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ORIGINAL RESEARCH ARTICLE

Compound drought and heatwave events in the eastern part of the Baltic Sea region

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Abstract Droughts and heatwaves are natural phenomena that can cause severe damage to the economy, infrastructure, human health, and agriculture, among others. However, in recent years, it has been noted that their combined effect, known as compound drought and heatwave events (CDHE), often results in even greater harm. The main aim of this study was to identify CDHEs in this region during summers from 1950 to 2022 and assess the frequency and intensity of these events. To this end, the periods of droughts and heatwaves that occurred between 1950 and 2022 were determined, and the recurrence, extent, and intensity of these phenomena were evaluated. In this study, 1-month Standard Precipitation Index (SPI) values calculated for each summer day were used to identify droughts, while heatwaves were defined as a period of five or more consecutive days when the daily maximum air temperature (T_{max}) was higher than the 90th percentile of T_{max}. Precipitation and T_{max} data (with a spatial resolution 0.25° x 0.25°) were obtained from the European Centre of Medium-Range Weather Forecast ERA-5 reanalysis dataset. The study showed that in most of the eastern part of the Baltic Sea region, the number of drought days had decreased from 1950 to 2022, while the number of heatwave days had increased significantly. In total, ten CDHEs were identified during the summers of 1950—2022. Eight of these events were recorded in 1994 or later. However, a statistically significant increase of CDHEs was found only in a small part of the study area.

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1. Introduction

Various extreme weather phenomena have become more frequent over the last decades due to climate change. They cause damage to different areas, including residents and their living environment, infrastructure, wildlife, the economy, etc. Therefore, acquiring a better understanding of the genesis of such phenomena and their possible impacts is particularly important, as it can help not only reduce economic losses but also save lives (Rutgersson et al., 2022; Zscheischler et al., 2020a). Until the middle of the last decade, most research focused only on the impacts of individual elements of the climate system and their potential alterations in a changing climate. However, in recent years, the most significant threats and damage have occurred when several physical processes interacted simultaneously, resulting in a compound climate event (CCE) (Leonard et al., 2014; Ridder et al., 2020; Seneviratne et al., 2012; Zscheischler et al., 2020a). According to Zscheischler et al. (2018), CCEs are defined as a combination of several processes or hazards that pose social or environmental risks. Currently, CCEs are classified into four different groups: 1) preconditioned; 2) multivariate; 3) spatially compounding events; and 4) temporally compounding events (Zscheischler et al., 2020b). Recently, a lot of attention has been paid to the events that belong to the second group, namely multivariate events. These are CCEs where several different recurring processes or phenomena, acting in the same geographical location, cause an impact (Messori et al., 2021; Zscheischler et al., 2020b). Droughts and heatwaves, which are the focus of this study, are examples of such multivariate CCEs as well.

Although droughts and heatwaves cause significant damage when acting individually, during the first decades of this century, it was noted that their combined effect, defined as a compound drought and heatwave event (CDHE), often resulted in even greater harm. Furthermore, these compound events can have a negative impact even when the individual components, droughts and heatwaves, are not extreme and do not pose a significant threat (Mazdiyasni and AghaKouchak, 2015). Indeed, CDHEs cause harm to various natural systems, water resources, and the economy, and can cause natural disasters, have a negative socio-economic impact, and pose a threat to human lives (Bezak and Mikoš, 2020; Feng et al., 2020; Mukherjee and Mishra, 2020; Shi et al., 2021; Wang et al., 2022; Wu et al., 2019; Zhang et al., 2022). One of the main consequences of CDHEs is an increased risk of forest fires and tree mortality (Gazol and Camarero, 2022; Markonis et al., 2021; Rutgersson et al., 2022; Zscheischler et al., 2020a). According to a study by Gazol and Camarero in 2022, 63% of tree mortality events in Europe between 1901 and 2018 were associated with these compound events. Another area affected by CDHEs is crop production and their yield (He et al., 2022; Ribeiro et al., 2020). It has been found that globally, during the period from 1981 to 2020, more than 92% of the areas where crops were grown were affected by at least one CDHE through the vegetation season. During this period, the areas affected by extreme CDHEs increased (from 62% to 75%) along with the likelihood of recurrence of such events (from 20% to 33%) (He et al., 2022). Compound droughts and heatwaves also have a negative impact on the carbon cycle. During the 2003 drought and heatwave in Europe, gross primary productivity in Europe decreased by 30%, leading to an anomalously strong flux of carbon dioxide into the atmosphere (Ciais et al., 2005).

The damage and negative impact caused by CDHEs have become an increasingly relevant topic in recent years, as it has been observed that such events are becoming more frequent in various regions of the world. From 2000 to 2016, the number of CDHEs in various parts of the planet had increased by 1—5 events per year (Mukherjee et al., 2022). Another study found that from 1983 to 2016, the frequency (by 1—3 events per year), duration (by 2—10 days per year), and intensity of these compound events had increased in different areas of the planet. The most significant changes were recorded in the United States, the Amazon basin, Central and Northern Europe, Eastern and Central Asia, and Australia (Mukherjee and Mishra, 2020; Ridder et al., 2020). In various regions of Europe, the frequency and intensity of CDHEs have also increased since the mid-20th century (Ionita and Nagavciuc, 2021b). Such changes have been observed in Eastern Europe as well (Vyshkvarkova and Sukhonos, 2022), with the greatest increases occurring in Central Europe and the Mediterranean region, where one-third of the most intense CDHEs were recorded between 2000 and 2015 (Ionita and Nagavciuc, 2021b; Markonis et al., 2021). In another study, the main hotspots of CDHEs on the continent were found to be in Northern and Eastern Europe, Western European regions, Italy, and the Balkan Peninsula (Bezak and Mikoš, 2020). The main causes of these changes, according to the latest IPCC report, are human influence and anthropogenic climate change (Seneviratne et al., 2021).

