HEAT WAVES IN THE SOUTH MORAVIAN REGION DURING THE PERIOD 1961-1995

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Summary: *Heat waves (periods of extremely hot summer weather) in the region of south Moravia are in the focus of this study. The introduced definition consists of three requirements imposed on the period that is considered a heat wave: at least three days with* $T_{MAX} \geq 30.0\,°C$ *must be observed; the mean* T_{MAX} *over the whole period is at least 30.0°C; and* T_{MAX} *must not drop below 25.0°C. To compare the severity of the individual heat waves, various characteristics (duration, number of tropical days, peak temperature, cumulative temperature excess, precipitation amount) are examined. The heat wave index HWI is defined to express the severity of heat waves in the most comprehensive way.*

An extraordinary heat wave occurred in July and August 1994; it lasted more than a month at several stations, while the duration of a typical heat wave is only 4 - 7 days. The extremely long unbroken period of tropical days, and even of days with $T_{MAX} \geq 32.0\,°C$*, represents the most distinct feature of the severe 1994 heat wave. With regard to heat wave characteristics, the summer temperature exceptionality of the early 1990s is indubitable.*

Keywords: extreme events, heat wave, tropical day, climate change

1. INTRODUCTION

Ecosystems and various sectors of human activity are sensitive to extreme weather and climate phenomena, including heavy rains and floods, droughts, and high and low temperature, especially when they occur over extended periods. The domains in which extreme temperature events affect human society were summarized by *Wigley (1985)*; they include agriculture, energy demand, mortality and water resources. Numerous climatological studies of the 1990s focused on the statistical characteristics and impacts of extreme high temperature events or temperature threshold exceedences (e.g. *Rohli and Keim, 1994; Changnon et al., 1996; DeGaetano, 1996; Kunkel et al., 1996; Karl and Knight, 1997; Domonkos, 1998; Karl and Easterling, 1999*).

Extreme climate phenomena are now at the centre of interest also because of the danger of their possible increase in frequency, length and severity in a climate perturbed by enhanced concentrations of greenhouse gases and aerosols in the atmosphere. Impacts of climate change would result rather from changes in climate variability and extreme event occurrence than from an increase in mean temperatures (*Houghton et al., 1996; Watson et al., 1996*). Even relatively small changes in the means and variation of climate variables can induce considerable changes in the severity of extreme events (*Katz and Brown, 1992; Hennessy and Pittock, 1995*). Such changes are likely to impact ecosystems and society severely.

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Many studies have pointed out that extreme temperature anomalies often occur in groups. High persistency of time series may be a sufficient explanation of the experienced accumulation of extreme anomalies (*Domonkos, 1998*). Long-lasting extreme events such as prolonged periods with no precipitation (dry spells) or with high temperatures (heat waves) impose enormous stress on animals and humans. Episodes of extremely high temperatures, especially in conjunction with water shortage, can damage plants (*Bassow et al., 1994; Kirschbaum, 1996*), e.g. by adversely affecting their key phenological stages.

Growing attention to extreme phenomena has recently also been paid in General Circulation Model (GCM) studies, both in validating the simulated present-day climate and analyzing the possible future climate. These studies have mostly concentrated on frequencies of extreme rainfall events (e.g. *Mason and Joubert, 1997; Hennessy et al., 1997*), dry spells (*Joubert et al., 1996; Gregory et al., 1997; Huth et al., 1999*) and extreme temperatures / heat waves (*Gershunov and Barnett, 1998; Huth and Kyselý, 1998; Huth et al., 1999*).

As regards impacts of extreme high temperatures, there are no generally given threshold values for delimitation of group of anomalies (which threshold must be exceeded, how long and how unbroken in time the exceedences should be). Thresholds and the time periods of sensitive phenological stages alter among plant species and the economical impact of some threshold value exceedence depends on other factors, such as the type of soil, applied agrotechnical methods, crop protection facilities, etc. (*Domonkos, 1998*). For example, *Mearns et al. (1984)* mention that the exceedence of 35°C on five consecutive days is a very harmful event for corn yield in the USA Corn Belt.

High summer temperatures are harmful to human health as well. For instance, the very intense heat wave in July 1995 that affected the midwestern United States caused well over 800 deaths, most of them in Chicago (*Whitman et al., 1997*). The analysis of *Karl and Knight (1997)* indicates that for Chicago such an extended period of continuously high day and nighttime apparent temperatures is unprecedented in modern times. The analysis cited did not consider the dry bulb temperature, but the apparent temperature T_{ap} which attempts to quantify the effects of temperature and moisture on the human body (*Steadman, 1984*).

Changnon et al. (1996) have presented the comparison of fatalities attributed to weather in the United States (e.g. tornadoes, floods, hurricanes, wind storms, etc.). The mean annual number of deaths caused by heat waves is much higher than that for any other extreme weather event.

