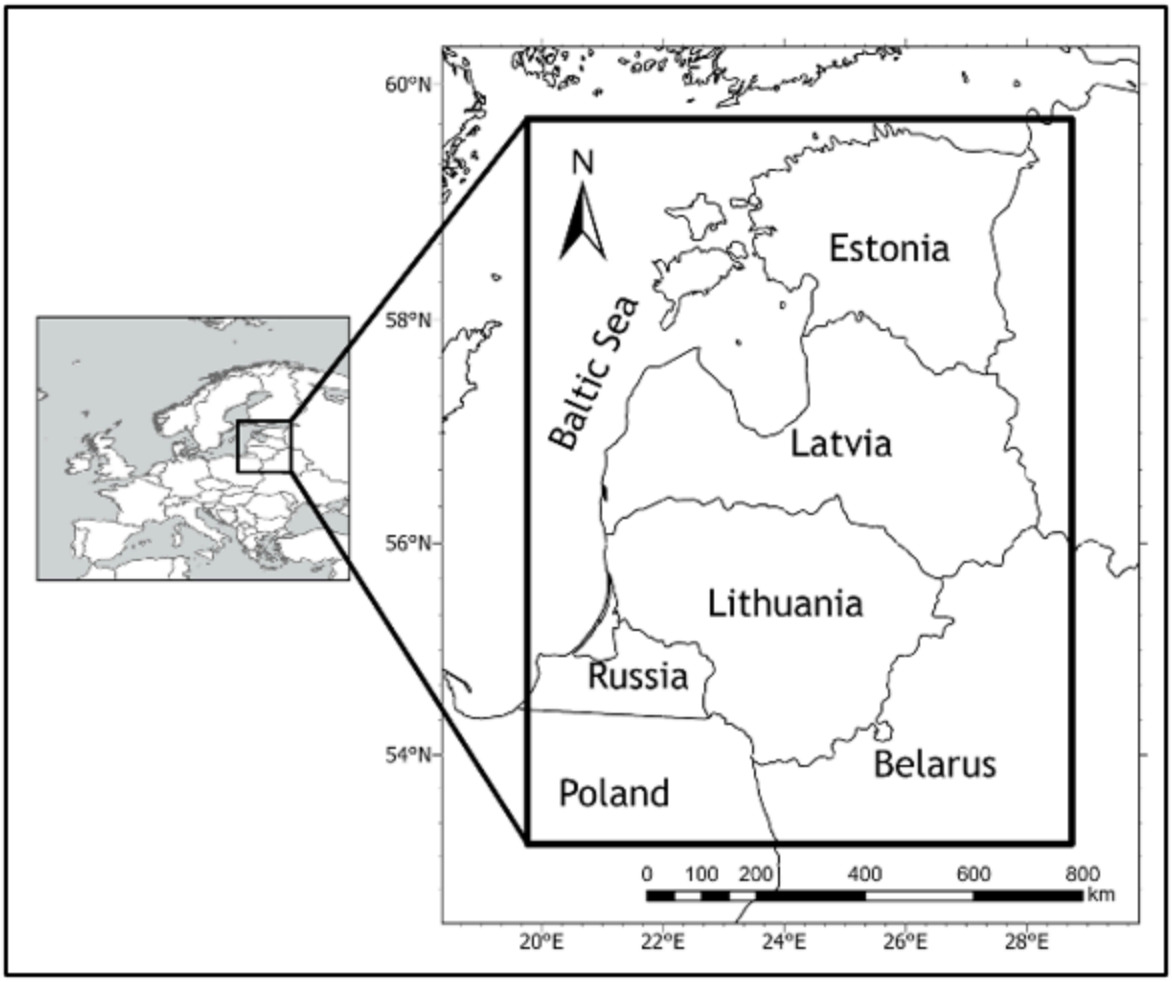


Figure 1

Study area

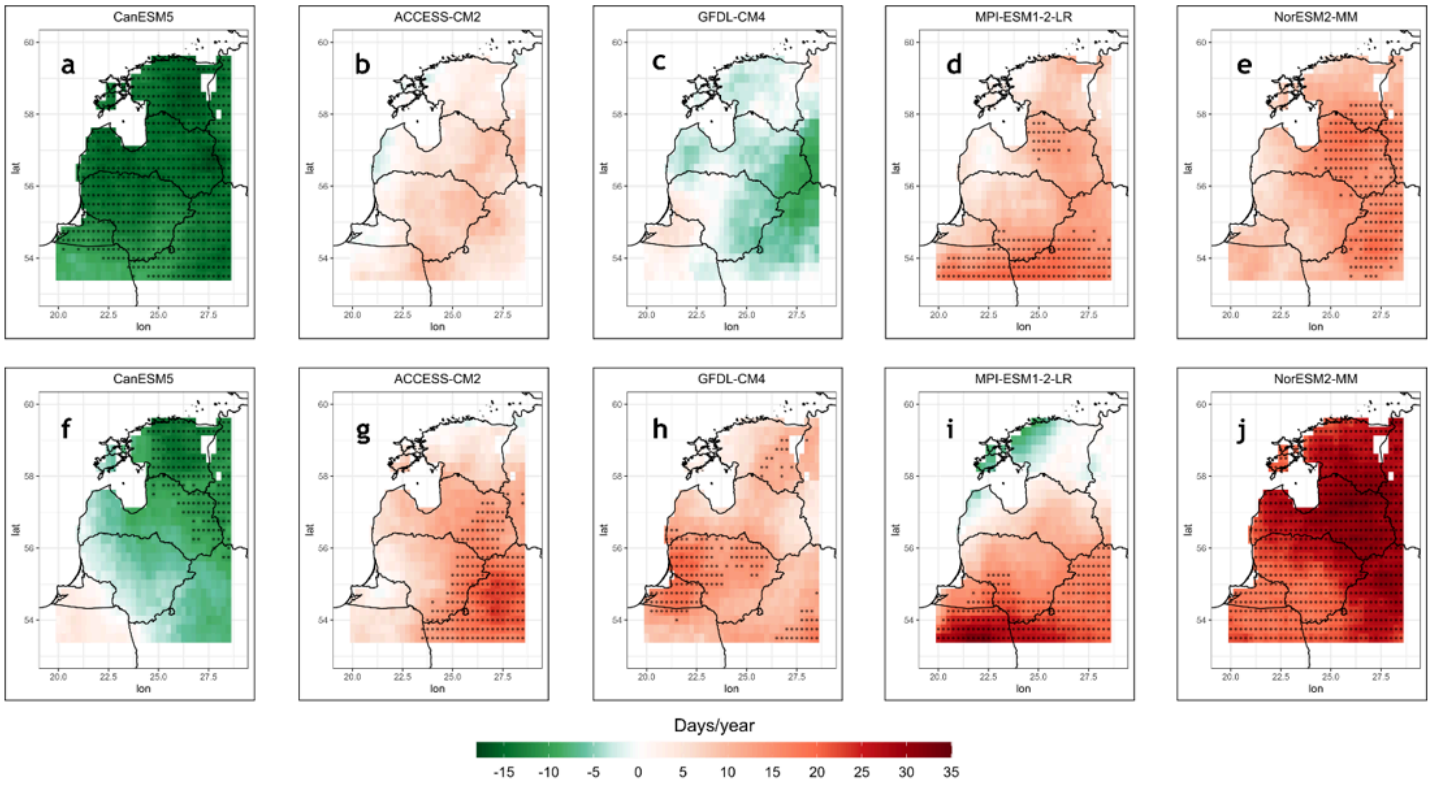


Figure 2

Change in the number of drought days at each point in the study area according to the data from five different CMIP6 models for the SSP2–4.5 (a–e) and SSP5–8.5 (f–j) scenarios, determined by comparing 2081–2100 with the baseline period of 1995–2014. The dots mark grid cells where the changes are statistically significant according to the Student's t-test ($p < 0.05$)

