Heat wave of August 2012 in the Czech Republic: Comparison of two approaches to assess high temperature events

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ABSTRACT

We present an analysis of a period of high air temperature that occurred in the second half of August 2012 in the Czech Republic (CZ). We use and compare the results of two different approaches for the evaluation of high air temperature events. The Weather Extremity Index (WEI) evaluates the extremity and spatial extent of the meteorological event of interest. The second method is based on the duration of daily maximum air temperature above specific thresholds. In 2012, the high air temperature in the CZ lasted from 18 August to 24 August (18/8 to 24/8). It was connected with the inflow of hot air from northern Africa between the low pressure trough over the eastern Atlantic and the region of high pressure in central Europe. The high air temperature culminated on 20/8 when its maximum was greater than 30°C across the whole of the CZ. The highest daily maximum air temperature on record in the CZ with a value of 40.4°C was observed at the Dobřichovice station. Our results demonstrate that the studied period was quite extraordinary, occurring so late in the summer with a relatively large areal extent and extremity of detected maximum air temperature. Furthermore, the WEI was found useful for identification of very extreme high air temperature events and facilitated inter-comparison in terms of extremity and spatial extent. However, WEI cannot be used for detection of periods with a persistent relatively high air temperature that could have severe impacts on both human activities and natural ecosystems but during which the extremity of observed air temperature values is not very high.

Keywords: maximum air temperature, Czech historical record, heat wave, weather extremity index

1. INTRODUCTION

The rise in near surface air temperature observed in many parts of the world during recent decades (e.g. *WMO, 2013*) has led to concerns about possible impacts on various human activities and natural ecosystems. Local changes in the occurrence of extreme climatic events probably represent the greatest threat resulting from global climate change (*Beniston et al., 2007*). Regarding extremes in near surface air temperature, both heat waves and cold spells can have a severe impact. Summer heat waves are associated with an increased rate of sickness and mortality, animal stress and crop damage, higher energy demand for air conditioning, risk of power failure and many other negative effects (e.g. *Beniston et al., 2007*; *Kyselý, 2010*). An understanding of the dynamic causes of extreme climatic events can enable assessment of changes in their occurrence under changing climate conditions (*Beniston and Stephenson, 2004*).

An increase in heat wave duration over most global continental areas during recent decades has been reported (*Donat et al., 2013*; *Perkins et al., 2012*). Concerning Central Europe, *Frich et al. (2002)* found a statistically significant positive change in the heat wave duration index (maximum period of at least 5 consecutive days with a daily maximum air temperature over 5°C above the 1961−1990 daily normal) during the second half of the 20th century. In the Czech Republic (CZ), increased duration and intensity of heat waves have been observed since the early 1990s (*Kyselý, 2010*).

There are many different approaches to assessment of extremely high air temperature events. Most commonly the occurrence of heat waves is analyzed. Heat waves are generally understood as periods lasting several days characterized by an unusually high air temperature. A detailed review of approaches to heat wave evaluation is provided by *Perkins and Alexander (2013)*. Generally, there are two groups of methods. The first incorporates fixed absolute thresholds for air temperature and the second makes use of thresholds based on selected quantiles. The main advantage of the latter is that the results are comparable across sites with different characteristics of air temperature distribution (*Radinović and Ćurić, 2013*). On the other hand, incorporating a set of fixed thresholds can be very useful in cases where they are specifically determined for the geographical area of interest or for a particular purpose.

In the present study two different approaches to the evaluation of extremely high air temperature occurrence are employed. One of them is based on fixed thresholds for daily maximum air temperature proposed by *Huth et al. (2000)*. According to these authors, a heat wave is defined as a continuous period of high air temperature during which the daily maximum air temperature is over 25°C, higher than 30°C for at least 3 days and the mean of daily maximum air temperature during the heat wave is above 30°C. The thresholds were specifically selected for the climatic conditions of the CZ with regard to the widely used definitions of summer and tropical days (*Huth et al., 2000*). This criterion has been broadly adopted in recent studies (e.g. *Schubert and Grossman-Clarke, 2013*; *Gao et al., 2012*). Its advantage is that it takes into account both the duration and intensity of heat waves and is easily applicable to observed and modeled time series. However, it is based on a single time series and does not consider the spatial extent of the heat wave. The other approach to evaluation of periods with extremely high air temperature used in the present study was proposed by *Müller and Kašpar (2013)* and requires computing the Weather Extremity Index (*WEI*) based on return periods of observed values. The *WEI* is a product of a measure of the spatial extent of the area where extremely high air temperature occurred and a measure of the extremity of these air temperature values. It is applied on daily values of maximum air temperature as well as its 2−7-day averages and results in identification of periods with high air temperature with a duration of between 1 and 7 days. For this reason, in connection with the *WEI* we will use the term "high air temperature event" (or simply "event") rather than "heat wave", because the latter refers to a period of more than 1 day. For details of the *WEI* evaluation procedure see Section 2. The extent of the area affected by high air temperature, the extremity and the length of the event are evaluated by the *WEI*, thus it enables easy inter-comparison of individual events in terms of spatial extent and extremity.