However, despite the changing climate and an increasing interest in compound climate events at the global and European level, droughts and heatwaves in the eastern part of the Baltic Sea region have only been studied separately. The formation and recurrence of CDHEs in this area have not been analysed, making this study the first of its kind in the region. Therefore, the main goal of this study was to identify CDHEs in the eastern part of the Baltic Sea region during summers from 1950 to 2022 and assess the frequency and intensity of these events. To achieve this objective, the periods of droughts and heatwaves between 1950 and 2022 were also determined, and the recurrence, extent, and intensity of these phenomena in the eastern part of the Baltic Sea region were evaluated.

2. Data and methods

2.1. Study area and data

The eastern part of the Baltic Sea region was investigated in this study, encompassing the region from 53.5° to 60° N and from 20° to 28.5° E. This area covers the entire territory of Lithuania, Latvia, Estonia, the Kaliningrad region of Russia, the northern-eastern part of Poland, the western part of Russia, and the north-western part of Belarus (Figure 1).

According to the W. Köppen climate classification, whole study area belongs to the warm-summer humid continental climate (*Dfb*) type as the average air temperature during the coldest months of the year (December—February) falls

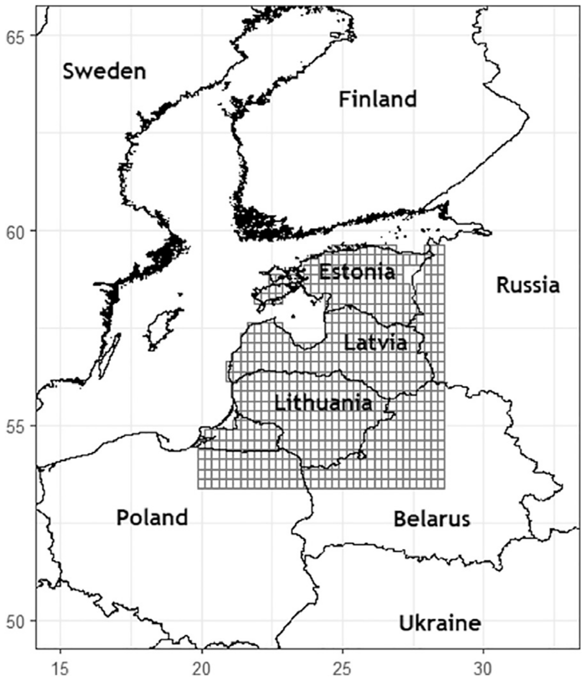

Figure 1 Map of the study area. Grey grid cells mark the territory analysed in this study.

below 0°C (Peel et al., 2007). The highest average monthly temperature in the region is recorded in July and reaches 17—18°C. The annual precipitation in the eastern part of the Baltic Sea region is 550—900 mm, with the highest amount recorded in the western part of Lithuania. The most rainfall in the study area occurs in July and August, with an average of 70—90 mm per month.

Daily data of maximum daily air temperature (T_{max}) and precipitation from 1950 to 2022 were used to identify and evaluate droughts, heatwaves, and CDHEs in the summer months in the eastern part of the Baltic Sea region. The data was obtained from the European Centre of Medium-range Weather Forecast ERA-5 reanalysis database. The grid size of the data was 0.25 × 0.25°. In total, 668 land grid cells covered the study area.

2.2. Evaluation of droughts

The SPI (Standardized Precipitation Index) was used to identify droughts during the study period (McKee et al., 1993). Daily precipitation data were used to calculate this index. The main advantage of the SPI is that it is universal and can be successfully applied to any location in the world, due to the normalisation of the precipitation data sequence during its calculation (Tsakiris and Vangelis, 2004; WMO, 2012). Finally, because of its simple calculation mechanism and applicability to various locations, the World Meteorological Organisation (WMO) recommends using this index for drought identification and evaluation (WMO, 2012). Another distinctive feature of the SPI is that it can be calculated at different time scales, from one to 48 months (WMO, 2012). However, in order to evaluate short-term changes, a 1-month time scale is typically used, as in other studies of droughts and CDHEs (He et al., 2022; Kong et al., 2020; Sharma and Mujumdar, 2017; Shi et al., 2021). SPI values range from $+3$ to -3. If $\text{SPI} > +1$, conditions are wet; when $+1 > \text{SPI} > -1$, average moisture conditions are identified; $\text{SPI} < -1$ represents dry conditions; and if $\text{SPI} < -2$, conditions are extremely dry (McKee et al., 1993).

In this study, 1-month SPI values were calculated for each day of the study period. Because 30 days of precipitation data are required to calculate the SPI values for June days, values of this meteorological variable for the months of May were also used. Droughts were distinguished if the SPI values were lower than -1 for at least five or more consecutive days and this condition was met in at least one third of the study area during the maximum extent of the drought. The beginning of a drought was considered when SPI values were lower than -1 in more than 10% of the points of the study area, and the end of a drought was determined when this criterion was no longer met. Drought recurrence and duration changes during the summer months were evaluated from 1950 to 2022. The statistical significance of changes was evaluated by performing a Mann-Kendall test. These changes were considered statistically significant if $p < 0.05$. The intensity of each drought was determined by calculating the median of the SPI values in the area affected by a drought. Then, during the maximum spread of each drought, the 5-day average of SPI medians was calculated and the Min-Max normalisation method was applied.

