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TEMPORAL FLUCTUATIONS IN HEAT WAVES AT PRAGUE–KLEMENTINUM, THE CZECH REPUBLIC, FROM 1901–97, AND THEIR RELATIONSHIPS TO ATMOSPHERIC CIRCULATION

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ABSTRACT

Temporal fluctuations in heat wave occurrence and severity are analysed in long-term daily temperature series at Prague–Klementinum, the Czech Republic. Although the observations have been continuous since 1775, the period 1901–97 with the most credible data is mainly examined. Most of the warmest summers of the 20th century appeared within the periods 1943–52 and 1992–95; the temporal distribution of heat waves corresponds to this pattern and shows two maxima, in the 1940s to early 1950s and in the 1990s. A very low occurrence of heat waves was typical of the beginning of the 20th century and around 1980. The peak of heat wave severity in the 1940s–early 1950s, as well as their almost total absence in the first two decades of the 20th century, may be a common feature for a large area, as indicated by the comparison between two stations within central Europe, Prague–Klementinum and Basel (Switzerland), and by other studies. An extraordinary heat wave occurred in July and August 1994. It greatly exceeded other heat waves, mainly in the much higher cumulative temperature excess above 30 °C and a record-breaking duration of a continuous period of tropical days.

Relationships between heat wave characteristics in warm and cold decades and circulation conditions were analysed using the subjective Hess–Brezowsky catalogue of weather types (Grosswetterlagen). The link to the atmospheric circulation is evident, e.g. situations with an anticyclone or a ridge over central Europe were more (less) frequent during all the warm (cold) decades. Moreover, the occurrence of long and severe heat waves in the 1990s may reflect an enhanced persistence of the atmospheric circulation over Europe in the summer season because all groups of weather types have considerably increased residence times in 1988–97 compared with long-term means. Copyright © 2002 Royal Meteorological Society.

KEY WORDS: central Europe; long-term temperature series; heat wave; atmospheric circulation; North Atlantic Oscillation index; Hess–Brezowsky weather types

1. INTRODUCTION

Extreme weather and climate phenomena (including heat waves) attract the attention of the scientific community because of both their current impacts on society and ecosystems and the threat of their possible increases in frequency, duration and severity in a climate changed by enhanced concentrations of greenhouse gases 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 temperature (Houghton *et al*., 1996; Watson *et al*., 1996; Parmesan *et al*., 2000), and even relatively small changes in the means and variations of climate variables can induce considerable changes in the severity of extreme events (Katz and Brown, 1992; Hennessy and Pittock, 1995; Colombo *et al*., 1999). Such changes are likely to influence ecosystems and society severely.

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The domains in which extreme events affect human society, among others, include agriculture, water resources, energy demand and mortality (Wigley, 1985). Impacts are larger when extreme weather conditions prevail over extended periods; that is why prolonged extreme temperature events (usually referred to as heat waves and cold spells) are frequently investigated. The impacts of extreme climate on terrestrial biota were reviewed by Parmesan *et al*. (2000); there has recently been increasing evidence that extreme weather events may act as drivers of broad ecological responses to climatic trends.

High summer temperatures are harmful to human health as well. Many analyses that deal with heat-stress-related mortality consider the apparent temperature, which attempts to quantify the joint effect of temperature and moisture on a human body (Steadman, 1984), or apply a synoptic approach proposed by Kalkstein (1991). For example, the very intense heat wave in July 1995 that affected the midwestern USA caused 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 daytime and night-time apparent temperatures is unprecedented in modern times. Changnon *et al*. (1996) have presented a comparison of fatalities attributed to weather in the USA (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.

Several climatological studies have recently focused on temporal and spatial fluctuations of extreme high-temperature events and temperature threshold exceedances. Prolonged extreme temperature events have been studied in long-term series as well (Kunkel *et al*., 1996, 1999; Domonkos, 1998; Karl and Easterling, 1999). Kunkel *et al*. (1999) found no evidence of changes in the frequency of intense heat waves since the 1930s in the USA. The most frequent exceedances of threshold temperatures above which mortality rises significantly were observed in the 1930s, with 1936 recording the highest number. Kunkel *et al*. (1996) presented statistics of the most intense 4 day heat waves in Chicago between 1901 and 1995; the peak in the 1930s–1940s is the dominant feature of their temporal distribution.

In the 1980s and 1990s, unusually hot summers recurred over continents of the Northern Hemisphere mid-latitudes, and Europe was one of the most affected regions. In particular, the 1994 and 1995 summer seasons established a lot of record-breaking temperatures in a large number of sites across Europe. The extremes of heat were located in central and eastern Europe in 1994, encompassing Sweden, Denmark, Belgium, the Netherlands, Germany and Poland, and in 1995 the principal warm areas were further west, extending from the British Isles to Spain (WMO, 1998). In addition to record-breaking daily temperatures (e.g. 36.7 °C at Lycksele, northern Sweden, 1994; 38.9 °C at Virton, Belgium, 1994; 46.6 °C at Cordoba, Spain, 1995), long periods with a gradual development of extreme heat were particularly notable in 1994 and 1995. Several studies have dealt with increases in daily mortality rates during these heat waves, e.g. Sartor *et al*. (1995) for the 1994 heat wave in Belgium and Rooney *et al*. (1998) for the 1995 heat wave in Great Britain. The economic impacts of the hot summer of 1995 in Great Britain were analysed by Agnew and Palutikof (1999).

This study focuses on the temporal distribution of heat waves at the Prague–Klementinum station (the Czech Republic) in the period of 1901–97, and their relationships to the atmospheric circulation. The paper is organized as follows. In Section 2, the data, methods and definitions used are described, including the issues of homogeneity of temperature measurements and urban heat island growth. The temporal variations in heat wave occurrence and severity are examined in Section 3, and the most severe heat waves (with a special emphasis on the 1994 heat wave) are discussed in more detail in Section 4. In Section 5, a comparison of the temporal fluctuations in heat waves in Prague with those in Basel (Switzerland), as well as with results of other studies, is given. Relationships between heat waves and atmospheric circulation (the North Atlantic Oscillation (NAO) index and Hess–Brezowsky types of large-scale circulation patterns) are examined in Section 6.

2. DATA AND METHODS

2.1. Prague–Klementinum station: the history of measurements and the urban heat island

Prague–Klementinum station (latitude 50°05′ N, longitude 14°25′ E, altitude 197 m a.s.l.; Figure 1) is located in the vast complex of buildings of the College of St Clement in the centre of Prague. The series is

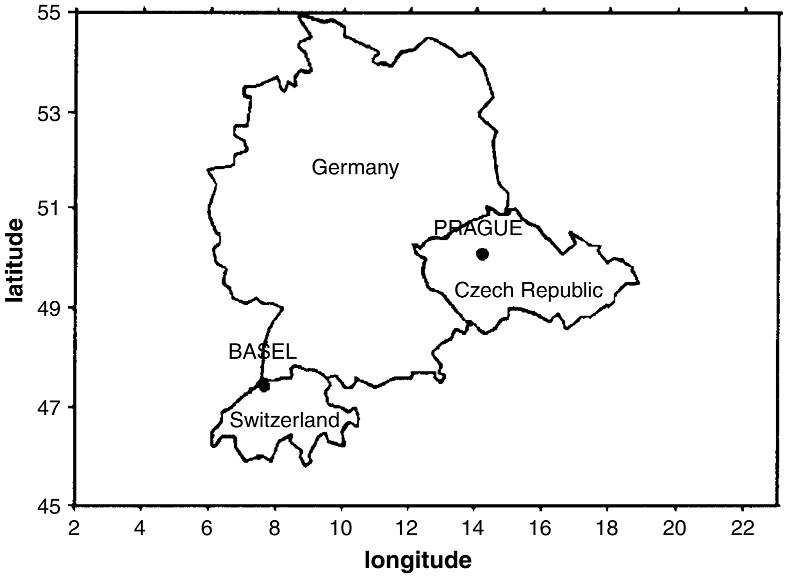

Figure 1. Locations of the Prague–Klementinum (Czech Republic) and Basel (Switzerland) stations

among the longest in Europe, as the measurements began there in 1752 and the daily series of air temperature is uninterrupted since 1 January 1775.

