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RESEARCH

Long-term changes in heat wave parameters in the eastern Baltic region

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Abstract

Temporal and spatial variabilities of heat waves in the three eastern Baltic countries – Lithuania, Latvia and Estonia – in 1951–2021 were studied. Three heat wave definitions – daily maximum temperature (CTX), daily minimum temperature (CTN) and excess heat factor (EHF) at 90 and 95 percentile levels – were used for the calculation of five heat wave indices – heat wave factor (HWF), heat wave number (HWN), heat wave duration (HWD), heat wave amplitude (HWA) and heat wave magnitude (HWM) – at 40 stations. Additionally, numbers of extremely warm days (Tmax > 27 °C) were analysed. Linear regression and Mann-Kendall tests were applied for trend analysis. The mean spatial distribution of the number of extremely warm days has clear regularities. Lower values are typical for the coastal zone and for the northern part of the study area while higher values are located in the continental region and in the southern part. Extremely warm days are mostly concentrated to the mid-summer period, from 6 July to 9 August. The results of the trend analysis indicate the presence of statistically significant increasing trends in the majority of heat wave indices. The number of extremely warm days has approximately doubled during 1951–2021 while the trend has been statistically significant at all stations. The strongest increasing trends were revealed in the case of HWF (total number of heat wave days). This increase has nearly doubled while the trend was significant at all stations. The increase is stronger also for other heat wave indices measured in days (number of heat waves HWN, duration of heat waves HWD). The indices showing temperature anomalies (HWA, HWM) have notably slower growth trends, which are mostly insignificant.

1 Introduction

Contemporary climate warming affects different aspects of the natural environment and society. Temperature increase inevitably causes an increase in the frequency of extremely high temperatures (IPCC 2021). They have a negative effect on human health (Liu et al. 2022). Amidst persistently high and extreme air temperatures, the associated health risks surge dramatically, resulting in a notable increase in mortality.

The most dangerous events are heat waves, i.e. consecutive days or even more extended periods with extremely high temperature. During the exceptional heat wave in summer 2003 in Europe, which was characterized by a combination of extreme daytime temperatures and lack of night-time cooling, 14 800 people died in France alone (Michelon et al. 2005). It is estimated that more than 40,000 people died due to heat in various European countries in 2003 (García-Herrera et al. 2010). In recent years, many studies have shown a sharp increase in mortality during heat waves (Campbell et al. 2018; Graczyk et al. 2022; Urban et al. 2022; Ruiz-Páez et al. 2023).

An immediate increase in mortality associated with temperatures exceeding the 75th percentile of summer

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maximum temperatures (about 23 °C) was detected in Estonia (Oudin Åström et al. 2016). This increase lasted for a couple of days. A significantly higher mortality was found in Estonia owing to external causes on hot (the same and previous day) and cold days (with a lag of 1–3 days). The cumulative relative risks for heat (an increase in temperature from the 75th to 99th percentile) were 1.24 (Orru and Oudin Åström 2017). Similar increase in mortality was observed in Lithuania during the period 2009–2015 when maximum daily temperature exceeded 30 °C (Sanchez Martinez et al. 2018). Relationships between temperature and mortality are studied also in Latvia (Avotniece et al. 2011).

Heat waves increase the drought risk, decrease water supply, worsen air quality, increase energy consumption, etc. Together with many other natural hazards, heat waves and their effects are among the largest challenges of the future climate (IPCC 2022). Due to climate change, it is projected that heat waves will become longer, more frequent and more intense (Meehl and Tebaldi 2004; Kysely 2010; Lau and Nath 2014; Perkins-Kirkpatrick and Gibson 2017; Campbell et al. 2018; Lhotka et al. 2018; IPCC 2022).

It is essential to acknowledge the challenge in defining a heat wave, as the threshold for extremely high air temperatures varies across diverse climatic conditions. A distinction has been made between heat waves and warm spells. Heat waves are periods that are hot in an absolute sense, and warm spells are periods that are hot in a relative sense (Nairn and Fawcett 2015). In this sense, warm spells may occur at any time of the year, while heat waves are restricted to the summer half-year. In climate terms, heatwaves are associated with unusually high temperatures, and warm spells with unusually high temperature anomalies.

Extremely high air temperature levels differ in various climatic conditions. Therefore, there are many definitions of heat waves, as well as of their characteristic indices. Indices characterising extreme heat conditions are often created for specific purposes, for example, the human heat stress index, and are difficult to compare with each other (Robinson 2001; Kuchcik 2006; Radinović and Ćurić 2012; Perkins and Alexander 2013; Awasthi et al. 2022).

Usually, a certain daily maximum temperature threshold is used to define a heat wave. The corresponding air temperature must occur for two or more consecutive days. The temperature threshold is often formal, for example + 30 °C (Wibig 2018), or corresponds to a certain score on a distribution curve – usually the 90th or 95th percentile of long-term daily maximum air temperatures (Anderson and Bell 2011; Acero et al. 2018). A combination of daily maximum (TX) and minimum air temperatures (TN) is also used (Robinson 2001; Kuglitsch et al. 2010; Croitoru et al. 2016; Sambou et al. 2020).

A relatively new way of describing a heat wave is the Excess Heat Factor (EHF) (Langlois et al. 2013; Nairn and Fawcett 2015) based on a three-day-averaged daily mean temperature (DMT). In recent years, this approach has been used in several cases both to characterise heat waves and to assess health risks (Nairn et al. 2018; Oliveira et al. 2022a; Díaz-Poso et al. 2023; Galanaki et al. 2023).

Numerous studies have demonstrated a significant increase in the frequency and magnitude of heat waves in different regions all over the world during past decades. Using the latest HadGHCND daily temperature dataset, global trends in the observed summertime heatwaves and annually calculated warm spells for 1950–2011 were analysed via a multi-index and multi-aspect framework (Perkins et al. 2012). Three indices that focus on maximum temperature (TX90pct), minimum temperature (TN90pct) and average temperature (EHF) were studied with respect to five characteristics of event intensity, frequency and duration. Increases in heat wave/warm spell intensity, frequency and duration were found in all indices (Perkins et al. 2012).

Increasing trends in all definitions and aspects of heat waves were detected on the Australian continent during the period 1951–2008 (Perkins and Alexander 2013). In the Czech Republic, probabilities of very long heat waves have already risen by an order of magnitude over the recent 25 years (Kysely 2010). Global estimations of frequency, intensity and duration of heat waves show significant increasing trends in many regions of the world since 1950 (Perkins-Kirkpatrick and Lewis 2020). These trends have accelerated in the 21st century (Christidis et al. 2015; Oliveira et al. 2022b).

Heat waves are more common for lower latitudes, although, it depends very much on the definition of the heat wave. At the same time, climate warming is expected to induce more heat waves also on higher latitudes where they have earlier been quite unusual events. We focussed this study on three countries – Lithuania, Latvia and Estonia – located on higher latitudes in the eastern Baltic region, which expands in the south/north direction between 55 and 60°N. The climate of the region is characterised by high variability due to the alternation of air masses of different origin.

Extremely high air temperatures are often observed in the study region when the weather conditions are determined by south–westerly and southerly anticyclonic flows, when a high-pressure area is situated over the eastern part of Europe, and with the warmer air flowing into the territory from western Russia (Avotniece et al. 2010). Extremely hot weather can also be observed when cyclonic conditions are dominant: south–westerly, southerly and westerly cyclonic flows are associated with the warm sector of a cyclone and an intensive inflow of warm air. The problem how to detect a heat wave in Estonia has been analysed earlier (Keevallik and Vint 2015). The number of hot days has increased in Lithuania during 1961–2010 particularly in July and August and in 1998–2010 (Kažys et al. 2011). Similar studies on the warm spell duration indicator, which characterises the duration of prolonged hot spells, have been carried out in Latvia for the period 1950–2010. A statistically significant increasing trend was found at all 14 observation stations used in the study (Kļaviņš et al. 2012).