2.3. Evaluation of heatwaves

Summer daily maximum temperature data (T_{max}) were used to identify heatwaves For each summer day and each grid cell of interest, the 90th percentile of the daily maximum air temperature (T_{90}) was calculated on a 5-day moving window. A heatwave was identified if it was found that $T_{max} > T_{90}$ for at least five consecutive days and this condition was met for at least one-third of the study area. This criterion has been used in other studies (Mazdiyasni and AghaKouchak, 2015; Sharma and Mujumdar, 2017) and the method of using the 90th percentile of daily maximum temperature is widely applied in identifying heatwaves in Europe (García-León et al., 2021; Kim et al., 2018; Prodhomme et al., 2022; Rousi et al., 2022) and globally (Mukherjee et al., 2020; Perkins-Kirkpatrick and Gibson, 2017; Ridder et al., 2020). Its main advantage is that the method is relative rather than absolute, so it can be successfully applied to any location at any time of the year (Basarin et al., 2020; Ridder et al., 2020). Calculations are usually performed using various moving averages (ranging from 3 to 31 days), but the most commonly used criterion is 15 days (Geirinhas et al., 2021; Perkins-Kirkpatrick and Gibson, 2017; Sharma and Mujumdar, 2017; Wang et al., 2022). However, there is no consensus on the number of days to be considered, which also depends on the duration of the period under investigation. Since only summer months (92 days) were analysed in this study, a 5-day moving average period, which has been used in other studies (He et al., 2022), was chosen.

In this study, the start date of a heatwave was defined as a day when a heatwave was recorded in at least 10% of the grid cells based on the 90th percentile criterion. The end date of a heatwave was defined as the last day when T_{max} still satisfied this criterion. Changes in the frequency and duration of heatwaves during the study period were

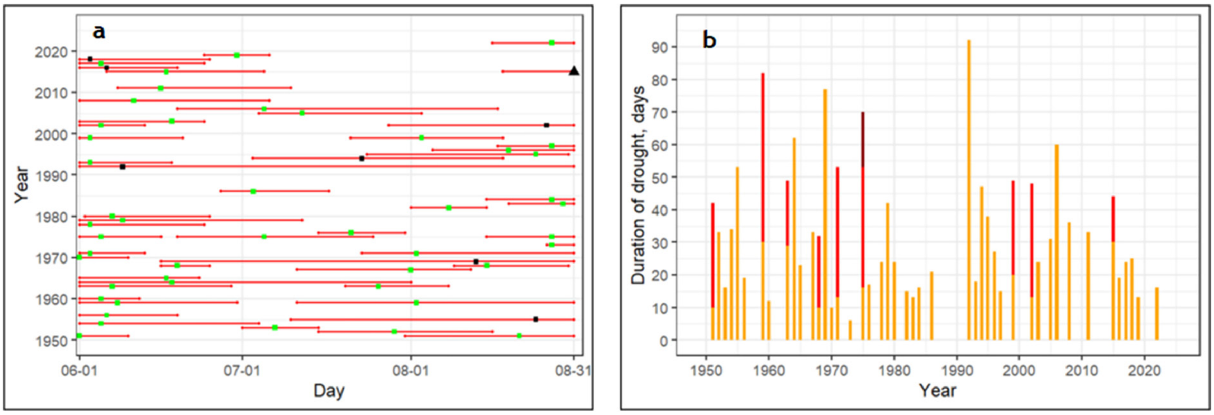

Figure 2 a) Droughts and their duration in the eastern part of the Baltic Sea region from 1950 to 2022. Squares indicate the days when each drought affected the largest part of the study area. Black squares indicate droughts whose intensity, according to the normalised 5-day SPI median average values, was greater than 0.5, while green squares indicate droughts whose intensity was less than 0.5. The black triangle indicates the date when the most intense drought reached its maximum extent. b) The duration of droughts (in days) from 1950 to 2022. The orange colour indicates the first drought in the corresponding year, red indicates the second, and dark red indicates the third.

assessed by evaluating the statistical significance of the observed changes. Heatwaves were also examined separately and assessed in each grid cell by evaluating the frequency of heatwave days and changes in the recurrence of this phenomenon over the period from 1950 to 2022. The intensity of the heatwaves was assessed by calculating the 5-day median average during the maximum spread of each heatwave and normalising the obtained values using the Min-Max method — the same principle was used in drought analysis.

2.4. Definition of CDHE

In this study, CDHEs were identified when both droughts and heatwaves reached their maximum extent in at least one-third of the studied area at the same time. The beginning of such events was considered as the day when the coincidence of these phenomena was detected in at least one-tenth of the study area points. Each CDHE lasted until the number of such grid cells no longer exceeded one-tenth of all points. The duration of each identified CDHE, the date of its maximum extent, and the percentage of the study area affected during that time were evaluated. The recurrence and duration of such events in the study area were also determined. The intensity of a CDHE was determined using the Min-Max normalization method, and the statistical significance of the changes in CDHE cases at each study grid cell was assessed by performing the Mann-Kendall test ($p < 0.05$).

