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ORIGINAL PAPER

Regional and altitudinal aspects in summer heatwave intensification in the Western Carpathians

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Abstract

The current warming of climate has led to an enhancement of the extreme temperature risks threatening various systems. Following that, we analysed the progress of the main type of the temperature-extreme weather events—heatwaves (HWs). We focused on the area of the Western Carpathians (Central Europe), since the Carpathian Mountains are widely recognised as an important biodiversity hot-spot particularly for mountain species in Europe. The HWs were identified for a range of elevations from low to high altitudes including a high mountain station. We used the percentile threshold-based calculation of HW, which in comparison to those using absolute thresholds allows for revealing the possible threats of climate warming extremes at the range of altitudes. We observed the HWs based on the maximum (HW_{MAX}) and average (HW_{AVG}) daily air temperatures in June–August during the period of 30 years (1989–2018) and we characterised them by the strength, frequency, and duration of the longest HW event. The Mann-Kendal trend test of these heatwave characteristics was significantly positive ($p < 0.05$) at most of stations throughout the region of Western Carpathians. At the high mountain station, particularly the maximum temperature exceedance increased, indicated by significant positive trends of HW_{MAX} in strength ($p = 0.02$), frequency ($p = 0.01$), and duration of the longest event ($p = 0.02$). The majority of the strongest HWs occurring across Europe over the last three decades hit the area of Western Carpathians. More importantly, the area experienced the regional HWs, severity of which was comparable to those of exceptionally strong HWs, although these regional HWs were less important from the large-scale aspect. The greatest intensification of HWs is evident particularly in the last decade, although the longest HW_{MAX} event from 1994 was not exceeded. Our results show potentially enhanced HW-induced stress to organisms as a consequence of the coincidence of HW_{MAX} and HW_{AVG} of the comparable strength during the last decade.

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1 Introduction

European weather is mainly influenced by large-scale circulation patterns such as the jet stream, Atlantic storm tracks, and atmospheric blocking (Woollings 2010). When the atmospheric blocking occurs, the persistent high-pressure systems (or anticyclones) remain quasi-stationary over a given location or region and block the climatological westerly flow at mid-latitudes for several days to weeks (Barriopedro et al. 2011; Brunner et al. 2017). This situation may lead to prolonged periods of extremely high temperatures for a particular region—heatwaves (HWs) (Perkins 2015)—via radiative forcing or advection. For the northern part of the Carpathian region, the centre of the high and anticyclonic wedge or ridge of high pressure was identified as air circulation having a significant impact on the thermal stress (Błażejczyk et al. 2020).

Heatwaves incur widespread devastating impacts on various systems, which were noticed throughout last decades in the regions worldwide (Russo et al. 2015; Ebi and Meehl 2007). During the past extreme heatwaves with both the abnormally high daytime and night-time temperatures, huge mortality of humans was observed (Coumou and Rahmstorf 2012; Kosatsky 2005; McMichael and Lindgren 2011; Trigo et al. 2005). Immediate consequences to human lives (Výberči et al. 2015; Tomczyk et al. 2020) and health are evident on the days of heatwave occurrence. However, the incidents of extreme heats affect many different systems. Dead mammals (Welbergen et al. 2008) or avians (McKechnie and Wolf 2010), destroyed human infrastructures (McEvoy et al. 2012), fires (Karoly 2009; Koutsias et al. 2012; Parente et al. 2018), loss of agricultural productions (Barriopedro et al. 2011; Dunn et al. 2014; Barlow et al. 2015), and other consequences happen during and after the HWs to mention but a few of the negative impacts.

Previous studies (Beniston and Stephenson 2004; Alexander et al. 2006; Fischer and Schär 2010; Barriopedro et al. 2011; Stott et al. 2011; Seneviratne et al. 2012; Sillmann et al. 2013) concluded that the global surface temperature increase would alter the strength and the frequency of heatwave events. A correlation between global warming and climate extremes has been discussed for heatwaves and the modelled results for Europe show that future heatwaves will become more intense, more frequent and longer-lasting in the second half of the twenty-first century (Meehl and Tebaldi 2004), and will further extend to months out of climatological summer (JJA) (Vaničková et al. 2017). The intensity of extreme temperatures is expected to increase more rapidly than the intensity of moderate temperatures over the continental interior due to increases in temperature variability (Beniston et al. 2007). Although the heatwaves are meteorological events, they can be studied from the climatological aspect as well. In the climate science literature, a variety of heatwave indices has been introduced. Some of them use the exceedance of percentiles of daily normal temperature (Meehl and Tebaldi 2004; Alexander et al. 2006; Fischer and Schär 2010; Stefanon et al. 2012; Russo et al. 2014), others account for exceedance of an absolute threshold (Robinson 2001; Lapin et al. 2016), and some combine the two (Alexander et al. 2006). In this study, we take advantage of relative-based threshold indices, such as high percentile values, since they allow measuring the heatwaves across various locations and altitudes over long periods. Since living organisms are adapted to the local climate, longer exposures to the temperatures substantially higher than the normal, although not extremely high, may contribute to the changes in ecosystem thermophilisation (Evangelista et al. 2016) or injuries. Heat stress is thought to be one of the most serious stresses for plants because of its direct effect on plant metabolism. Photochemistry of photosynthesis may be directly strangled by extremely high temperatures, and when this accompanies soil water deficit, trees may experience drought stress (Rennenberg et al. 2006). The replacement of vegetation or animals, which are acclimated to colder climates by those profiting from the warmer climate, may cause the decline in the ecosystem biodiversity and services. Significantly threatened are mountain habitats in Europe with unique ecosystem diversity with highly specialised plants and animals (Barthlott et al. 1996; Myers et al. 2000; Barkasi 2016) and many endemics (Pauli et al. 2007; Mráz et al. 2016; Tordoni et al. 2020). The endemics as autochthonous components of an ecosystem are more susceptible to environmental changes, in particular, climate change, which could be related to the disappearance of the existing niche they occupy (Hermant et al. 2013). Relative threshold-based calculation of HW along the altitudinal range allows for revealing the possible threats of climate warming extremes at the range of altitudes, including the high mountains. In the high mountains, the absolute threshold exceedance, e.g. maximum temperature (T_{MAX}) reaching or exceeding 30.0 °C and 25.0 °C as tropical and summer days, respectively (Kyselý 2010), usually does not occur.

In Europe, the Carpathian Mountains are widely recognised as an important biodiversity hot-spot particularly for mountain species (Hlásny et al. 2015; Stewart 2009). The increase in the events related to high temperatures, as the expected increase of extreme events in the context of global temperature rise (IPCC 2014), was found in the Carpathians. The Carpathian Mts. are under annual and seasonal warming of both daytime and night-time air temperatures and the warming process shows a great spatial inhomogeneity (Micu et al. 2020). Over the period 1961–2010, the greatest warming was observed in summer (between 1.0 and 2.4 °C) with higher increase of the frequency and intensity of heatwaves in the western part of the Carpathians region compared to the east (Spinoni et al. 2015). In addition, by the end of the twentieth century, increased frequency of temperature extremes (the number of hot days and hot nights) was observed in the Carpathian Basin region (Csáki et al. 2020).