In the current study, we analysed long-term changes in heat wave characteristics in the eastern Baltic region and tried to point out their latitudinal and longitudinal peculiarities. Our preliminary hypothesis was that heat waves have increased more strongly in the higher latitudes than in the lower ones, especially during the last 30 years.

2 Data and methods

Heat wave parameters were analysed during the warm season (May ¬-September) in the 71-year period ¬1951-¬2021. Initial data for their calculation included the daily mean, maximum and minimum temperatures measured at 40 stations, 15 of which were from Lithuania, 13 from Latvia, and 12 from Estonia (Fig. 1). They were obtained from the national weather services of these countries. This region represents a transitional meridional belt in Europe between the maritime climate in the west and the continental one in the east. According to the Köppen classification, it belongs to the climate type Dfb. Only the western coastal region of the study area near to the Baltic Sea belongs to the climate type Cfb.

All the stations used in this study have nearly complete temperature datasets. Gaps in the data were filled by calculating the average value between the previous and the next day's values. If the gaps were longer, we took data from the nearest station using the mean difference method. The data completeness was more than 99%. The history of the stations was studied and the homogeneity of temperature time series was checked. Metadata of the stations are provided in Table 1.

Some stations have had relocations during the study period. In 1997, Tartu station was moved from the airport to Tõravere village 20 km from Tartu. A special study on comparison of temperature time series (Sits and Post 2006) demonstrated that the last location has been warmer by 0.2 °C in the average. Tallinn station was moved from the airport to Harku suburb village in 1980. Natural conditions at the two locations are similar – open limestone plateau and the same distance from the sea (2.5 km). Jelgava station is gradually becoming overgrown with bushes. The bushes were cut down in 1983 but it was overgrown again. In August 2016, the station was moved to the vicinity of Stalģene, 10 km away. The location of Ventspils station has not changed but there are various changes in the area around the station in connection with the development of the Port of Ventspils.

Heat wave parameters were selected following the methodology presented by Perkins and Alexander (2013). That study was performed for Australia located in much lower latitudes. Hereby, we tested this approach for the northern part of the temperate climate zone. We found that the methodology is rather universal for applying in various climatic regions.

According to the methodology, a heat wave is defined if there are three or more consecutive days above the 90th percentile for daily maximum temperature (CTX90), the 90th percentile for daily minimum temperature (CTN90) or positive extreme heat factor (EHF) conditions. The EHF is a quadratic function of both the long-term and short-term air temperature anomalies, and its magnitude reflects human acclimatization to the local climate (Oliveira et al. 2022b). These are the three heat wave definitions. For each of these definitions five heat wave indices or aspects are calculated: the number of heat wave events (HWN), the heat wave duration, i.e. the length of the longest annual heat wave event in days (HWD), the heat wave frequency, i.e. the sum of the participating heat wave days per year (HWF), the heat wave amplitude, i.e. the temperature anomaly in the hottest day of the hottest annual heat wave event from the five-month mean summer temperature (HWA), and the heat wave magnitude (HWM), i.e. the average of daily temperature anomalies from the five-month mean summer temperature across all heat wave events within a year (Perkins and Alexander 2013). The unit of three heat wave indices (HWF, HWN and HWD) is the number of days while the unit of the remaining two indices (HWA and HWM) is degree centigrade.

The heat wave definitions CTX90pct and CTN90pct are the calendar day 90th percentiles of daily maximum and minimum temperatures, respectively, based on a 15-day window, which is centred on the day in question. The authors have stated that the 90th percentile had been chosen due to the sufficient occurrence of measurable events. For example, in the case of 95th percentiles there were very few heat wave events being measured (Perkins and Alexander 2013).

In this study, we used both options, the 90th as well as the 95th percentiles, to define a heat wave. The reason for that was the fact that the 90th percentiles represent temperatures in the study region that can scarcely be characterized as warm extremes. The percentile values of maximum and minimum temperatures are analysed in the first subsection of the results. The calculation of the third heat wave definition EHF is described in detail by Perkins and Alexander

Fig. 1 Location of the study region and the stations used in this study

Table 1 Metadata of stations used in this study

Station	Longitude	Latitude	Elevation (m)	Distance from city centre (km)	Character of the station
Kihnu	23.97	58.10	3	48	coastal station
Kunda	26.54	59.52	3	3	coastal station
Kuusiku	24.73	58.97	53	6	out of town
Ristna	22.07	58.92	7	44	coastal station
Tallinn	24.60	59.40	33	6	outskirts of town
Tartu	26.46	58.26	70	20	out of town
Tiirikoja	26.95	58.87	33	2	lake side
Türi	25.41	58.81	60	1	in town
Valga	26.04	57.79	64	1	outskirts of town
Viljandi	25.60	58.38	86	1	in town
Vilsandi	21.81	58.38	6	47	coastal station
Võru	27.02	57.85	82	2	in town
Ainaži	24.37	57.87	6	1	coastal town outskirts
Alūksne	27.04	57.44	196	4	out of town
Dobele	23.32	56.62	41	5	out of town
Gulbene	26.72	57.13	143	9	out of town
Jelgava	23.74	56.68	5	6	suburban
Kolka	22.59	57.75	3	3	coastal station in town
Liepāja	21.02	56.48	3	6	suburban
Priekuļi	25.34	57.32	122	3	suburban, outskirts of town
Rūjiena	25.37	57.89	67	6	out of town
Saldus	22.50	56.68	121	2	in town
Stende	22.55	57.18	80	2	suburban, outskirts of town
Ventspils	21.54	57.40	2	3	port area in town
Zosēni	25.91	57.14	188	2	out of village
Biržai	24.77	56.19	60	1	in town
Kaunas	23.84	54.88	76	4	outskirts of town
Klaipėda	21.09	55.73	6	4	outskirts of town
Kybartai	22.78	54.63	58	2	outskirts of town
Lazdijai	23.51	54.23	133	1	outskirts of town
Laukuva	22.24	55.61	165	1	out of town
Nida	21.01	55.3	2	1	coastal station
Panevėžys	24.42	55.74	57	4	outskirts of town
Raseiniai	23.13	55.39	111	1	in town
Šiauliai	23.33	55.94	106	1	in town
Šilutė	21.45	55.35	3	2	outskirts of town
Telšiai	22.26	55.99	153	1	in town
Ukmergė	24.76	55.26	72	1	outskirts of town
Utena	25.59	55.52	105	2	outskirts of town
Varėna	24.55	54.25	109	4	in village

(2013). There, two anomaly-based indices were multiplied, resulting in units of degrees Celsius squared.

Additionally, we analysed changes in the total number of extremely warm days. An extremely warm day was defined when the daily maximum temperature was 27 °C or higher. The Estonian Weather Service uses this threshold value for warm extremes. It has been found that the mortality in Estonia has increased more than 10 per cent when daily maximum temperature has been above 27 °C (Sammul et al. 2016).

Mean values of the five heat wave aspects for the three heat wave definitions are analysed. Trend analysis is performed using the Mann-Kendall test. Slope values are calculated using the Theil-Sen method. Trend values are expressed in changes per a decade. It allows to compare trends in heat wave indices obtained from other studies. Trends are considered statistically significant on the $P < 0.05$ level. In that case, the Mann-Kendall statistic Z should be higher than 1.96.

The results of trend analysis are presented on maps. Spatial interpolation was made using the radial basis function (RBF).