We present an analysis of a period of high air temperature in the CZ during August 2012. We focus on this event because during it the new maximum of observed air temperature for the CZ was recorded. Our objective is to describe the course and duration of the high air temperature event, estimate its extremity and compare it to selected events that occurred during the period 1961–2012. Moreover, we describe the differences between the results of the evaluation based on the two different methods - the novel *WEI* method suggested by *Müller and Kašpar (2013)* and the traditional approach proposed by *Huth et al. (2000)*. Until now, most studies aimed at evaluating high temperature events in the CZ incorporated the latter method. In our future work we will use the *WEI* index for identification of extreme high air temperature events, and therefore in the present study we analyze the differences between the results of the two methods. In Section 2 we describe the methods and data used in the study. In Section 3 we present a brief overview of summer 2012 to place the analysis of the August high air temperature event in a broader context. Section 4 is dedicated to a description of the event itself. In Section 5 we analyze the results of the *WEI* evaluation and compare them with those obtained by the method of *Huth et al. (2000)*. In the final section of the paper we summarize the outcomes of our analysis and highlight several interesting aspects of the methods employed.

2. DATA AND METHODS

To evaluate the extremity of the observed daily maximum air temperature ($T_{\max}$) we used an event-adjusted evaluation of extreme weather events described by *Müller and Kašpar (2013)*. In the first step of the procedure, the rarity of $T_{\max}$ at individual meteorological stations is evaluated and observed values are transformed into return periods estimated by means of GEV distribution (*Coles, 2001*) of annual maxima. In our study, the GEV parameters were estimated using the method of maximum likelihood (*Coles, 2001*). Furthermore, the logarithm of return periods was interpolated into a regular grid with a horizontal resolution of 1 km using local linear regression between interpolated value and elevation. Grid points from the whole area of the CZ were ordered from highest to lowest according to their interpolated return period value. We then identified the optimal number of grid points from this ordered sequence where the normalized extremity reaches its maximum (which represents the area affected by the extreme event). The procedure results in evaluation of the *WEI* defined as:

$$WEI = \max_{n=1,\ldots M} \left(\frac{\sum_{i=1}^{n} \log N_i}{a} \sqrt{\frac{a}{\pi}} \right), \tag{1}$$

where N_i is the return period in grid point i, a is the area equivalent to n grid boxes and M is the number of grid points over the CZ. As we used a 1×1 km grid for interpolation of return periods, a expressed in square kilometers equals $n_{\max}$, which corresponds to the solution of Eq. (1). The expression in brackets in Eq. (1) can be broken down into a measure of extremity E and a measure of areal extent A:

$$E = \frac{\sum_{i=1}^{n_{\max}} \log N_i}{n_{\max}}, \tag{2}$$

$$A = \sqrt{\frac{n_{\max}}{\pi}}. \tag{3}$$

The measure of areal extent A corresponds to the radius of a hypothetical circle with the same area as is affected by the extreme event. A detailed explanation and description of *WEI* evaluation can be found in *Müller and Kašpar (2013)*.

The return periods were evaluated for daily $T_{\max}$ and its 2−7-day running means for the period 1961–2012. Time series of $T_{\max}$ from the climatological database operated by the Czech Hydrometeorological Institute were used. A quality check of the data was carried out before the actual analysis. The data have not been homogenized, as only erroneous $T_{\max}$ values were corrected. For detection of potentially erroneous values a combination of the following methods was used: analysis of series of differences between candidate and neighboring stations, i.e. pairwise comparisons, application of limits derived from inter-quartile ranges and comparison of the tested series with expected (theoretical) values based on technical series created by means of statistical methods for spatial data (for more details see *Štěpánek et al., 2009*). Only stations with data available for at least 20 years during the period 1961–2010 were included. The number of stations in individual years was not constant and varied between 134 and 197. For *WEI* evaluation, we only processed cases when the return period of the observed $T_{\max}$ exceeded 10 years at a minimum of one station in the area of the CZ.

For comparison of results obtained by the *WEI*, the definition of heat wave proposed by *Huth et al. (2000)* was also incorporated. As described in Section 1, a heat wave is defined as a continuous period during which the $T_{\max}$ is over 25°C, higher than 30°C for at least 3 days and the mean of $T_{\max}$ during the heat wave is above 30°C. The occurence and length of the heat wave of August 2012 were determined for 119 meteorological stations according to the definition by *Huth et al. (2000)*. The number of heat waves since 1961 has been assessed for the Prague-Karlov and Kuchařovice stations.

