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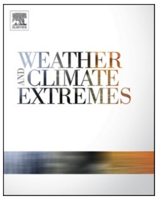

CZEXWED: The unified Czech extreme weather database

Marek Kašpar[a,*], Miloslav Müller[a,b], Vojtěch Bližňák[a], Anna Valeriánová[c]

[a] The Czech Academy of Sciences, Institute of Atmospheric Physics, Boční II 1401, Prague, 141 00, Czech Republic
[b] Charles University, Faculty of Science, Albertov 6, Prague, 128 43, Czech Republic
[c] Czech Hydrometeorological Institute, Na Šabatce 2050/17, Prague, 143 06, Czech Republic

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ABSTRACT

A crucial step in developing a strategy against natural hazards is the analysis of weather extremes in the past. Due to the multiplication of their impacts when occurring in a larger area, we strongly recommend not evaluating the extremes only at individual sites but assessing regional extreme weather events. The presented Czech Extreme Weather Database (CZEXWED) comprises six types of extreme events, namely, heat waves, cold waves, air temperature drops, windstorms, heavy precipitation events, and heavy snowfalls. To date, it covers the period 1961–2020. To minimize methodological differences in the process of evaluating various types of extreme weather events including compound events, we employed the weather extremity index (WEI), a universal indicator based on the evaluation of return periods of relevant variables. Each event is characterized not only by the WEI value but also by its spatial extent and duration.

Heat and cold waves in Czechia generally reach higher WEI values than other types of extreme weather because they usually affect larger areas. The number and extremity of heat waves are increasing significantly, while the opposite may be true for cold waves and windstorms. Air temperature drops defined by declines in daily maximum air temperature are frequent in the warm half-year, but three of four top events occurred in January. Windstorms and heavy precipitation events prevailed in the cold and warm half-years, respectively, but weaker events of these types also occurred during the opposite season. A comparison of CZEXWED with event lists from the wider Central European region shows that Czech and Central European extreme events correspond well with each other.

1. Introduction

Due to climate change issues, many countries currently develop or improve their national strategies against natural hazards, especially against those related to weather phenomena. An important part of such a strategy is the analysis of past weather extremes. It usually starts with evaluation of the extremes from relevant data sources, or an existing database of extreme events can be employed. Two basic approaches can be distinguished: the evaluation of meteorological phenomena (hazard evaluation) or the evaluation of human, economic, or environmental losses (disaster estimation including aspects of exposure and vulnerability). To show the diversity of such databases, we present selected examples of them at different spatial levels.

The World Meteorological Organization (WMO)'s World Weather & Climate Extremes Archive (Cerveny, 2018) collects maximum/minimum values of the various meteorological variables ever recorded on Earth, its hemispheres, and in seven WMO regions. Similar databases at the national level are administered by the respective national authorities. The usefulness of such a database lies in knowing the range of values of meteorological elements that have ever occurred in the area concerned. However, extreme events are represented by only one extreme value, so it is not possible to infer the areal extent of such an event.

In contrast, global disaster databases consider extreme events as a whole but primarily by data on losses. Most likely, the most famous global database of (not only) natural disasters is the Emergency Events Database (EM-DAT) operated by the Centre for Research on the Epidemiology of Disasters (CRED) within the Université catholique de Louvain, Belgium. The database covers the period from 1900 to the present day and is frequently used to research natural disasters in general or a certain type of disasters, such as extreme temperature events (Lee, 2014). Based on these data, the World Meteorological Organization (WMO) has published lists of the most devastating natural disasters on Earth and in individual WMO regions (WMO, 2014). Similar global and

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[*] Corresponding author.

E-mail addresses: kaspar@ufa.cas.cz (M. Kašpar), muller@ufa.cas.cz (M. Müller), bliznak@ufa.cas.cz (V. Bližňák), anna.valerianova@chmi.cz (A. Valeriánová).

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multiple-peril databases are operated by world's leading reinsurance companies, such as MunichRe's NatCatSERVICE database and SwissRe's Sigma database (Wirtz et al., 2014). Several tens of disaster databases also exist at the national level (Gall, 2015).

As far as databases that focus mainly on weather phenomena, the European Severe Weather Database (ESWD) operated by the European Severe Storm Laboratory (Dotzek et al., 2009) is an important dataset. Originally oriented toward severe thunderstorms only, it currently covers a large variety of extreme weather phenomena including snowstorms, heavy rain and avalanches. The database consists of reports from participating meteorological services or volunteers. Based on ESWD data, European climatology of severe weather has been published, such as of tornadoes (Groenemeijer and Kühne, 2014) or hail (Púčik et al., 2019). In the USA, the Storm Events Database also comprised only tornadoes, thunderstorm winds, and hail for the period 1955–1996. Since then, as many as 46 types of weather events have been recorded there by NOAA's National Weather Service (NWS).

To extend the time period covered by extreme weather reports, historical weather data can be employed. One of the region's best covered by such free available data is the United Kingdom thanks to the TEMPEST database. It covers a period of over 400 years with data extracted from a wide range of archival documents (Veale et al., 2017). At the global scale, the TAMBORA database is probably the most comprehensive source of historical weather data.

Apart from general extreme weather databases, some authors published sets of extreme events of a certain type. Special indices are usually applied in this type of work to define extreme events. A classic example of such work was published by Lamb and Frydendahl (1991), who suggested and employed the Storm Severity Index (SSI) to evaluate 166 storms in northwestern Europe between 1 509 and 1990. Lamb's research was followed up by Roberts et al. (2014), who cataloged extreme European windstorms from 1979 to 2012 by even more advanced methods. At a national level, e.g., Lengfeld et al. (2021) have compiled a catalog of heavy rainfall events in Germany using radar data. Another example of such a specialized database is the catalog of snowstorms in the USA, evaluated by the Regional Snowfall Index designed by Squires et al. (2014).

Regarding the territory of Czechia or all of Central Europe, catalogs of extreme weather events can be found in relevant papers. Lhotka and Kyselý (2015) identified major heat waves and cold spells over Central Europe during 1950–2012, with a later extension of the series of heat waves up to 2016 (Lhotka et al., 2018). Brázdil et al. (2018) selected 14 outstanding windstorms from the 1801–2015 period; apart from documentary evidence and instrumental records, they also employed data on forest disturbances for this purpose. A list of significant tornadoes in the Czech Lands was most recently published by Brázdil et al. (2020).

Extreme precipitation events (EPEs) in Czechia was previously defined very simplistically according to the station maximum daily precipitation totals. In contrast, Kašpar and Müller (2008) evaluated EPEs within 8 regions of Czechia by weighted 3-day areal precipitation totals. Furthermore, Müller and Kašpar (2014) suggested the Weather Extremity Index (WEI), an advanced tool for the evaluation of (not only) precipitation extremes. The index was used for the evaluation of extreme precipitation events in Czechia (Müller et al., 2015) and throughout Central Europe (Gvoždíková et al., 2019). Because it is a universal index, it also enabled analyses of extremely high air temperature events (Valeriánová et al., 2017) and windstorms in Czechia (Kašpar et al., 2017). The possibility of evaluating different types of weather extremes using a uniform methodology motivated us to create the comprehensive Czech Extreme Weather Database (CZEXWED), which is presented in this paper.