3 Results

3.1 Seasonal and territorial distribution of heat waves

Latitude is the most critical factor determining the distribution of extremely high temperatures. The number of extremely warm days (Tmax ≥ 27 °C) is higher in the south (Lithuania) and lower in the north (Estonia). Their average annual value for Lithuanian stations was 11.8, for Latvia 7.4 and for Estonia 6.4 days.

The seasonal distribution of mean numbers of extremely warm days during 1951–2021 is presented on Fig. 2. The highest number of extremely warm days in the study region is concentrated in mid-summer. The maximum values are concentrated from 6 July to 8 August with the peak on 25 and 26 July. In May, the mean numbers are gradually increasing. Since 7 June, the level of the numbers of extremely warm days is more or less stable up to the mid-summer maximum. The number of extremely warm days rapidly decreases in mid-August.

Significant spatial differences exist in the number of extremely warm days between the coastal region and the hinterland (Fig. 3a). Sea surface temperature is lower than land surface temperature, especially in spring and in the first half of summer. Therefore, air temperature over the sea is also much lower and very rarely exceeds the extreme value of 27 °C. The lowest mean numbers of extremely warm days (1–3 days) are typical for the coastal stations of Estonia and Latvia while the highest ones, more than ten days, are located in the continental part of Lithuania. A smaller number of extremely warm days have also occurred at the upland stations at Alūksne and Zosēni in Latvia (Fig. 3a).

Annual mean values of the heat wave indices in 1951–2021, used in this study, are presented in Table 2. These values do not vary much between stations because they are mostly percentile-based. Their mean values vary within the following range: HWF – 12–17 days; HWN – 2.5–4; HWD – 5–6 days; HWA – 3–6 °C; HWM – 1–3 °C for the 95th percentile, and HWF – 17–24 days; HWN – 3–5; HWD – 6.5–8 days; HWA – 4–7 °C; HWM – 1.5–3 °C for the 90th percentile.

The annual mean number of heat wave days (HWF) is approximately 15 in the case of CTX95 and CTN95, and up to 22 in the case of CTX90 and CTN90. Thereby, this value is remarkably lower at the coastal stations and higher in the hinterland (Fig. 4). Spatial distribution similar to HWF is also typical for the annual number of heat waves (HWN). Generally, there have been 3–4 heat waves per year if we use the heat wave definition of the 95th percentile, and 4–5 heat waves per year in the case of the 90th percentile. The average heat wave duration or the duration of the longest annual heat wave (HWD) is quite similar at all stations. There are no significant differences between coastal and continental stations.

Mean values of heat wave amplitudes (HWA) are always much higher than mean values of heat wave magnitudes (HWM) (Table 2). It is because the first index shows the maximum difference from the summer mean temperature and the second one shows the mean difference from it. There are no remarkable geographical differences in HWA and HWM between the stations. They are higher in the case of CTX and lower for the definition CTN. It is natural because

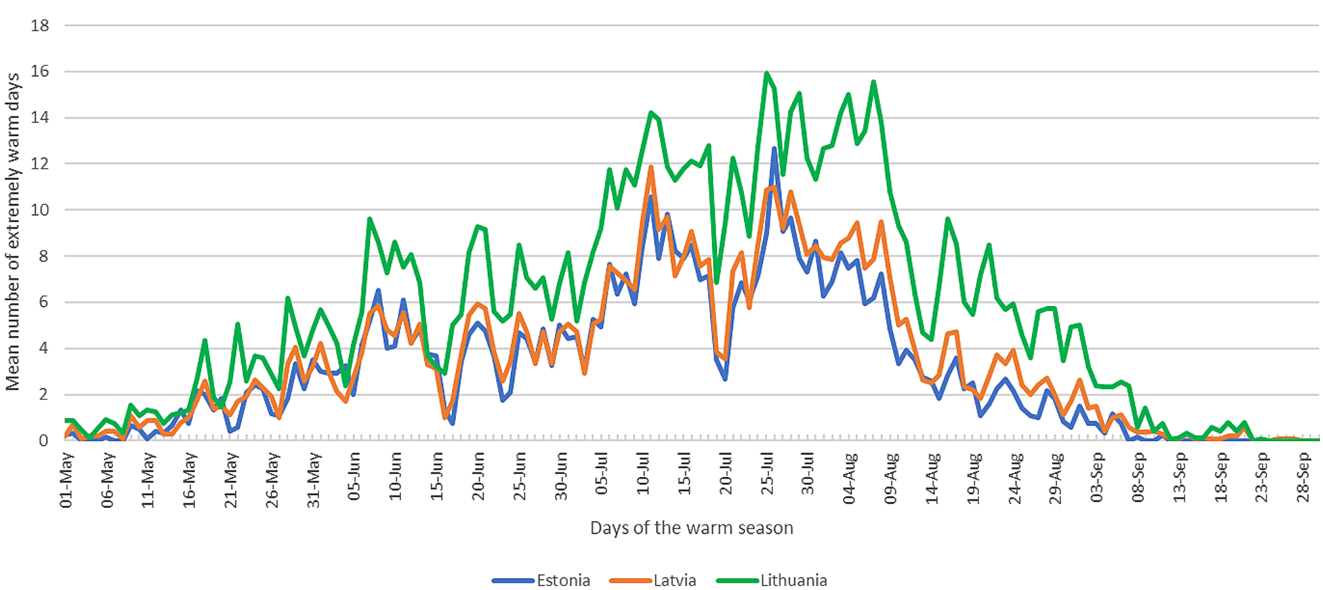

Fig. 2 Seasonal distribution of mean numbers of extremely warm days (Tmax ≥ 27 °C) averaged by stations in Lithuania, Latvia and Estonia during 1951–2021

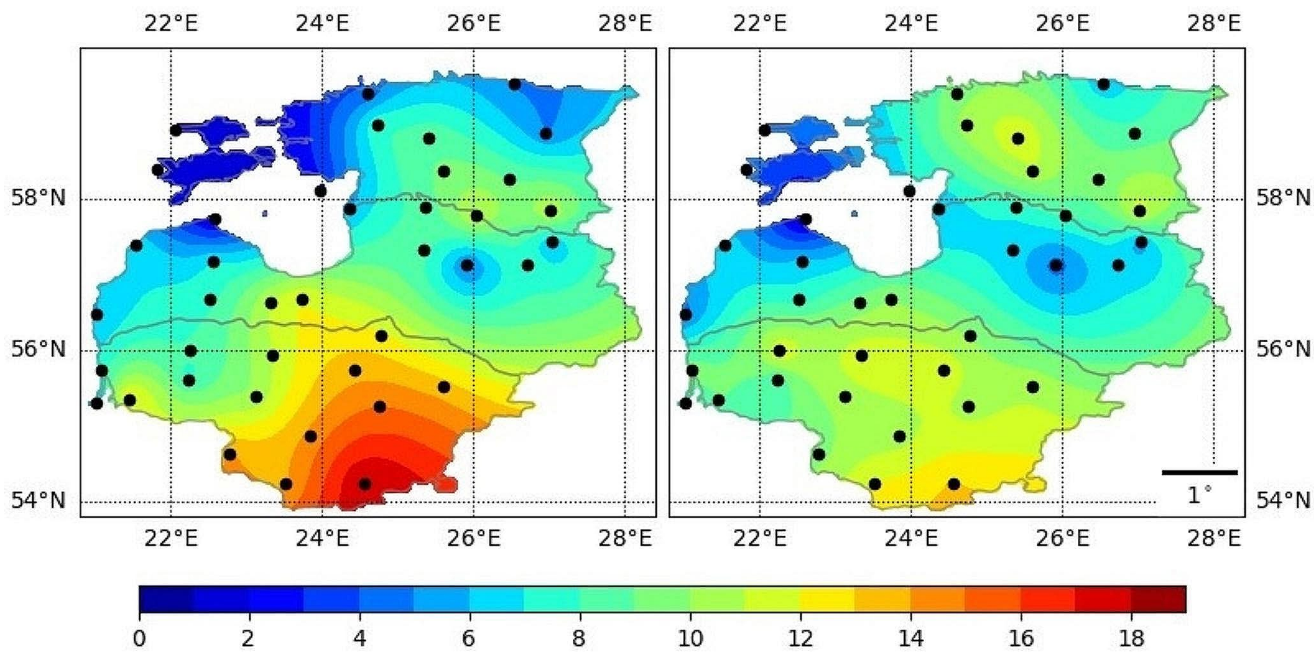

Fig. 3 Mean annual number of extremely warm days (> 27 °C) (**a**) and total change in number of extremely warm days per 1951–2021 (**b**)