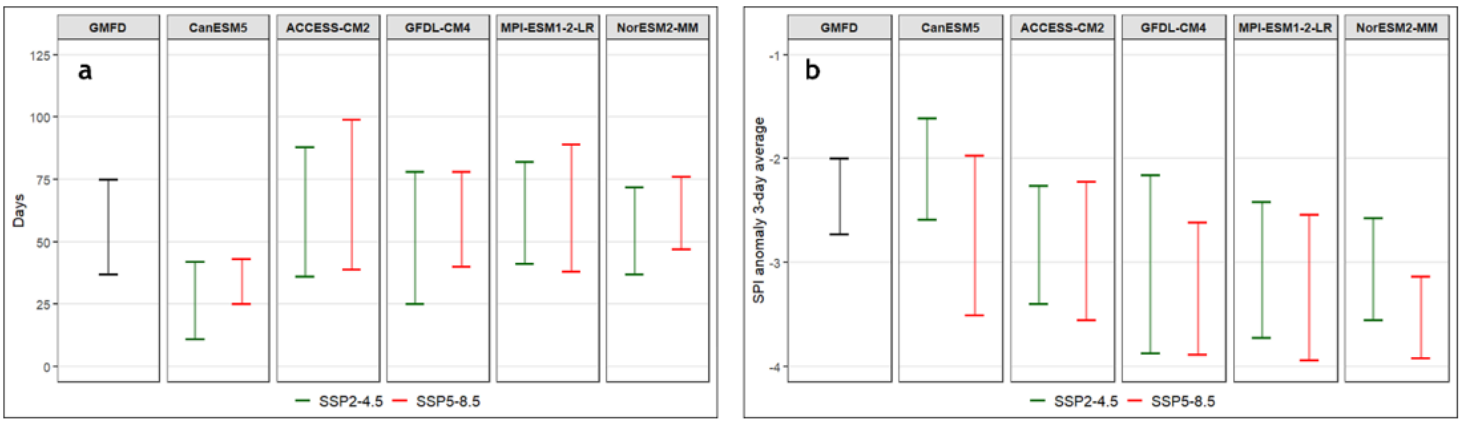


Figure 3

Amplitude of the ten longest drought durations (a) and the 3-day average of the SPI median values of the ten strongest droughts (b) obtained for the period 1995–2014 (GMFD) and 2081–2100 (based on data from five different CMIP6 models and two climate scenarios)