In CZEXWED, six types of extreme weather events in the Czech territory are present because of their possible impacts. Heat waves (HWs) and cold waves (CWs) significantly increase human mortality (Urban et al., 2022) and harm vegetation. The cold stress can be even intensified in case of air temperature drops (TDs) when there is an increased risk of hypothermia due to not enough time for acclimatization (Holmér et al., 2012); in the cold part of the year, TDs can also result in economic problems (Výberči et al., 2021), first of all the energy supply instability because of the suddenly increase in the electricity consumption (Jovanovic et al., 2015). Windstorms (WSs) together with floods due to heavy precipitation events (PPs) produce most damage of all weather-related phenomena (WMO, 2014). If precipitation falls in the solid form, heavy snowfalls (SFs) can substantially affect transport systems (Vajda et al., 2014) as well as damage trees or even buildings due to the weight of snow accumulations.

In the following section, we present the process of evaluating the events.

2. Data and methods

2.1. Selection of data

Recently, CZEXWED has covered the 60-year period 1961–2020. To evaluate the events, we employed all available daily data from Czech meteorological stations (Table 1) with long data series, mostly operated by the Czech Hydrometeorological Institute (CHMI). Fig. 1 presents the spatial distribution of stations whose data we used to evaluate extreme events.

All station data provided by the national weather service CHMI continuously undergo thorough quality control. We performed the additional quality control of wind data where we focused on the determination of outliers and suppression of false alarms and on the homogenization of series using a statistical correction technique based on the relationship between measurements and reanalysis data (Kašpar et al., 2017). In addition, we applied several criteria in the selection of stations for the purposes of the frequency analysis described in Section 2.2. Regarding air temperature, snow and wind data, we considered only stations with series covering at least 30 calendar years with a minimum of 95% available daily measurements in the year/season with the expected occurrence of respective block maxima. Regarding precipitation data, we considered stations with series covering at least 20 calendar years with respect to the application of the robust region-of-influence method in the frequency analysis. Moreover, in rare cases, we computed daily precipitation totals missing at a station from totals at the most correlated neighboring stations using the MATLAB stepwise linear regression model. Thus, we had measurements from the same number of gauge stations every day. Regarding air temperature, snow and precipitation data, we also considered only stations with the possible change of their position up to 10 km in the horizontal direction and 100 m in altitude in the study period.

To evaluate extreme events that lasted more than one day, we further calculated the means or sums of daily data for *t*-day time windows specified in Section 2.3. These data were the basis for the calculation of the WEI.

Table 1
Six types of extreme weather events included in the CZEXWED and variables used in their evaluation.

Type of extreme weather events	Abbreviation	Variable	No. of data series
Heat wave	HW	Daily maximum air temperature	168
Cold wave	CW	Daily minimum air temperature	165
Air temperature drop	TD	Daily maximum air temperature	163
Windstorm	WS	Daily maximum wind gust	18
Heavy precipitation event	PP	Daily precipitation total	814
Heavy snowfall	SF	Increase of total snow depth	416

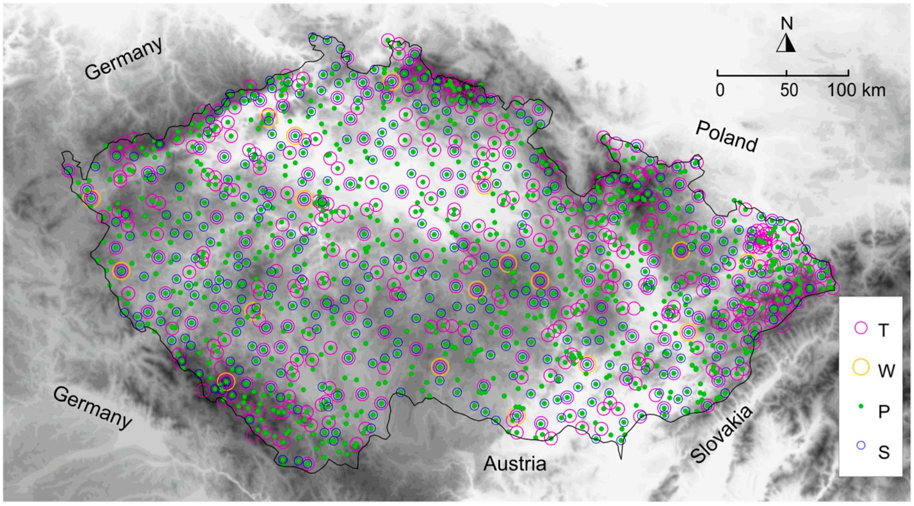

Fig. 1. Map of weather stations whose data were used for evaluation of Czech extreme weather events, namely, data of air temperature (T), wind (W), precipitation (P), and snow (S).

2.2. Weather extremity index

The derivation and an example of the application of the WEI, a comparison with other approaches of quantifying weather extremes and discussion of its benefits and limits, can be found in Müller and Kašpar (2014). Because the WEI is based on the rarity evaluation, the first step of the methodology is transformation of *t*-day values of the considered variable into their return periods (N_t). For this purpose, we use parameters of the generalized extreme value (GEV) distribution, determined from the annual maxima (minima) during the study period. Since precipitation totals are characterized by high spatiotemporal variability and owing to a relatively dense network of available gauge stations, we estimate the GEV parameters describing the distribution of high totals with the L-moment-based index storm procedure (Hosking and Wallis, 1997) and the region-of-influence method (ROI; Burn, 1990) following the recommendations in Kyselý et al. (2011). The advantage of ROI compared to a local analysis consists of identifying the unique pooling group of each station, in which all regional data are used for the estimate of the GEV parameters. In rare cases, the estimated return period can reach the order of 10^3 years or more. Due to the low plausibility of such estimates, we replace all values of $N_t > 1\,000$ by 1 000. Due to the approximately exponential dependence between the values of meteorological variables and their return periods, the WEI works with the values of decimal logarithms of the return periods ($logN_t$), which, with regard to the abovementioned limitation, reach values between zero and three.

Next, we interpolate $logN_t$ values from stations into a regular grid covering the study area with the horizontal resolution proportional to the number of respective data series (10 km for WSs, 2 km for other phenomena, compare with Fig. 1). Because the return period values show a weaker dependence on altitude than the values of the respective meteorological variables, standard kriging appears to be a sufficiently accurate method for interpolating $logN_t$ values.

The grid values of $logN_t$ are then considered in descending order, regardless of the distances among grid points where they occurred. Starting from the grid point with the highest $logN_t$, we gradually increase the considered area (a), where we calculate the variable E_{ta} as the product of the average $logN_t$ in area a and the radius R of a circle equal to area a (Fig. 2):

$$E_{ta} = \overline{(\log N_t)}_a \sqrt{a/\pi} = \log N_{ta} R \tag{1}$$

We search the maximum E_{ta} value from all a and t considered, which is the sought WEI value; the maximum can correspond with the whole study area (as during the HW in August 2015) or for its part (as during the PP in July 1997). Thus, each weather event is characterized not only by its extremity WEI but also by the duration t_{WEI}, the size of the affected area a_{WEI} and the geometrical mean of return periods of the considered variable in the affected area N_{WEI}.