The location of the thermometer changed several times before 1889. Since 30 May 1889, however, it has been permanently installed in the screen near a window on the second floor (6 m above the ground) of a building in the southeastern part of the largest courtyard. Structural changes in the courtyard, which happened afterwards (1924, 1929), have not affected the homogeneity of measurements (Hlaváč, 1937). Changes in the instrumentation are not supposed to have had any effect on the homogeneity of the temperature series either, because simultaneous observations were carried out in such instances, and resulting corrections were made (Hlaváč, 1937). The history of measurements is described in more detail by Hlaváč (1937) and Brázdil and Budíková (1999).

Because the station is located in the historical heavily built-up centre of Prague, an urban heat island intensification resulting from a development of the city may play a role in temperature observations. This issue was addressed in the recent study of Brázdil and Budíková (1999), who found that in summer the urban warming (0.01 °C/10 years) is by far the least pronounced (compared with other seasons) and statistically insignificant for the period 1922–95. The degree of urban warming prior to 1922 is difficult to assess because of a lack of a suitable set of homogeneous reference stations.

2.2. *Definition of heat waves and heat wave characteristics*

Defining a heat wave is itself a challenge. In this study, the definition based on three conditions imposed on a heat wave period was adopted; the definition is the same as that used by Huth *et al.* (2000). According to this definition, the heat wave is a continuous period during which (i) TMAX (daily maximum air temperature) is higher than T1 on at least 3 days; (ii) mean TMAX over the whole period is higher than T1; and (iii) TMAX does not drop below T2. The threshold values were set to $T1 = 30.0\,°C$, $T2 = 25.0\,°C$, in accordance with a climatological practice commonly applied in the Czech Republic, which refers to the days with TMAX reaching or exceeding 30.0 °C and 25.0 °C as tropical and summer days respectively. This definition of a heat wave allows two periods of tropical days separated by a slight drop in temperature to make up one heat wave, but, on the other hand, two periods of tropical days separated by a pronounced temperature drop below 25 °C are treated as separate heat waves.

To characterize heat waves, the duration, the peak temperature, and the cumulative TMAX excess above 30.0 °C during heat waves (TS30) are used. The cumulative TMAX excess TS30 is probably the most appropriate variable to characterize the severity of heat waves (Kyselý, 2000). Mean temperature conditions of a summer season are usually given by the mean July–August daily maximum temperature (TX78) expressed as an anomaly from the long-term (1901–97) mean. The 2 month period of July–August is employed in TX78 instead of the more common 3 month June–August period since the majority of heat-wave days in the Czech Republic occur in those months (Huth *et al.*, 2000). The mean May–September daily maximum temperature is also introduced to capture the conditions of the extended (5 month) warm season of the year, which covers all the days with TMAX ≥30 °C at Prague–Klementinum.

3. TEMPORAL FLUCTUATIONS IN HEAT WAVES AT PRAGUE–KLEMENTINUM IN 1901–97

The temporal distribution of heat waves at Prague–Klementinum during the 1901–97 period is shown in Figure 2, which compares it with the course of the mean July–August summer temperature (TX78). Heat waves are characterized in Figure 2 by annual cumulative TMAX excess above 30.0 °C (TS30). The extreme years as regards the annual heat-wave severity (measured by TS30) and duration were 1994, 1947, 1992 and 1952; all of them are among the years with the warmest summers (Table I). Among the seasons with the most severe heat waves, the summer of 1994 is exceptional, particularly its much higher TS30, whereas other annual heat-wave characteristics (duration, peak temperature, number of tropical days) are of similar magnitudes in the extreme years. It is worth noting that some of the hot summers listed in Table I do not have pronounced heat waves; mainly 1995, 1944, 1950 and 1951.

Most of the warmest summers of the 20th century (in terms of TX78) occurred within the periods 1943–52 and 1992–95, and only a few occurred as isolated events outside these two periods (namely in 1983, 1971 and 1911; Table I). The temporal distribution of heat waves corresponds to this pattern and shows two peaks in the 1940s to early 1950s and in the 1990s (5 year running means of TS30 and TX78 are shown in Figure 2

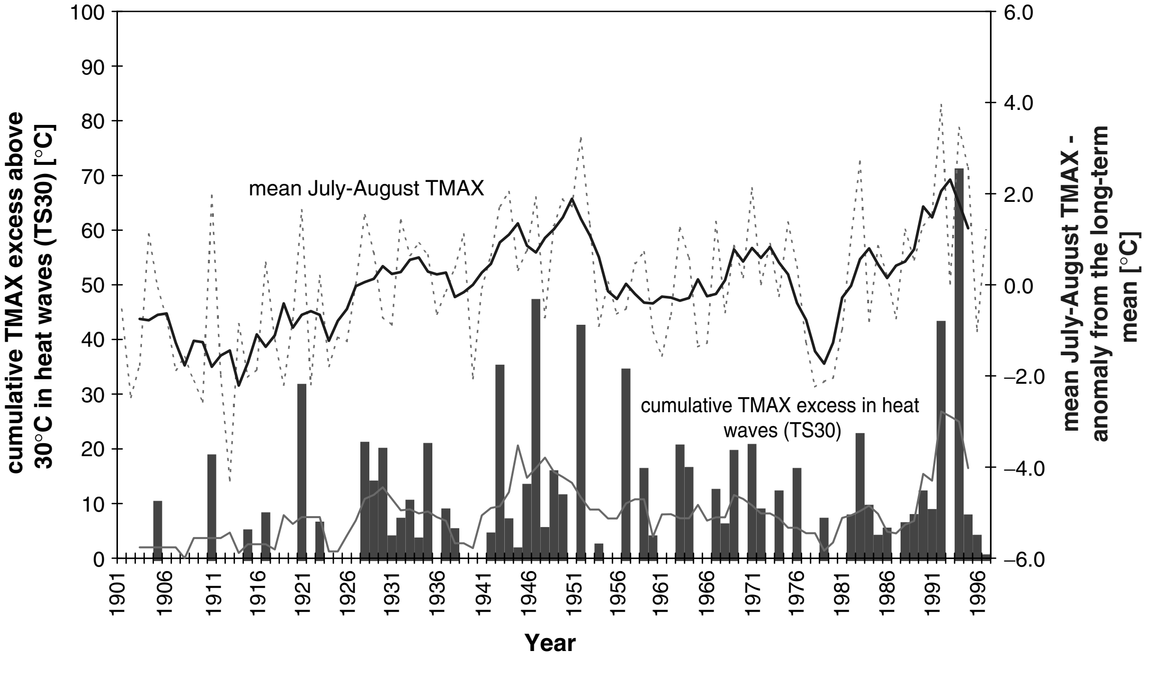

Figure 2. Heat waves at Prague–Klementinum from 1901–97 as measured by cumulative TMAX excess above 30 °C in heat waves (TS30), and the mean JA TMAX anomaly (TX78). Both TS30 and TX78 are also smoothed by 5 year running means (solid lines)