Table 2 Annual mean values of the heat wave parameters averaged over all stations used in this study

	HWF	HWN	HWD	HWA	HWM
CTX95	14.8	3.2	5.8	5.0	2.3
CTN95	15.1	3.4	5.7	4.1	1.8
EHF95	4.1	0.9	2.7	9.7	4.4
CTX90	21.6	4.3	7.5	6.1	2.6
CTN90	21.8	4.6	7.2	4.9	2.0
EHF90	9.7	1.9	5.1	20.2	7.5

air temperature can rise significantly during the daytime, while temperature differences usually decrease in the nighttime. The variability of maximum temperature is higher than that of minimum temperature during the warm season.

The heat wave definition EHF presents quite different mean values for the heat wave parameters than the definitions CTX and CTN (Table 2). The parameters showing the number of days (HWF, HWN, HWD) have much lower mean values in the case of EHF, while the parameters expressing temperature (HWA, HWM) have much higher mean values than in the case of the definitions CTX and CTN. This is due to the calculation of EHF where two anomaly-based indices are multiplied, resulting in the units of degrees Celsius squared. The average values of HWA and HWM do not vary much between the stations.

3.2 Trends in heat wave parameters

We assumed that heat wave parameters have had general increasing trends in the eastern Baltic region during the study period that correspond to the global climate warming tendency. Our results confirm this hypothesis but there have been quite significant differences between different indices and heat wave definitions.

The annual number of warm days (Tmax > 27 °C) has increased statistically significantly at all stations. The mean change by trend during 1951–2021 was 1.5 days per decade in Lithuania, and1.2 days per decade in Latvia and in Estonia. It is a very significant change, a doubling of the values during the study period. Spatial distribution of this change is provided on Fig. 3b. There can be noticed a tendency that trend values are higher when mean values have been also higher, and vice versa.

It is typical that these time series are highly correlated between different stations. Time series and trend lines of the annual number of warm days at three stations located in the central parts of the three countries are provided on Fig. 5. Warm summers have been observed in the same years in all three countries. The warmest years have been concentrated to the 21st century, i.e. to the end of the study period. The maximum numbers of warm days were observed in 2002, 2010, 2014, 2018 and 2021. The highest correlation – 0.88

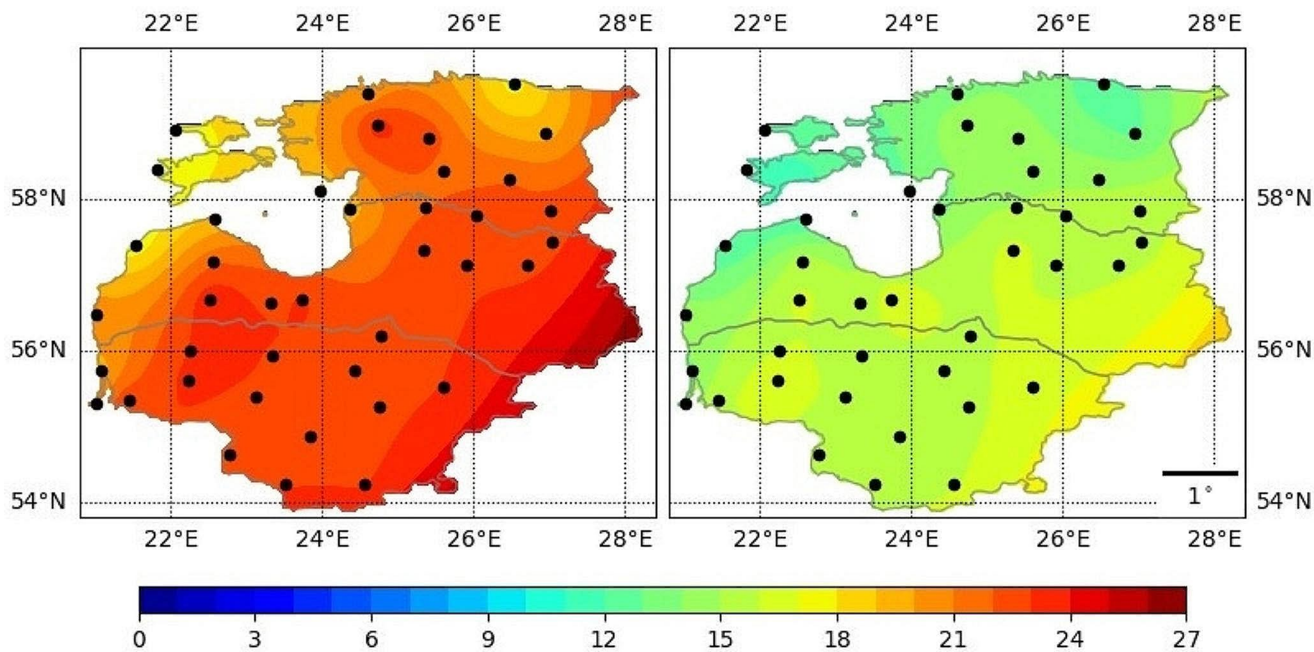

Fig. 4 Mean annual number of heat wave days (HWF) in 1951–2021 for the heat wave definitions CTX90 (**a**) and CTX95 (**b**)