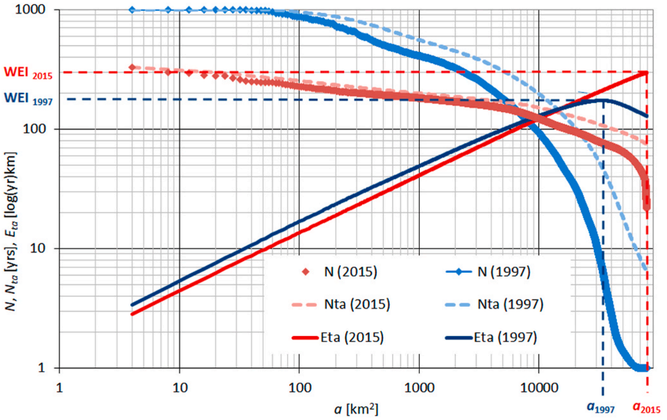

Fig. 2. Determining the weather extremity index (WEI) for the maximum detected heat wave (HW) 6–14 August 2015 (in red) and the maximum precipitation event (PP) 4–7 July 1997 (in blue). The presented HW and PP are evaluated using the 9-day mean of daily maximum air temperature and the 4-day precipitation total, respectively. The evaluation is demonstrated by return periods of respective variables in individual pixels in descending order (N), geometric means of return periods in the gradually increasing area (N_{ta}), and the variable E_{ta}, whose maximum equals WEI. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

For each event, we also determined two additional concentration indices. The area concentration index C_a is proportional to a ratio of the relative magnitude of N_{WEI} (to the possible maximum $N = 1\,000$) and the relative magnitude of the affected area a_{WEI} (to the whole study area). It is calculated according to

$$C_a = \frac{\log N_{WEI}}{\log 1000} \Big/ \frac{R_{WEI}}{R_{max}} = k \frac{\log N_{WEI}}{R_{WEI}} \tag{2}$$

where R_{WEI} is the equivalent radius of the affected area and $R_{\max}$ is the equivalent radius of the whole study area; for the area of Czechia of almost 79.000 km^2, parameter k equals 52.82. The higher the index value is, the greater the effect of the intensity of the phenomenon relative to the effect of the size of the affected area. The time concentration index C_t follows a similar format, comparing the highest 1-day E_{ta} to the WEI value:

$$C_t = \frac{\max(E_{1a})}{\mathrm{WEI}} \tag{3}$$

The higher the index value, the greater the phenomenon was concentrated in one day during the event.

The general methodology needs some specifications when applied to different types of weather extremes because of their different durations and characteristics. These modifications are described in the following section.

2.3. Modifications of the WEI for individual extreme weather types

Mean values of daily maximum and minimum air temperatures ($T_{\max}$ and $T_{\min}$) are used for evaluation of HWs and CWs, respectively. In both cases, duration plays an important role in their effects. When defining these temperatures, a minimum length of three days is usually considered (Lhotka and Kyselý, 2015). Therefore, we take the parameter t to be between 3 and 20 days when evaluating HWs and CWs. Thus, the time concentration index C_t can overcome 1 in some cases. To distinguish individual events, we start from an extra warm/cold three-day period and determine the maximum values of E_{ta} for progressively increasing t. We consider the WEI value to be the E_{ta} value from the shortest time window for which an increase in t by one day does not increase the value of E_{ta}. Nevertheless, it may happen that two or even three apparently independent events are detected in sequence with no break. If so, they are considered as one event, with t_{WEI} as the accumulative duration of such consecutive events and with the WEI and a_{WEI} equal to the maximum of the WEI from all these events and corresponding a_{WEI}, respectively.

TDs are an entirely different type of event where unlike HWs and CWs, the rapidity of the drop in air temperature plays a major role. From the various air temperature characteristics, we selected $T_{\max}$ to determine the magnitude of interdaily cooling. $T_{\max}$ is determined in different countries from different time periods (Janis, 2002); in Czechia, it is the period between 9 p.m. of the previous day and 9 p.m. of the current day. As the cooling gradually spreads through the country, some stations may experience a drop in $T_{\max}$ a day later. Therefore, we always consider the larger of the two consecutive interdaily $T_{\max}$ decreases at each station. We convert these values to their return periods and determine the WEI without considering the parameter t in this case. The date of the event is the first of the two considered days $T_{\max}$ decreased.

Similarly, the duration of WSs seems to be not a very important aspect of their extremity because even very short events can produce significant damage. Thus, we consider only daily maximum wind gusts and their return periods at individual stations for individual events. Again, the maxima may not occur at all stations on the same day, so we search them for a given day during a time window of up to five following days. The number of consecutive days in which the maximum wind gust occurred at least at one station determines the value of the parameter t in this case.

Regarding PPs, their accumulation over several days increases their hydrological effects. We therefore evaluate E_{ta} for individual days with high daily precipitation totals and analyze the possible increase in this variable when increasing the parameter t up to five days. As in the case of HWs and CWs, we consider the WEI value to be the E_{ta} value from the shortest time window for which an increase in t by one day does not increase the value of E_{ta}.

Basic data for SFs are total snow depth values (S_d), which are measured every morning. For a given Day D, we calculate the differences in S_d between Days D + t and D, where t is between 1 and 5. Again, the WEI is determined as the E_{ta} value from the shortest time window for which an increase in t by one day does not increase the value of E_{ta}.

2.4. Detection and evaluation of compound events

Weather extremity index also allows the detection of compound weather events that may cause more severe impacts than individual weather extremes. Within CZEXWED, we evaluate two of four main types of compound events recognized by Zscheischler et al. (2020), namely temporally compounding and multivariate ones.

For temporally compounding HWs, CWs, WSs, PPs and SFs, we consider successive events of the same nature with a gap of up to five days between them. In this case, in addition to the individual WEI values, we also determine the E_{ta} value for the period that two or more such events span together. This value reflects not only the intensity of the individual episodes forming the compound event, but also the length of the gap between them, which reduces the E_{ta} value with the increase of the t parameter.

For multivariate compound events, we first evaluate frequency of combinations of the six phenomena, identify most frequent types presented in Table 2 and analyze them in more detail. Depending on the nature of the event, we consider only immediately consecutive episodes or consecutive episodes with a gap of no more than five days. To express the magnitude of a multivariate compound event, we consider the smaller value of the WEI values for individual phenomena.

3. Analysis of the database

For the 60-year period 1961–2020, CZEXWED comprises the top 60 events of each extreme weather type. Trinities of maximum events are presented in Table 3; for the others, see the supplementary material, where additional remarks on some events are also noted. In this section, we present a basic analysis of the events in terms of their structures and time distribution.