In the 1980s and 1990s, some unusually hot summers occurred in several continental territories of the Northern Hemisphere. Central Europe was one of the affected regions (*Míková, 1995; Domonkos, 1998*). Hot summers in this area, often accompanied by droughts, cause considerable harm to agriculture.

This paper focuses on heat waves (HWs) in the southeastern part of the Czech Republic in the period 1961-1995. The analysis of HWs in south Moravia during the period 1961-1990 was the subject of a diploma thesis (*Kyselý, 1997*) and a paper (*Kyselý and Kalvová, 1998*). In this work the period is extended to 1995 to include the extraordinarily hot summer seasons of 1992 and 1994 (cf. *Krška and Racko, 1993; Krška and Racko, 1996*). The heat wave index *HWI*, based on temperature and precipitation characteristics, is suggested to express the severity of HWs.

2. DATA

The observed daily maximum (T_{MAX}) and minimum (T_{MIN}) air temperatures and the precipitation sums were measured at eight stations located in south Moravia (Table 1). The data were provided by the Czech Hydrometeorological Institute and span the period 1961-1995. The selection of stations was made according to the following criteria:

- the station was not moved during 1961-1995 or was moved only insignificantly;
- the observation series is complete;

Table 1. List of stations.

Station index	Station	Altitude a.s.l. [m]	Latitude	Longitude
636	Kostelní Myslová	569	49°11'	15°28'
687	Velké Meziříčí	452	49°21'	16°01'
698	Kuchařovice	334	48°53'	16°05'
723	Brno - Tuřany	241	49°09'	16°42'
754	Uherské Hradiště - Staré Město	235	49°06'	17°26'
755	Strážnice	176	48°54'	17°20'
774	Holešov	224	49°19'	17°34'
779	Strání	421	48°54'	17°42'

• all altitudes are represented.

In exceptional cases, the missing daily values were estimated on the basis of a comparison with neighbouring stations (*Květoň and Reinhart, 1994*).

The stations can be divided into two groups by elevation; one group contains 5 "lower-elevation" stations (Kuchařovice, 698; Brno-Tuřany, 723; Staré Město, 754; Strážnice, 755; and Holešov, 774; altitudes 176 - 334 m) and the other group includes 3 "higher-elevation" stations (Kostelní Myslová, 636; Velké Meziříčí, 687; and Strání, 779; altitudes 421 - 569 m). This division was used, e.g., by *Kalvová and Nemešová (1998)*.

3. DEFINITION OF A HEAT WAVE

Defining the heat wave (HW) is in itself a challenge. In the meteorological literature HWs are usually determined with a noticeable degree of uncertainity, e.g. in the Czech meteorological dictionary (*Sobíšek, 1993*), a HW is defined as *"a period of N or more days of summer heat with a maximum daily temperature (T_{MAX}) of 30°C or higher"*. The minimum number of days (N) in a HW is not determined here; we can set, e.g., $N = 3$.

Generally, there are two approaches to defining HWs:

- the most extreme event lasting a required period (typically one to three days) in each summer is selected,
- all HWs with conditions exceeding a certain threshold are selected and analyzed.

In this paper the latter approach was adopted, as it allows several HWs in one year to be considered. The disadvantage of the former method is that it does not appropriately describe the differences between the individual HWs, namely their real duration, time development and cumulative temperature excess determined, for example, as the sum over all the days in the HW of the T_{MAX} excess above 30°C. Consequently, even a very intense HW may be excluded if it occurs within the same summer season as a more intense one.

We found it useful to define the HW (*Kyselý, 1997; Kyselý and Kalvová, 1998*) as the longest continuous period during which

- T_{MAX} reached at least $T1$ for at least 3 days;

- the mean T_{MAX} was at least *T1* over the whole period;
- T_{MAX} did not drop below *T2*.

The threshold values were set to $T1 = 30°C$, $T2 = 25°C$, in accordance with a climatological practice commonly applied in the Czech Republic, which refers to the days with T_{MAX} reaching or exceeding 30°C and 25°C as tropical and summer days, respectively.

The definition of the HW allows two periods of tropical days separated by a slight drop of temperature to make up one HW but, on the other hand, two periods of tropical days separated by a pronounced temperature drop below 25°C to be treated as separate HWs.

4. PRIMARY CHARACTERISTICS OF A HEAT WAVE

The following characteristics describing HWs have been defined:

- *d* ... the duration in days
- *N30* ... the number of days with $T_{MAX} \geq 30.0°C$
- *TX1* ... the highest T_{MAX} during the HW
- *TX3* ... the mean T_{MAX} of three days at the peak of the HW
- *TS30* ... the cumulative T_{MAX} excess above 30.0°C
- *TS16* ... the cumulative T_{MIN} excess above 16.1°C
- *R* ... the precipitation amount for the period of the HW (in mm)
- *R1* ... the precipitation amount for the period of the HW excluding the last day (in mm)

The peak of a HW is defined as the 3-day period with the highest mean T_{MAX}. The threshold minimum daily temperature for the cumulative T_{MIN} excess ($T_{MIN} = 16.1°C$) was established so that the probability of its exceedence would be the same as the probability of the exceedence of $T_{MAX} = 30.0°C$. The probabilities were evaluated from the daily data at 8 south Moravian stations during 1961-1995 and averaged over the stations. The characteristics conform to evident inequalities resulting from their definition and the definition of a HW: $d \geq N30 \geq 3$, $TX1 \geq 30.0°C$, while the inequality $TX3 \geq$ $\geq 30.0°C$ need not hold (even a HW peak may bridge a cooler day).