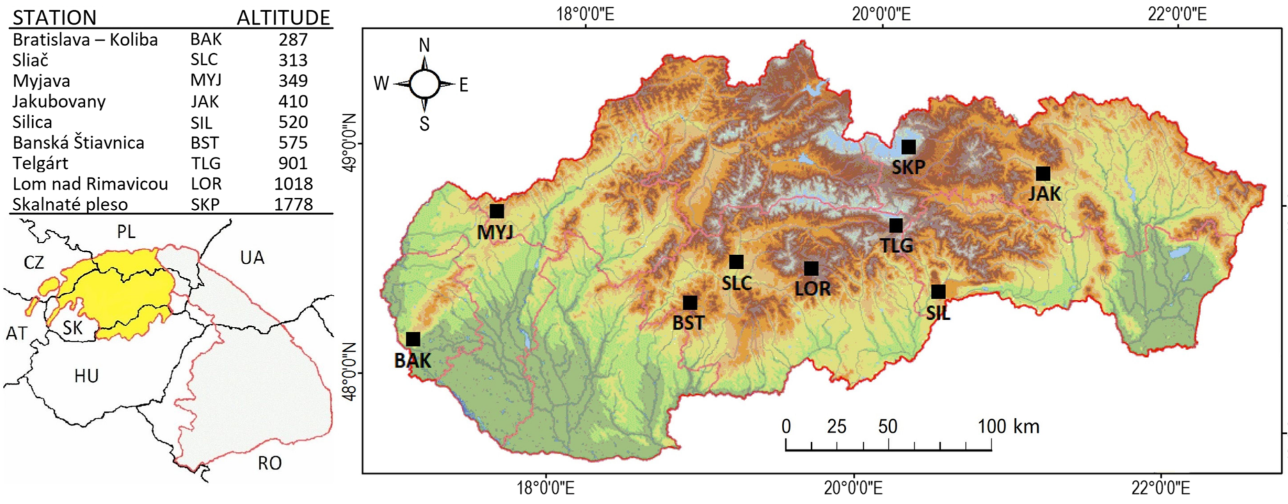
In this study, we hypothesised regionally and altitudinally conditioned differences in heatwave intensification in the Western Carpathians over the last 30 years (1989–2018). Employing the relative threshold-based method referring to the referenced period 1981–2010, we quantified the incidence of heatwaves, their strength, frequency of events, and the longest event in current climate at nine meteorological stations along a range of altitudes. Including the stations from low to the highest altitudes provided an opportunity to analyse HWs at the areas representing altitudinally and spatially different temperature regimes of the Western Carpathians. Furthermore, we emphasise the regional approach in HW observations, to identify areas particularly exposed to climate change extremes. We assume that a heatwave may hit the individual regions even in year's circumstances when the large-scale extreme temperature events do not occur.

2 Methods

2.1 Climatic stations and data

Studied areas are located in the latitudes between 48 and 49° N and in the longitudes between 17 and 22° E (Fig. 1). The meteorological data used in this study were measured at the stations belonging to the climatological station network of the Slovak Hydrometeorological Institute (SHMI) and Earth Science Institute of Slovak Academy of Sciences (ESI SAS). SHMI is a state organisation operating under the Slovak Ministry of Environment providing hydrological and meteorological services at the national and international levels.

This study utilises air temperature data obtained from nine climatological stations located at altitudes from 287 to 1778 m a.s.l. (Fig. 1). The meteorological data were subject to internal quality control within the SHMI and the homogenisation procedures are applied as standard (SHMI 2008). The weather stations were adopted from the list of climatological stations published in the SHMI report about the climatic normals in Slovakia in the period of 1981–2010, where the stations with homogenised meteorological data were included (SHMI 2016). The stations adequately represent the territory of Western Carpathians with regard to dominating climatic regions (Lapin et al. 2002), different vegetation stages (Stanová and Valachovič 2002; Škvarenina et al. 2004), and altitudes, including the high mountains (Table 1). Four stations are situated at altitudes below 500 m a.s.l. in valleys, basins, and at foothills. The lowest station Bratislava—Koliba (BAK—287 m) is located in the area of the capital city—Bratislava, on the southern slope of Little Carpathians. The station Sliač (SLC—313 m) is located in the Zvolen Basin, Myjava (MYJ—349 m) in the Myjava Hills, and Jakubovany (JAK—440 m) in the river valley between Čergov and Šariš Highlands. Four stations are located at altitudes 500–1100 m a.s.l. in mountain areas of Silica Plain—Silica (SIL—520 m), Štiavnica Mts.—Banská Štiavnica (BST—575 m), Low Tatra Mts.—Telgárt (TLG—901 m), and Vepor Mts.—Lom nad Rimavicou (LOR—1018 m). The only high mountain station is Skalnaté pleso (Fig. 1, Table 1). This station was included in



STATION		ALTITUDE
Bratislava – Koliba	BAK	287
Sliač	SLC	313
Myjava	MYJ	349
Jakubovany	JAK	410
Silica	SIL	520
Banská Štiavnica	BST	575
Telgárt	TLG	901
Lom nad Rimavicou	LOR	1018
Skalnaté pleso	SKP	1778

Fig. 1 The map of the spatial distribution of meteorological stations in Slovakia considered in this study is shown in the right figure. Stations are distributed to represent temperature conditions of Western Carpathians (yellow filing) illustrated in the left figure. A list of selected meteorological stations highlights the elevation profiles from lowlands to high-mountain altitudes

Table 1 The climatological and ecological characteristics of areas with the meteorological stations