Table I. The 12 warmest summer (JA) seasons (ranked with respect to the mean JA temperature) at Prague–Klementinum, 1901–97. TX78 (TX59) denotes the anomaly of the mean JA (May–September) daily maximum temperature from the 1901–97 mean, TS30 is the annual cumulative daily maximum temperature excess above 30 °C in heat waves and *D* is the annual duration of heat waves. The four years with the most severe heat waves are in boldface

Year	TX78 (°C)	TX59 (°C)	TS30 (°C)	D (days)
1992	**3.95**	**2.92**	**42.9**	**34**
1994	**3.45**	**1.85**	**70.8**	**41**
1952	**3.22**	**0.65**	**42.2**	**35**
1983	2.71	1.47	22.4	21
1995	2.57	0.56	7.5	8
1971	2.12	0.35	20.4	20
1944	2.04	0.39	6.8	11
1911	1.96	0.67	18.5	16
1947	**1.92**	**3.04**	**46.9**	**40**
1950	1.88	1.98	11.2	9
1943	1.73	0.69	34.9	22
1951	1.72	1.01	0	0

to filter out the high-frequency variability). A very low occurrence of heat waves is typical of the beginning of the 20th century and (to a lesser degree) of the period around 1980. The coolness of the first two decades of the 20th century is demonstrated by the fact that only four summers experienced a heat wave, and that all the years when the annual temperature maximum remained below 30.0 °C (1902, 1903, 1909, 1910, 1912, 1914 and 1916) occurred in this period. The period of 1901–30 was described as a period of increased westerly winds and cyclonicity over the mid-latitude Atlantic Ocean, with a minimum in the frequency of blocking (Moses *et al*., 1987; Parker *et al*., 1994; Hurrell, 1995; Slonosky *et al*., 2000). Very low heat-wave frequency at the beginning of the 20th century also coincides with the period of decreased continentality of European climate, with warm winters and cold summers, whereas in the 1940s a pronounced local maximum in continentality (and some extremely cold winters) was observed in large parts of Europe (e.g. Koźuchowski *et al*., 1994; Thompson, 1995). Such considerable changes in the continentality of central Europe's climate have not probably appeared thereafter; the period of hot summers in the 1990s was also within a period of prevailing mild winters.

One of main differences between the two comparable intervals of severe heat waves in Prague, the 1940s–50s and the 1990s, consists of a different pattern in the interannual variability of mean summer temperature (defined as the absolute value of the difference between TX78 in two successive years). The beginning of the 20th century (especially the 1910s–20s) was a period of low summer temperature and large year-to-year changes (Figure 3); the decrease in the interannual variability from the 1910s to the 1930s (from ∼3.0 °C to as low as ∼0.5 °C in 5 year means) was concomitant with an increase in the mean temperature, and small year-to-year temperature changes characterized the periods of frequent heat waves in the 1930s and 1940s–50s. In the early 1990s, when another heat-wave severity peak was observed, the interannual variability reached its highest level since the 1910s. A similar, but less pronounced pattern is present when the mean May–September temperature is used to characterize the summer season (not shown) instead of the July–August temperature. Small year-to-year temperature changes in the generally warm period of the 1940s to early 1950s were typical of other sites in central Europe as well; e.g. see Schönwiese *et al*. (1994) and Weber *et al*. (1997).

Upward trends in both the heat-wave characteristics and mean summer temperature during the 1910s–40s and late 1970s–early 1990s are dominant features of the temporal distribution (Figure 2). These trends are in

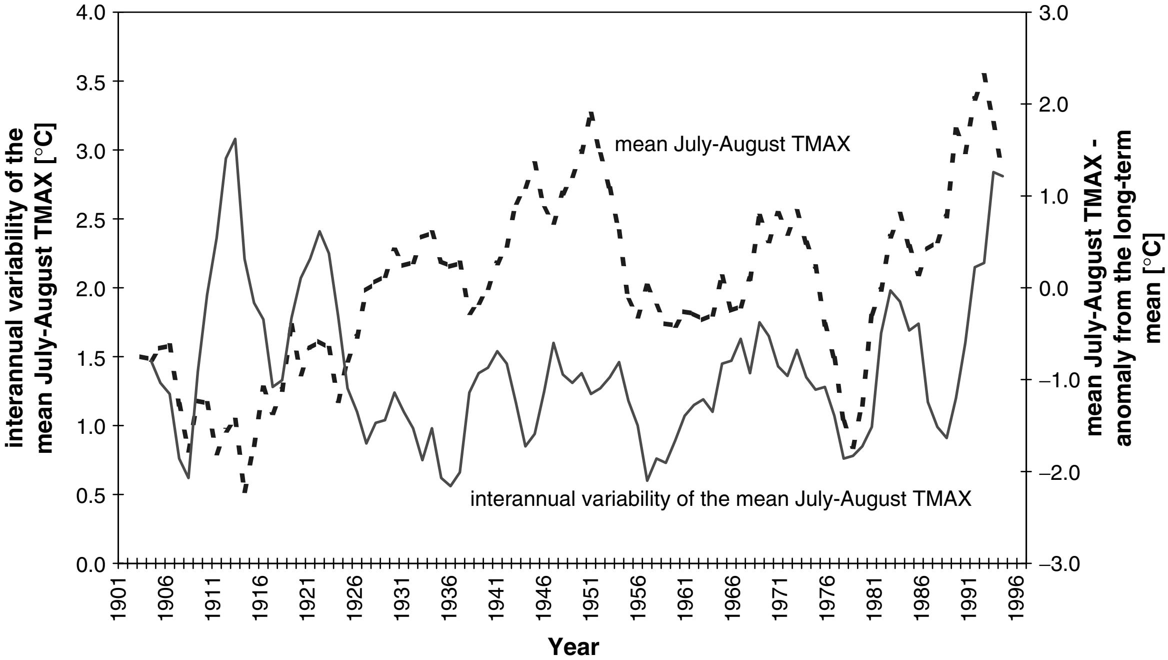

Figure 3. Mean JA TMAX anomaly from the long-term mean, TX78, and its interannual variability (computed as the absolute value of the difference between TX78 in two successive years) at Prague–Klementinum in 1901–97. Both the variables are smoothed by 5 year running means

general consensus with trends in the global mean surface temperature since the late 19th century, which show the most rapid increase during the periods of 1920–40 and since the mid-1970s (Houghton *et al.*, 1996; Fu *et al.*, 1999; Jones *et al.*, 1999). The warming of the 1920s–30s was particularly strong in the North Atlantic sector. Peterssen (1949) suggested that it was accompanied with a shift of the atmospheric circulation over the northern North Atlantic from a zonal to a more meridional one, and the extent to which the temperature increase in the 1920s may be explained by changes in circulation was further studied by several authors (Rogers, 1985; Moses *et al.*, 1987; Fu *et al.*, 1999). Recent rapid warming since the 1970s has been well documented in a number of studies (e.g. Jones *et al.*, 1999; Karl *et al.*, 2000) and is further investigated. It is likely that this is more or less associated with the dominant patterns of atmospheric circulation variability and their anomalous behaviour in recent decades; however, it cannot be readily explained by natural climate variability. Barnett *et al.* (1999), in their paper dealing with the causes attribution of recent climate change, concluded that the most probable cause of the observed warming is a combination of internally and externally forced natural variability and anthropogenic sources.