The location of meteorological stations mentioned in the paper is shown in Fig. 1.

In Section 3, the areal monthly mean air temperature for the CZ was determined as an average of monthly mean air temperature values from 221 stations interpolated into a regular 1 km grid using local linear regression. Areal daily mean air temperature was computed as a simple mean from all station data available for the day of interest. The same methods were used for the long-term monthly and daily air temperature areal means.

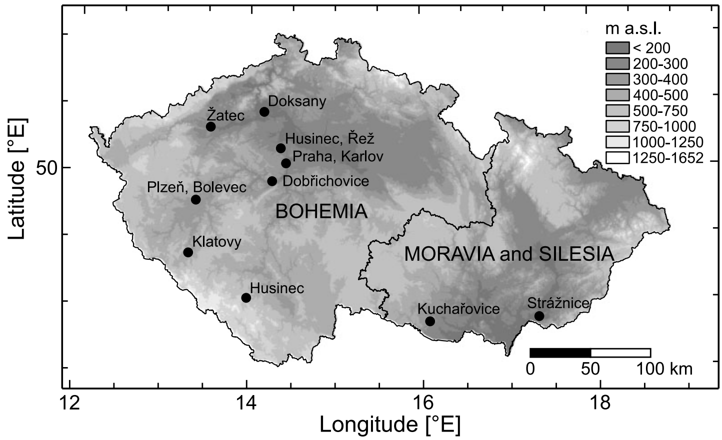

Fig. 1. Map of the Czech Republic with the location of selected meteorological stations mentioned in the text. Border between Bohemia and Moravia with Silesia is also depicted.

3. WEATHER DURING THE SUMMER OF 2012 IN THE CZECH REPUBLIC BEFORE THE AUGUST HIGH AIR TEMPERATURE EVENT

Summer 2012 in the CZ was very warm, the monthly mean air temperature in June and July was 1.4°C and 1.3°C above the long-term mean (1961–1990). August had a temperature anomaly of 1.8°C, which was well above normal. Fig. 2 documents the daily mean air temperature in the CZ during the summer of 2012 and shows that from June to August about 59% of daily values were above the long-term mean.

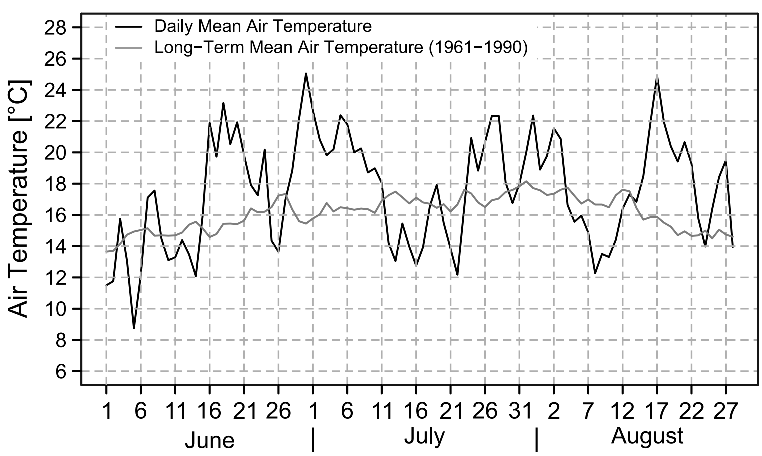

Fig. 2. The daily mean air temperature over the Czech Republic during summer 2012 (black curve) in comparison with the long-term mean for 1961–1990 (grey curve).

At the beginning of June low-pressure systems occurred over Central Europe, therefore the weather was relatively cool and rainy. During the first heat wave from 16/6 to 20/6, which was linked with a southwesterly warm flow, the maximum air temperature reached values of 30 to 35°C in the lowland regions of the CZ. After a short period with a relatively lower air temperature (on 25/6 and 26/6 the observed $T_{\max}$ did not exceed 25°C), thunderstorms and precipitation, the flow of very hot air from the south-southwest returned. On 30/6 the daily maximum air temperature was above 30°C across the whole territory of the CZ with the exception of the mountains. The very hot weather persisted in the eastern part of the CZ (Moravia and Silesia) until 8/7, while the western part was influenced by a cold front. A very severe thunderstorm with hail that caused local floods (south and north Bohemia) occurred there. The second 10-day period of July was moderately warm, the next heat waves were observed at the end of July and at the beginning of August, when in some areas the maximum air temperature rose above 35°C.