Characteristics *d* and *N30* describe (in a generalized sense) the *duration* of a HW, while *TX1* - 30°C and *TX3* - 30°C (rather than *TX1* and *TX3*) are good measures of its *elevation*. Variables *TS30* and *TS16* describe the temperature *bulk* of a HW, both in T_{MAX} and T_{MIN}. The last two characteristics (*R, R1*) give a picture of the precipitation conditions (*dryness*) of the hot period. The last day of a HW is excluded in the variable *R1* because precipitation on the last day of a HW is frequently connected with a cold front passage which ends the HW period. Thus, characteristic *R1* represents the dryness better than *R*.

Combining the measures of the duration, elevation, bulk and dryness of an individual HW, we have introduced the *heat wave index HWI* which expresses the *intensity* (*severity*) of the HW period as

$$HWI = \left(k_0(d + N30) + k_1(TX1 + TX3 - 60) + k_2(TS30 + TS16)\right) \cdot f(R1),$$

where k_0, k_1 and k_2 are coefficients (see below) and f is the dryness function. This relatively simple form was chosen so that the measures of duration, elevation and bulk would have the same weight. *HWI* is a characteristic with no unit, which can be ensured by establishing appropriate multiplicative constants in front of the individual variables.

Dryness function f, an important characteristic from the point of view of impacts on agriculture and water resources, has been chosen to have the form

$$f = \frac{1}{\ln\left(\frac{R1}{(d-1)} + e\right)},$$

where the precipitation amount $R1$ is given in mm and $\ln(e) = 1$. The logarithmic scale has been selected to lessen the variation of f with the amount of rain.

Function f takes values in the range from about 0.4 (very intense precipitation during the HW, averaging about 10 mm per day) to 1.0 (no precipitation during the HW). In typical cases (daily precipitation during the HW averaging ≤ 2 mm) it ranges from 0.65 to 1.0 (Table 2). The dryness function, therefore, leads to a decrease of the HW index that would be calculated from temperature variables only.

Table 2. Values of function f for various mean daily precipitation amounts of a heat wave (excluding the last day).

Precipitation [mm]	0	1	2	3	4	6	8	10	15
f	1.00	0.76	0.65	0.57	0.53	0.46	0.42	0.39	0.35

The value of coefficient k_0 has been set ($k_0 = 1$), while coefficients k_1 and k_2 were determined from HWs analyzed at 8 stations in the region of south Moravia during 1961-1995 so that all three terms in the numerator contribute (in the mean) the same relative amount to the final magnitude of the *HWI*. The values of the coefficients were similar at the stations, and averaged over all stations they were assessed to be $k_1 = 2.6$, $k_2 = 1.0$.

The final form of the *HWI* is

$$HWI = \frac{1.0(d + N30) + 2.6(TX1 + TX3 - 60) + 1.0(TS30 + TS16)}{\ln\left(\frac{R1}{(d-1)} + e\right)}.$$

Besides the "individual" HW indices it is desirable to introduce an annual index *HWIa* which summarizes the severity of HWs over an entire year. We define *HWIa* as the sum of the *HWI* over all individual HWs in a year.

5. HEAT WAVES IN SOUTH MORAVIA IN THE PERIOD OF 1961-1995

5.1. Basic description of HWs

Table 3 gives the summary of the HW characteristics at individual stations averaged over the period 1961-1995. At the "warmest" station (Strážnice, 755) 53 HWs were recorded during 1961-1995, at the "coldest" (Kostelní Myslová, 636) only 13. With increasing altitude, both the frequency and annual duration of HWs decreases, and their location in the year shifts towards the end of summer. At the 3 higher-elevation stations a typical (average) HW begins on July 27-28 and ends on August 1, whereas at the 5 lower-elevation stations it lasts on the average from July 22 to July 27. This shift cannot be explained as the shift of the annual temperature maximum with altitude because the latter was not found in the mean annual T_{MAX} cycle in the period 1961-1995 within the elevations of the stations in question (Fig. 1). The existence of this "heat wave shift" must be explained taking into account the asymmetric shape of the curve of the annual T_{MAX} course. Temperatures above 30°C are preferred in early summer (before the annual peak of T_{MAX}) to late summer (after the peak of T_{MAX}), and their probabilities are higher at "warm" lower-elevation stations. This is the reason for the relatively more frequent occurrence of early summer HWs at lower-elevation as compared with higher-elevation stations.