4. EXTREME HEAT WAVES WITH PARTICULAR REFERENCE TO THE 1994 HEAT WAVE

Some of the heat-wave characteristics are of comparable magnitude in the most severe years of the 1990s and 1940s–50s, but there are clear differences between them, particularly as regards individual heat waves.

Heat waves were more severe (as measured by TS30) in 1992 and 1994 than in the 1940s–50s; TS30 reached 47.6 °C and 33.3 °C in the 1994 and 1992 heat waves respectively, but only 21.9 °C in the most severe heat wave within the 1940s–50s period. The 1992 and 1994 heat waves were also the two longest in the 20th century (26 days and 22 days respectively), whereas the longest one in the 1940s–50s lasted only 18 days. Extreme heat waves also occurred outside the generally hot periods, namely in 1957 (TS30 = 34 °C) and 1921 (TS30 = 31 °C). Particularly worth noting is the fact that the second most severe heat wave (in

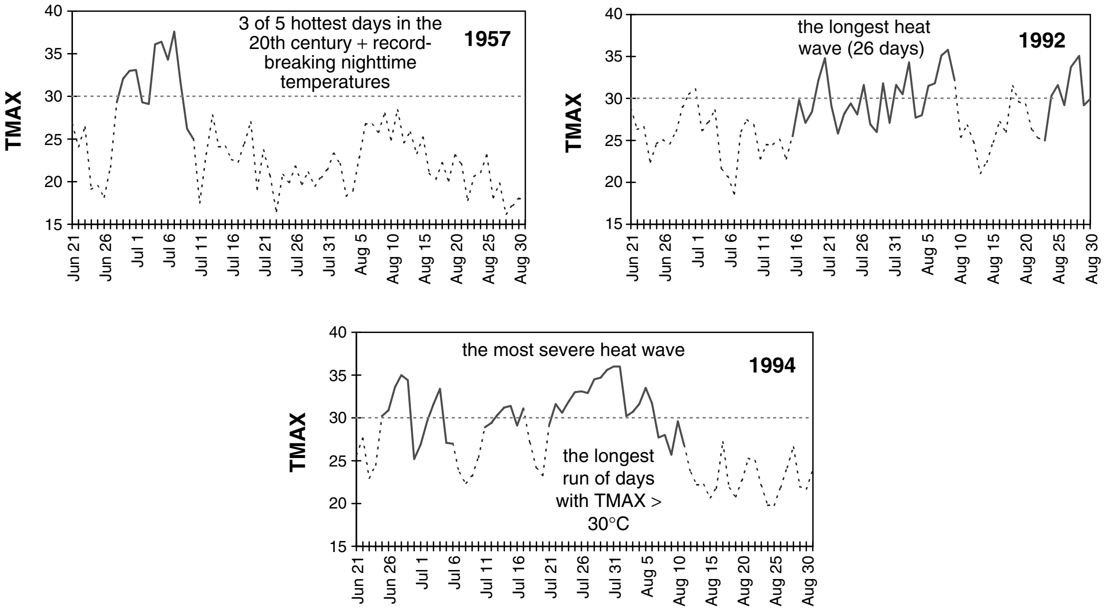

Figure 4. Extreme heat waves in 1957, 1992 and 1994 at Prague–Klementinum. The course of TMAX in summer (21 June–31 August) is shown; the heat waves are shown in bold. The horizontal line gives the limit for a tropical day (30 °C). The range of both axes is the same in all figures

Table II. The most severe heat waves (as measured by cumulative TMAX excess above 30 °C, TS30) and the longest continuous periods of days with TMAX ≥30.0 °C at Prague–Klementinum, 1901–97

Year	Beginning	End	Duration (days)	Peak temperature (°C)	TS30 (°C)
Most severe heat waves					
1994	July 21	August 11	22	36.0	47.6
1957	June 28	July 10	13	37.6	34.2
1992	July 16	August 10	26	35.8	33.3
1921	July 23	August 12	21	34.7	31.4
1952	July 31	August 16	17	35.5	21.9
Longest continuous period of days with TMAX ≥30.0 °C					
1994			16	36.0	
1911			9	33.5	
1921			7	34.7	
1929			7	34.0	
1942			7	31.5	

1957), which was associated with record-breaking daytime and night-time temperatures, appeared in a year when mean summer temperature was well below normal.

Probably the most conspicuous difference between the 1994 heat wave and any other is a very long run of days with TMAX ≥30.0 °C (tropical days). The period lasted 16 days (22 July–6 August) in Prague. The gradual development of very high TMAX (although record-breaking daytime temperatures were not reached) is demonstrated in Figure 4, which compares the temperature course of the 1994 heat wave with the other two extreme heat waves in the 20th century (1957, 1992). See also Table II, where the most severe heat waves and the longest runs of tropical days are listed. A period of more than six consecutive tropical days did not appear after 1942 until the 1994 extreme heat wave.

Within central Europe, the duration of the period of successive tropical days in 1994 rose towards the east; it reached 19 days at a few sites in eastern parts of the Czech Republic (the period lasted 18 days even at sites above 450 m a.s.l.), and 22 days in eastern Slovakia (Krška and Racko, 1996). At some higher-elevated stations in the Czech Republic, the number of tropical days within the 1994 heat wave was nearly the same as during the whole 30 year 1961–90 period (Kyselý, 2000). Nevertheless, the absolute record-breaking daytime and night-time temperatures were not reached. The highest temperatures ever recorded in the Czech Republic, reaching 40 °C in south and central Bohemia (Krška and Munzar, 1984), were observed in 1983, but the extreme warmth was confined to a relatively short period, and the heat waves did not attain a severity comparable to 1994.

The July and August 1994 heat wave must be treated as exceptional in the context of the 20th century. Moreover, it was very likely to have been the most severe heat wave even from the beginning of continuous temperature measurements at Prague–Klementinum in 1775, as indicated by a preliminary analysis that extends back to 1775; all heat waves in 1775–1900 experienced much lower cumulative temperature excess TS30 than the 1994, 1957 and 1992 heat waves.

Long periods with high air temperature and decreased inter-diurnal temperature variability in 1992 and 1994 were related to persistent circulation patterns with high-pressure systems influencing central Europe for a long time. A few other unusually long heat waves emerged in the Czech Republic in the 1990s (Kyselý, 2000). The recent occurrence of long and severe heat waves may reflect an enhanced persistence of the atmospheric circulation over central Europe in the summer season, because all groups of the Hess–Brezowsky large-scale circulation patterns (Hess and Brezowsky, 1952; Gerstengarbe *et al*., 1999) have considerably increased residence times in the 1990s compared with long-term means; see Section 6.