4. THE HIGH AIR TEMPERATURE EVENT OF AUGUST 2012

The high daily maximum air temperature in the CZ lasted from 18/8 to 24/8. On 18/8 the hot air from northern Africa (Sahara) started flowing to the CZ between the low pressure trough over the eastern Atlantic and the region of high pressure in central Europe. The air temperature rose above 30°C at 11 stations in Bohemia, the highest value of 31.8°C was observed at the Prague-Karlov station. The inflow of warm air intensified until 20/8. The frontal analysis of the surface pressure field over Europe on 20/8 at 12 UTC is depicted in Fig. 3. It is worth mentioning that the warming in a free atmosphere was unusually strong. While the temperature on 17/8 at 12 UTC was 9°C at a level of 850 hPa over Prague, it rose to 23°C at 00 UTC on 19/8 (Fig. 4). Furthermore, on 19/8 the surface air temperature exceeded 30°C over most of the CZ (Fig. 5) and a temperature above 35°C was even recorded at 11 stations in the central and north-eastern part of Bohemia (with the maximum of 36.4°C at the Husinec-Řež station). The high air temperature culminated on 20/8 when the $T_{\max}$ was higher than 30°C across the whole area of the CZ (except for a few mountain stations) (Fig. 5). The area with the highest air temperature was located in the central and north-eastern part of Bohemia (see Fig. 5), where the $T_{\max}$ rose above 38°C at 22 stations. The highest daily maximum air temperature on record in the CZ with value of 40.4°C was observed at the Dobřichovice station (Fig. 6a). The cold front passing over the CZ during the night of 20/8 to 21/8 brought a slight drop in temperature across most of the area (see Fig. 6). On 21/8 the $T_{\max}$ remained above 30°C in the central and northern part of Bohemia and in south Moravia, with the highest daily maximum air temperature of 34.6°C observed at the Doksany station (Fig. 6b). On 22/8 the region of high air temperature moved east to south Moravia, where the $T_{\max}$ was above 30°C until 24/8, while the air temperature did not exceed 30°C at most stations in Bohemia (see Fig. 6). The period with a very high air temperature was ended on 25/8 by a cold front advancing from the south-west. The return periods of the observed $T_{\max}$ values and its two and three day means from 19/8 to 21/8 in central and north-eastern Bohemia exceeded 100 years (Fig. 5).

During the period with high air temperature large differences between the daily maximum and minimum air temperature were observed (Fig. 6). Daily air temperature

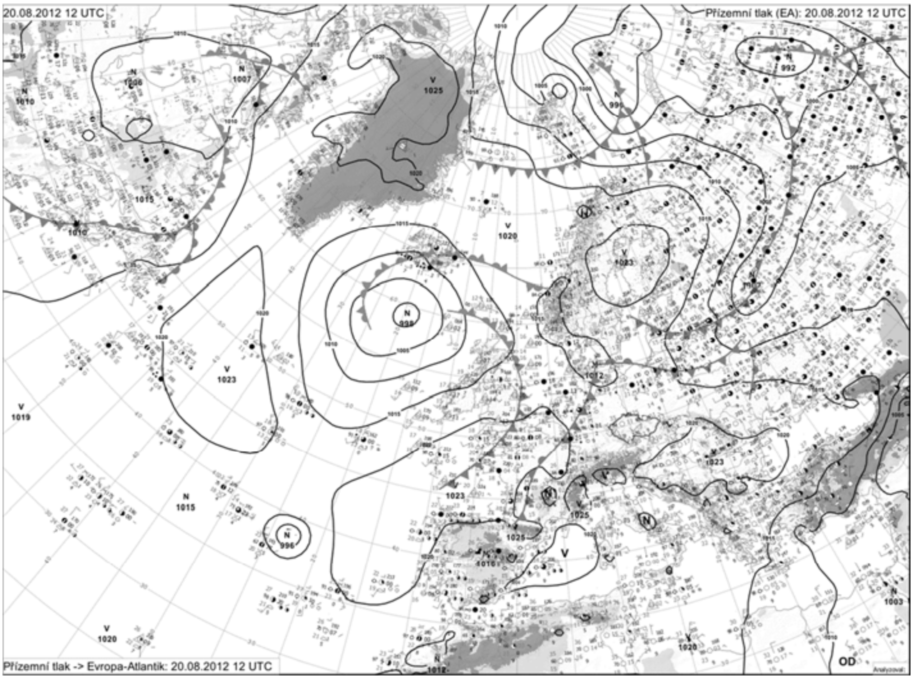

Fig. 3. Frontal analysis of surface pressure field over Europe for 20 August 2012, 12 UTC. The map is from archive of the Central Forecasting Office of the Czech Hydrometeorological Institute.

amplitude exceeded 27°C at several stations, e.g. it was 27.3°C at the Plzeň (not shown), Žatec (not shown) and Dobřichovice stations (Fig. 6a), which is more than 12°C above the long-term mean amplitude for August.