The average duration (*d*) of HWs is 6.9 to 8.9 days at all stations, but HWs lasting from 4 to 7 days are most frequent; they comprise (except for Kuchařovice where the value is 47%) 57-70% of all HWs. The average number of tropical days in a HW (*N30*) is between 4.6 and 5.2 days at all stations.

The relative location of the temperature peak (*P*) is shifted towards the end of a typical HW which corresponds to the continuous radiative heating of the surface during the HW period. Neither of these variables (*d, N30, P*) depends significantly on altitude.

Table 3. Heat waves (HWs) at the individual stations - average characteristics for the period 1961-1995. *N* denotes the total number of HWs in the period 1961-1995, *P* is the average relative location of a temperature peak from the beginning of a HW. The meaning of the other symbols is the same as in the text. The last three columns show the average *annual* characteristics of HWs (duration *D*, temperature sum *TS30*, and annual HW index *HWIa*). The highest (lowest) values in each column are shown in boldface (italics).

Station	*N*	*d* [days]	*N30* [days]	*P*	*TX1* [°C]	*TX3* [°C]	*D* [days]	*TS30* [°C]	*HWIa*
(636) Kostelní Myslová	*13*	7.1	*4.6*	**0.79**	33.0	*31.7*	*2.6*	*2.7*	*10.8*
(687) Velké Meziříčí	22	*6.9*	4.7	0.66	32.9	31.9	4.3	5.5	19.1
(698) Kuchařovice	38	**8.9**	**5.2**	0.69	**33.5**	**32.2**	9.7	11.0	43.2
(723) Brno-Tuřany	42	8.2	5.0	0.70	32.8	31.9	9.9	11.0	42.3
(754) Staré Město	49	8.4	**5.2**	0.62	33.0	32.1	11.7	**14.8**	50.6
(755) Strážnice	**53**	8.0	5.1	*0.61*	32.8	31.9	**12.1**	13.8	**50.7**
(774) Holešov	40	7.3	4.7	0.66	*32.7*	*31.7*	8.4	9.7	37.4
(779) Strání	17	7.7	**5.2**	0.63	*32.7*	31.8	3.7	4.6	16.3

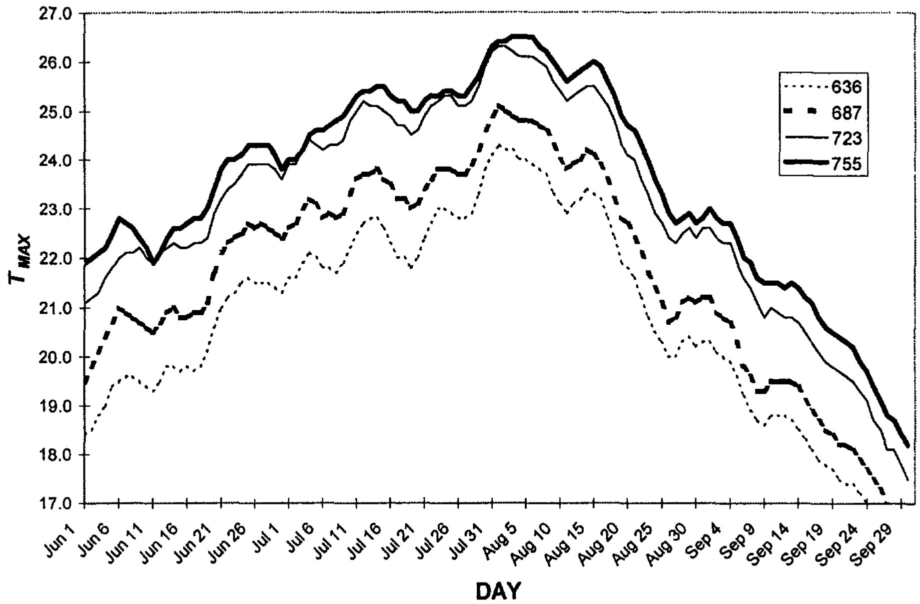

Fig. 1. Mean annual (June-September) cycle of T_{MAX} at stations Kostelní Myslová (636), Velké Meziříčí (687), Brno-Tuřany (723) and Strážnice (755) in 1961-1995.

On the whole, HWs are slightly more frequent in July than in August, but the numbers are almost the same at the warmest stations. An interesting feature of the HW occurrences at lower-elevation stations is that short HWs (3-6 days) usually occur in August (63%), while HWs of a medium duration (7-12 days) are observed in most cases (74%) in July. The numbers of extremely long HWs (> 12 days) are roughly equal in both months.

The longest and most intense HW within the period of 1961-1995 occurred in July and August 1994. At the stations Brno-Tuřany (723), Staré Město (754) and Strážnice (755) it lasted between 32 and 34 days; at each of the 8 stations the duration was at least 19 days which, e.g., at the station Kostelní Myslová (636) is more than 7 times longer than the average annual duration of HWs. This event is unprecedented within the last 35 years (see Table 4). For the 1994 HW, the temperature sum *TS30*, which includes the bulk of the HW, exceeded by factors of 2-4 the value for the most extreme HW within the period of 1961-1990 at all 8 stations. A similar conclusion can be drawn for *N30* and *HWI* as well.