3.1. Structures of individual extreme events

In general, HWs and CWs reach relatively higher WEI values because they, unlike other types of weather extremes, typically affect almost the whole Czech Republic and thus reach rather low values of the area concentration index (Fig. 3). The order of large events is therefore mainly determined by their intensity; exceptions were two HWs in which the return periods exceeded 10 years but only in less than half of Czechia. On average, CWs reached a slightly higher extremity than HWs. The absolute maximum WEI was recorded in January 1985 during the extremely cold period 6–10 January; nevertheless, other cold days before and after this pentad set the duration of the event up to 18 days. Due to excessive consumption and outages in the transmission network, there was an acute shortage of electricity in Czechoslovakia at that time; there were also numerous water supply failures due to deep freezing of the ground (Kakos and Krška, 1985).

The length of HWs and CWs generally contributed to their extremity, so that among the top 6 events of both types, there were four events of 10 days or more. Interestingly, almost a quarter of the HWs reached a time concentration index value over 1 due to one extremely hot day (Fig. 4).

TDs usually do not affect more than two-thirds of Czechia, but three of the top four events did. Prominent among these was the New Year's Day event of 1979, in which the mean return period of $T_{\max}$ decrease

Table 2
Types of multivariate compound events identified in CZEXWED. For abbreviations, see Table 1.

Event type	Description
HW-TD	HW immediately followed by a TD
HW-WS	HW immediately followed by a WS
HW-PP	PP up to five days after a HW
TD-PP	PP immediately after a TD
TD-CW	CW immediately after a TD
CW + SF	SF up to five days before, during, or up to five days after a CW

Table 3
Basic characteristics of three extreme events of six types in Czechia between 1961 and 2020. Each event is characterized by the value of the weather extremity index (WEI), its duration t_{WEI}, affected area a_{WEI}, geometric mean of return periods in the affected area N_{WEI}, area concentration index C_a, and time concentration index C_t. For abbreviations, see Table 1.

Type	First day	t_{WEI} [day]	WEI	a_{WEI} [km^2]	N_{WEI} [yr]	C_a	C_t
HW	August 06, 2015	9	296.3	78 884	74	0.62	0.58
HW	July 28, 1994	17	273.2	78 884	53	0.57	0.54
HW	July 19, 2006	10	202.1	78 880	19	0.43	0.36
CW	January 03, 1985	18	324.4	78 184	114	0.69	0.75
CW	December 21, 1996	14	235.7	78 424	31	0.50	0.65
CW	January 07, 1987	9	232.7	74 580	32	0.52	0.76
TD	January 01, 1979	.	256.4	66 352	58	0.64	.
TD	June 22, 2018	.	176.3	66 696	16	0.44	.
TD	January 23, 2006	.	147.4	30 764	31	0.80	.
WS	January 18, 2007	2	212.6	73 300	25	0.48	.
WS	November 23, 1984	2	178.4	71 400	15	0.41	.
WS	February 23, 1967	1	111.9	50 600	8	0.37	.
PR	July 04, 1997	4	173.6	33 464	48	0.86	0.49
PR	July 17, 1981	4	168.5	39 272	32	0.71	0.76
PR	August 11, 2002	3	166.4	49 380	21	0.56	0.78
SF	January 08, 2010	3	146.4	32 164	28	0.76	0.59
SF	November 25, 1969	2	131.2	20 224	43	1.08	0.67
SF	January 23, 2007	2	117.0	53 928	8	0.36	0.48

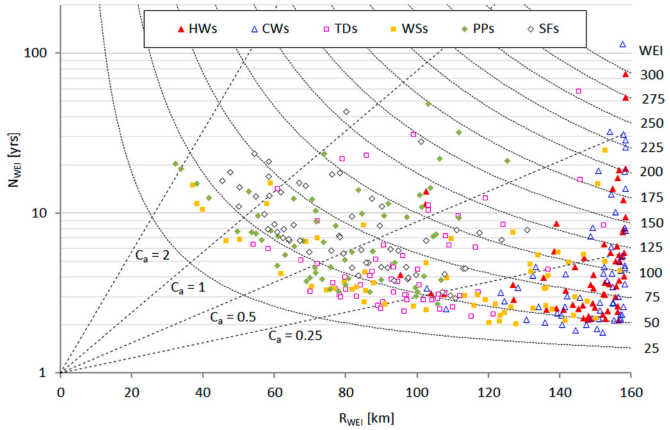

Fig. 3. The weather extremity index values for 60 extreme events of each type in Czechia between 1961 and 2020 as the result of two main characteristics: the size of the affected area expressed by its equivalent radius (R_{WEI}) and the rarity of the relevant meteorological variable expressed by the geometric mean of return period values within the affected area (N_{WEI}). Dashed lines are isolines of the weather extremity index (WEI) and of the area concentration index (C_a). For abbreviations, see Table 1.

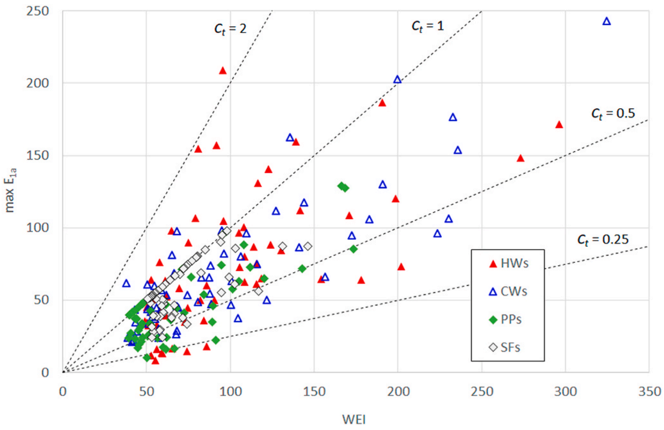

Fig. 4. Comparison between the weather extremity index (WEI) and maximum 1-day E_{ta} (max E_{1a}) for 60 extreme events of four types in Czechia between 1961 and 2020. Dashed lines are isolines of the time concentration index (C_t). For abbreviations, see Table 1.

reached almost 60 years and the WEI value exceeded the second maximum event by almost half. The sudden cooling caught many people unprepared, a large number of animals died. Coal soaked by previous rains froze, which caused blackouts in electricity and heat supplies (Rein, Štekl, 1981); e.g. schools had to remain closed for several weeks. The event was accompanied by freezing rain in Czechoslovakia, and exceptionally heavy snowfall in Germany (Wege, 1979). Similar to HWs, we detected three other TDs with relatively high mean return periods ($N_{WEI} > 20$ yrs), whose extremity was nevertheless reduced by affected areas of less than 40% of Czechia (Fig. 3).

WSs are the type of extreme weather events with the greatest range in the size of the affected area because they include not only area-wide events associated with deep cyclones but also thunderstorm windstorms. In general, the smaller the size of the affected area is, the greater the average return period of wind gusts and vice versa. The events of November 1984 and especially January 2007 (“Kyrill”) stand out from this rule, where the combination of large affected areas and high return periods resulted in outlying WEI values. As the result, both these events damaged roofs of houses, power lines, forests etc. in many regions of Czechia. As much as almost 7 and 9 million m^3 of timber was damaged in November 1984 (Setvák and Strachota, 1986) and in January 2007 (Hostýnek et al., 2008).