The situation was exceptional not only because of the fact that the new absolute maximum air temperature record was reached, but as it was only the second occasion in the period of instrumental air temperature measurement in the CZ that a temperature of 40°C was reached and exceeded. The highest measured air temperature values are presented in Table 1.

5. WEATHER EXTREMITY INDEX AND COMPARISON OF THE AUGUST 2012 EVENT TO HIGH AIR TEMPERATURE EVENTS IN THE PERIOD 1961–2012

The *WEI* and characteristics of extremity E and areal extent A (Eqs (1)–(3)) for the daily maximum air temperature and its two and three day means during the period 19/8 to 21/8 are shown in Table 2. The values of 4–7-day means of T_{max} in August 2012 did not meet the criteria for *WEI* evaluation. The highest *WEI* value was reached for the duration of one day on 20/8, followed by a two day duration that began on 19/08. The *WEI* for the three day period from 19/8 to 21/8 is relatively low in comparison to the two highest

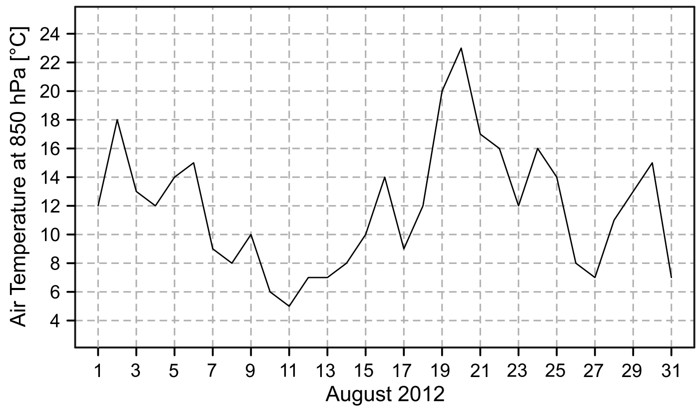

Fig. 4. The course of air temperature at 850 hPa at 12 UTC in the period from 1/8 to 31/8/2012 in Prague.

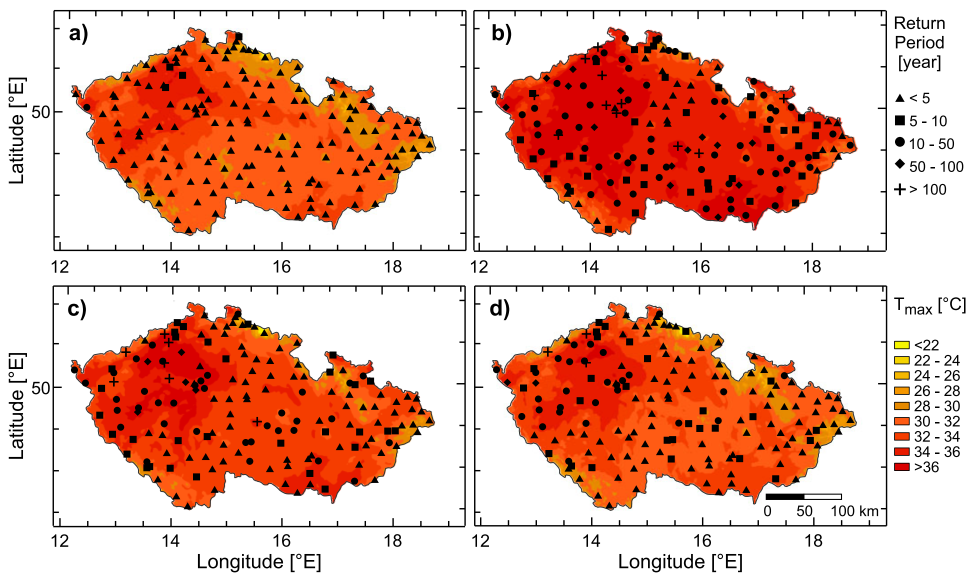

Fig. 5. **a)** and **b)** daily maximum air temperature on 19/8/2012 and 20/8/2012, respectively. **c)** 2-day mean of maximum air temperature from 19/8/2012 to 20/8/2012, and **d)** 3-day mean of maximum air temperature from 19/8/2012 to 21/8/2012 and its return periods at selected stations.

values in Table 2, but still the highest value in 2012 for the T_{max} three day mean. The high *WEI* value for 20/8 was due to both large spatial extent *A* and extremity *E* (Table 2). The areal extent *A* of the three day event is larger than that of the two day event, but the extremity *E* is higher for the two day period (Table 2).