As regards long-lasting HWs ($d \geq 12$ days), their number is higher in the first half of the 1990s (1991-1995) than for the whole 1961-1990 period at all stations. For instance, no HW with $d \geq 12$ days was observed before 1992 at the 3 higher-elevation stations, but 2 or 3 long-lasting HWs occurred in 1992 and 1994 at each of this stations. On the whole, almost 75% of the long-lasting HWs occurred in the first half of the 1990s (1992, 1994, 1995). An idea of how severe the temperature extremes of the early 1990s were can be further illustrated by the fact that both the temperature sum *TS30* and the HW index *HWI*

Table 4. Extreme 1994 heat wave and comparison with the data recorded within the period 1961-1990. Symbol p denotes the ratio of the temperature sum $TS30$ during the 1994 heat wave to the maximum value of $TS30$ during any heat wave within 1961-1990. The meaning of the other symbols is the same as in the text. The maximum values in a column are in boldface.

Station	1994 heat wave			maximum within 1961-1990			p
	d [days]	$N30$ [days]	$TS30$ [°C]	d [days]	$N30$ [days]	$TS30$ [°C]	
(636) Kostelní Myslová	19	13	18.3	7	5	9.4	1.9
(687) Velké Meziříčí	19	18	42.3	10	6	11.2	3.8
(698) Kuchařovice	22	17	47.5	16	8	17.7	2.7
(723) Brno-Tuřany	32	22	67.2	**19**	9	21.0	3.2
(754) Staré Město	33	22	**76.8**	**19**	**10**	**23.8**	3.2
(755) Strážnice	**34**	**24**	67.1	18	**10**	18.4	3.6
(774) Holešov	23	19	63.3	17	9	20.2	3.1
(779) Strání	20	17	40.8	8	5	10.1	**4.0**

also reached absolute record values in the 1990s (the three highest values refer to the HWs in 1992 and 1994) at all stations. There is no doubt that the three most severe HWs within the period of 1961-1995 by any measure occurred after 1991.

The earliest HW during the period 1961-1995 occurred at station Strážnice (755) in 1979: it lasted from May 30 to June 8. On the other hand, the latest HW was observed in 1973 at all stations except one (Strání), and lasted from September 4 to 9. Extraordinary temperature conditions in the middle of September 1947 when, e.g., at station Brno-Tuřany 10 successive tropical days were recorded (Sept. 12-21) (*Krška and Racko, 1996*) had no analogy in the period of 1961-1995.

5.2. Intercomparison of extraordinary hot summer seasons with regard to HW occurrence

Since 1961, the warmest summer seasons (as measured in terms of the mean 3-month temperature) occurred in the Czech Republic in 1983, 1992 and 1994; see also Fig. 2.

The differences between extremely hot summer seasons correspond to the synoptic weather patterns that dominated those years (*Krška and Munzar, 1984; Krška and Racko, 1993; Krška and Racko, 1996*). In 1983, the region of south Moravia experienced the highest number of HWs, but their total annual duration was much shorter than during the other two years. This evidently corresponds to the relatively frequent cold front passages in 1983 (*Krška and Munzar, 1984*). The cold fronts were weak, but they interrupted the hot period several times. The individual HWs were also less severe in 1983, which is evident both from the total annual HW index *HWIa* and the temperature sum *TS30*. In 1992 and 1994 the *HWIa* and *TS30* values were much higher than in 1983 at all stations. It is also worth noting that at the south Moravian stations, higher temperatures were recorded both in 1992 and 1994 than in 1983 when the absolute air temperature maximum on the territory of the Czech Republic was observed in Prague-Uhříněves (40.2°C on July 27; *Krška and Munzar, 1984*).