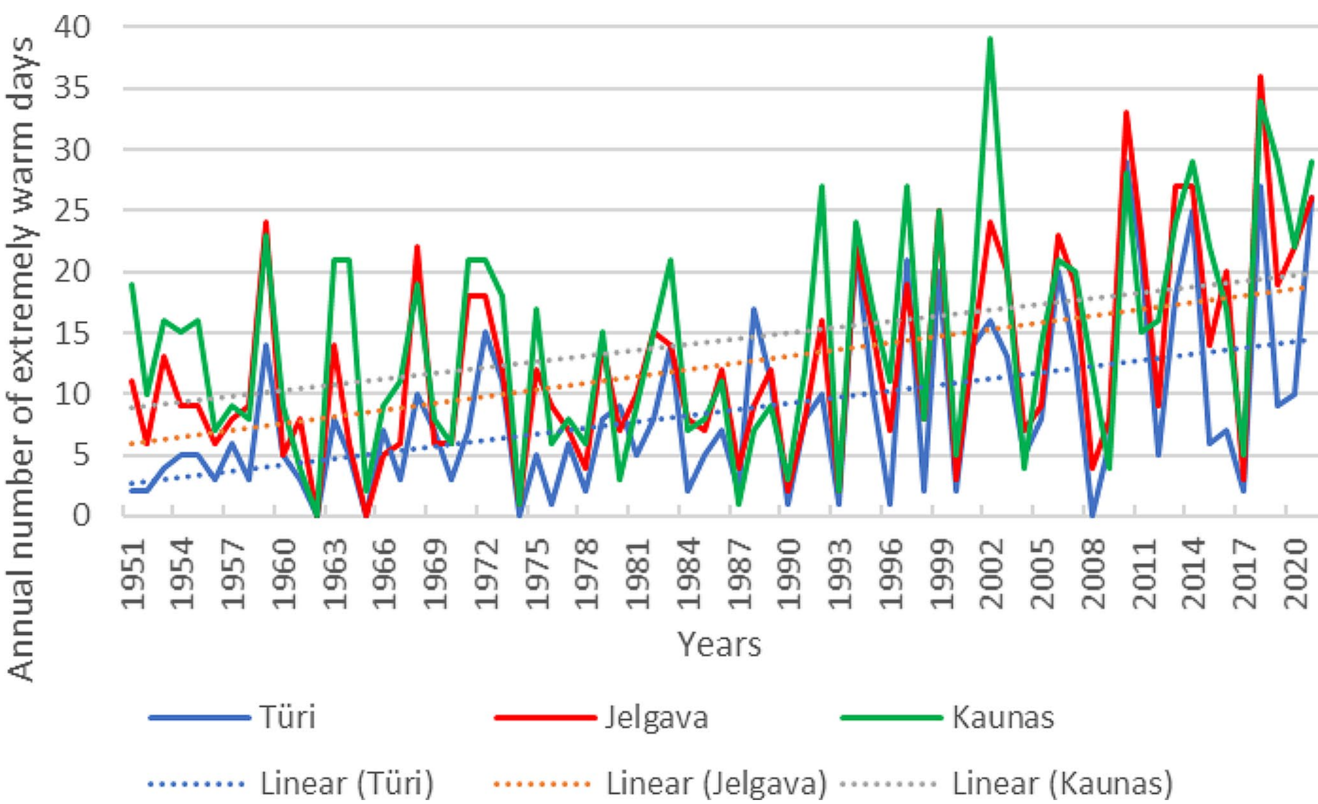

Fig. 5 Time series of the annual number of extremely warm days (Tmax > 27 °C) in Türi, Jelgava and Kaunas, and their linear trend lines

– was between Jelgava and Türi while the lowest one was between Kaunas and Türi (0.75).

Table 3 summarises the changes in the heat waves indices by countries. In the case of heat wave definitions CTX and CTN changes by trend are calculated with the Sen's method while for EHF they are found using linear regression.

Changes in the reoccurrence and duration of heatwaves (HWF, HWN, HWD) are more significant than changes in magnitude (HWA, HWM). At the same time, trends for the 90th percentile values of the heat wave definition are stronger and more significant than in the case of trends for the 95th percentile. Thereby, trend value in the case of CTN are mostly higher than in the case of CTX. It means that heat waves related to daily minimum temperature have a stronger increase than heat waves calculated using daily maximum temperature. In the average, changes are higher in Estonia than in Latvia and Lithuania.

The heat wave frequency (HWF), i.e. the total number of heat wave days per year is one of the most important heat wave characteristics. It has experienced a substantial increase in the study region. Its trends are highly significant nearly at all stations. The change values for the whole 71-year period are comparable with corresponding mean values in Table 2 and, in some cases, they even exceed means. We can conclude that HWF has increased by more than twice during 1951–2021. There are only some stations where the trend is insignificant: Ainaži (CTX95), Alūksne (CTN95, CTN90), Jelgava (CTN95, CTN90), Utena (CTN95), Laukuva (EHF95, CTN90) and Varena (CTN90).

The spatial distribution of changes by trend in HWF is demonstrated on Fig. 6. Higher trend values can be found for the heat wave definition CTN and lower for CTX. Interannual dynamics of HWF at the three stations indicate quite high correlation with very similar trend values (Fig. 7). Correlation coefficient between Jelgava and Türi was 0.89 while Kaunas has much lower correlations with these two stations – 0.72.

The mean number of heat waves (HWN) in the study region is 3–5 per year in the case of the heat wave definitions CTX and CTN while it is only 1–2 in the case of the definition EHF. In the majority of stations trends in HWN are statistically significant. 2–3 heat waves have been added during the study period. In the case of CTX the increase was stronger in the southern part of the study region while for CTN it was higher in the northern part (Fig. 8). In the latter case, the highest trend values can be found in the coastal stations (Fig. 8b).

The third heat wave index, the duration of the longest heat wave per a year (HWD), has more or less similar to HWF and HWN tendencies during 1951–2021. Its mean values are up to six days for CTX95 and CTN95, and 7–8 days for CTX90 and CTN90. Heat wave durations for EHF are lower but their changes by trend are much higher, especially for EHF95. It is interesting that changes in CTX are notably lower in the Lithuanian stations while they are higher in the case of the definition CTN (Fig. 9).

Changes in heat wave amplitudes HWA are also increasing but much less significant than in the cases of the previous heat wave indices (Table 3). For the definition CTN, they are mostly significant but not for the definition CTX. Changes for the definition EHF are variable (Fig. 10). Higher values revealed in the coastal region and in the northern part of the study region while changes in the southern part are mostly

Table 3 Trend values, i.e. changes by trend per decade in heat wave indices averaged by countries. Bold indicates that statistically significant change revealed in the majority of stations

		HWF	HWN	HWD	HWA	HWM
CTX90	Estonia	**2.39**	**0.34**	**0.42**	**0.25**	0.06
	Latvia	**2.15**	**0.32**	**0.35**	0.21	0.07
	Lithuania	**2.25**	**0.38**	0.28	**0.25**	**0.10**
CTX95	Estonia	**1.73**	**0.27**	**0.32**	0.25	0.07
	Latvia	**1.62**	**0.27**	0.23	0.20	0.07
	Lithuania	**1.82**	**0.34**	0.18	**0.30**	**0.10**
CTN90	Estonia	**2.76**	**0.49**	**0.41**	**0.30**	0.06
	Latvia	**2.21**	**0.35**	**0.32**	**0.25**	0.04
	Lithuania	**2.37**	**0.32**	**0.41**	**0.28**	**0.07**
CTN95	Estonia	**1.99**	**0.41**	**0.32**	**0.30**	0.07
	Latvia	**1.65**	**0.30**	**0.24**	**0.24**	0.06
	Lithuania	**1.92**	**0.30**	**0.38**	**0.30**	**0.08**
EHF90	Estonia	**1.92**	**0.28**	**0.66**	**2.93**	0.42
	Latvia	**1.97**	**0.27**	**0.77**	2.25	0.27
	Lithuania	**1.69**	**0.28**	**0.55**	1.56	0.15
EHF95	Estonia	**1.13**	**0.24**	**0.42**	**2.51**	**0.82**
	Latvia	**1.04**	**0.21**	0.41	**1.79**	0.59
	Lithuania	**0.87**	**0.18**	**0.38**	1.49	0.39