5. TEMPORAL FLUCTUATIONS IN HEAT WAVES IN CENTRAL EUROPE DURING THE 20TH CENTURY

In this section, the temporal distribution of heat waves at Prague–Klementinum is first compared with heat waves analysed in long-term daily temperature records in Basel (Switzerland), 1901–96 (see Figure 1), and then the results of a few other studies dealing with central-European temperature series are summarized.

Station Basel is located 317 m a.s.l. and the series of daily maximum temperature is continuous during the 20th century. The temporal distribution of heat waves shows a peak in the middle of the 20th century (1943–52), which is a common feature of both the Prague and Basel temperature series, but is much more pronounced in Basel (Figure 5). The five most severe heat-wave seasons appeared within the period 1943–52, and only a few others reached a partly comparable severity, namely in 1921, 1929, 1964 and 1976. On the other hand, the peak in the 1990s is by far not so pronounced as in Prague, and higher values of 5 year running means of TS30 were reached in the 1920s, 1930s and 1960s. Another common feature of the temporal heat-wave distribution at Prague–Klementinum and Basel is an almost total absence of heat waves in the first two decades of the 20th century and around 1980. Concerning individual years and/or individual heat waves in Basel, 1992 and 1994 were not remarkable in the context of the 20th century; out of the 20 most severe heat waves, 11 emerged within the period 1943–52 and only one after 1976.

An investigation of long-term changes in extreme temperature events over a larger region is a task for a future study. The maximum in heat-wave severity in the 1940s–early 1950s and minimum in the first two decades of the 20th century may be common features for at least the area of central Europe, as indicated by the comparison between Prague–Klementinum and Basel stations, and is supported by other studies. According to Gerstengarbe (1992), who analysed extreme hot and cold summers in central Europe, a frequent occurrence of hot summers was typical of the period 1928–53, with a peak in the 1940s. Cold summers prevailed in 1901–27. Koźuchowski *et al*. (1994) pointed out that the lowest values of the annual maximum mean monthly temperature at Cracow (Poland) since 1826 occurred at the turn of the 20th century, and the highest occurred in the 1940s. An analysis of tropical-day frequencies in Potsdam (Germany) during 1893–1989 (Wagner,

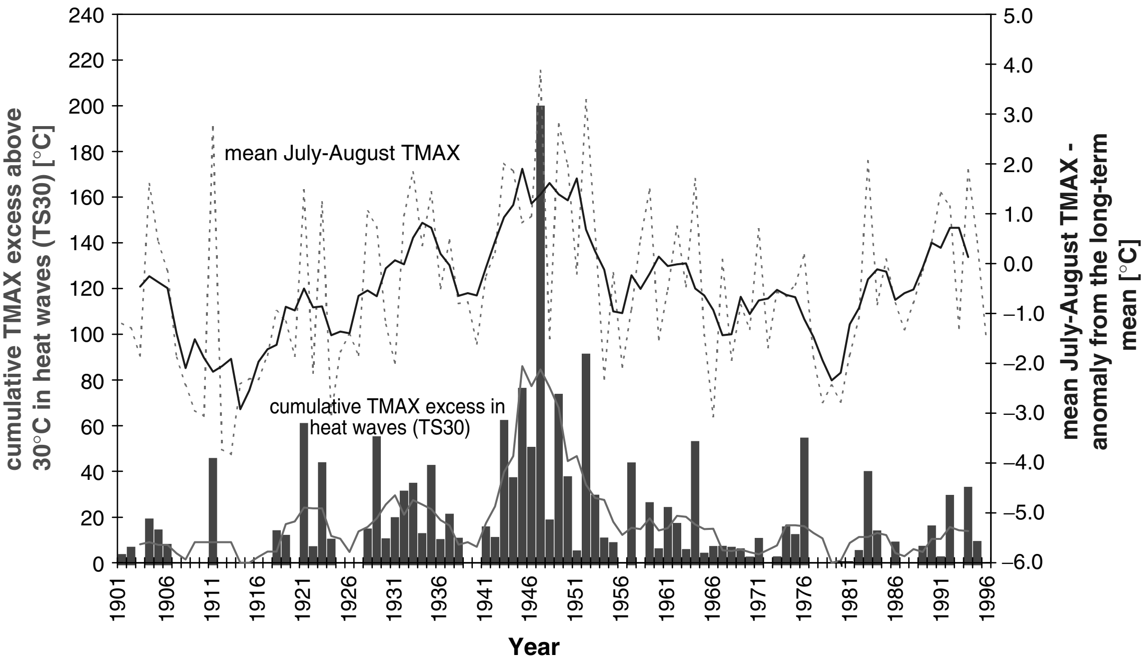

Figure 5. As in Figure 2, except for Basel (Switzerland) in 1901–96

1996) also demonstrated a pronounced maximum in the late 1940s and minima in the first two decades of the 20th century and around 1960 and 1980.

The period of minimum heat-wave occurrence at the beginning of the 20th century coincided with the most significant departure in the continentality of European climate since the mid-16th century (Thompson, 1995). The maritime period of 1900s–20s, associated with the intensification of the westerlies across the North Atlantic, was manifested in most of Europe in a decrease of the annual temperature range and the occurrence of cold summers and mild winters. A rapid increase in continentality followed after the late 1920s, with a pronounced maximum in large parts of Europe in the 1940s (manifested in warm summers and cold winters), although the levels reached in the 19th and particularly the 18th centuries were not matched (Thompson, 1995). As similar changes from continentality towards oceanity and *vice versa* were observed in central Europe as well as in Britain, Scandinavia, the Alpine region and the Low Countries, it is likely that more or less similar fluctuations in heat-wave severity will be typical of large parts of Europe. In the second half of the 20th century, such pronounced and consistent changes in continentality were not found.

6. RELATIONSHIP BETWEEN HEAT WAVES AND ATMOSPHERIC CIRCULATION

Surface meteorological variables are, to a certain extent (which differs among variables), influenced by atmospheric circulation. In this section, the relationships between heat waves and circulation conditions are analysed using (i) the index of the NAO and (ii) the subjective Hess–Brezowsky catalogue of large-scale circulation patterns (Grosswetterlagen, GWL).

6.1. Heat waves and the NAO

One of the major modes of Northern Hemisphere climate variability is the NAO. It is particularly important in winter, where it exerts strong control on the European climate. The NAO index (NAOI) is commonly defined as the difference in normalized sea-level pressure (SLP) between a station in the Azores and one in Iceland; an extended version of the NAOI using a station in the southwestern part

Table III. Pearson correlation coefficients between seasonal means of NAOI (columns) and temperature characteristics of a summer season (rows) at Prague–Klementinum, 1901–97

	NAOI — seasonal mean						
	DJF	DJFM	NDJFM	MAM	AM	JJA	JA
Mean May–September temperature	−0.05	−0.03	−0.01	−0.05	−0.08	0.11	0.19
Mean JA temperature	0.08	0.09	0.11	0.01	−0.04	0.00	0.11
Cumulative TMAX excess above 30.0 °C in heat waves	0.09	0.11	0.13	0.23*	0.23*	−0.01	−0.03

* Statistically significant relationships (at 0.05 level).

of the Iberian Peninsula can be used for the winter half of the year only (Hurrell, 1995; Jones *et al.*, 1997).