PPs generally affect the smallest part of Czechia of the six types of weather extremes. Among 60 extreme events, there were five cases that affected less than 10% of the territory but only one (11–13 August 2002) when heavy rains occurred over more than half of the territory. This event belongs to the top three events with rather small differences in WEI. All these events produced serious flooding in Czechia (Müller et al., 2015). The maximum PP event occurred in July 1997, when the mean return period of four-day precipitation totals was almost 50 years; the extremity of this event was mainly due to its long duration, as shown by the relatively smaller value of the time concentration index.

SFs show the smallest differences among the top 60 events of the six types of weather extremes in terms of WEI values. The events also do not differ much from each other in terms of time concentration, as 75% of them lasted only one or two days. However, differences among events in the areal extent and of the area concentration index values are evident, such as between the second and the third largest events. This is because in some cases, heavy snowfall was limited to higher altitudes only. In this respect, the seasonality of SFs plays an important role (Section 3.4).

3.2. Chronology of extreme events

The distribution of detected extreme events during the entire study period is presented in Fig. 5. Differences between six decades of the study period are further highlighted in Fig. 6.

The decadal frequency of HWs increased fivefold between 1961–1970 and 2011–2020, with none of the top 12 events occurring in the first half of the study period. However, the second and fourth largest events appeared as early as the first half of the 1990s. CWs show the opposite trend, with many large events accumulated in 1981–1990;

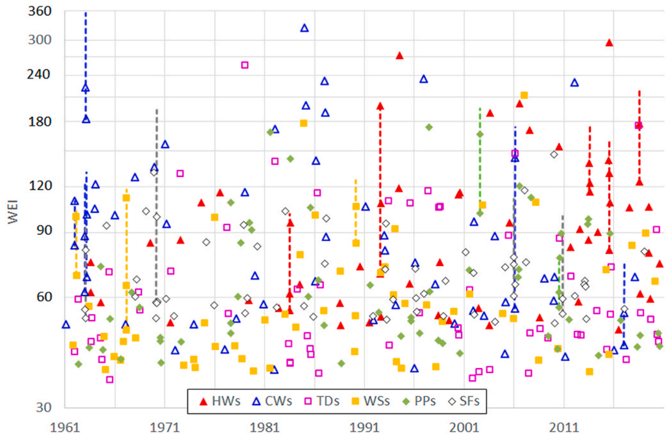

Fig. 5. Chronological distribution of 60 extreme weather events of six types in Czechia between 1961 and 2020. Dashed lines depict temporally compounding events, see Section 2.4; the upper end of the line marks the extremity of the compound event. For abbreviations, see Table 1.

their frequency was particularly low in the last decade, which nevertheless saw the fourth largest event (in February 2012). No significant pattern can be recognized in the chronology of TDs. WSs have seen a decline in frequency since 1990, but three of the top five events occurred in the first decade of the new millennium. Regarding PPs and SFs, we also see a concentration of the top events in the decade 2001–2010.

Looking at the study period in terms of all types of extreme weather together and generalizing results for various thresholds, about 20% more events were detected in the second half of the study period in comparison to the first one. On the contrary, the last decade was substantially less represented than the previous one, mainly in terms of more extreme events (apart from HWs). Moreover, we can also try to identify several different periods in terms of combinations of the extreme weather types. The 1972–1976, 1991–1996 and 2016–2020 periods were characterized by relatively large HWs, while PPs were almost absent, and stronger CWs, WSs and SFs did not occur. In contrast, during the 1981–1987 and 2001–2008 periods, we observed many strong CWs, PPs and WSs.

3.3. *Compound events*

The analysis of the time distribution of EWEs also shows that 11 HWs, 12 CWs, 7 WSs, 4 PPs, and 10 SFs of the top 60 events in the period 1961–2020 were clustered into temporally compounding events (Fig. 5).

The maximum of five compound HWs occurred in the summer of 2018 (Hoy et al., 2020), when the sixth maximum event was followed by the twelfth event just two days apart. If the value of E_{ta} for the compound event (222.7) of 18 days is included among the WEI values for individual HWs, its ranking rises to the third place behind the August 2015 and July/August 1994 events. Thus, the number of heat-attributable deaths in 2018 was the second highest one between 1982 and 2019 in Prague (Urban et al., 2022). The events in July/August 2013 and in July 2015 would also move into the top 10 events when considered as compound events, which further emphasizes the increase in the extremity of HWs in the last decade of the study period. On the other hand, in the case of CWs, we detect four of the six compound events only in 1961–1963, with the compound event of January/February 1963 lasting altogether 28 days and exceeding even the maximum CW of January 1985 in its E_{ta} value (355.6).

As for WSs, there were three compound events during the study period, all in February. The largest increase in E_{ta} over the WEI for individual events was recorded at the turn of February and March 1990. If

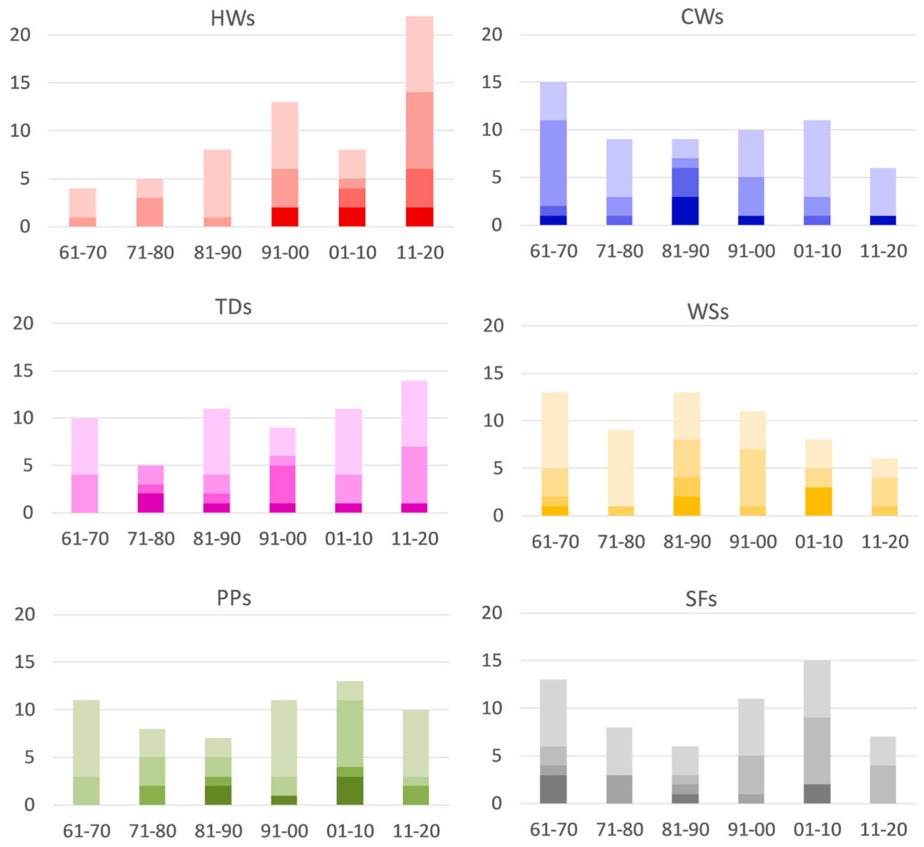

Fig. 6. Decadal frequencies of 60 extreme weather events of six types in Czechia between 1961 and 2020. Darker shades highlight the distribution of the top 30, 12 and 6 events, which roughly correspond to events occurring on average once every 2, 5 and 10 years. For abbreviations, see Table 1.

the WSs associated with cyclones Vivian and Wiebke are considered as a compound event, it reaches the third highest extremity after the January 2007 and November 1984 events. Thus, salvage felling related to windstorms in 1990 reached the volume of timber (8.4 million m^3) very similar to the other two events (Nekovář and Vater, 1998).