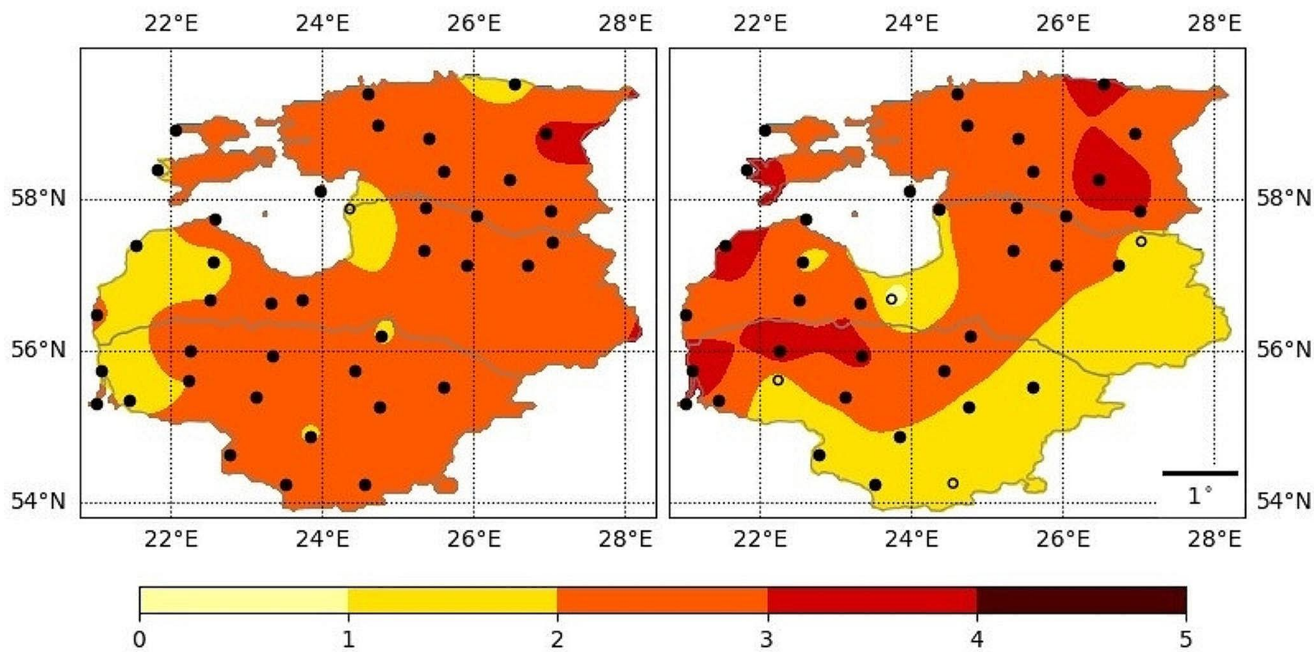

Fig. 6 Trend values (change per decade) of HWF for the heat wave definitions CTX90 and CTN90 in 1951–2021. Black dots indicate stations with a statistically significant trend and circles show stations without a significant trend

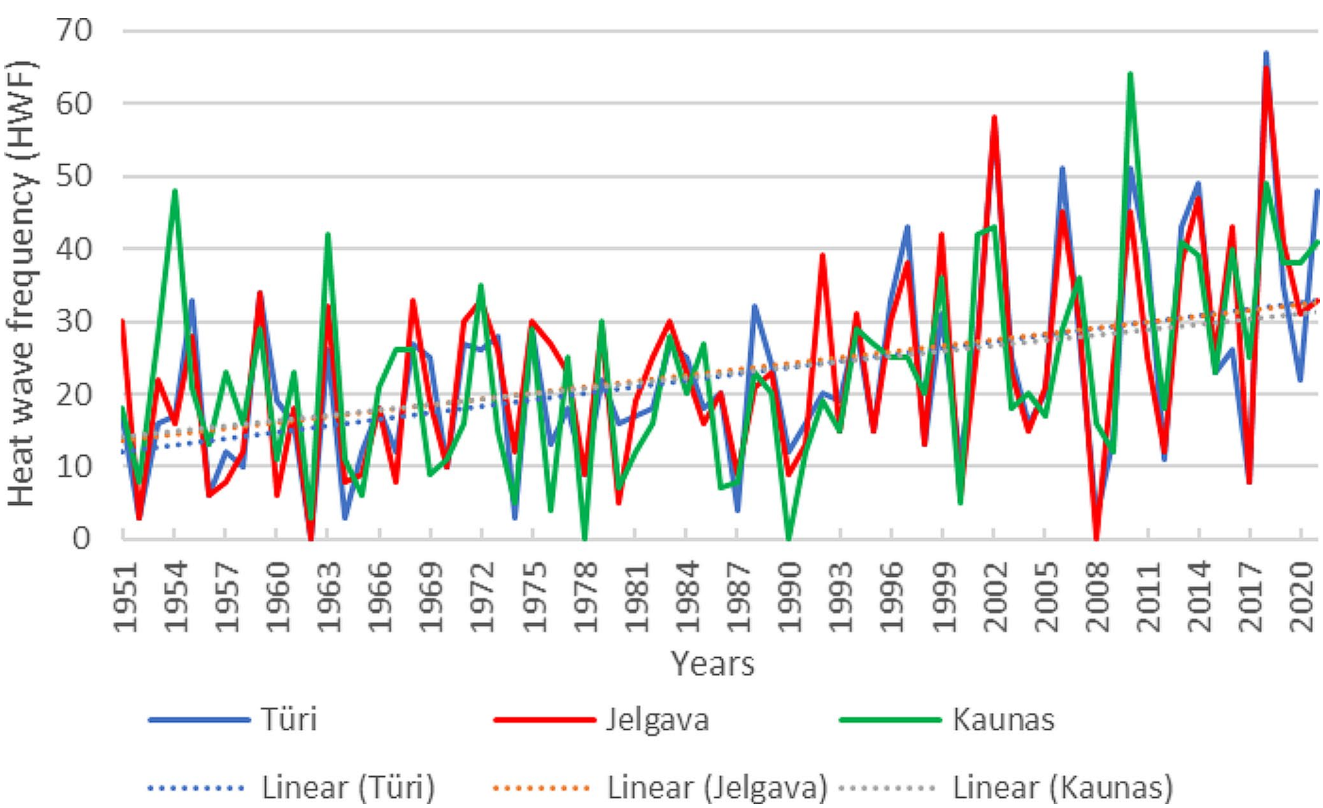

Fig. 7 Time series of the heat wave frequency (HWF) in days for the heat wave definition CTX90 in Türi, Jelgava and Kaunas, and their linear trends

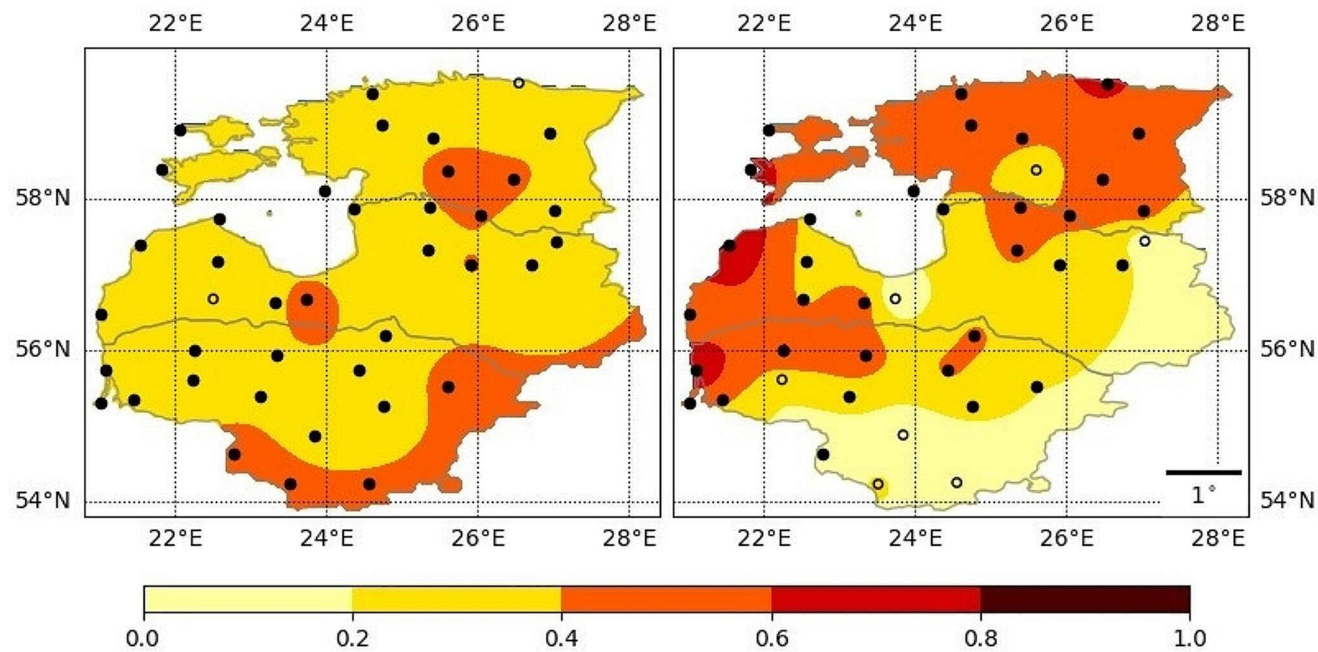

Fig. 8 Trend values (change per decade) of HWN for the heat wave definitions CTX90 (**a**) and CTN90 (**b**) in 1951–2021. Black dots indicate stations with a statistically significant trend and circles show stations without a significant trend