Monthly NAOI values were taken as the difference in normalized SLP between Ponta Delgada (Azores) and Stykkisholmur (Iceland); the SLP anomalies at each station were normalized by division of each monthly pressure anomaly by the long-term (1901–97) standard deviation. The SLP data were obtained from the Climatic Research Unit (University of East Anglia, Norwich; see Jones *et al.* 1997). November–March (NDJFM), December–March (DJFM), December–February (DJF), March–May (MAM), April–May (AM), June–August (JJA) and July–August (JA) means of monthly NAOI were introduced to characterize the state of the NAO in the period preceding or during the heat-wave (summer) season.

The relationship between heat waves and NAOI was assessed in two ways. First, a correlation was calculated between seasonal means of NAOI and heat-wave/temperature characteristics (Table III). A statistically significant positive relationship was found between NAOI in spring (MAM, AM) and the severity of heat waves at Prague–Klementinum in the following summer. This linkage does not hold for the mean summer (both JA and May–September) temperature, which may indicate that the state of the NAO in spring influences the occurrence of extremes rather than the mean temperature in summer. However, the percentage of variation explained by the relationship is very low. Furthermore, seasonal means of NAOI are sensitive to the reference period that is used to standardize monthly SLP data from the Azores and Iceland (from which NAOI is computed), and the relationship loses its statistical significance when another reference period (1864–1994, as used by Hurrell (1995)) instead of 1901–97 is employed.

The relationship between heat waves at Prague–Klementinum and the NAOI in the preceding winter (NDJFM, DJFM, DJF) is weak, and neither is the mean summer temperature affected by the winter state of the NAO. For the summer NAOI, the linkage with concurrent temperature characteristics is statistically insignificant. All these conclusions remain unchanged when the Spearman rank correlation coefficient is used instead of the Pearson coefficient, except that the rank correlation between the NAOI in spring and heat waves in the following summer is slightly below the 5% significance level.

It is likely that more interesting results are obtained when a subset of ten of the most severe heat-wave seasons in Prague is analysed separately. Positive values of the NAOI prevail in the preceding November to May, as well as in the seasonal means (Table IV). For example, the NAOI was positive in the preceding DJF (DJFM) in eight (nine) out of ten cases. This indicates that a severe heat-wave season tends to come after a winter half-year with a positive phase of the NAO and an increased zonal flow over the northern North Atlantic/European sector. Circulation-related changes in sea-surface temperature (SST) may act as drivers for mechanisms that support heat-wave development in the following summer, but the question as to whether this linkage is physically based or not is difficult to answer. (For example, see Colman (1997) and Colman and Davey (1999) for a discussion on issues related to the long-term predictability of European summer temperature from SST anomalies in the North Atlantic during the preceding winter.)

Table IV. The ten most severe heat-wave seasons in Prague and seasonal means of NAOI. *D* (TS30) is the annual duration of heat waves (cumulative TMAX excess above 30.0 °C). The average NAOI over the 10 years is shown in the last row

Year	D (days)	TS30 (°C)	NAOI — seasonal mean						
			DJF	DJFM	NDJFM	MAM	AM	JJA	JA
1994	41	70.8	1.36	2.05	2.12	1.48	0.17	0.44	−0.45
1947	40	46.9	−0.77	−1.28	−1.21	0.25	1.78	−0.08	−0.18
1992	34	42.9	0.30	0.66	0.83	1.18	0.90	0.49	0.86
1952	35	42.2	0.99	0.16	0.12	−0.61	0.25	0.01	−0.06
1943	22	34.9	0.76	0.64	0.11	1.30	1.81	−0.01	−0.51
1957	13	34.2	0.78	0.16	0.40	−0.21	0.53	−1.20	−0.28
1921	21	31.4	−0.08	0.70	0.89	1.82	1.21	−0.38	−0.06
1983	21	22.4	1.20	1.32	1.49	−0.10	−0.99	0.42	0.34
1928	14	20.8	0.36	0.01	0.07	−1.13	−1.17	−1.35	−0.60
1935	11	20.6	0.28	0.21	−0.01	−1.34	−2.01	2.34	2.97
Average			0.52	0.46	0.48	0.26	0.25	0.07	0.20

6.2. Heat waves and circulation types

The Hess–Brezowsky catalogue of large-scale circulation patterns (GWL; Hess and Brezowsky, 1952; Gerstengarbe and Werner, 1993; Gerstengarbe *et al*., 1999) is frequently used to characterize the atmospheric circulation over western and central Europe (Klaus and Stein, 1978; Bárdossy and Caspary, 1990; Matyasovszky and Weidinger, 1998; Werner *et al*., 2000). The classification recognizes three groups of circulations (zonal, half-meridional and meridional) divided into ten major types and 29 subtypes (see Table V). Any circulation type (GWL) persists for several days (normally at least 3 days).

The heat-wave occurrence is preferred under certain circulation conditions (Table V). Almost 75% of all heat-wave days in Prague occur under three prevailing groups of GWL, which are characterized by (i) central European high (major type HM), (ii) Fennoscandian or Norwegian Sea/Fennoscandian high (major type E) or (iii) circulation with an inflow of warm air from southwest to southeast into central Europe (major types S, SW and SE).

The Hess–Brezowsky classification of GWL was used to examine the relationships between atmospheric circulation and heat waves in three cold (1901–10, 1911–20, 1973–82) and three warm decades (1928–37, 1943–52, 1988–97) of the 20th century; 'cold' and 'warm' decades were determined according to the heat-wave severity in Prague. The analysis was performed for groups of (i) circulation types that are predominantly anticyclonic/cyclonic over central Europe (Gerstengarbe and Werner, 1993), and (ii) major circulation types with a typically increased/decreased heat-wave frequency. The frequencies of these groups of GWLs in cold and warm decades (for months of May to September) were compared with the climatological mean for the 1901–97 period. Another characteristic of the atmospheric circulation analysed was the mean residence time of a GWL in May–September.

Differences in frequencies of some groups of GWLs between cold and warm decades are evident (Table VI); for example, situations with central European high and ridge were more (less) frequent during all the warm (cold) decades compared with the long-term mean. A general absence of the circulation types with southerly flow and the types with an anticyclone over Fennoscandia is typical of the cold decades of 1901–10 and 1911–20, for which the frequencies of GWLs with northerly flow were considerably increased. The connection between high summer temperatures and the atmospheric circulation is particularly strong for 1988–97, when all the groups of GWLs favourable (unfavourable) for heat waves have higher (lower) frequencies relative to their long-term means. Furthermore, for the decade of 1988–97 the frequencies of anticyclonic (A) situations over central Europe were higher at the expense of cyclonic (C) ones. The prevalence of A (56%) over C (36%) is clear for 1988–97, whereas in terms of the long-term mean the frequencies of both the groups are approximately the same (A, 46%, C, 44%). If circulation types favourable for heat waves are pooled

Table V. Relative frequencies of Hess–Brezowsky GWL in summer and during heat waves at Prague–Klementinum, 1901–97. Relative frequencies of GWL in May to September (GWL59) and in heat-wave days (GWL_HW) are shown. Last column gives the ratio of GWL_HW to GWL59. Major types and subtypes are the same as in Bárdossy and Caspary (1990) for example