Stations		Bratislava—Koliba (BAK)	Sliač (SLC)	Myjava (MYJ)	Jakubovany (JAK)	Silica (SIL)	Banská Štiavnica (BST)	Telgárt (TLG)	Lom nad Rimavicou (LOR)	Skalnaté pleso (SKP)
Altitude (m)		287	313	349	440	520	575	901	1018	1778
GPS	N	48°10′7″	48°38′3″	48°45′14″	49°6′32″	48°33′17″	48°26′58″	48°50′55″	48°39′38″	49°11′22″
	E	17°6′38″	19°08′3″	17°33′42″	21°8′27″	20°31′15″	18°55′18″	20°11′21″	19°39′57″	20°14′9″
Geomorpholog. unit		Little Carpathians	Zvolen Basin	Myjava Hills	Saris Highlands	Silica Plain	Stiavnica Mts	Low Tatra Mts	Vepor Mts	Tatra Mts
Position		South slope	Inter-mountain basin	Foothills	River valley	Plateau	South-west slope	South slope, Foothills	Plateau	South-west slope
Annual T [°C]		10.1	8.6	9.2	8.1	7.9	8.0	5.2	5.7	2.2
T January [°C]		−0.8	−3.0	−2.1	−3.2	−3.3	−2.4	−4.4	−3.9	−4.8
T July [°C]		20.6	19.5	20.0	18.5	18.7	18.3	15.1	15.6	10.5
Annual P [mm]		675	691	690	644	689	745	827	863	1388
WI—Warmth Index [°C]1)		76	67	69	63	62	60	39	43	17
CI—Coldness Index [°C] 1)		−15	−24	−21	−26	−27	−25	−37	−35	−50
HI—Humidity Index [mm/°C] 1)		9.0	10.3	9.9	10.2	11.0	12.4	22.0	20.0	83.0
Climatic sub-region 2)		T5	T7	M1	M3	M3	M6	C1	C1	C3
Altitudinal vegetation stage3)		1st oak stage *Carpineto-Quercetum*	2nd beech – oak stage *Fageto-Quercetum*	2nd beech – oak stage *Fageto-Quercetum*	3rd oak–beech stage *Querceto-Fagetum*	3rd oak–beech stage *Querceto-Fagetum dealpinum*	4th beech stage *Fagetum quercino-abietinum*	6th spruce-beech-fir stage *Fageto-Abietum*	5th fir-beech stage *Abieto-Fagetum*	8th dwarf pine stage *Mughetum acidifilum*
NATURA potential vegetation 4)		Pannonian white oak woods	Pannonic oak-hornbeam forests	Pannonic oak-hornbeam forests	Medio-European acidophil. beech forests	Limestone beech forests	Medio-European acidophil beech forests	Medio-European neutrophil. beech forests	Medio-European neutrophil. beech forests	Subalpine mountain pine scrub

1)WI, CI, and HI according Kira (1948) and Xu (1985); 2)climatic regions according Lapin et al. (2002) (T5—warm, moderately dry, with cool winter; T7—warm, moderately humid, with cool winter; M1—moderately warm, moderately humid, with mild winter, hilly land; M3—moderately warm, moderately humid, with mild winter, hilly land or highlands; M6—moderately warm, humid, highlands; C1—moderately cool; C3—cold mountainous; 3)altitudinal vegetation stages according to Škvarenina et al. (2004); 4)potential vegetation according to Stanová and Valachovič (2002) the analyses due to its unique position in the High Tatra Mts. (SKP—1778 m a.s.l.). High-mountain stations are usually omitted from the heatwave analyses because the probability to reach the extreme temperatures at such high altitudes is limited. It is worth mentioning that plants and animals occupying the subalpine and alpine zones may suffer from long exposures to the temperatures substantially higher than normal, correspondingly.

2.2 Heatwave (HW) definition, calculation, and trend analyses

In this study, we utilised a relative threshold-based calculation of heatwaves, since it allows to reveal the possible threats of the heatwaves across various locations and altitudes over long periods by considering the local climate conditions. Regarding the variety of HW definitions, we prefer the definition introduced by the Expert Team on Climate Change Detection and Indices (ETCCDI) adjusted according to Russo et al. (2014) to analyse the HW in a current climate. They characterised the heatwave as 3 or more consecutive days when the maximum temperatures are above the 90th percentile of that during the reference normal period 1981–2010. Following that, we calculated the 90th percentile of the daily normal maximum temperatures (TN_{MAX}), and the periods, when the daily T_{MAX} exceeded this threshold for at least 3 days in a row, which was considered as a heatwave event (HW_{MAX}). Since organisms tolerate the heatwaves better when the temperatures decrease during the nights, in this study we included the calculation of HW_{AVG} when the daily averages T_{AVG} exceeded the daily normal averages (TN_{AVG}) of 1981–2010. The total strength of the HW during JJA, as a sum of the individual heatwave events with a duration of more than 3 days, was classified into five stages of HW strengths (Table 2).

The additional basic characteristics of HW are as follows:

- the frequency of occurrence of the discrete HW events (f_{HW})—number of heatwave events during JJA in individual years,
- the duration of the longest discrete event (l_{HW}) in JJA.

Table 2 Classification of heatwave strengths according to the sum of the single HW events in a JJA season

n (HW days)	Categories of heatwaves
0 to 2	No HW
3 to 10	Weak HW
11 to 20	Moderate HW
21 to 30	Severe HW
> 30	Extreme HW

Since the occurrence of HWs depends on atmospheric circulation patterns (Russo et al. 2015), the spatial distribution of their incidence was evaluated. Trends of HW characteristics in 1989–2018 were calculated by the nonparametric Mann-Kendal (M–K) trend test. The significance level was set for $p > 0.05$ and highly significant was for $p > 0.01$. The rate of change per year increase was calculated using Sen's slopes of the M–K trend.

3 Results

3.1 Heatwave strength

As seen in Fig. 2, the strength of heatwaves rapidly increased in the last decade compared to the first two. In the first decade, 1989–1998, summers with none and weak HW were prevalent and the moderate HWs occurred only twice, in 1992 and 1994. While the HW_{MAX} in 1992 affected weakly to moderately the whole area evenly, in 1994 the effect differed spatially (Fig. 2a). In 1994, the severe HW_{MAX} occurred at Banská Štiavnica (BST) and Jakubovany (JAK), while the strength at the other stands was weak to moderate (Fig. 2a). At the most eastern station, Jakubovany, the total duration of HWs in 1994 was 28 days, out which 21 days was the longest episode. In this year, moderate HW_{AVG} occurred the only time over the decade 1989–1998. In addition, at this station, we noticed the highest number of moderate to severe HW_{MAX} in this first decade. This indicates a sufficient decrease of morning and evening temperatures during those moderate HW_{MAX}. Overall, the maximum frequency of moderate to severe HWs at individual stands in this decade was 3.

The strongest HW in the second decade 1999–2008, which occurred in 2000, was only moderate. Nevertheless, a slight increase of weak and moderate HWs was noticed. Compared to the previous decade, no severe or extreme HWs occurred (Fig. 2a, b). The highest number of moderate HW_{AVG} over 1999–2008 was 5 identified at the most western station, Bratislava—Koliba (BAK), while the highest frequency of HW_{MAX} was 3 observed at the most stations.