3. Results

3.1. Droughts

Fifty-five droughts were identified in the eastern part of the Baltic Sea region during the period of 1950—2022 according to selected criteria (Figure 2a). The highest number of droughts (10) was identified during the period of 1970—1979 while three separate drought events were detected in the summer of 1975 (Figure 2b). Later on, there was a decrease in the number of droughts in the region — only five of them were recorded in the 1990s, and no droughts were identified in the study area between 1987 and 1991. Another period of increased drought reoccurrence was observed from 1992 to 1999, during which eight droughts were identified. In particular, in 1992, the longest drought lasting throughout the entire summer (92 days) was recorded according to selected criteria (Figure 2a). Despite this, it was noted that the number and duration of droughts decreased over the entire study period of 1950—2022 (Figure 2b). However, these changes were not statistically significant (when $p < 0.05$).

Two droughts that affected the majority of the study area were distinguished in 1955 (lasting from July 10th to August 31st) and 1994 (lasting from July 3rd to August 18th). Both of these droughts covered the entire study area at their maximum spatial extent. According to the normalised values of the 5-day median average, the most severe (intense) drought was the one that occurred at the end of the summer of 2015 (Figure 2a).

The largest number of drought days (>140 per decade) was identified in the eastern part of the study region, while the lowest number of such days (around 100) was found in the southwestern part of the study area (Figure 3a). It was calculated that the number of drought days from 1950 to 2022 had decreased in 89% of the study area's grid cells. However, statistically significant changes (when $p < 0.05$) were only found at three points in Estonia. In the majority of the study area, although the changes were negative, they were close to zero. The number of days with droughts had slightly increased only in the central part of Latvia and the southeastern edge of the study area over the 73-year period (Figure 3b).

3.2. Heatwaves

Thirty-seven heatwave events were identified in the eastern part of the Baltic Sea region from 1950 to 2022. Remarkably, heatwaves have become increasingly frequent in

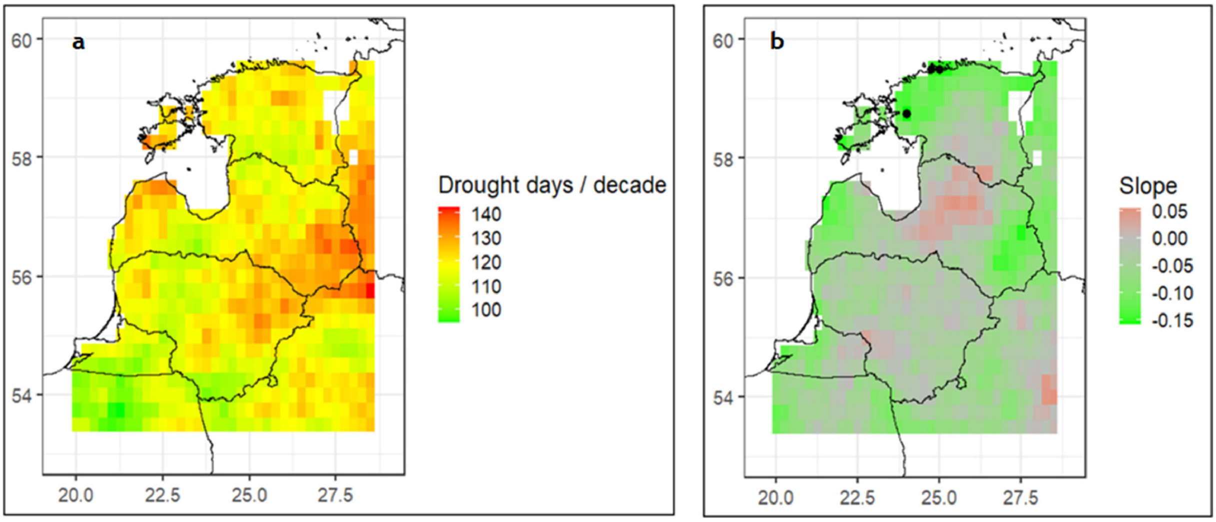

Figure 3 The number of drought days per decade in the study area (a) and the change in the number of drought days from 1950 to 2022 in each grid cell (b). Black dots indicate grid cells where the changes were statistically significant ($p < 0.05$).

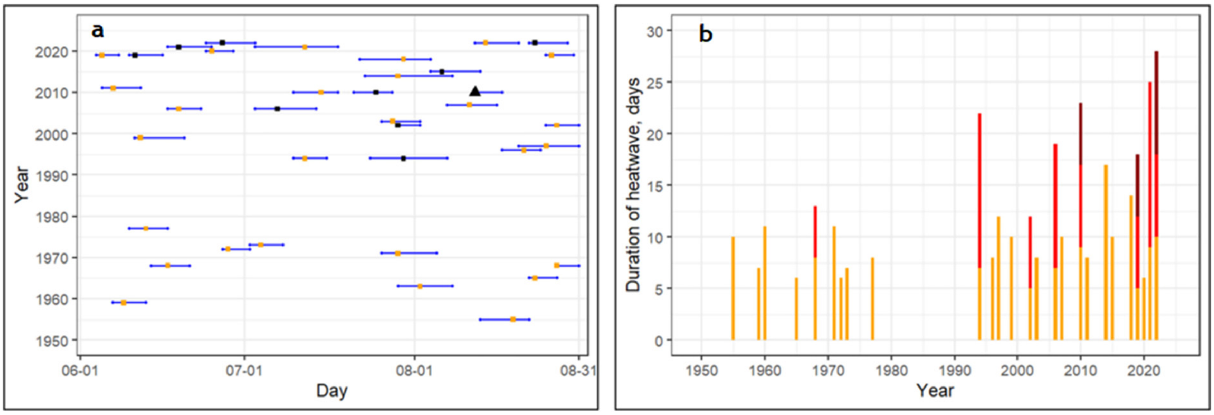

Figure 4 a) Heatwaves and their duration in the eastern part of the Baltic Sea region from 1950 to 2022. Squares indicate the days when each heatwave affected the largest part of the study area. Black squares indicate heatwaves whose intensity, according to the normalised 5-day SPI median average values, was greater than 0.5, while green squares indicate heatwaves whose intensity was less than 0.5. The black triangle indicates the date when the most intense heatwave reached its maximum extent. b) The duration of heatwaves (in days) from 1950 to 2022. The orange colour indicates the first heatwave in the corresponding year, red indicates the second, and dark red indicates the third.