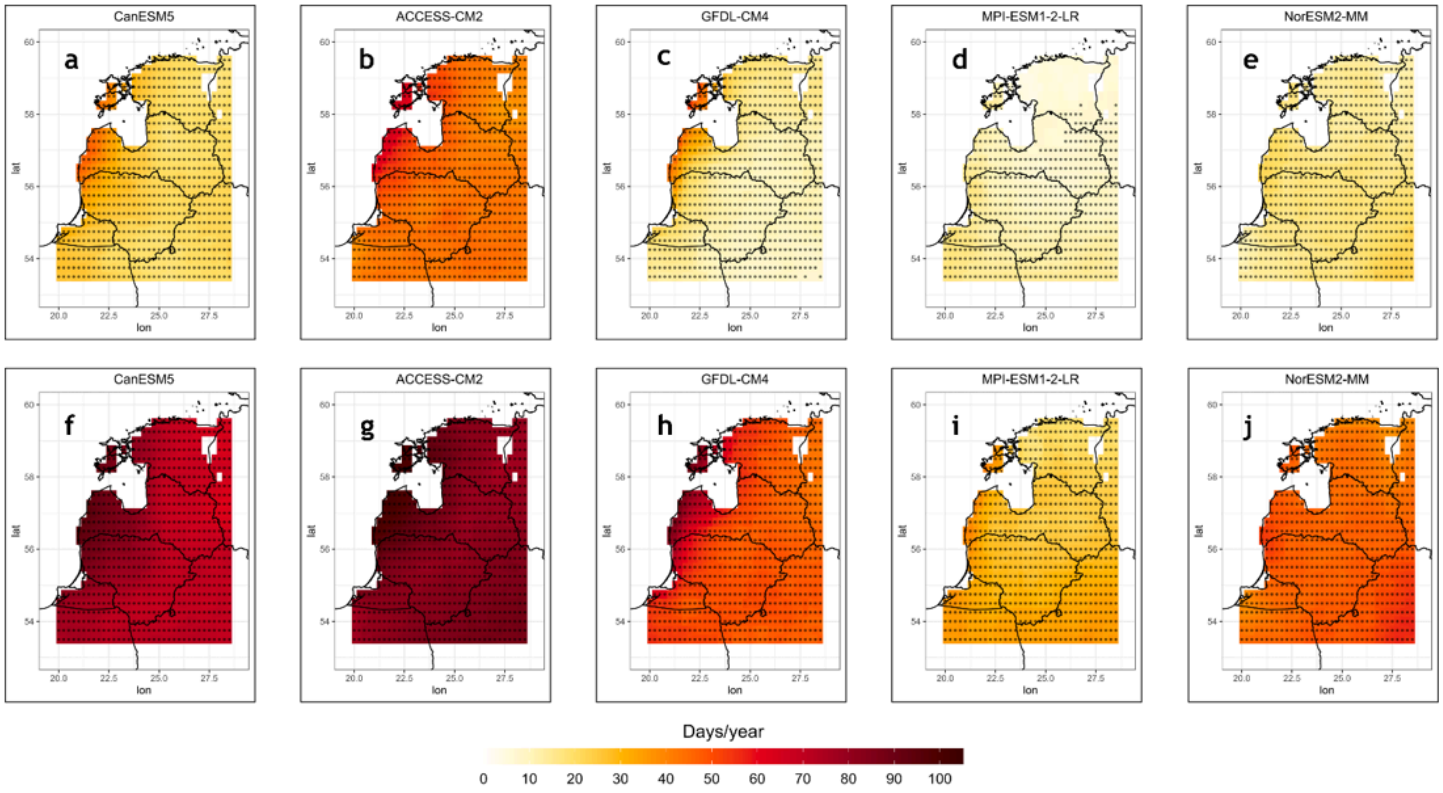


Figure 4

Change in the number of heatwave days at each grid cell in the study area according to the data from five different CMIP6 models for the SSP2–4.5 (a–e) and SSP5–8.5 (f–j) scenarios, determined by comparing 2081–2100 with the baseline period of 1995–2014. The dots mark grid cells where the changes are statistically significant according to the Student's t-test ($p < 0.05$)

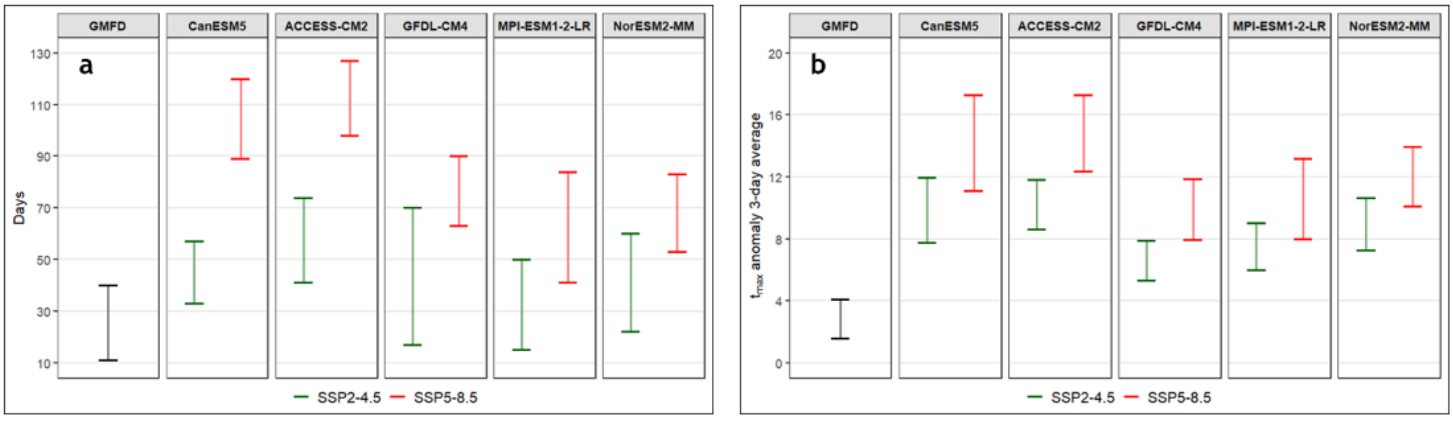


Figure 5

Amplitude of the ten longest heatwave durations (a) and the 3-day average of median values of t_{max} deviation from the 90th percentile value of the ten strongest heatwaves (b), obtained from 1995 to 2014 (GMFD) and 2081–2100 (based on data from five different CMIP6 models and two SSP scenarios)