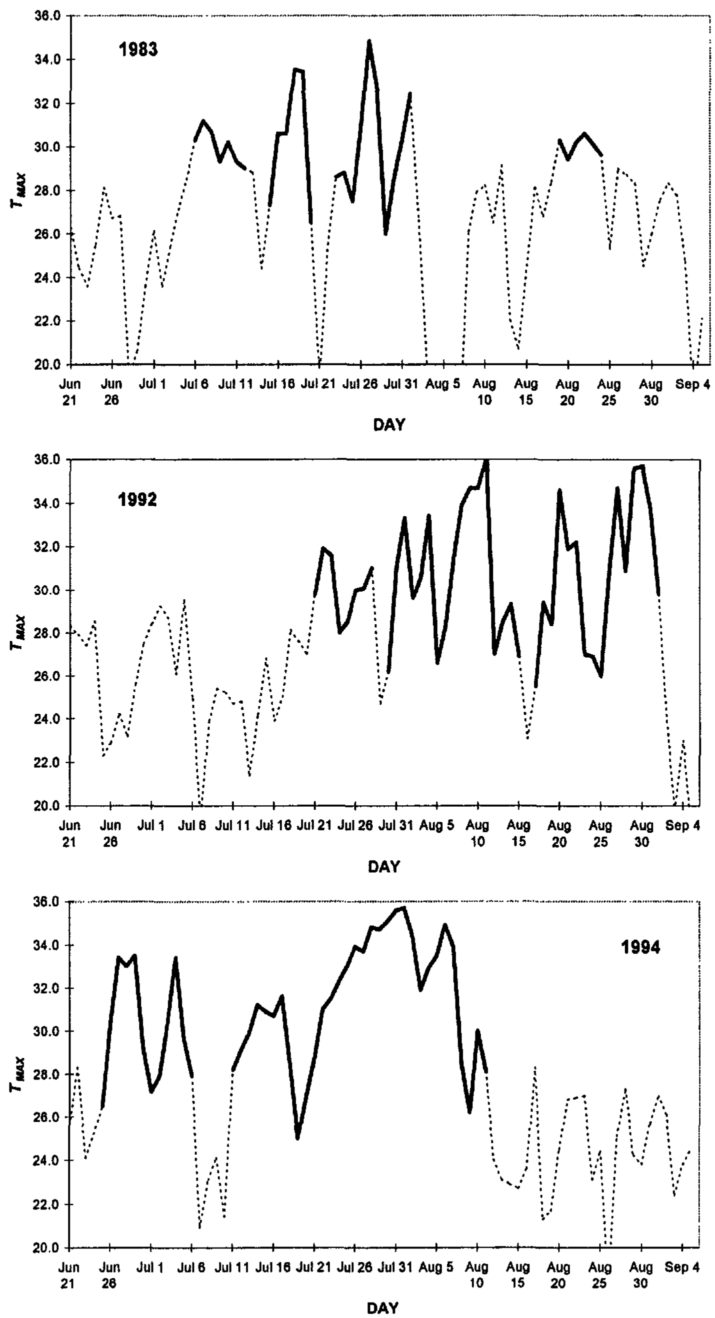

Fig. 2. Course of T_{MAX} in summer (June 21 - September 6) of 1983, 1992 and 1994 at station Brno-Tuřany (723). Heat waves are shown as the bold curve.

The most characteristic distinctness of the severe 1994 HW was an extremely long unbroken period of tropical days (with $T_{MAX} \geq 30.0$°C), cf. *Krška and Racko (1996)*. This period lasted between 17 and 18 days at all stations involved, except for the coldest (Kostelní Myslová) where its duration was 13 days. Moreover, a period of 10-15 consecutive days with $T_{MAX} \geq 32.0$°C can be found at all 5 lower-elevation stations, with the maximum value of 15 days at Staré Město (754). The maximum duration of other unbroken periods with $T_{MAX} \geq 32.0$°C is 4-5 days during 1961-1995 at all lower-elevation stations, and only 3-4 days during 1961-1990. The exceptionality is clear from Fig. 2 which compares the course of extreme 1994 HW to any HW in 1983 or 1992.

5.3. Temporal distribution of HW occurrence

The comparison of the HWs in five summer seasons with their maximum occurrence (1963, 1983, 1988, 1992 and 1994) is given in Table 5. The average annual duration of HWs (*D*) and the number of tropical days in the HWs (*N30*) at 8 stations in 1992 and 1994 were approximately two to three times larger than in 1963, 1983 and 1988. For temperature sums (*TS30* and *TS16*), the values are more than three times higher.

These facts support the hypothesis that the year 1992 was the most extreme within the period 1961-1995 in annual HW occurrence in south Moravia, closely followed by 1994. In 1994, at most stations *HWIa* is lower because the heat periods, otherwise comparable with 1992, were accompanied by more intense rainfall. Both the precipitation amounts and the frequency of rainy days were approximately twice as high as in 1992. This corresponds to the higher air humidity and intense storm activity that occurs after a front decay over the involved region, which is mentioned in the synoptic interpretation of summer 1994 (*Krška and Racko, 1996*). Next in intensity were the summers of 1983, 1963 and 1988.

Table 6 and Figs. 3 and 4 present the temporal distribution of HWs (on the average at eight stations) in the period 1961-1995. The characteristics of the HWs are calculated for 5-year periods in Table 6 (5-year running means are depicted in Fig. 4). The maximum HW occurrence and intensity fall unambiguously in the 1990s, whereas the minimum frequency occurred in the late 1970s. A secondary maximum can be found in the early

Table 5. Comparison of the heat wave characteristics and mean summer temperature in the years with the maximum heat wave occurrence (average values for 8 stations). Symbol *N* denotes the number of HWs, *T678* is the mean summer temperature. The meaning of the other symbols is the same as in the text. The highest value in each column is shown in boldface.