recent decades. These phenomena were not identified between 1978 and 1993, whereas in the past 13 years (from 2010 to 2022), as many as 16 heatwaves have been distinguished (Figure 4a). The longest heatwave was identified in the summer of 2014. It lasted for 17 days (from July 23rd to August 8th). More heatwaves were observed in the second half of the summer (Figure 4a). It was also found that during the summers of 2010, 2019, and 2022, three heatwaves were recorded in the eastern part of the Baltic Sea region, whereas no such cases were identified prior to 2010. When assessing the changes in the frequency and duration of heatwaves from 1950 to 2022, our analyses showed that the number of days when a heatwave was identified in the entire study area during the summer season exhibited statistically significant increase (Figure 4b).

The heatwave which covered the highest number of grid cells during its maximum extent date occurred in 2021. On its peak day, June 19th, it covered the entire study area. The 2014 and 2006 heatwaves also covered almost the entire study area at their peak, with the 2014 heatwave reaching 99.85% of the study area on July 29th and the 2006 heatwave reaching 99.55% of the area on July 7th. The most severe heatwave was also identified in the 21st century, in 2010 (Figure 4a). Finally, it should be noted that of the ten most intense heatwaves, nine were recorded during the period from 2002 to 2022 (Figure 4a).

The highest number of heatwave days, when considering their occurrence in separate grid cells in the study area, was found in the northern part of the study area in Estonia. Here, the number of such cases in some places exceeded 40 per decade. The lowest number of heatwave days occurred in the southern and southwestern parts of the analysed area, where the number of such days per decade was just over 20 (Figure 5a). It was also found that the number

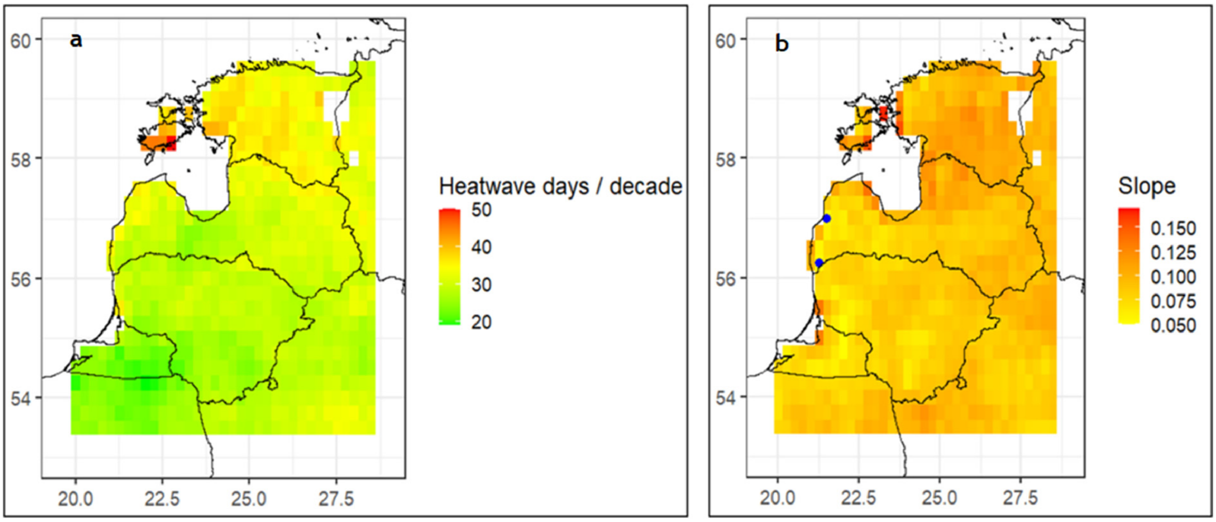

Figure 5 Heatwave days per decade in different points of the eastern part of the Baltic Sea region (a) and the change in the number of heatwave days from 1950 to 2022 in each point of the study area (b). Blue dots indicate those points where the changes were statistically insignificant (when $p > 0.05$).