Temporally compounding PPs were even less common, occurring only twice during the entire study period. The August 2002 compound event, composed of two top 10 events which followed each other with only a three-day break, appears to be quite exceptional because the E_{ta} value for the cumulative period (195.7) not only exceeded the WEI during the stronger second episode, but also represents the highest ever detected precipitation-related E_{ta} value. It resulted into the maximum recorded flood in many parts of Czechia; in Prague, the peak discharge of the Vltava river was the highest since 1 432 (Elleder, 2015).

Regarding the magnitude of compound events, a similar situation occurred during one of the four compound heavy snowfall events. If we evaluate the trio of events during the two weeks in February/March 1970 as a compound event, its E_{ta} value (193.5) exceeds by far the maximum WEI achieved for a single event. Serious traffic interruptions due to the accumulation of snow were documented in newspapers in late winter of 1970.

Regarding multivariate compound events, we present frequencies of combinations of the six phenomena in Table 4. We detected seven HW-TD, five HW-WS, five HW-PP, and five TD-PP events in summer months. In fact, on two occasions (June 1998 and July 2010) a HW was terminated by a TD together with a PP. A similar event occurred in July/August 1983, but the TD and the PP did not occur until three days after the end of the HW. These events can be understood as compound in the sense of the amplification of the subsequent WSs or PPs due to the previous HW and/or TD. For example, extra high air temperature in some HWs attributed to the severity of subsequent convective storms and WSs related to them, which produced significant damage in forests e.g. in July 1984 (Kašpar et al., 2009) or in July 1988 (Nekovář and Valter, 1998). The TD at the beginning of August 1985 indicates a significant contrast in the temperature of air masses; a cyclone originated on the frontal boundary and produced the subsequent PP which resulted into a flood (Müller et al., 2015).

In the winter months we detected 3 TD-CW and 16 CW + SF events. All three significant January TDs were followed by CWs, with a SF following later in January 1979. The CW lasted 16 days and resulted into extra-long effects of the above mentioned extreme TD at the beginning of this year (Rein and Štekl, 1981). Of the 16 CW + SF events, only in four cases CW and SF occurred simultaneously which is quite natural because cold air mass cannot contain much water vapor needed for heavy snowfall. In seven cases a SF preceded a CW which could be enhanced due to the effect of the snow cover (high albedo, prevention of heat fluxes from the ground). In the remaining five cases, a CW was followed by a SF; in this case, snow is easier to hold on frozen ground and snowfall can be eventually enhanced by the intensity of the warm front as happened e.g. in February 2012.

Table 4

Frequencies of combinations of six types of extreme evens detected in Czechia between 1961 and 2020. In additional 4 cases, a SF occurred during a CW. For abbreviations, see Table 1.

		Following event.					
		HW	CW	TD	WS	PP	SF
Initial event	HW	x	0	7	5	5	0
	CW	0	x	0	1	0	5
	TD	0	3	x	0	5	0
	WS	0	1	0	x	1	2
	PP	1	0	0	1	x	0
	SF	0	7	0	0	0	x

3.4. Seasonal distribution of extreme events

Naturally, there are large differences among the six types of extreme weather events in terms of their seasonality (Fig. 7). The most concentrated events in time were HWs; all 60 events occurred during the three summer months, and the top 12 events occurred between the beginning of July and the middle of August. CWs also occurred almost exclusively for three months, but the top 12 events were spread out from the last decade of December to the end of February. The seasonal distribution of TDs is deeply interesting: as many as 90% of them occurred in the warm half-year, but three of the four largest events occurred in January. WSs are the most evenly distributed throughout the year of the extreme weather types, but the top 12 events occurred only in the cold half-year. PPs are concentrated in the period from May to September; however, two weaker events were also recorded in October and one even in December. SFs also occurred mainly in five months, in this case from November to March, with three additional events detected in April.

In some cases, we can also observe differences in the seasonal distribution of specific features of extreme events and obvious changes in their seasonality (Fig. 8). This is especially true for HWs, which initially occurred only in the second half of July and the first half of August; in the last decade they are spread over all three summer months. The December CWs and SFs disappeared completely at the same time. The SFs with extra small affected areas are concentrated in March and April, when they often affect only higher altitudes. This is also related to the shift in the seasonal distribution of the largest events: after 2000, two such events occurred in January, while the older ten of the top 12 events occurred between February and April or in November. In the case of WSs, we can also observe a specific seasonal distribution of events with respect to their affected areas. Larger events occur exclusively in the cold half-year, while events in the warm half-year affect significantly smaller areas due to their different causes.

4. Discussion

In this section, we compare CZEXWED with analogous lists of

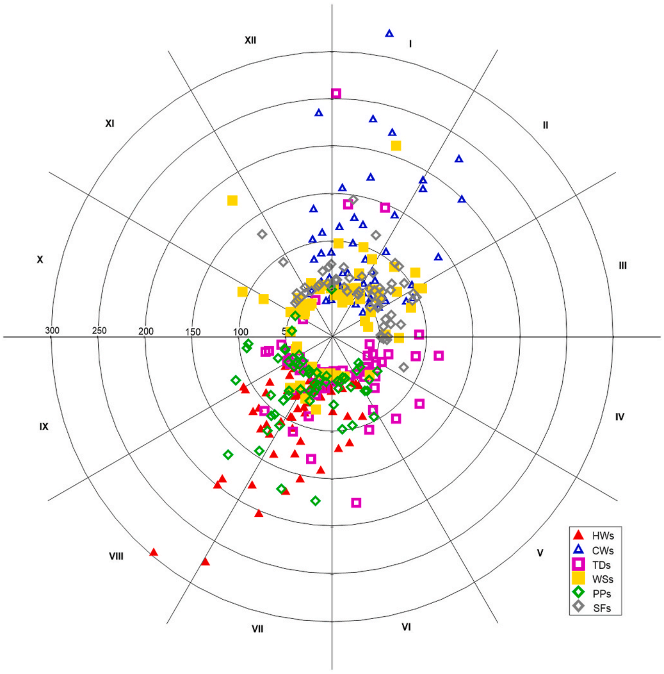

Fig. 7. Seasonal distribution of 60 extreme weather events of six types in Czechia in the period 1961–2020. The direction and the distance from the center of the diagram to the sign depict the day of the year and the weather extremity index value, respectively. For abbreviations, see Table 1.