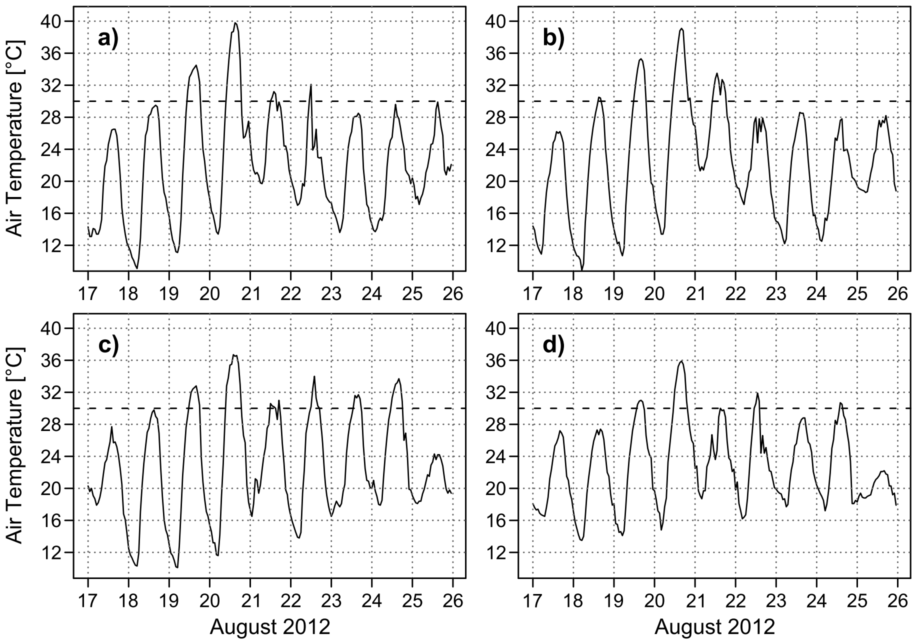

Fig. 6. The course of hourly 2-m air temperature from 17/8/2012 to 25/8/2012 at **a)** Dobřichovice station, **b)** Doksany station (representing the area of central Bohemia), **c)** Strážnice station and **d)** Kuchařovice station (representing the area of south Moravia). The value of 30°C is denoted by a dashed line.

Table 2 (Columns 6−8) also shows the comparison with other events during the 1961−2012 period based on *E*, *A* and *WEI*. The one day event of 20/8 was the third strongest one day event in terms of extremity and combined *WEI* value. The extremity and *WEI* value of the two day event were also relatively high. Overall comparison with one, two and three day events during the period 1961−2012 is presented in Fig. 7, which shows both components of the *WEI* for all events that meet the criteria for *WEI* calculation (the number of events is listed in the last column of Table 2). The most extreme one day event (highest *E* value) in the period 1961−2012 was on 27/7/1983, the most extreme two day event took place on 31/7/1994 and the most extreme three day event on 30/7/1994. In comparison to these events, the studied case in August 2012 had almost the same spatial extent, but a slightly lower extremity (Fig. 7).

In Fig. 7, it can be clearly seen that the extremity of events observed during the last three decades (1981−2012) is higher than for the period 1961−1980. Proper analysis of the time evolution of extremity is beyond the scope of our study, but the results indicate that especially in 1991−2000, the detected events had a higher extremity irrespective of spatial extent (Fig. 7). No increasing or decreasing pattern was found for areal extent. Fig. 7 also illustrates that the spatial extent of events increases with higher extremity. There are basically no events with very high extremity and small spatial extent. This result suggests that the occurrence of extremely high air temperature is probably connected with large

Table 1. Maximum air temperature above 40°C recorded in the Czech Republic.

Meteorological Station	Location	Date	Maximum Air Temperature [°C]	Elevation [m a.s.l.]
Prague, Uhříněves	Central Bohemia	27/7/1983	40.2	299
Plzeň, Bolevec	Western Bohemia	27/7/1983	40.1	328
Klatovy	Western Bohemia	27/7/1983	40.0	425
Sedlčany	Central Bohemia	27/7/1983	40.1	363
Dobřichovice	Central Bohemia	20/8/2012	40.4	205
Prague, Řež	Central Bohemia	20/8/2012	40.0	250

Table 2. Summary of evaluation of the Weather Extremity Index (*WEI*, Eq. (1)) for the studied high air temperature event of August 2012. *E*: extremity of the event (Eq. (2)), *A*: areal extent of the event (Eq. (3)). Columns 6–8 provide information about the ranking of the event under study in comparison with all detected events of respective duration in 1961–2012 (the number of these events is in the last column) based on *E*, *A* and the *WEI* itself.