Major type	Abbrevation	Subtype	Abbrevation	GWL59 (%)	GWL_HW (%)	GWL_HW/ GWL59
Central European high	HM	Central European high	HM	8.97	21.26	2.37
		Central European ridge	BM	7.80	16.32	2.09
East	E	Fennoscandian high anticyclonic	HFA	3.29	6.14	1.86
		Norwegian Sea/Fennoscandian high anticyclonic	HNFA	1.77	4.19	2.37
		Fennoscandian high cyclonic	HFZ	1.01	1.50	1.48
		Norwegian Sea/Fennoscandian high cyclonic	HNFZ	1.24	1.65	1.33
South	S	South anticyclonic	SA	1.04	1.05	1.00
		South cyclonic	SZ	0.13	0	0
		British Isles low	TB	3.09	2.99	0.97
		Western Europe trough	TRW	4.41	7.78	1.76
Southwest	SW	Southwest anticyclonic	SWA	1.65	6.74	4.08
		Southwest cyclonic	SWZ	1.65	2.84	1.72
Southeast	SE	Southeast anticyclonic	SEA	1.11	1.50	1.35
		Southeast cyclonic	SEZ	0.34	0	0
West	W	West cyclonic	WZ	15.83	8.08	0.51
		West anticyclonic	WA	6.91	5.39	0.78
		West angular	WW	1.91	0.90	0.47
		Southern West	WS	1.60	1.35	0.84
North	N	North anticyclonic	NA	1.46	0.30	0.20
		North cyclonic	NZ	3.10	0.15	0.05
		North, Iceland high, anticyclonic	HNA	4.10	1.80	0.44
		North, Iceland high, cyclonic	HNZ	1.75	0.75	0.43
		British Isles high	HB	3.25	0	0
		Central European trough	TRM	3.83	0.30	0.08
Northwest	NW	Northwest anticyclonic	NWA	4.91	2.40	0.49
		Northwest cyclonic	NWZ	4.27	0.60	0.14
Northeast	NE	Northeast anticyclonic	NEA	3.40	1.50	0.44
		Northeast cyclonic	NEZ	2.85	1.35	0.47
Central European low	TM	Central European low	TM	2.29	0.45	0.20
Indefinite	U	Indefinite	U	1.03	0.75	0.73

Table VI. Relative frequencies of groups of GWL in May–September (GWL59) and JA (GWL78) and mean residence times of GWL in May–September (d) in cold (1901–10, 1911–20, 1973–82) and warm (1928–37, 1943–52, 1988–97) decades compared with the long-term (1901–97) mean. For groups of GWL, their relative share on heat-wave days at Prague–Klementinum is shown in parentheses

Character of period	Period	Group of GWL	*d* (days)	GWL59 (%)	GWL78 (%)
Situations favourable for heat waves					
Long-term mean	1901–97	Central European high: HM, BM (37.6%)	4.1	16.8	16.8
Cold	1901–10		3.9	14.3	13.6
	1911–20		4.0	17.8	13.9
	1973–82		4.1	16.2	14.4
Warm	1928–37		4.1	19.8	19.5
	1943–52		3.8	17.3	20.8
	1988–97		6.2	20.6	24.2
Long-term mean	1901–97	East: HNFA, HFA, HNFZ, HFZ (13.5%)	4.2	7.3	6.1
Cold	1901–10		3.9	7.1	0.8
	1911–20		5.3	7.7	4.8
	1973–82		4.3	10.2	12.1
Warm	1928–37		3.4	4.8	1.0
	1943–52		3.5	5.5	3.7
	1988–97		6.7	8.7	9.8
Long-term mean	1901–97	South, Southwest and Southeast: SA, SZ, TB, TRW, SWA, SWZ, SEA, SEZ (22.9%)	3.9	13.4	11.9
Cold	1901–10		3.9	7.9	6.3
	1911–20		3.6	8.3	6.6
	1973–82		3.9	17.4	9.8
Warm	1928–37		3.3	7.1	8.7
	1943–52		3.8	16.0	15.8
	1988–97		5.6	16.3	13.1
Situations unfavourable for heat waves					
Long-term mean	1901–97	North, Northwest and Northeast: NA, NZ, HNA, HNZ, HB, TRM, NWA, NWZ, NEA, NEZ (9.2%)	3.9	32.9	31.5
Cold	1901–10		3.7	41.4	39.2
	1911–20		3.8	40.0	41.6
	1973–82		4.1	27.0	31.1
Warm	1928–37		3.8	36.1	34.0
	1943–52		3.5	29.7	25.8
	1988–97		5.9	28.0	24.2
Long-term mean	1901–97	West: WZ, WA, WW, WS (15.7%)	4.8	26.3	30.9
Cold	1901–10		5.2	26.7	37.9
	1911–20		4.6	24.0	30.5
	1973–82		4.6	25.8	29.5

(*continued overleaf*)

Table VI. (*Continued*)

Character of period	Period	Group of GWL	d (days)	GWL59 (%)	GWL78 (%)
Warm	1928–37		4.3	28.4	33.4
	1943–52		4.7	28.8	30.7
	1988–97		7.0	23.8	25.8
Anticyclonic and cyclonic conditions					
Long-term mean	1901–97	Anticyclonic	4.1	46.4	46.1
Cold	1901–10		4.0	52.2	48.2
	1911–20		4.1	51.6	49.7
	1973–82		4.1	42.9	44.2
Warm	1928–37		3.9	50.8	48.4
	1943–52		3.9	49.5	50.8
	1988–97		6.3	47.9	56.1
Long-term mean	1901–97	Cyclonic	4.2	42.7	43.6
Cold	1901–10		4.1	40.5	44.7
	1911–20		4.1	38.1	39.0
	1973–82		4.2	44.5	46.1
Warm	1928–37		3.9	38.9	40.7
	1943–52		3.9	39.9	39.5
	1988–97		6.0	42.6	35.7

together, the relationship between heat waves and circulation conditions is also manifested for the 1943–52 period.

For cold decades, the link to atmospheric circulation does not consist of the enhanced occurrence of cyclonic GWLs at the expense of anticyclonic ones, but mostly in a redistribution of frequencies between the groups of GWLs that are favourable and unfavourable for heat waves. However, it is also clear that changes in the occurrence of extreme events do not necessarily reflect changes in circulation conditions characterized by GWLs. The pressure pattern and the location of fronts differ in any single occasion from the 'mean' pattern of a relevant GWL, which can further influence the advection, vertical motions, cloudiness, etc. This is the reason why temperatures can be very different in the same GWL and in the same part of a year. The two longest HM events (anticyclone over central Europe) in summer during the 20th century may serve as an example; they occurred for the periods 3–14 July 1923 (12 days) and 27 June–7 July 1957 (11 days). During the former the TMAX exceeded 30.0 °C in Prague on 2 days only, with a maximum of 32.5 °C; the second most severe heat wave developed during the latter period, with TMAX exceeding 30.0 °C (36.0 °C) on 7 days (3 days) — see Section 4.

A conspicuous feature of the atmospheric circulation in 1988–97 is an enhanced mean residence time of circulation types in all the above-mentioned groups of GWL in May to September (Table VI). For example, the mean residence time of a central European high or ridge (HM/BM) is 6.2 days during 1988–97 but only 4.1 days for the long-term mean; the mean residence time of a zonal GWL (WA/WZ/WS/WW) is 7.0 days in 1988–97 but only 4.8 days for the long-term mean, etc. If weather types are treated individually (Figure 6), then the mean residence time is higher in 1988–97 compared with the long-term mean for all the types with the exception of WS.