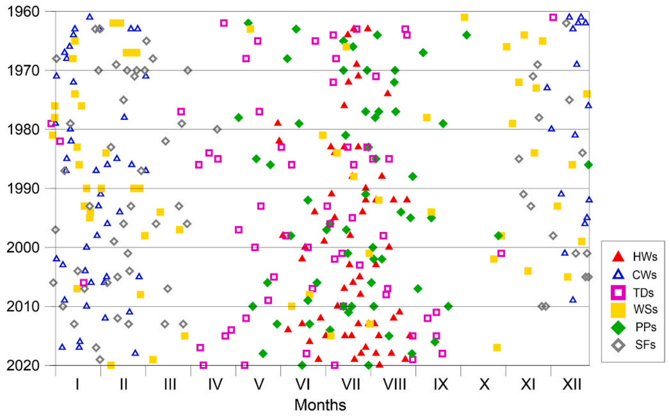

Fig. 8. Changes in the seasonal distribution of extreme weather events in Czechia over the study period. For abbreviations, see Table 1.

extreme weather events mentioned in the introduction. We also discuss the possible influence of the WEI design on the results.

4.1. *Events related to air temperature*

To assess HWs in CZEXWED, the list of Central European HWs between 1950 and 2016 by Lhotka et al. (2018) is the most suitable. They employed $T_{\max}$ grid data from the E-OBS database with a horizontal resolution of 0.22° and an area of interest approximately eight times larger than the territory of Czechia. Their extremity index was calculated as the sum of positive $T_{\max}$ anomalies from the 90th percentile of the summer $T_{\max}$ distribution. Because Lhotka et al. (2018) selected only 37 HWs from this period, their catalog does not comprise all 52 HWs evaluated by the WEI. Despite differences in methodology and the study area size, both lists of HWs are very similar for the common period 1961–2016. Only two HWs which were detected exclusively by Lhotka et al. (2018) belong to 5 least extreme ones in their catalog where only 3 from 30 maximum HWs detected by the WEI are missing. The similarity is mainly pronounced with respect to maximum events: for example, 9 of the top 10 events of both catalogs overlap. The only more significant difference is a different length of some events, when, for example, instead of one 13-day HW in August 2003, Lhotka et al. (2018) detected two shorter waves.

The same applies to the top 10 CWs in CZEXWED and in Lhotka and Kyselý (2015), where Central European CWs were defined by an analogous method as HWs but for $T_{\min}$ in comparison with their distribution in winter. Again, 9 of the top 10 events of both catalogs overlap. However, CWs evaluated by the WEI are generally longer than those evaluated by Lhotka and Kyselý (2015).

Because Kašpar et al. (2017) have already published a list of the top 25 HWs evaluated by the WEI for 1961–2010, we can also compare our recent results with older ones. Most events are common for both datasets, with approximately 15% lower WEI values in CZEXWED because of generally lower return period estimates when including the last, extra hot decade in the analysis. However, because the duration of HWs was considered to be between one and seven days by Kašpar et al. (2017), there are other differences in some cases due to the shift in the methodology. The most prominent change was due to the extension of the minimum duration up to three days. If we set the WEI as the maximum of E_{ta} starting from one day, as for other types of events, the ranking of some HWs would be significantly higher (Fig. 4). Among such events are the only two in which the air temperature has thus far exceeded 40 °C in Czechia, namely, in July 1983 and August 2012.

HWs could also be evaluated using other air temperature characteristics than $T_{\max}$. because elevated minimum temperatures play an important role in increasing heat-related mortality (Laaidi et al., 2012). To study the sensitivity with this respect, we performed an additional calculation of the WEI based on daily means of air temperature (T_{mean}). Both datasets of HWs fit well: 7 of 8 maximum events correspond to each other, with 2015 and 1994 events being the first and the second one in both datasets, respectively. In several cases, the evaluations differ more significantly because of different delimitation of the event duration (for example, the 2003 HW was divided into two less extreme events according to T_{mean}). More than 30% of HWs according to T_{mean} virtually started one or even two days later which can be explained by a slower increase of night air temperature than $T_{\max}$ at the beginning of HWs. Because both $T_{\max}$ and T_{mean} usually decrease on the same day at the end of a HW, about 25% of HWs were detected shorter according to T_{mean} than $T_{\max}$.

Since there is no other list of TDs in Czechia, we have at least tested the role of the considered variable. If we were to evaluate TDs using interdaily declines in $T_{\min}$, the resulting set of extreme events would be substantially different, which is also true for the seasonal distribution of the events. Because of the greater variability of $T_{\min}$ in the cold part of the year, TDs defined in this way would be concentrated primarily in winter. This comparison further highlights the trio of January TDs, which are among the four largest events in terms of not only $T_{\max}$ but also $T_{\min}$ declines. Moreover, the uniqueness of one of these events at the turn of 1978 and 1979 is confirmed by Výberči et al. (2021), who analyzed the magnitude of the air temperature drop in neighboring Slovakia. Because Wege (1979) also referred to the temperature drop in Germany at that time, it is obvious that not only individual HWs and CWs but also a single TD can affect a significant part of Central Europe.

4.2. *Windstorms*

The maximum WSs in CZEXWED can be compared with the "outstanding windstorms" identified by Brázdil et al. (2018) with at least one million m^3 of windthrown timber in Czechia. As many as nine of those events occurred during the period 1961–2015. The correspondence between the two lists of events is very good: eight of the nine "outstanding windstorms" belong among 12 maximum WSs selected by the WEI from the overlapping period. The event of July 1984 is among them, although it was not caused by a deep cyclone, but by a large convective storm that hit Munich with heavy hail before arriving in the Czech Republic (Kašpar et al., 2009). Although the remaining one of the nine "outstanding windstorms" (on February 21, 1967) ranked only 18th with respect to the WEI, it was followed only two days later by the third maximum WSs from CZEXWED. Obviously, we can attribute the forest damage to both events together, and thus, the agreement between the two lists of extreme events is even better.

Kašpar et al. (2017) already pointed out an interesting coincidence between top Czech and European WSs, the latter of which was evaluated by Roberts et al. (2014) by the storm severity index (SSI) combining maximum wind speed and the size of the affected area. Unfortunately, the online catalog of European windstorms (http://www.europeanwindstorms.org) has not been updated since 2015, so it is not possible to refine the results for events in recent years. In the overlapping period (October–March 1979–2014), three of the top four events in each dataset belong to the top four events in the other dataset. Moreover, 8 of the top 10 Czech WSs belong to the top 20 European WSs, and conversely, 7 of the top 10 European WSs belong to the top 22 Czech WSs in the overlapping period. The explanation is that if a WS in the cold half-year affects Czechia in Central Europe, it often hits Western Europe as well, and thus, high values of the SSI are recorded for Europe.