Year	*N*	*D* [days]	*N30* [days]	*TS30* [°C]	*TS16* [°C]	*HWIa*	*T678* [°C]
1963	1.75	17.0	10.2	20.0	8.7	75.7	18.2
1983	**2.75**	18.6	11.0	18.3	8.4	78.0	18.7
1988	1.50	13.6	8.8	18.1	8.4	72.7	17.8
1992	2.38	34.4	20.5	58.3	**29.8**	**168.1**	**20.2**
1994	2.25	**37.0**	**25.4**	**66.7**	27.7	155.8	19.6

Table 6. Total characteristics of heat waves (averaged over 8 stations) in 5-year periods. *N* denotes the total number of HWs, the meaning of the other symbols is the same as in the text. The maximum (minimum) values in each column are shown in boldface (italics).

Period	*N*	*D* [days]	*N30* [days]	*TS30* [°C]	*TS16* [°C]	*HWIa*
1961-1965	4.89	35.6	21.2	36.4	15.1	152.5
1966-1970	3.51	24.2	13.9	21.6	7.2	98.5
1971-1975	5.89	43.4	27.6	41.4	25.0	174.5
1976-1980	*2.26*	*16.7*	*10.5*	*16.4*	*4.9*	*68.5*
1981-1985	4.01	24.9	15.0	21.6	11.0	101.5
1986-1990	5.26	31.7	21.0	31.6	17.5	149.5
1991-1995	**8.51**	**97.2**	**61.8**	**150.7**	**72.5**	**438.0**

1970s (cf. *Kyselý and Kalvová, 1998*). In the first half of the 1990s, the characteristics *TS30, TS16* and *HWIa* exceeded their magnitudes in any other 5-year period many times over, and the number of tropical days (*N30*) and the total duration (*D*) of HWs were more than twice as large. Moreover, the temperature sums *TS30* and *TS16* were only slightly higher for the whole period of 1961-1990 than for 1991-1995.

These findings support the idea of the extremeness of the summer temperature in the early 1990s.

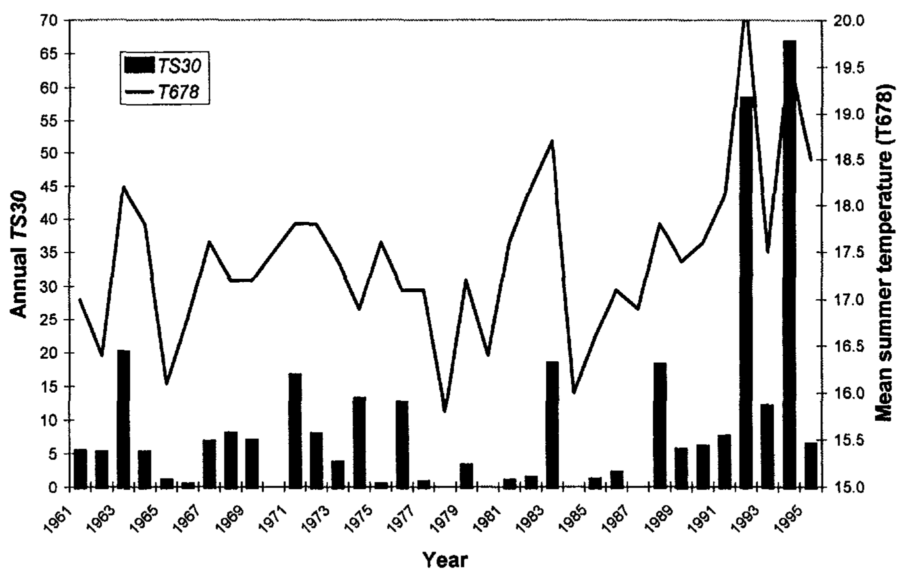

Fig. 3. Annual cumulative T_{MAX} excess above 30°C (*TS30*) during heat waves and mean summer temperature (*T678*) in 1961-1995, both averaged over 8 south Moravian stations.

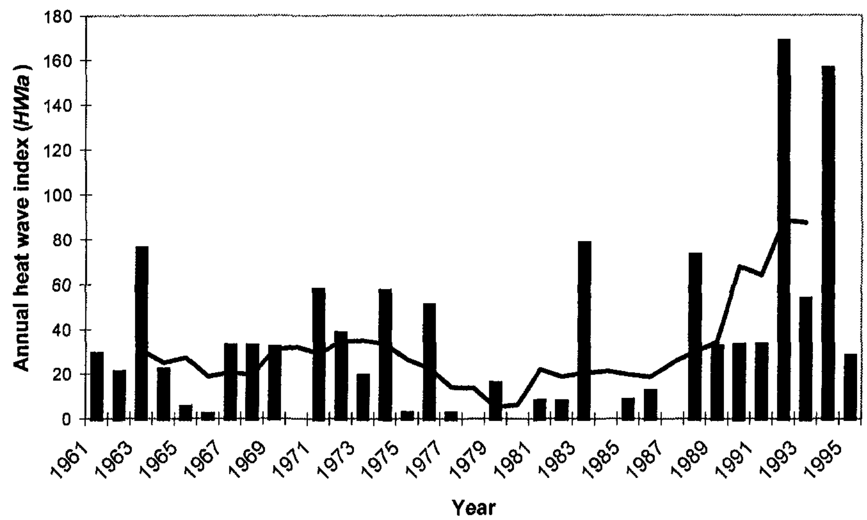

Fig. 4. Annual heat wave index (*HWIa*) smoothed by 5-year running means in 1961-1995, averaged over 8 stations.