Length of the Event [days]	Date of Beginning (August 2012)	*E*	*A* [km]	*WEI*	Rank Based on			Number of Detected Events During 1961–2012
					E	*A*	*WEI*	
1	19	0.76	118.0	89.9	83	112	80	253
	20	2.93	156.3	458.8	3	16	3	253
2	19–20	2.16	151.3	327.4	11	42	10	229
3	19–21	1.69	154.5	261.4	23	44	21	204

scale atmospheric circulation patterns and not caused by local conditions in a sub-region of the CZ. A deeper analysis of the circulation causes of high air temperature events in the area of the CZ will be presented in our new study that we are currently preparing for publication. Naturally, the affected area of events with relatively low extremity ranges from small to large.

A different perspective on the studied period of high T_{max} is provided by the heat wave definition suggested by *Huth et al. (2000)* (see Section 2). Based on this definition, the heat wave was detected at 129 meteorological stations (Fig. 8). It began between 13/8 and 18/8 and lasted for 6–8 days at most stations. Just 7 stations had the heat wave for only 4 days, while the duration was 13 days at the Dobřichovice station. The longest duration of the heat wave was experienced in Central Bohemia and Southern Moravia and naturally corresponds with the earliest onset. *Kyselý (2010)* analyzed the occurrence of heat waves based on the method proposed by *Huth et al. (2000)* at 46 meteorological stations in the CZ over the period 1961–2006. When compared to his results, the heat wave of August 2012 had a more or less average length. This is confirmed by our results for the Praha-Karlov and Kuchařovice stations (not shown).

Nevertheless, the period of high air temperature in August 2012 was a quite extraordinary event not only due to the new maximum air temperature for the CZ but also

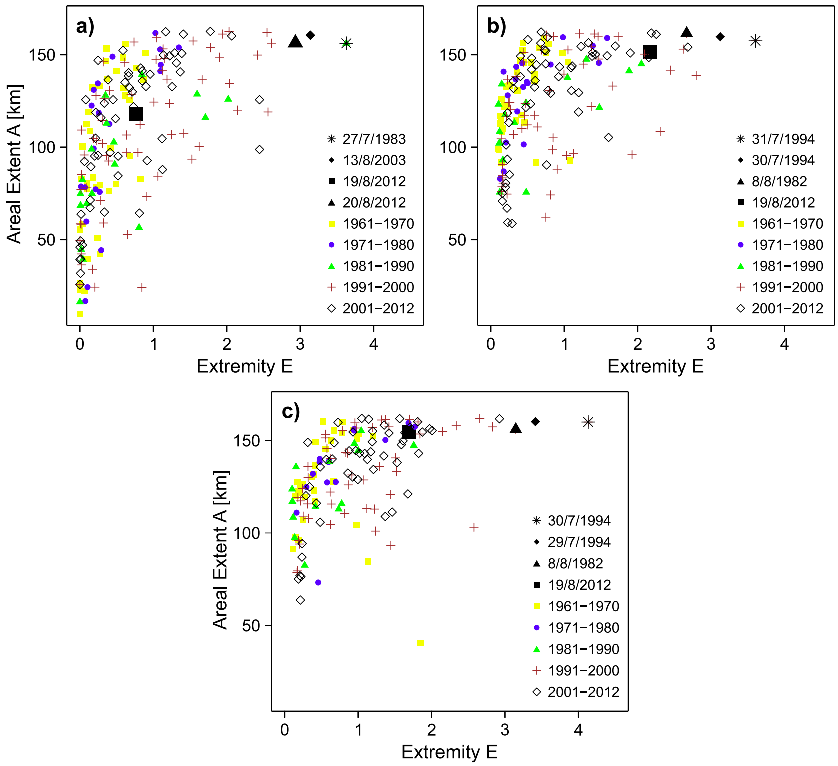

Fig. 7. Distribution of Weather Extremity Index components (extremity E and areal extent A) for **a)** daily, **b)** 2-day mean, and **c)** 3-day mean of maximum air temperature for the period 1961–2012. The most extreme events, along with the studied event of August 2012, are depicted by full black symbols (individual days in the legend).

because of the fact that the daily maximum air temperature is not usually so high in the second half of August. There have been only six years since 1961 when the maximum air temperature exceeded 35°C in the second half of August at a minimum of two stations in the CZ. Regarding the course of detected high air temperature events based on the *WEI* during the summer season, most cases are concentrated in the second half of July and the beginning of August. Only 5% of events during the period 1961–2012 were detected in the last third of August (Fig. 9a). From this point of view, the event of August 2012 was quite extraordinary, occurring so late in the summer with a relatively large spatial extent and extremity of detected T_{max}. Similarly, the occurrence of the heat wave based on the definition proposed by *Huth et al. (2000)* beginning in the second decade of August and ending during the third decade is quite unusual. For example, at Prague-Karlov and Kuchařovice stations such cases represent 5–10% of all detected heat waves since 1961 (Fig. 9b).