Because the density of the considered weather stations with wind data is very small in comparison with other phenomena (Fig. 1), we also analyzed WSs for a shorter period of 1999–2020 covered by up to 69 station data series. The estimation of return periods is less reliable in this case, but the higher density of stations may help to improve the detection and evaluation of warm seasons, mostly convective events that usually affect rather small areas. For the top 44 WSs from 1999 to 2020, the Pearson correlation coefficient between the two sets of WEI values reaches 0.89; for the top 22 WSs, it increases to up to 0.95. The ranking of the top 10 events is very similar in both datasets. On the one hand, the ranking of all five warm-season events decreases when using a denser database, which can be explained by the reduced influence of affected but rather isolated stations on the interpolation of return period values. On the other hand, the increased density of the database enables the detection of at least two warm-season events that should belong to WSs in this period, namely, June 20–21, 2002, and July 23, 2009. Of the events in the cold half-year, the following WSs seem to be missing in the CZEXWED due to the small station density: February 4–6, 1999; December 2–5, 1999 (Anatol); March 8–9, 2000. We can conclude that the small station density probably leads to a partial overestimation of the proportion of warm-season WSs in CZEXWED.

Another source of uncertainty in WS evaluation is homogenization of maximum wind gust data before calculating the WEI, motivated by the exchange of older types of anemometers for Vaisala WAV 151 or WAV 251 cup anemometers in the late 1990s and frequent changes in the station surroundings or relocation of the sensors (Kašpar et al., 2017). From nonhomogenized data series, statistically significant decreases in maximum wind gusts in the Czech Republic were generally observed between 1961 and 2014 by Brázdil et al. (2017). If nonhomogenized data were used for evaluation of the WEI, both relatively later events of January 2007 (Kyrill) and March 2008 (Emma) would be rated as weaker than several earlier events. In the case of Kyrill in particular, this would be at odds with the extraordinary scale of the damage caused by it (Brázdil et al., 2018). From the point of view of the decreasing trend of the frequency and extremity of windstorms in the Czech Republic observed in recent decades, we can say that without the homogenization of the data, it would be even more pronounced.

4.3. Precipitation and snowfall events

Štekl et al. (2001) selected and analyzed all days when the daily precipitation total reached at least 150 mm ($P_d \geq 150$ mm) at any rain-gauge station in Czechia in the period 1879–2000; for the next two decades, this series can be extended by data published by the Czech Hydrometeorological Institute. Between 1961 and 2000, 18 days with $P_d \geq 150$ mm were detected. At least one such a day occurred during almost 25% of PPs detected by the WEI. The 18 days were grouped into 13 events: 1 three-day, 3 two-day and 9 one-day events. Of them, only four one-day events do not belong to PPs with respect to the WEI. Two of these missing events were very localized and Štekl et al. (2001) mentioned no hydrological response of them on any Czech river; the other two events also affected only limited areas where flash floods occurred, which in one case (July 22, 1998) killed 6 people and produced serious damage (Štekl et al., 2001). On this day, the value of WEI was enhanced (33.9) but not high enough for the event to be included into 60 maximum PPs. On the contrary, during the second and fourth maximum PP in July 1981 and August 1983, respectively, the threshold ($P_d \geq 150$ mm) was not reached at any Czech station. In 1983, the hydrological response was substantially reduced due to previous heat and drought (Krška and Munzar, 1984); anyway, we detected three HWs lasting altogether 17 days in July 1983. In 1981, the subsequent flood (Kakos, 1982) was evaluated to be the fourth largest one of warm half-year floods in Czechia since 1961 (Müller et al., 2015) and the fifth one in whole central Europe (Gvoždíková and Müller, 2017). The presented comparison confirms the fact that CZEXWED includes all large PPs possibly producing floods on main rivers but some local events could be omitted.

As expected, there is thus a better agreement between the PPs in CZEXWED and precipitation events evaluated by the weighted average of one-day area precipitation totals in a three-day period in one of the eight river basin clusters in Czechia (Kašpar and Müller, 2008). The top nine PPs by the WEI were among the top five events by area rainfall in at least one of these regions; the top three events then ranked first or second even in three of these regions.

A similarly good match is found when comparing the Czech PPs with events in Central Europe (more than seven times larger than the Czech Republic), evaluated by Gvoždíková et al. (2019) by the WEI. In the overlapping period 1961–2013, almost half of Czech PPs belong to Central European PPs and vice versa. Moreover, the top 11 European PPs belong among the top 17 Czech PPs, while the top 9 Czech PPs belong among the top 16 European ones. Finally, three of the four top events in each dataset belong to the top four events in the other dataset.

Regarding SFs, no catalog of them has been published in Czechia yet. Květoň and Žák (2011) analyzed SFs in three mountainous regions of Czechia in terms of circulation patterns, but for each circulation type, they only presented the mean new snow depth on the day when it reached the maximum value in the region. Although the days when this variable reached an absolute maximum in one of the study regions (the Beskydy Mts., Krkonoše Mts. and Šumava Mts.) belong to the SFs defined by the WEI, they rank only 15th, 22nd and 30th among SFs from 1961 to 2010. This suggests that the one-day snowfall in mountainous areas is not crucial in terms of the extremity of SFs in the whole country.

4.4. Compound events

Regarding temporally compounding events, we analyzed the sensitivity of our results to the arbitrary set maximum length of the gap between individual events to 5 days. The number of detected compound events could naturally increase if increasing the threshold. Only the set of compound HWs would be substantially changed if the length of the gap was enhanced up to 7 days: two of them would be prolonged (1983; 2018) and two new HWs would be determined (1963; 1992). Regarding other phenomena, only one additional compound PP (1977) and one such SF (2001) would be detected but neither a CW, nor a WS. Nevertheless, the respective E_{ta} values in no case would exceed the original WEI values which confirms 5 days as a proper maximum length of the gap between temporally compounding events.

Most of detected multivariate compound events did not increase the amount of damage in the sense of the sum of the effects of both phenomena. Nevertheless, we can rightly call them compound events because the presence of the initial event intensified the effect of the following one.

5. Conclusions

Using the events in the Czech Republic, the presented paper demonstrates that it is possible to create a unified database of extreme weather events for a certain region. The WEI is a suitable tool for this purpose; with only minor modifications for individual phenomena, it allowed the extremes of six different phenomena including temporally compounding and multivariate compound events to be compared. In addition to expressing the extremity of the event, the design of the index also provides information on the duration of the event, its areal extent, and the average return period of the given phenomenon in the affected area. The comparison of CZEXWED with event lists from the wider Central European region shows that the Czech and Central European extreme events correspond well with each other.

We understand CZEXWED both as a data source for follow-up analyses of presented extreme events in Czechia and as a database for comparison with events in neighboring countries. The analysis of the meteorological conditions under which the events occurred promises interesting results, not only in relation to the extremity of the events but also in relation to other characteristics of the events determined by the methodology used. For temperature events, heavy precipitation and heavy snowfall, we plan to compare the presented events with older events, for which we intend to use a less dense network of longer data series. To detect also locally intense events with lower WEI values for the whole Czechia due to their small spatial extents, we plan to evaluate them also within selected sub-regions (catchments in case of heavy rains). Our intention is to maintain CZEXWED as an open database updated with possible future extreme events. It is available on the website http://czexwed.ufa.cas.cz/.

Author statement

Marek Kašpar: Methodology, Software, Validation, Formal analysis, Writing - Original Draft. Miloslav Müller: Conceptualization, Methodology, Visualization, Writing - Original Draft. Vojtěch Bližňák: Data Curation, Writing - Review & Editing. Anna Valeriánová: Data Curation, Formal analysis.

Declaration of competing 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.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wace.2022.100540.

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