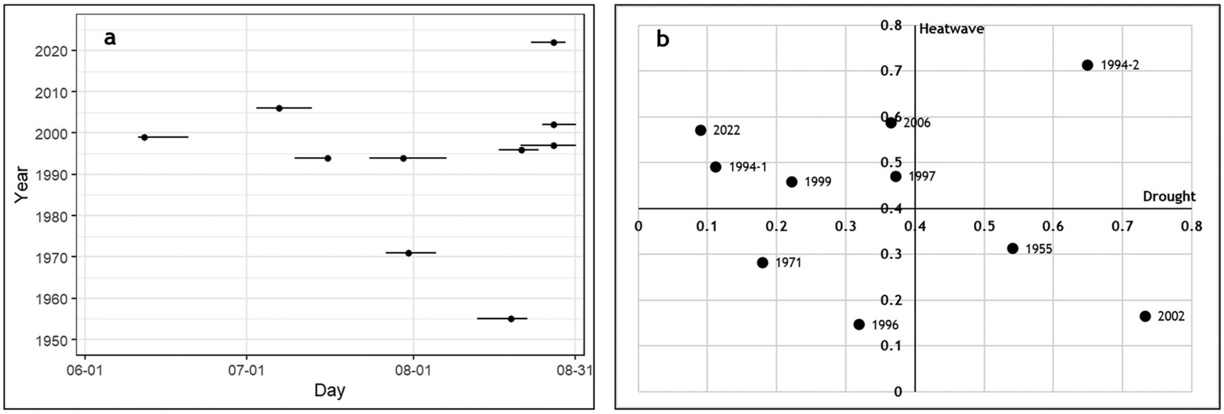

Figure 6 a) Compound drought and heatwave events (CDHE) over 1950—2022 and their duration in the eastern part of the Baltic Sea region. Black dots mark the days when the corresponding CDHE covered the largest part of the studied area. b) The intensity of each CDHE obtained by calculating the normalised SPI and $T_{max} - T_{90}$ values. 1994-1 indicates the first CDHE of that year, and 1994-2 indicates the second one.

of heatwave days from 1950 to 2022 increased throughout the whole eastern part of the Baltic Sea region, and this change was not statistically significant (when $p < 0.05$) in only two grid cells located in western Latvia. The greatest increase in the number of heatwave days over 73 years was found in coastal regions (Figure 5b).

3.3. Compound drought and heatwave events

A total of ten CDHEs (periods when a compound event was recorded in more than a third of the study area during its largest extent) were identified in the eastern part of the Baltic Sea region during the summer months of 1950—2022 (Figure 6a). The majority of these were recorded in the second half of summer, with only one CDHE identified in June (in 1999, from June 11th to 20th). Most of CDHEs (half of all cases) were recorded in the 1990s, specifically from 1994 to 1999. The year 1994 was the only year when two CDHEs were identified during the summer. The second complex event in that year was the longest of all CDHEs identified in this study, lasting for 15 days (from July 24th to August 7th) (Figure 6a). This event also covered the largest part of the study area (94.2%) and was the most intense (Figure 6b). When considering the intensity of the CDHEs, the one recorded in 2002 also stood out among all compound events. In fact, it was accompanied by the most intense drought (among those that coincided with heatwaves in at least a third of the study area points). However, the heatwave was weak, which resulted in a lower intensity of this CDHE compared to the second CDHE in 1994 (Figure 6b).

During the analysis of individual grid cells within the study area, the largest number of CDHEs (when droughts and heatwaves coincided only in individual points) during the summer months of 1950—2022 was identified in the eastern and southeastern parts of the study area, which were characterised by a high number of droughts. In these areas, the

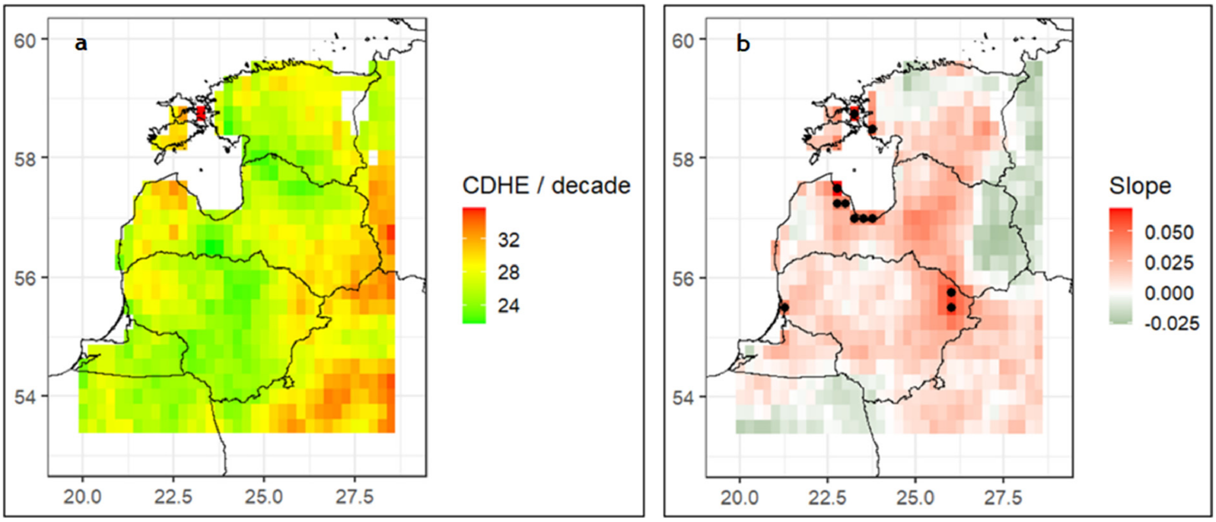

Figure 7 Number of compound drought and heatwave events (CDHE) per decade in different points of the eastern part of the Baltic Sea region (a) and changes in the number of CDHE cases from 1950 to 2022 in each point of the study area (b). Black dots indicate those grid points where the changes were statistically significant (when $p < 0.05$).

number of CDHE days in individual grid cells over the entire study period exceeded 240 (more than 33 per decade). However, the largest number of CDHEs was recorded on Muhu Island, which belongs to Estonia, where 261 CDHE days were identified from 1950 to 2022 (Figure 7a).