Compared to the previous two decades, in the period 2009–2018, the highest number of severe to extreme HWs occurred across all the altitudes (Fig. 2a, b). The severe HW (HW_{MAX}) in 2010 was noticed at Myjava (MYJ, HW_{MAX}) and Sliač (SLC, HW_{AVG}). Additionally, in 2012, the severe HW hit almost the whole area except for mountain station Skalnaté pleso (SKP) and eastern station Jakubovany, with the moderate strength indicated by both indices. Subsequently, in 2013, severe HW_{AVG} struck the stations Bratislava—Koliba, Myjava, and Banská Štiavnica (BAK, MYJ, and BSK) and HW_{MAX} occurred at Banská Štiavnica and Lom nad Rimavicou (BSK and LOR), while at the rest of the

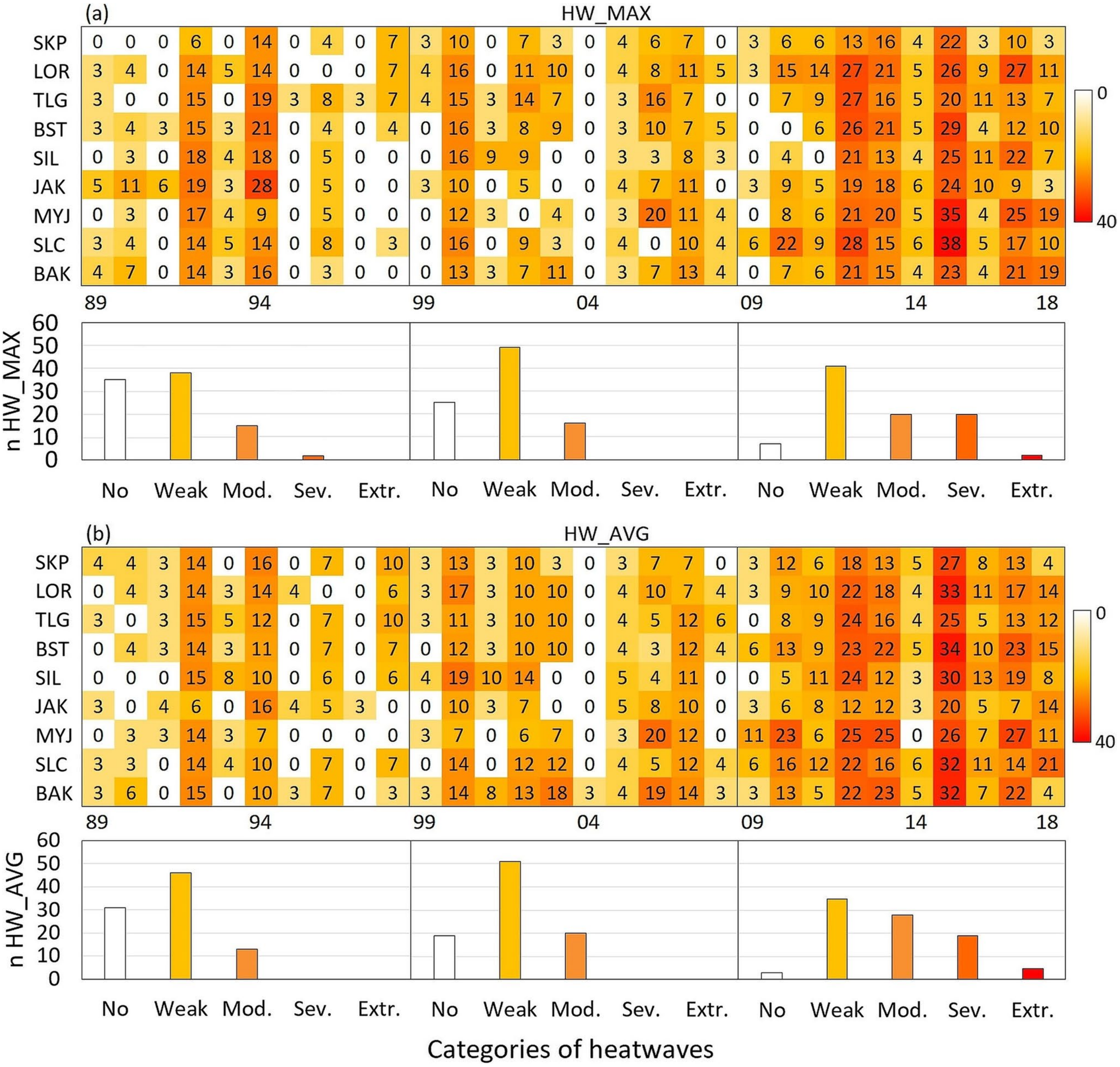


Fig. 2 The strength of HWs during the studied period 1989–2018 divided into 3 single decades. **a** The strength of HW_{MAX} calculated from maximum daily temperatures T_{MAX} in JJA. **b** The strength of HW_{AVG} calculated from the daily average T_{AVG}. The bar charts indicate the number of heatwaves in the categories: no HW, weak HW, moderate HW, severe HW, and extreme HW over the three decades: 1989–1998, 1999–2008, and 2009–2018. The colour scale represents the classification presented in Table 2

stations, the HWs were moderate. The relatively calm year 2014 was followed by the strongest HW of the whole period 1989–2018, in 2015, when the whole area of the Western Carpathians was hit by severe to extreme HWs. The extreme HW_{MAX} occurred at Sliač and Myjava and HW_{AVG} occurred at Bratislava—Koliba, Myjava, Banská Štiavnica, and Lom nad Rimavicou. In this year, we observed the severe HW at the mountain station Skalnaté pleso for the very first time in the studied period. Subsequently, in 2017, additional severe HWs occurred at Bratislava—Koliba, Myjava, Banská Štiavnica, and Lom nad Rimavicou, and in 2018 at Sliač (Fig. 2a, b). The highest number of severe to extreme HW_{AVG} over 2009–2018 was 5 observed at station Myjava, while the highest frequency of HW_{MAX} was 4 at station Lom nad Rimavicou.

The transition from the mostly none to weak HWs in the first studied decade, through the occurrence of weak to moderate HWs in the second decade, to the domination of moderate to severe with the incidence of extreme HWs in the last decade, is evident. There is a little doubt of the progress of the intensification towards the more frequent occurrence of stronger HWs in the current climate in the Western Carpathian region. This trend is clearly demonstrated with the Mann–Kendall trend test presented in Table 3. Except for the stations Jakubovany and Banská Štiavnica, where the severe HW_{MAX} occurred in 1994, the significant positive trends of HW_{MAX} were observed at all stations. Similarly, significant positive trends in HW_{AVG} were identified at these stations. Only at the high mountain station Skalnaté pleso (SKP) the trend was positive but not significant.

3.2 Frequency of the heatwave events and duration of the longest heatwave events in individual years

The Mann-Kendal trend test revealed the intensification of HWs towards the higher number of single events (f_{HW}) in individual years and the greater duration of the longest events (l_{HW}). The quantification of these characteristics and their trends are shown in Table 4 and the associated Fig. 3.

We prioritised the evaluation of the duration and frequency of HW_{MAX}, which indicates the extreme maximum temperatures at individual stations. Apart from the stations Jakubovany (JAK) and Banská Štiavnica (BST), where the longest HW events occurred in the first decade, the l_{HW_MAX} significantly increased during 1989–2018. The greater prolongation of l_{HW_MAX} with Sen's slope 0.24 day per year was noticed at the Myjava (MYJ) station. Similarly, the significant increase of f_{HW_MAX}, except for Jakubovany, Banská Štiavnica, and Telgárt (TLG), is indicated. The number of single HW events in individual year rose most significantly at mountain station Lom nad Rimavicou (LOR) (Table 4).