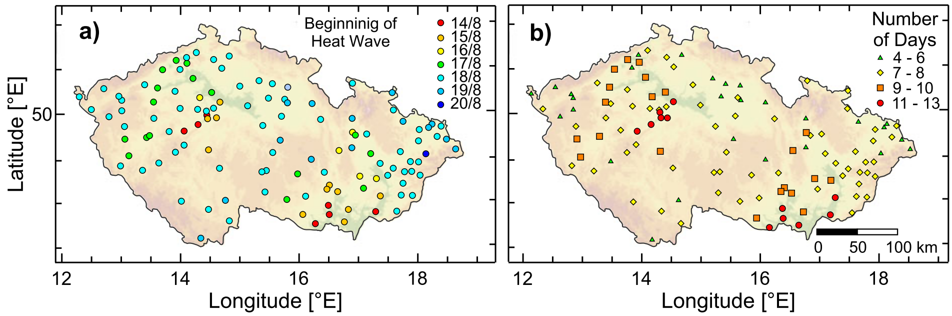

Fig. 8. **a)** The date of the beginning, and **b)** length (days) of the August 2012 heat wave at meteorological stations where the heat wave was detected based on the method proposed by *Huth et al. (2000)*.

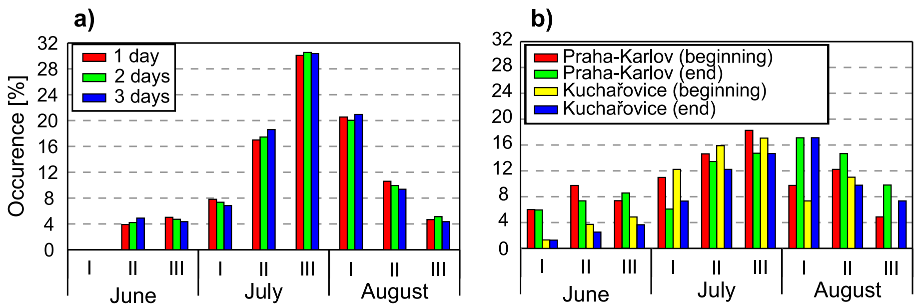

Fig. 9. Distribution of summer heat waves in the Czech Republic in the period 1961–2012 by decade; **a)** 1 to 3 day heat waves based on the Weather Extremity Index, **b)** beginning and end of heat waves detected at selected stations based on the definition by *Huth et al. (2000)*.

6. CONCLUDING REMARKS

We have presented an analysis of the period with an extremely high air temperature that occurred in the CZ in the second half of August 2012. We incorporated two different evaluation approaches and compared the results obtained by means of a novel Weather Extremity Index method suggested by *Müller and Kašpar (2013)* with a rather traditional approach described by *Huth et al. (2000)*. The first evaluates the extremity and extent of the area affected by the event of interest. The second evaluates single observed time series and is based on the length of the period during which the high air temperature persisted. The main advantage of the *WEI* method is its transferability, i.e. it is easily applicable in regions with various climatic conditions. Because the two methods evaluate the high air temperature event of interest from different perspectives (persistence of air temperature above specific thresholds vs. return periods of observed T_{max}) their results highlight different aspects. One of these differences is the evaluation of the length of the event.

Müller and Kašpar (2013) suggested that the length of an extreme event corresponds to the average time period (spanning 1–7 days) with the highest *WEI* value. According to this approach, the high air temperature event of August 2012 in the CZ lasted only 1 day and took place on 20/8/2012. In contrast, the definition suggested by *Huth et al. (2000)* assumes a minimum heat wave length of 3 days and the studied heat wave lasted 6–7 days in most of the affected area. Furthermore, it started before the 19/8 at some locations, which is not recognized by the *WEI*. Despite the fact that the T_{max} during these days was relatively high and exceeded the threshold of 25°C, the return periods were less than 10 years and therefore not classified by the *WEI* as extreme. This suggests that while the *WEI* is useful for the identification of really extreme high air temperature events and facilitates inter-comparison in terms of extremity and spatial extent, it cannot detect all cases where relatively high air temperature persisting for a longer time could have a severe impact on both human activities and natural ecosystems. This problem might be at least partly solved by setting the *WEI* evaluation criteria to a lower value of return periods of observed T_{max} values.

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