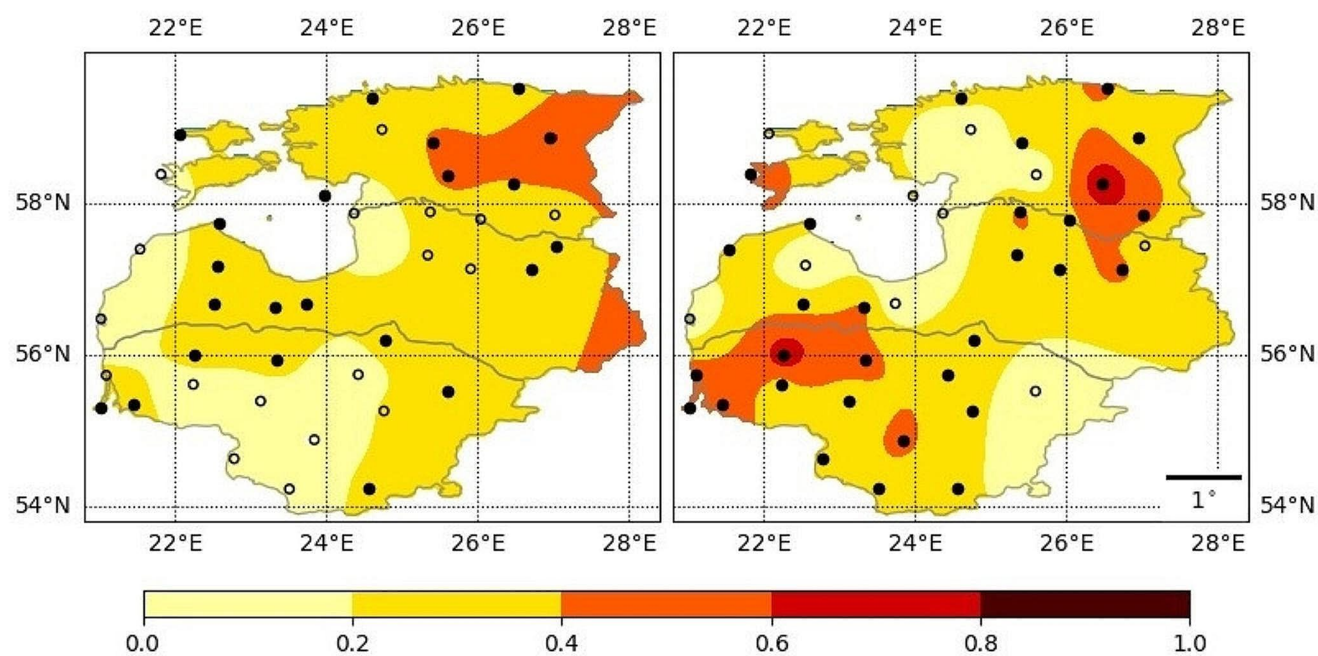

Fig. 9 Trend values (change per decade) of HWD for the heat wave definitions CTX95 and CTN95 in 1951–2021. Black dots indicate stations with a statistically significant trend and circles show stations without a significant trend

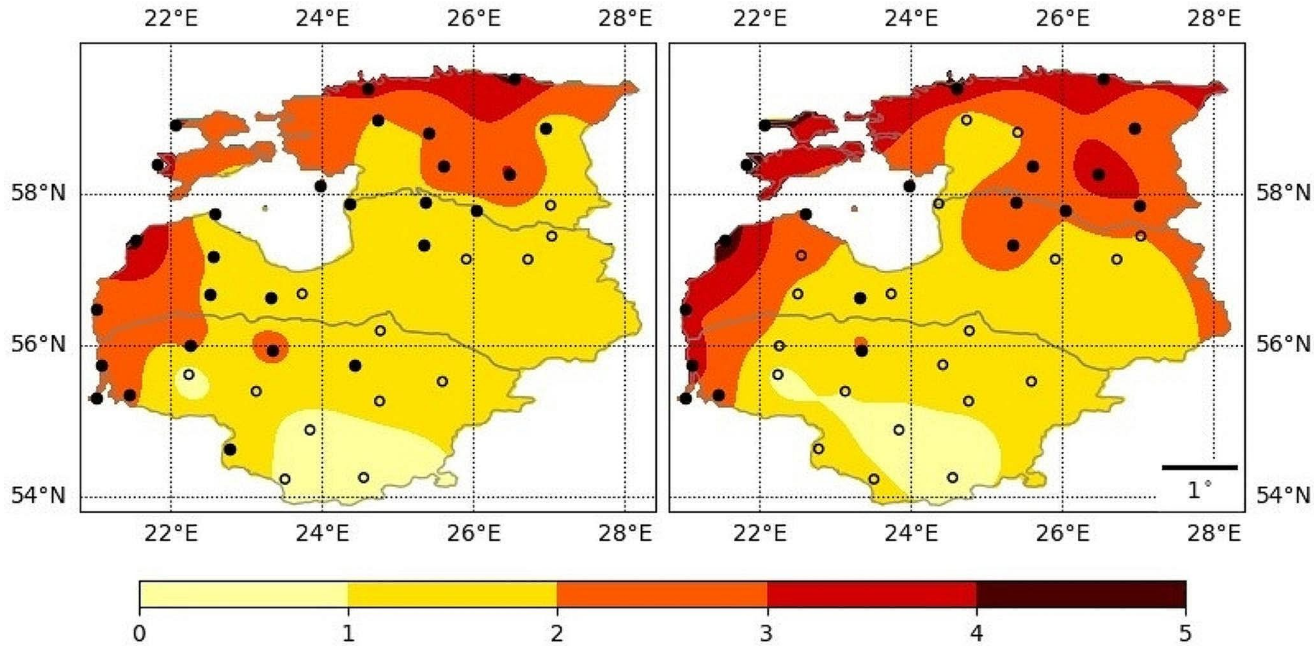

Fig. 10 Trend values (change per decade) of HWA for the heat wave definitions EHF95 (**a**) and EHF90 (**b**) in 1951–2021. Black dots indicate stations with a statistically significant trend and circles show stations without a significant trend

insignificant. This definition of heat waves exaggerates heat values so that their unit is squared centigrade.

Heat wave magnitude (HWM) is the index that has the lowest increasing trends in the study region. Its changes are much lower and of less significance. The majority of stations have statistically significant change only in Lithuania in the case of heat wave definitions CTX and CTN (Table 3).

4 Discussion

The occurrence of days with high temperature is concentrated to mid-summer. It is very natural for the eastern Baltic region because of a short warm season due to comparatively high latitude. It is interesting that the mean number of extremely warm days (Tmax > 27 °C) varies much day by day (Fig. 2). This fluctuation might be random, which diminishes with the addition of years of observations. At the same time, these fluctuations might reflect certain regularities in atmospheric circulation causing higher frequency of heat waves in some dates and lower frequency in other dates.