The l_{HW_AVG} significantly increased at all stations except for Jakubovany and Skalnaté pleso (SKP). The highest prolongation with Sen's slope of 0.19 day per year was noticed at Banská Štiavnica. In comparison, the f_{HW_AVG} significantly increased only at five stations, Sliač (SLC), Myjava, Jakubovany, Banská Štiavnica, and Lom nad Rimavicou (Table 4).

These results indicate that the increasing strength of HWs (Fig. 2, Table 3) related to both the increasing number of single HW events (f_{HW}) and the prolongation of those longest (l_{HW}). Furthermore, the average length of single heatwave

Table 3 Mann–Kendall trend test with Sen's slope (S) of the heatwave strengths. Significant trends with $p < 0.05$ are shown in bold. Stations are ranked from the lowest altitude to the highest

Station	HW_{MAX}			HW_{AWG}		
	tau	p	S	tau	p	S
BAK	0.30	**0.03**	0.3	0.33	**0.01**	0.3
SLC	0.34	**0.01**	0.3	0.42	**0.00**	0.5
MYJ	0.38	**0.00**	0.3	0.40	**0.00**	0.5
JAK	0.13	0.34	0.1	0.32	**0.02**	0.3
SIL	0.30	**0.02**	0.3	0.29	**0.03**	0.3
BST	0.23	0.09	0.2	0.41	**0.00**	0.5
TLG	0.26	**0.05**	0.3	0.30	**0.02**	0.3
LOR	0.38	**0.00**	0.4	0.39	**0.00**	0.4
SKP	0.32	**0.02**	0.2	0.20	0.13	0.2

Table 4 Mann–Kendall trend test with Sen's slope (S) of the duration of the longest HW event (l_{HW}) and the frequency of HW events (f_{HW}) in a single year. Significant trends with $p < 0.05$ are shown in bold. Stations are ranked from the lowest altitude to the highest

	Duration of the longest single HW (l_{HW})						Frequency of HWs per year (f_{HW})					
	HW_{MAX}			HW_{AVG}			HW_{MAX}			HW_{AVG}		
Station	K-tau	p	S	K-tau	p	S	K-tau	p	S	K-tau	p	S
BAK	0.27	**0.04**	0.13	0.38	**0.00**	0.14	0.31	**0.03**	0.00	0.25	0.08	0.04
SLC	0.34	**0.01**	0.16	0.37	**0.01**	0.13	0.28	**0.04**	0.05	0.39	**0.00**	0.08
MYJ	0.43	**0.00**	0.24	0.37	**0.01**	0.18	0.35	**0.01**	0.06	0.37	**0.01**	0.09
JAK	0.17	0.20	0.07	0.26	0.06	0.11	0.12	0.38	0.00	0.35	**0.01**	0.05
SIL	0.31	**0.02**	0.15	0.35	**0.01**	0.18	0.31	**0.03**	0.06	0.27	0.06	0.06
BST	0.24	0.08	0.09	0.41	**0.00**	0.19	0.16	0.25	0.00	0.40	**0.00**	0.08
TLG	0.30	**0.03**	0.14	0.34	**0.01**	0.12	0.24	0.09	0.04	0.23	0.11	0.00
LOR	0.34	**0.01**	0.14	0.34	**0.01**	0.14	0.39	**0.01**	0.08	0.40	**0.00**	0.07
SKP	0.32	**0.02**	0.16	0.24	0.07	0.09	0.37	**0.01**	0.04	0.16	0.25	0.00

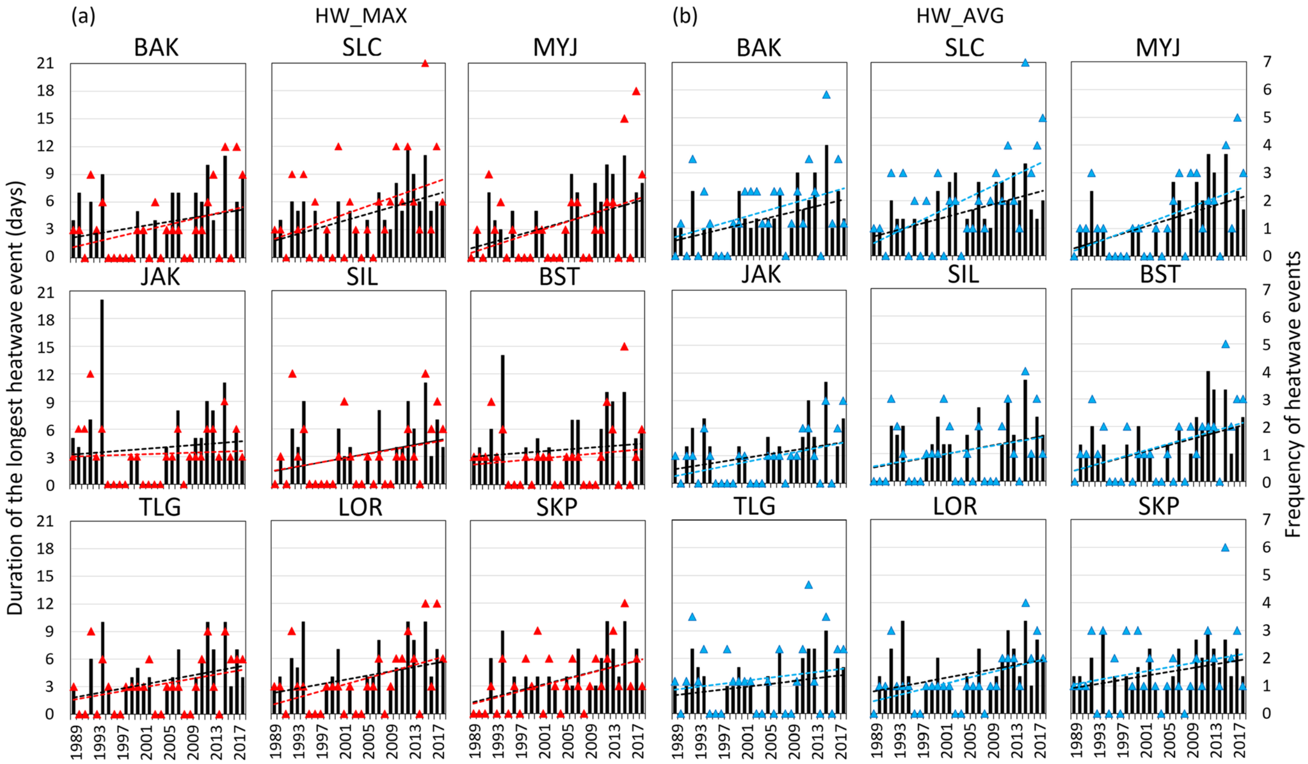


Fig. 3 Heatwave characteristics over the studied period 1989–2018. Figures with red lines and triangles represent the HW events calculated from maximum daily temperatures (HW_MAX) and that with blue lines and triangles represent the HWs calculated from average daily temperatures (HW_AVG). The bars indicate the duration of the longest single heatwave in individual summer seasons (left scale) and the black lines mark their time trends as seen in Table 4. Triangles indicate the frequency of single heatwave events in the individual summer seasons (right scale) and the colour lines, blue and red, mark the trends in the frequency of HWs as seen in Table 4

events, when excluding the years with no HWs, calculated from T_{MAX} (T_{AVG}) increased at all stations—from 4.4 (3.8) days in 1989–1998 through 4.3 (4.4) days in 1999–2008 to 5.1 (5.0) days in 2009–2018.