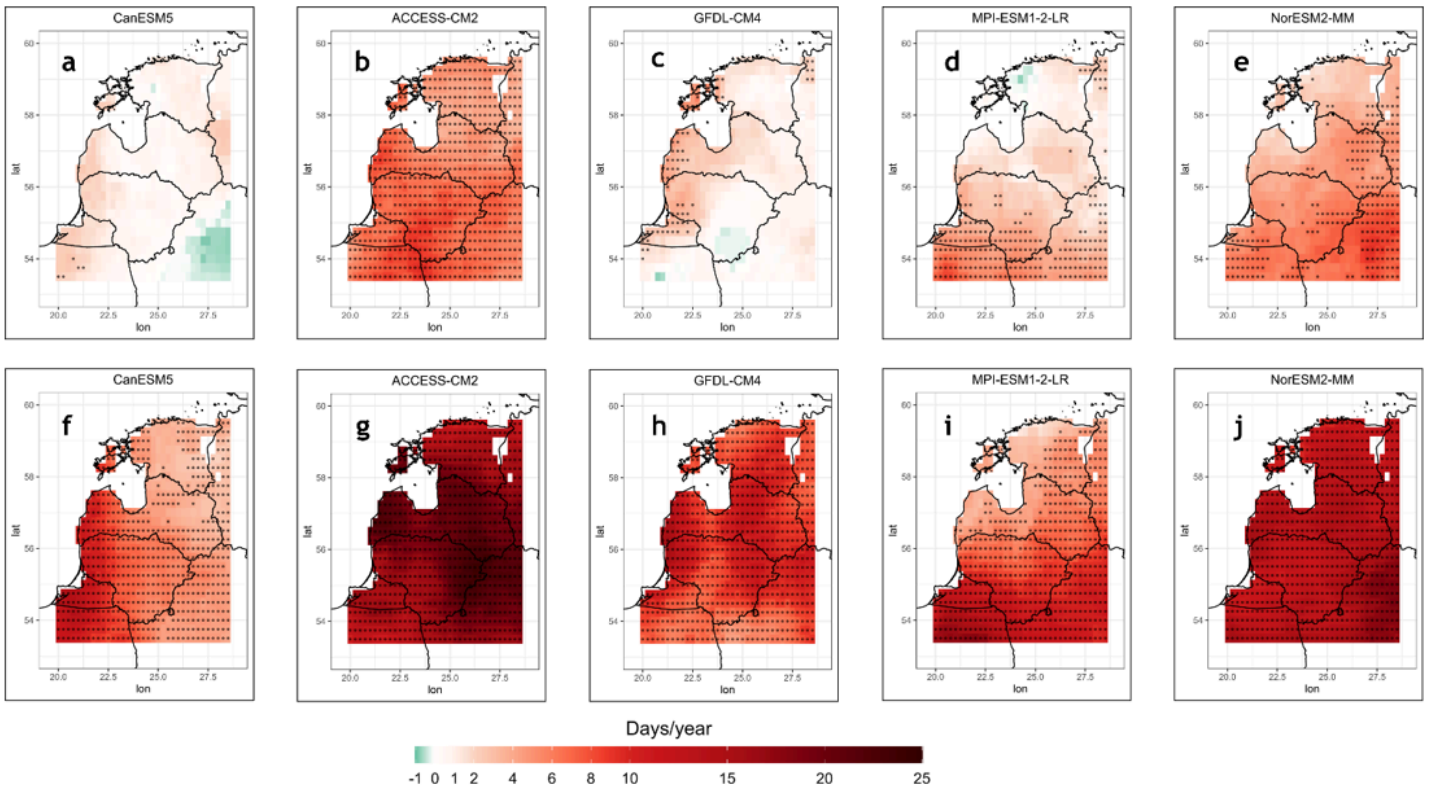


Figure 6

Change in the number of CDHE days at each grid cell in the study area according to five different CMIP6 models for the SSP2–4.5 (a–e) and SSP5–8.5 (f–j) scenarios. The changes were determined by comparing the period 2081–2100 with the baseline period 1995–2014. The dots mark grid cells where the changes are statistically significant according to the Mann–Whitney–Wilcoxon test (when $p < 0.05$)