The results of trend analysis show a statistically significant increase in the variables of heat waves that corresponds well to the climate warming. They also indicate that the changes in the higher latitudes, i.e. in Estonia, are a bit higher than in the lower latitudes, in Lithuania. This result approves our preliminary hypothesis. In the first half of the study period, heat waves were quite rare in the north. Therefore, the increase in heat waves is proportionally higher there. Increase in air temperature in Estonia has been slightly faster than in Lithuania during last decades (Jaagus et al. 2014, 2017; Rutgersson et al. 2014).

We suggest that the results of this study adequately reflect real changes. Such artificial changes as urbanisation and urban sprawl have no significant influence on temperature measurements in this region where the population has not significantly increased. There have no examples where a station was located out of an urban area in the beginning of the study period and later stayed within city limits. The only factor that may artificially increase air temperature during the study period is the growing of trees around the observation site. It has decreased wind speed and, therefore, increased local temperature during summer season.

We detected nearly a doubling of the number of days with extremely high temperature (above 27 °C) during the study period. Comparing this change with the results of trend analysis of extremely high temperature in the neighbouring regions we found clear similarities. Ustrnul et al. (2021) analysed temperature changes in 58 stations in Poland during 1951–2018. An extremely high warming by 0.4 °C per decade or by 2.7 °C for the whole period was detected in Warsaw and Krakow. Especially strong increase revealed in the case of the number of days with maximum air temperature exceeding 90 percentile values in summer. It has increased by 1.9 days per decade arriving values above 20 days per summer season in the last decades as depicted on Fig. 11.13b in Ustrnul et al. (2021).

Heat wave frequency and severity was analysed on a basis of daily maximum temperature from 26 stations in Poland during 1951–2015 (Wibig 2018). Heat waves were defined as the longest continuous period during which daily maximum air temperature (Tmax) is equal to or higher than 30 °C in at least three days, the mean Tmax during the whole heat wave is equal or higher than 30 °C and Tmax does not drop below 25 °C during the whole period of heat wave duration. An increasing trend in heat wave frequency and intensity was observed, however the increase was statistically significant at only about 60% of analysed stations (Wibig 2018). Hot days and heat waves were related to certain types of atmospheric circulation over Poland (Wibig 2021).

Statistically significant increasing trends in daily maximum temperature was found in the Nordic countries during the second half of the 20th century (Tuomenvirta et al. 2000). This result is confirmed in the study on warm extremes over the whole Europe (Klein Tank and Können 2003). The length of summer heat waves in the western Europe has doubled and the frequency of hot days has even tripled in 1880–2005 (Della-Marta et al. 2007).

Results of the trend analysis of the five heat wave indices are in line with the results described above. Increasing trends are dominating in the majority cases but there are some remarkable differences. Heat wave frequency (HWF) or the total number of days with a heat wave seems to be one of the best indicators of heat wave activity. Its increase has been significant in all stations. This number is almost doubled during 1951–2021.

The heat wave definition CTN using daily minimum temperature have usually higher change values than the definition CTX using daily maximum temperature. This corresponds well to the fact that the increase in daily minimum temperature has been faster than the increase in daily maximum temperature (Jaagus et al. 2014).

The results of this study generally are in line with the results on changes in heat waves in other regions. The IPCC reports an increase in the frequency, magnitude and duration of heat waves all over the World and projects the continuation of this change during this century (IPCC 2021). A significant increase in three heat wave indices (HWF, HWN, HWD) has been observed in Australia (Perkins and Alexander 2013). These indices had the strongest changes also in this study. Similar tendency is detected also in Europe (Kysely 2010). Using global temperature datasets statistically significant increasing trends for several heat wave parameters (number of heat wave days, length of the longest heat wave, cumulative intensity of heat waves) were detected in Europe including the eastern Baltic region (Perkins-Kirkpatrick and Lewis 2020).

Increase in heat waves in Europe is related to shrinking Arctic sea ice and Eurasian snow cover (Zhang et al. 2020). Similar changes have been observed all over the World, in British Isles (Sanderson et al. 2017), Ukraine (Shevchenko et al. 2014), China (Luo and Lau 2017; Xie et al. 2020), India (Rohini et al. 2016), Pakistan (Khan et al. 2019), North Africa (Fontaine et al. 2013), the United States (Habeeb et al. 2015), Mexico (Martínez-Austria et al. 2016), Chile (Piticar 2018), Mongolia (Erdenebat and Sato 2016) and in the terrestrial Arctic (Dobricic et al. 2020).

It is not surprising that the results of this study are in line with other studies on changes in heat wave indices. Air temperature is spatially highly correlated. It means that if there have been a warm or cold summer in any station then it has been warm or cold in the whole region. As air temperature measurements are highly correlated, heat wave characteristics calculated on the base of temperature data are also highly correlated. Temporal variation and trends of these values are very similar.

5 Conclusions

The analysis of heat waves in the eastern Baltic region, in Lithuania, Latvia and Estonia revealed the following main results.

- The mean annual number of days with extremely high temperature (above +27 °C) varies in the study region between 1 and 18. It is the lowest on the Baltic Sea coast and much higher in the continental region with the maximum in southern Lithuania.
- The days with extremely high temperature have been concentrated to mid-summer, to the period from 6 July to 9 August with the peak in 25 and 26 July. The mean distribution of these days before and after the mid-summer maximum is not even. Before it, there has been a period with more or less stable mean number of extremely warm days starting with 7 June. Since 9 August the number has decreased rapidly. There have been significant day by day fluctuations in the mean numbers of these days during the summer season.
- The geographical distribution of extremely high temperature has been determined by two main factors – latitude and the Baltic Sea. In the southern part of the study region the number of days with extremely high temperature (above 27 °C) is much higher than in the northern part, especially during the warmest part of summer in the end of July and in the beginning of August. The

number of such days in the coastal region is much lower than in the continental part. Due to the fact that the percentage of coastal stations in Estonia and Latvia is much higher than in Lithuania, the country mean numbers of days with extremely high temperature are there significantly lower.

- Territorial variability of mean values of the heat wave parameters is comparatively low due to the fact that heat waves are defined using percentiles. Their mean values are the following: HWF – 12–17 days; HWN – 2.5–4; HWD – 5–6 days; HWA – 3–6 °C; HWM – 1–3 °C for the 95th percentile, and HWF – 17–24 days; HWN – 3–5; HWD – 6.5–8 days; HWA – 4–7 °C; HWM – 1.5–3 °C for the 90th percentile.
- The increase in the number of days with extremely high temperatures (> 27 °C) was statistically significant at all stations during 1951–2021. The mean change has been by 9.2 days, which corresponds to the trend value 1.3 days per decade. It means a very high increase, practically a doubling of the number of days with extremely high temperature.
- Increasing trends in the heat wave parameters are prevailing. The strongest changes were detected for HWF, which are statistically significant in all stations. The total number of days with heat wave has nearly two times higher in the end of study period in comparison with its beginning. Generally, the increase is stronger and mostly statistically significant for the parameters measured in days (HWF, HWN, HWD). Parameters showing temperature anomalies (HWA, HWM) have much lower increasing tendencies, which are in the case of HWM mostly insignificant.
- The heat wave definition CTN using daily minimum temperature have usually higher change values than the definition CTX using daily maximum temperature.

Author contributions All authors contributed to the study conception and design. Material preparation was made by J.J., A.B. and E.R. Heat wave indices were calculated and maps were designed by V.S. The trend analysis was realised by J.J., A.A. and J.K. The first draft of the manuscript was written by J.J. and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability No datasets were generated or analysed during the current study.

Code availability Not applicable.

Declarations

Competing interests The authors declare no competing interests.

Ethics approval Not applicable.

Consent participate Not applicable.

Consent for publication Not applicable.

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