3.3 The longest heatwave of the period 1989–2018

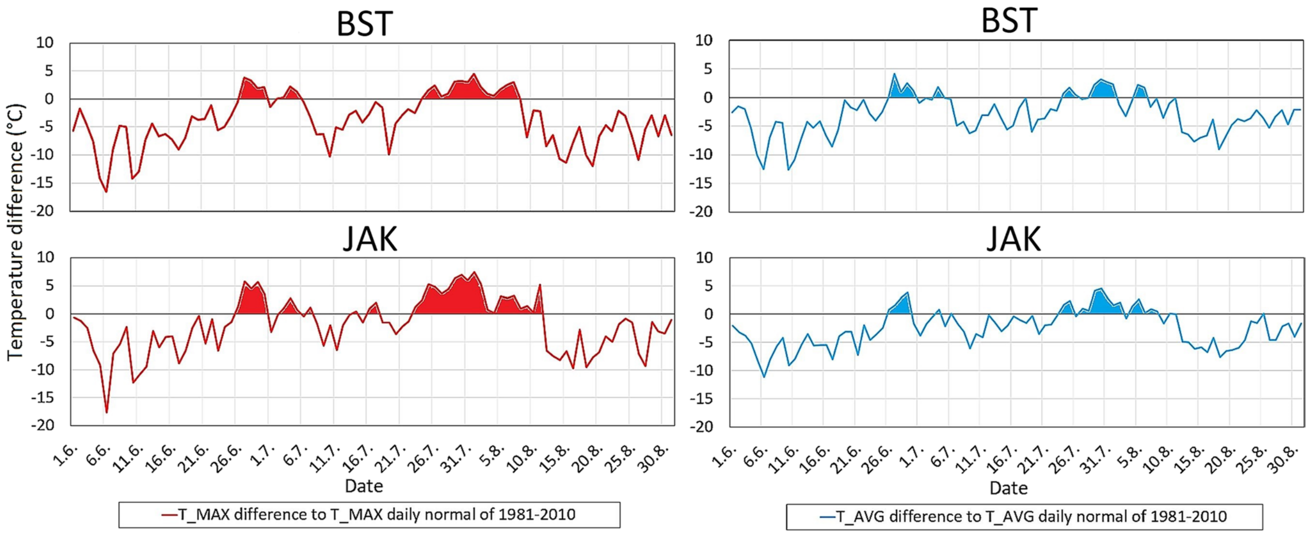
In 1994, the longest single HW event of the studied period occurred at stations Jakubovany (JAK) and Banská Štiavnica (BST), when the maximum daily temperature exceeded the 90th percentile of the referenced period for 20 and 14 days, respectively (Fig. 4a). At the station Banská Štiavnica, the total duration of HW_{MAX} over JJA was 21 days (Fig. 5). The maximum temperatures during the HWs did not exceed 35 °C. In this year, the considerably greater strength of HW_{MAX} was noticed at the station Jakubovany reaching the total duration of 28 days. In addition, we noticed the temperatures exceeded the threshold temperature 35 °C for 5 days in a row during the longest heatwave event. The HWs of summer 1994 culminated at the end of July and the beginning of August as a result of the long-term radiation heating of the lower atmospheric layer on the border of the anticyclone advection from Scandinavia to the south (Krška and Racko 1996).

In 1994, the weak to moderate strength of HW_{AVG} (Fig. 4b) indicate the drop of the evening and morning temperatures during the days with maximum temperatures considerably higher than the normal. However, in the last decade, such a decrease of the average temperatures that could alleviate the negative effects of extreme temperatures did not supervene. During the heatwaves, the HW_{AVG} occurred simultaneously with the HW_{MAX} (Fig. 2).

4 Discussion

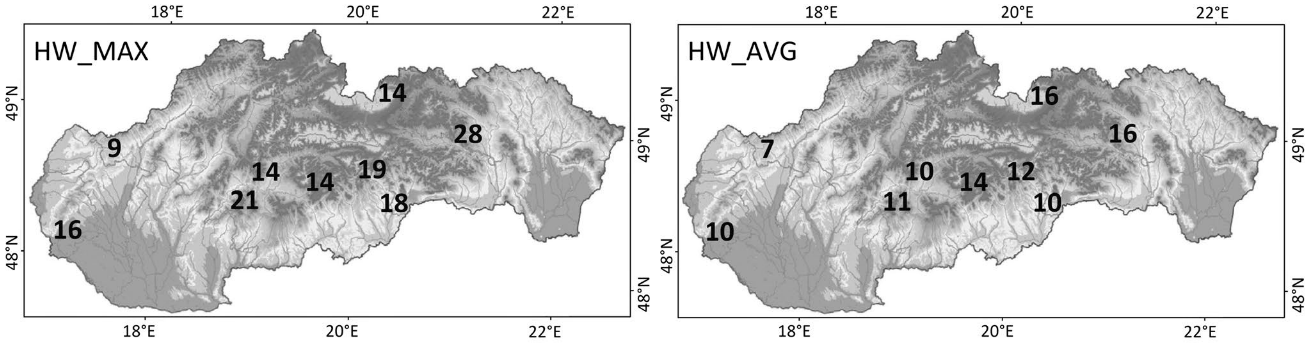
4.1 Regional aspects of the incidence of heatwaves in Europe

Our study analyses heatwaves in the Western Carpathians over the last three decades. The HW calculation based on the exceedance of the 90th percentile of daily temperatures was able to capture the HW occurrence along altitudes, including the high-mountain station Skalnaté pleso (SKP).