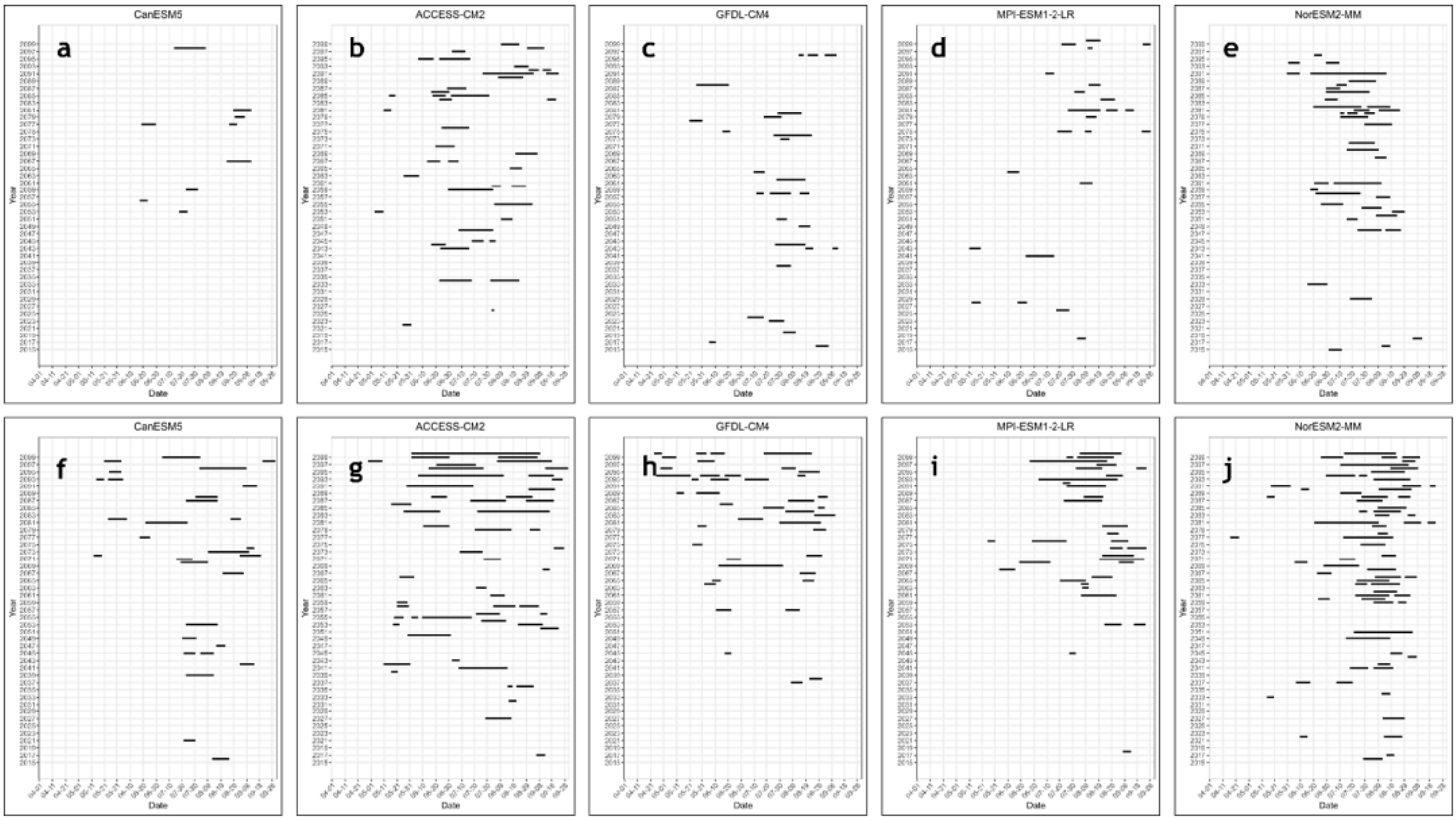


Figure 7

CDHEs and their duration during the warm season (April–September) in the eastern part of the Baltic Sea region in 2015–2100. The projections were obtained using five different CMIP6 models SSP2–4.5 (a–e) and SSP5–8.5 (f–j) scenario data