An analysis of the variability of CDHEs in individual points over the entire study period showed that such events were occurring more frequently in a large part of the study area. However, this change was statistically significant ($p < 0.05$) in only 1.6% of the entire study area (11 grid cells), and most of the points showing such changes are located along the coast of the Gulf of Riga (Figure 7b). Meanwhile, decreasing tendencies in the occurrence of CDHEs were observed in the northeast-eastern and southwestern parts of the study area. This was primarily due to less frequent droughts occurring in these regions (Figure 4b). However, the changes in this case were small and statistically insignificant.

4. Discussion

The main factor determining the decrease in the number of droughts since the mid-20th century in this and other studies (Jaagus and Aasa, 2018; Jaagus et al., 2022; Rimkus et al., 2013; Valiukas, 2015) was an increased amount of rainfall. However, in most cases, the changes are small and statistically insignificant. The greatest (and statistically significant) decrease in the number of drought days was observed in the northern part of the study area (Estonia), where a statistically significant increase in rainfall has been recorded since the mid-20th century (Jaagus and Aasa, 2018). Although the number of droughts has not changed significantly in various parts of the Baltic Sea region over the past few decades, their intensity has been increasing, and they have been becoming more extreme (Somorowska, 2016; Valiukas, 2015). This study confirmed these trends, with eight out of the ten of the most intense droughts identified in 1994 or later, and the most intense drought occurring in August 2015. It is predicted that in the future, due to a rapidly changing climate, the unevenness of rainfall distribution will further increase and temperatures will rise, leading to more intense droughts in the eastern Baltic Sea region as well as various regions of the world (Keršytė et al., 2015; Rimkus et al., 2020; Seneviratne et al., 2021).

In contrast to droughts, the number and duration of heatwaves increased in the eastern Baltic Sea region during the period from 1950 to 2022. Changes were statistically significant in almost the entire study area. Such trends have been observed in various parts of the world, including the eastern part of the Baltic Sea region (Awasthi et al., 2022; BACC II, 2015; Basarin et al., 2020; Seneviratne et al., 2021; Suursaar, 2022; Yoon et al., 2020). The main explanation for this is an increasing maximum daily temperature caused by climate change.

The highest number of heatwave days was identified in the northern part of the study area, which may be related to the 90th percentile method used to determine them. In the northern part of the study area (Estonia), the T_{90} values on a corresponding summer day during the study period were generally lower than in the areas further south. Therefore, when a heatwave formed and the temperature was similar throughout the study area, the T_{90} was often exceeded on more days at higher latitudes than in the southern part of the study area. The largest increase in the number of heatwave days since the mid-20th century was observed in coastal territories and the Muhu and Sarema islands.

It has been noted that the number and extremeness (the maximum area covered and intensity) of heatwave days had both increased during the study period. This was also a consequence of a warming climate. Similar trends have been observed in Poland when studying heatwaves — 11 heatwaves have been recorded since 1980, covering more than a quarter of the country's territory and lasting for at least a week. However, only one such event had been recorded prior to 1990, and more than half have occurred in the last decade (Wibig, 2021). The longest heatwaves in Poland were recorded in 1994 and 2015 (Tomczyk et al., 2020; Wibig, 2017).

All the characteristics defining the aforementioned heatwaves (number of heatwave days, intensity, covered area) are expected to increase in the future (Basarin et al., 2020; Rutgersson et al., 2022; Seneviratne et al., 2021). It has been determined that the number of heatwave days will increase by 4—34 days per season for each degree Celsius of global warming, depending on the region. The duration of heatwaves is expected to increase by 2—10 days/°C, with the greatest changes predicted to occur at lower latitudes (Perkins-Kirkpatrick and Gibson, 2017). These changes will also increase the damage caused by heatwaves. If adaptation and mitigation measures are not taken, it is likely that their impact in Europe could increase by a factor of five by 2060, compared to the historical period of 1981—2010 (García-León et al., 2021); in some areas of the Baltic Sea region, the risk of heatwaves may double by the end of this century (Rutgersson et al., 2022).

When evaluating the recurrence of CDHEs in the eastern part of the Baltic Sea region, it was observed that the vast majority of these (8 out of 10 events) were recorded from 1994 onwards. When assessing changes of CDHEs in individual grid cells, it was also found that the CDHE frequency increased in 73% of these cells during the 1950—2022 period. Similar results, indicating an increasingly frequent recurrence of CDHEs, have been obtained through studies of such events in various regions of the world and Europe (Bezak and Mikoš, 2020; Geirinhas et al., 2021; Kong et al., 2020; Mazdiyasni and AghaKouchak, 2015; Sedlmeier et al., 2018; Shi et al., 2021). However, during this study, a statistically significant increase in the occurrence of CDHEs was found in a very small area due to the decreasing frequency of droughts.

The majority of CDHEs occurred during the second half of the summers, which was closely related to the occurrences of heatwaves during the summers. The distribution of CDHEs in different points of the studied territory largely coincided with the distribution of dry days — in both cases, the most frequent occurrences of droughts and CDHEs were identified in the eastern and southeastern parts of the study area, as well as in the northwestern part of Latvia and on the islands of Muhu and Saaremaa. The most exceptional CDHE occurred between July 24 and August 7, 1994. This was the longest-lasting and the most intense event, covering the largest part of the studied territory at its maximum extent. This was also the only case when a CDHE was identified twice during the same summer (1994), which could have contributed to the extremeness of this complex event.