(a) (b)

Fig. 4 **a** The longest heatwave derived from daily maximum temperatures (HW_MAX) at the two most affected stations in 1994. **b** Heatwaves in the same year, derived from the daily average temperatures (HW_AVG). The temperature normal of referenced period 1981–2010 is set as zero



(a) (b)

Fig. 5 The total duration of the heatwaves observed over JJA in 1994 at all stations. **a** The HW_MAX derived from daily maximum temperatures. **b** The HW_AVG derived from the daily averages

Table 5 Heatwaves in Europe and their effect on extreme temperatures in Western Carpathian Mountains (WCM) during 1989–2018

HW	Characteristic	WCM
1992	The C European HW (Lhotka and Kyselý 2015)	✓
1994	The long-lasting HW (Russo et al. 2015; Zhang et al. 2020)	✓
2000	The C European HW (Lhotka and Kyselý 2015)	✓
2003	The widespread HW in W and C Europe (Trigo et al. 2005; Beniston et al. 2004)	
2006	The HW in C Europe (Rebetez et al. 2009)	✓
2007	The SE Europe HW (Founda and Giannakopoulos 2009)	
2010	The Russian and E Europe HW (Barriopedro et al. 2011; Zhang et al. 2020)	
2012	HW in Czechia (Holtanová et al. 2015), Greece (Founda and Santamouris 2017)	✓
2013	C Europe and British islands HW (Scott 2013)	✓
2014	The N and E Europe HW (Wilcke et al. 2020)	
2015	The C and S European HW (Russo et al. 2015; Zhang et al. 2020)	✓
2017	W Europe and Euro-Mediteranean HW (Kew et al. 2019)	✓
2018	The N Europe HW (Yiou et al. 2020; Wilcke et al. 2020; Spensberger et al. 2020)	✓

As can be seen in Table 5, Europe has experienced many extreme temperature events over the last 30 years (Russo et al. 2015; Trigo et al. 2005; Beniston and Stephenson 2004; Rebetez et al. 2009; Founda and Giannakopoulos 2009; Barriopedro et al. 2011; Wilcke et al. 2020; Yiou et al. 2020), and earlier in years 1954, 1969, 1972, and 1979 that hit mainly the area of Northern and Eastern Europe (Russo et al. 2015). This exhaustive list of large-scale heatwaves that occurred in Europe (Table 5) during the last three decades shows that most of them took place in the region of Western Carpathians. However, the Western Carpathian Mountains experienced the regional HWs, severity of which was comparable to those exceptionally strong, but less important from the large-scale aspect.

During the first decade, two heatwaves of moderate to severe strength occurred in the studied region. While the 1992 HWs were at most moderate, the summer 1994 was considered one of the hottest summers from the beginning of meteorological observations (Krška and Racko 1996; Russo et al. 2015; Zhang et al. 2020). It was unusually hot, setting a record for high temperature in many areas on the Northern Hemisphere (Bai et al. 1995). In the summer of 1994, we noticed the longest HW_{MAX} events at some stations that were not surpassed even in the next decades.

The following regionally important HW of a moderate strength occurred in 2000, which was in the Western Carpathians, stronger than the exceptionally intense European HW of 2003, with mean temperatures exceeding the averages of the past 500 summers (Trigo et al. 2005). The weather conditions, which characterise heatwaves, are highly conductive to toxic gas—tropospheric ozone formation and persistence (Pellegrini et al. 2007). Inducing the oxidative stress, tropospheric ozone is regarded as one of the major stressors for biota, which decreases photosynthesis, plant growth, and biomass accumulation (Braun et al. 2014) and causes respiratory diseases (WHO 2013). In 2003, the measurements at most of the European ground level ozone monitoring stations showed exceptionally high values of tropospheric ozone concentration related to the heatwave. Confirmed throughout the studied region, the extremely high tropospheric ozone concentrations were noticed only in the SW Slovakia (Bičárová et al. 2005), which corresponds to the heatwave occurrence observed only on the foot of the Western Carpathian Mts at Bratislava—Koliba station (Fig. 2). During the heatwave in Central Europe in 2006 (Rebetez et al. 2009) and the heatwave in Southeastern Europe in 2007 (Founda and Giannakopoulos 2009), only a weak to moderate effect of HWs was noticed in Western Carpathians. In 2010, the anomalous warmth that caused adverse impacts exceeded the amplitude and spatial extent of the previous hottest European summer of 2003. In most of Eastern Europe, mainly Ukraine (Shevchenko et al. 2014) and large parts of Russia (Barriopedro et al. 2011; Zhang et al. 2020), the summer of 2010 was exceptionally hot. This year, some stations in the Western Carpathian region experienced severe HWs that have not occurred since 1994. So-called mega-heatwaves, such as the heatwaves of 2003, 2010 (Barriopedro et al. 2011), or 2015 (Krzyżewska and Dyer 2018), likely broke the 500-year-long seasonal temperature records over approximately 50% of Europe (Barriopedro et al. 2011).

In the last analysed decade 2009–2018, several heatwaves occurred in the Western Carpathians (Fig. 3), the influence of which was far more severe than well-known events of the summers of 2003 and 2010. In 2012 and 2013, the severe HWs hit the studied region almost entirely; however, these HWs were not identified as the most severe HWs in Europe (Russo et al. 2015; Zhang et al. 2020), even though in 2012 they hit also Czechia (Holtanová et al. 2015) and Greece (Founda and Santamouris 2017), and in 2013 the Central Europe and British islands (Scott 2013). The climate-induced stress to organisms is exacerbated when the extreme events occur together, as happened in 2012, when the HW accompanied by the exceptional drought periods threatened the Western Carpathian region (Vido and Nalevanková 2020). However, while pan-European droughts were recorded particularly in 2003 and 2007, the drought stress was not amplified by the HW actions in the studied region. The next HW that occurred in 2014 in North and Eastern Europe (Wilcke et al. 2020) did not reach Western Carpathians. However, 1 year later, in summer 2015, the exceptionally hot HW dominated in the Central and Southern Europe (Russo et al. 2015) with all-time temperature maxima recorded in several regions in the UK, France, Switzerland, Germany, and Spain (Di Liberto 2015). In Poland, the 2015 HW was considered as the mega-heatwave, lasting from 9 days in Bialystok to 14 days in Warsaw and Poznan (Krzyżewska and Dyer 2018). According to our results, this was the most extreme heatwave in terms of severity in the studied region in the analysed 30-year period (Fig. 2). In 2015, in addition to Europe, regions worldwide, including Western North America and large parts of Asia (particularly India, Pakistan, and Indonesia), experienced a number of notable extreme temperature events during this summer. Furthermore, there was a warm spring and fall in Australia, Alaska, and western Russia (Greenhalgh 2016). HWs with abnormally high night temperatures that occurred in the European and Euro-Mediterranean region in summer 2017 (Kew et al. 2019) hit the Western Carpathians with moderate to severe strength.

4.2 Implications of heatwaves in forest ecosystems along altitudes

By comparing the heatwaves using coefficients derived from average and maximum temperatures, we identified the summers when both HW_{AVG} and HW_{MAX} occurred simultaneously. Such a summer was considered more dangerous to organisms than a summer when only HW_{MAX} occurred because the opportunity to recuperate was minimised in above-normal daily temperatures. During the longest HW_{MAX} period in 1994, the weak to moderate strength of HW_{AVG} (Fig. 4b) showed that during the HW_{MAX} days, the average temperatures dropped below the normal. The heatwave was thus more bearable as the organisms could potentialy regenerate. However, the difference between summer above-normal average and maximum air temperatures continually decreased, what is conditioned by a higher increase of daily minima compared to maxima (Švec et al. 2016). The HW_{AVG} occurred along with the severe and extreme HW_{MAX} at most of the stations in 2012, 2013, 2015, and 2017. The heatwaves thus become more difficult to be tolerable for living organisms.