5.4. Occurrence of tropical days within/outside HWs

Particularly from an agrometeorological point of view, an important climate characteristic is the occurrence of tropical days (the days with $T_{MAX} \geq 30.0°C$). The interesting characteristics are both the total number of tropical days per year (summer season, etc.) no matter whether the tropical day is part of a HW or not, and the number of tropical days within the HW periods (see Table 7).

We can draw these conclusions:

- The higher the total duration of HWs at the station, the higher the ratio of the number of tropical days within the HWs to the total number of tropical days (*W/T*); at the "warm" stations Brno-Tuřany (723), Staré Město (754) and Strážnice (755) this ratio lies in the range of 69-71%, while at the "cold" stations Kostelní Myslová (636), Velké Meziříčí (687) and Strání (779) it is only slightly above 50% (51-58%).
- A similar conclusion can be drawn for the individual months June, July and August.
- Over the period 1961-1995 the *W/T* ratio in July and August is of a comparable magnitude at most stations. Conclusions drawn about the occurrence of tropical days within HWs being more frequent in July than in August (*Kyselý, 1997*) cannot be confirmed.
- The *W/T* ratio tends to be higher in years with a higher mean summer temperature. The extremely long and intense HWs in 1992 and 1994 resulted in a considerable increase of tropical days occurring within HWs (5-15% in mean values) at all stations.

Table 7. The occurrence of tropical days in heat waves in 1961-1995. *T* denotes the total number of tropical days, *W* the number of tropical days within heat waves. The *W/T* ratio is in per cent.

Station	*T* [days]	*W* [days]	*W/T* [%]
(636) Kostelní Myslová	116	60	**51.7**
(687) Velké Meziříčí	200	103	**51.5**
(698) Kuchařovice	306	197	**64.4**
(723) Brno-Tuřany	301	209	**69.4**
(754) Staré Město	364	254	**69.8**
(755) Strážnice	377	269	**71.4**
(774) Holešov	282	187	**66.3**
(779) Strání	151	88	**58.3**

6. CONCLUSIONS

Heat waves represent dangerous weather events and increased attention is now paid to them in connection with a possible climate change. The introduced definition of the HW enhances the standard approach by taking into account the real perception of a HW period and meteorological conditions. The definition consists of three conditions a temperature extreme period has to satisfy and, in general form, can be used both under climatic conditions different from the present and in other geographical regions. The threshold values employed in the definition can be adjusted for different temperature conditions using statistical methods (e.g., expressing percentiles of a probability distribution of T_{MAX} in the summer season). This provides an opportunity to compare the HW occurrence between the observed data and the outputs of a climate model with the distribution of daily temperatures different from reality (for the control climate).

The presented analysis of HWs at 8 south Moravian stations during 1961-1995 employs various HW characteristics (e.g., duration, number of tropical days, peak temperature, cumulative T_{MAX} and T_{MIN} excesses, precipitation amount). The heat wave index *HWI* based on temperature and precipitation characteristics has been proposed to express the severity of HWs in the most comprehensive way.

With increasing altitude (within the range of the stations involved), both the frequency and annual duration of HWs decreases, and their mean location in the year shifts towards the end of summer. The ratio of the number of tropical days within the HWs to the total number of tropical days is between 50 and 70%; higher values are observed at lower-elevation stations.

The average duration of the HWs is about 8 days at all stations, and HWs lasting between 4 to 7 days are mostly preferred, but the longest and most intense HW that occurred in July and August 1994 lasted more than a month (32-34 days) at several stations, and included a period of 17-18 consecutive tropical days.

The summer temperature exceptionality of the early 1990s has been demonstrated. The three most severe HWs within the period of 1961-1995 by any measure occurred in 1992 and 1994. During 1991-1995 the characteristics *TS30*, *TS16* and *HWIa* exceeded their magnitudes in any other 5-year period many times over.

The occurrence of HWs in secular time series (at least from the beginning of the 20th century) will be the subject of a further study. The presently available analysis of the long-term daily temperature records from Prague-Klementinum (over the period 1901-1997) shows that the exceptionality of the 1994 HW is also evident in the context of the whole 20th century. Among the warmest summer seasons (measured in terms of HW occurrence) that were experienced in 1947, 1952, 1992 and 1994, the year 1994 is distinguished particularly in the much higher cumulative temperature excess of HWs, and the record duration of unbroken tropical days period. The difference between the 1994 HW and any other HW recorded during the 20th century is so large that it cannot be attributed to the increased urban heat island only.

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