It is predicted that in the future, with ongoing climate change and increasing global mean temperatures, CDHEs will occur more frequently and an increase in intensity and duration will also be expected (Seneviratne et al., 2021). It has been calculated that with every degree Celsius of global warming, the duration of these complex events will increase by an average of ten days (Zhang et al., 2022). The frequency and occurrence of CDHEs in Europe will also increase in the future (Mukherjee et al., 2022; Sedlmeier et al., 2018), leading to a growing probability of negative impacts and damages. The forestry sector will be most affected, with an increased risk of forest fires and tree mortality (Feng et al., 2020; Gazol and Camarero, 2022; Seneviratne et al., 2021).

Atmospheric processes and their dynamics play a significant role in the formation of both droughts, heatwaves, and CDHE. One notable process is the prevalence of anticyclonic circulation and atmospheric blocking (Ionita et al., 2021a; Liu et al., 2020; Sousa et al., 2018; Spensberger et al., 2020). It has been observed that drought formation in the Baltic countries is almost always influenced by strong anticyclonic circulation (Rimkus et al., 2014). Similar tendencies were identified when studying the drought that affected Poland during the summer of 2019 (Ziernicka-Wojtaszek, 2021). Furthermore, it was determined that 60% of heatwaves in Central Europe during the period of 2001—2011 coincided with the formation of blocking systems (Porebska and Zdunek, 2013). However, statistically significant changes in the recurrence of such systems in the Northern Hemisphere from 1901 to 2010 have not been detected. Nevertheless, it has been observed that the duration of blocking systems is becoming longer (Wazneh et al., 2021).

The formation of droughts and/or heatwaves is also influenced by large-scale atmospheric circulation, not just local atmospheric processes. When studying the recurrence of heatwaves in Poland, it has been observed that several synoptic features play a role in their formation. These include a strong Azores high-pressure system, higher-than-usual atmospheric pressure over Central Europe, resulting in calm and sunny weather, and a strong blocking system over the North Atlantic (Wibig, 2017).

Finally, several aspects must be considered in further research. First, an important aspect that can influence the accuracy and reliability of obtained results and trends is the uncertainties and biases of the data obtained from the ERA5 database. ERA5 uses a 10-member ensemble that provides uncertainty information. However, in this case, one of the problems encountered is the lack of small-scale variability in ensemble members, and the model itself tends to have overconfidence in the uncertainty characterization (Bandhauer et al., 2022). This is because the perturbations are oriented towards large-scale dynamic variables (Hersbach et al., 2020).

However, the inaccuracies of ERA5 reanalysis data are mostly encountered in mountainous regions (e.g., in the Alps) or continents other than Europe (Bell et al., 2021; Hersbach et al., 2020; Lavers et al., 2022; Velikou et al., 2022). Only a few issues were found while analysing the performance of ERA5 in mid-latitudes. During the evaluation of extremely high temperature (above 95th percentile), it was observed that ERA5 tends to overestimate values of this variable, but the differences compared to observations are not statistically significant (Velikou et al., 2022). It was also found that random errors of precipitation data increase during the summer in mid-latitudes (Lavers et al., 2022). However, in more than 90% of cases, the variability of monthly precipitation values in Europe coincides with observations (Bell et al., 2021). Therefore, despite the shortcomings, ERA5 precipitation and temperature data are sufficiently accurate to use in mid-latitudes in Europe (Bandhauer et al., 2022; Lavers et al., 2022; Nogueira, 2020; Velikou et al., 2022).

Also, when evaluating long-term trends, it is important to emphasize that the accuracy of ERA5, like any other reanalysis data, decreases and errors increase going further back in time. The reason for this is simple — a significantly smaller number of observations were available at the beginning of the period (1950's) compared to the past decades (Bell et al., 2021). Additionally, the number of satellite observations and their quality increased rapidly, which also plays a significant role in the accuracy of the obtained data (ECMWF, 2023).

The choice of the index used to identify droughts is also crucial. Although the SPI which was used in this study was suitable for assessing droughts in the study region, it has several limitations. The main one is that it only considers precipitation and does not take into account the effect of temperature on drought formation. As the climate changes and mean temperature rapidly increase, the latter factor will become crucial in accurately identifying droughts (Vicente-Serrano et al., 2010; WMO, 2012). It is also important to investigate the processes that lead to the formation of CDHEs in the eastern part of the Baltic Sea region and to evaluate the possible changes in CDHE characteristics in the future. This would help develop more effective adaptation and mitigation strategies and thus minimise the risks posed by CDHEs (Bezak and Mikoš, 2020; Mazdiyasni and AghaKouchak, 2015; Sedlmeier et al., 2018).

5. Conclusions

A decrease in the number of drought days was observed from 1950 to 2022 in most of the eastern part of the Baltic Sea region (89%). However, almost all these changes were statistically insignificant. Only a slight increase in the number of drought days was identified in the central part of Latvia and the southeastern outskirts of the study area. In contrast to droughts, the number and duration of heatwaves, have increased in the entire research area. The obtained changes were statistically significant in 99.7% of the study area. The extremeness of heatwaves (intensity and the area covered during their maximum extent) has also increased in the region due to rising temperatures caused by changing climate. The largest number of heatwave days was identified in the northern part of the study region and on the coast of the Baltic Sea. Ten CDHEs were identified in the eastern part of the Baltic Sea region, with eight of them recorded in 1994 or later. Moreover, an increase in the number of CDHEs was observed in 73% of the study area, but statistically significant changes were only found in 1.9% of the region. The largest positive changes were found in coastal regions, as well as in the northeastern part of Lithuania.

Declaration of competeing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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