The Carpathian mountain region is one of the most significant biodiversity refuges on the European continent (Werners et al. 2016). Extreme temperatures together with drought and wind gusts were identified as the most significant threats of a natural origin with a close link to forest destabilisation (Středová et al. 2020). The coincidence of extreme summer air temperatures and drought influences directly vegetation physiological processes (Střelcová et al. 2013). Even populations living under regular suitable climatic conditions may be vulnerable to extreme climate events, such as heatwaves or droughts (Lloret and Kitzberger 2018; Margalef-Marrase et al. 2020). The extreme summer temperatures aggregated in heatwaves, which were analysed in this study, significantly increase the vapour pressure deficit leading to the increase of evaporative demands of the atmosphere on vegetation transpiration. Although the decline in gross primary productivity of forest ecosystems caused by heatwaves is smaller than that of other ecosystems, and the forests recover rapidly afterwards (Xu et al. 2020), many studies documented the negative effects of heatwaves on forest tree species along altitudes. During summer months, Leštianska et al. (2020) reported considerably decreased stem circumference increase and also tree water deficit in relation with the heatwaves, precipitation deficits, and consequently the decreased soil water potential mainly for European larch (*Larix decidua* Mill.), but present also in the smaller extent for other conifers growing at low altitudes in Western Carpathians. If the soil moisture is adequate, trees experience negative effects in photosynthetic performance only with the occurrence of extreme heatwaves (Ameye et al. 2012). The elevated evapotranspiration demands caused by the extreme temperatures lead to an earlier end of the growing season in European beech (*Fagus sylvatica* L.) forests at the low altitudes in the 1st and 2nd vegetation stage (Table 1), and in regions with less annual precipitation (< 700 mm), this started to occur in the 3rd and 4th vegetation stage (Lukasová et al. 2020). In this study, the 1st vegetation stage is represented by the station Bratislava—Koliba, the 2nd by Sliač and Myjava, the 3rd by Jakubovany and Silica, and the 4th by Banská Štiavnica.

Climate warming and extreme summer heatwaves since 2000 have induced a synchronous decline in the growth rates of Norway spruce (*Picea abies* Karst.) across the biogeographical gradients in the Carpathian arc (Bošela et al. 2020). Norway spruce reacts to the heatwaves by radial growth increment decrease particularly on the dry-mesic sites. This decrease is caused by early stop of cambial activity indicated by pronounced decrease in latewood width (Pichler and Oberhuber 2007). The summer extreme temperatures beyond the species thermal tolerance threshold may even cause the mortality of Norway spruce (Kunert 2020). In addition, the rising extreme temperature events aid the activity of some biotic harmful agents. The insolation, consequent heat accumulation, and temperature of the environment affect both the activity of spruce bark beetles (*Ips typographus* L.) and the release of pheromones and primary attractants (Mezei et al. 2012). Norway spruce forests, which grow mainly from 5 to 7th vegetation stage of the Western Carpathian Mts, have been subject to unprecedented tree mortality caused by attacks of the spruce bark beetle in recent decades, preceded and accompanied by wind-throw events and periods of increased seasonal temperatures. Intensification of heatwaves along altitudes shown in our data, stations Telgárt in 5th and Lom nad Rimavicou in 6th vegetation stage, gives consistently favourable conditions for the development of spruce bark beetle populations in this area and expected shift from the now predominantly univoltine to multivoltine populations might increase the attack pressure at high altitudes (Mezei et al. 2017).

The data presented in this study confirm our hypothesis about the increase of temperature extremes at a range of altitudes, not excluding the high mountain areas. At the station Skalnaté pleso (SKP) in 8th vegetation stage, particularly the maximum temperature exceedance was increasing over the period 1989–2018 indicated by significant positive trends of HW_{MAX} in total duration ($p = 0.02$), and also in the frequency ($p = 0.01$) and duration of the longest HW_{MAX} ($p = 0.02$) in the JJA. Typical habitats of mountain species in 8th vegetation stage (Table 1) have thus been already violated, which may lead to a gradual reduction and eventual disappearing due to a strict ecological specialisation of montane species (Barkasi 2016). Recent research in Europe's mountain summits, including High Tatra Mts in Western Carpathians (Kanka et al. 2005), confirmed the warming-related colonisation of subalpine vascular species, particularly shrubs into alpine summits (Lukasová et al. 2021), while the populations of cold-adapted alpine species have gradually decreased (Pauli et al. 2012; Steinbauer et al. 2018). The colonisation is more pronounced on south-facing aspects (Winkler et al. 2016), which were in this study represented by the station Skalnaté pleso. Besides terrestrial ecosystems, the alpine lakes, such as Skalnaté pleso and many others in High Tatra Mts, are sensitive to high temperatures and solar radiation (Novikmec et al. 2013). The increased temperatures of water surface related to the climate warming contribute to water level fluctuations which lead to changes of the aquatic ecosystem structure (Preston et al. 2016). Furthermore, the successive development of surrounding vegetation cover increases the interception and evapotranspiration and decreases the water sources and stores of alpine lakes (Ptak et al. 2017).

5 Conclusions

Recently, several specific heatwave indices were proposed in the climate science literature, which can make it very difficult to compare changes in heatwaves at regional to global scales, although there are some commonalities between them (Perkins 2015). Regardless of these methodological differences, out results approved those previous and they unequivocally confirm that the heatwaves in Europe have been intensifying over the last decades. Comparing the last three decades, our data revealed an amplified strength of HWs as well as the increased frequency and duration of HW events particularly in the last decade, when the several to extreme heatwaves lasting more than 20 days in JJA repeated several times. Such severe HWs occurred in the Western Carpathian Mts even in the years when the rest of Europe was not struck with comparably strong HWs. Furthermore, stations at all altitudes, including the high mountains, were affected with these extreme temperature events. The coincidence between HW_{MAX} and HW_{AVG} of the same strength throughout 2009–2018 indicates minimised opportunities for organisms to recover during the temperature drop.

Our results provide regional and altitudinal classification of the strongest heatwaves that occurred in the Western Carpathian Mts (Central Europe) after 1989, showing that the investigation of spatial variability of climate can help identify regions that are particularly exposed to climate change extremes. Given the documented enhanced occurrence of the severe heatwaves in the recent past, an enhanced risk of climate change–associated impacts on biodiversity arises in Western Carpathians.

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Availability of data and material The data that support the findings of this study are available from the Slovak Hydrometeorological Institute but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission from the Slovak Hydrometeorological Institute.

Code availability No software application or custom code is published.

Declarations

Ethics approval No studies involving humans or animals were made.

Consent to participate No studies involving humans or animals were made.

Consent for publication No studies involving humans or animals were made.

Conflict of interest The authors declare no competing interests.

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