The catalogue of GWLs has been revised recently (Gerstengarbe *et al.*, 1999) and found to be homogeneous (Bárdossy and Caspary, 1990; Gerstengarbe *et al.*, 1999). This means that a change in the mean residence time of a GWL does not reflect artificial disturbances in the time series. The character of the atmospheric circulation over Europe in summer has likely changed towards higher persistence in the 1990s. Changes in the persistence of circulation in the North Atlantic/European sector have been studied by a few authors recently; however, the results presented above appear to be new. For example, Bárdossy and Caspary (1990) found no significant changes in the duration of periods with the same GWL over the 1881–1989 period. Stefanicki

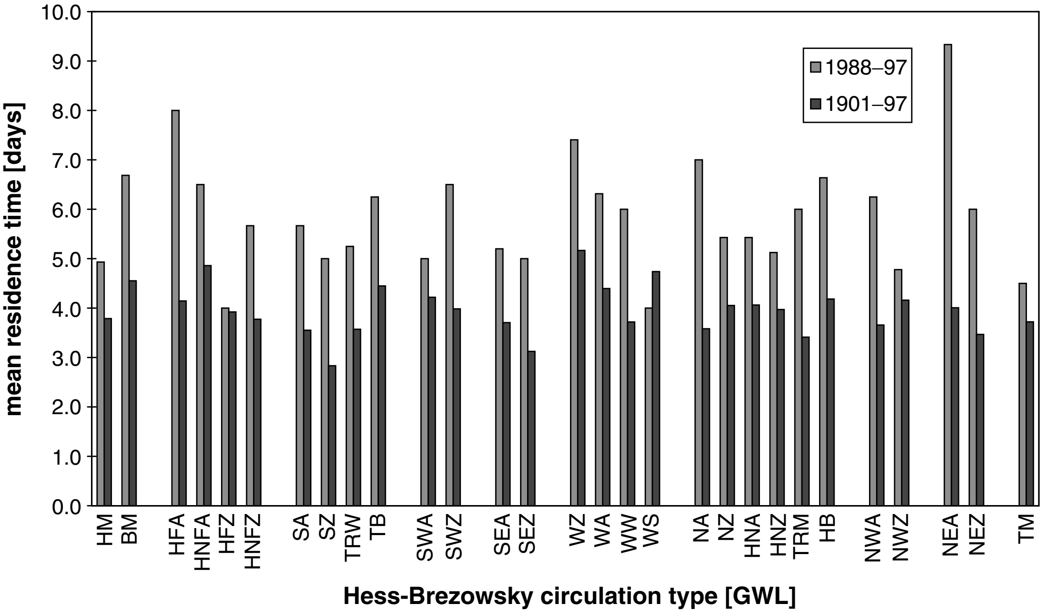

Figure 6. Mean residence time of Hess–Brezowsky weather types in 1988–97 compared with the long-term (1901–97) mean. The months of May–September are considered

et al. (1998) analysed changes in residence times of the convective and advective weather types of Schüepp's classification over the Alpine region since 1945; they found that the average length of convective episodes rose and that of advective episodes fell for the period 1970–94 compared with 1945–69, mainly in winter. Werner *et al*. (2000) dealt with the mean residence time of zonal circulation in winter and found that the zonal weather state has been considerably more persistent since the 1970s.

The enhanced persistence of the atmospheric circulation (regardless of whether the circulation types are favourable or unfavourable for heat waves) may be one of the causes of the occurrence of extremely long and severe heat waves in the 1990s. Unchanged or only slightly variable circulation conditions that persist for relatively long periods of time support anomalies of air temperature in one direction and the occurrence of continuous periods with temperatures above/below normal. This can be demonstrated for the two longest heat waves in Prague, which occurred in 1992 (26 days) and 1994 (22 days). During both these heat waves, long sequences of days classified with one GWL appeared (10 day HM followed by 6 day WA in 1992; 8 day BM followed by 7 day SA in 1994). The increases in frequencies of the anticyclonic circulation types at the expense of the cyclonic ones, and situations favourable for heat waves at the expense of the unfavourable ones, lead to the observed fact that the higher persistence of the circulation in the 1990s was reflected mainly in the occurrence of positive temperature extremes in central Europe.

7. CONCLUSIONS

Prague–Klementinum is one of the stations with the longest uninterrupted daily air temperature series in central Europe (since 1775). Because possible sources of inhomogeneity (changes in the time of measurement, location of the thermometer, instrumentation, different observing practices, etc.) may be reflected in the series, the period 1901–97 with the most credible data was analysed. The influence of the urban heat island intensification since 1922 was evaluated in an earlier study and found to be insignificant for the summer season (Brázdil and Budíková, 1999). As other possible sources of inhomogeneity (e.g. listed in Peterson *et al*. (1998)) were either not present in the period examined or assessed as negligible, the temperature series can be treated as homogeneous since 1901.

The temporal distributions of both the heat waves and the mean summer temperature show two peaks during the 20th century, in the 1940s to early 1950s and in the 1990s. A very low frequency of heat waves is typical for the beginning of the 20th century (in the period of decreased continentality of climate in Europe; see Thompson (1995)). The upward trends in both the heat-wave severity and mean summer temperature during the 1910s–40s and late 1970s–early 1990s are prominent features of the temporal distributions. These trends are in general consensus with trends in the global mean surface temperature, which shows the most rapid increase since the late 19th century during the periods of 1920–40 and since the mid-1970s (Houghton *et al*., 1996; Jones *et al*., 1999). The decrease in the interannual temperature variability from the 1910s to the 1930s was concomitant with an increase in the mean summer temperature.

An extraordinary heat wave occurred in a large area of Europe in July and August 1994. It was exceptional, particularly with regard to the much higher cumulative temperature excess above 30 °C and the extremely long period of successive tropical days, although absolute record-breaking daytime and night-time temperatures were not reached. The difference between the 1994 heat wave and the others cannot be attributed to the increased urban heat island.

The maximum heat-wave severity in the 1940s to early 1950s, coupled with the almost total absence of heat waves in the first two decades of the 20th century and around 1980, may be a common feature for at least the area of central Europe, as indicated by a comparison with the records of the Basel station (Switzerland) and by other studies dealing with central-European long-term temperature series (Gerstengarbe, 1992; Koźuchowski *et al*., 1994; Wagner, 1996). In contrast to Prague, the enhanced heat-wave severity in the 1990s was not observed in Basel. The nature of the temporal heat-wave distribution in central Europe, which is dominated by a small number of large peaks, is probably similar to the USA, where the maximum heat-wave severity occurred in the 1930s. Thus, the estimated trends of extreme temperature event frequency or intensity are strongly influenced (even in their signs) by the fact of whether the period with enhanced heat-wave characteristics is included in the analysis or not (see Kunkel *et al*. (1999)).

The relationship between heat waves and circulation conditions was analysed using the NAOI and the subjective Hess–Brezowsky catalogue of weather types (GWL). A statistically significant positive relationship was found between the NAOI in spring (MAM, AM) and the severity of heat waves in the following summer; this linkage does not hold for the mean summer temperature. Although the low percentage of variation explained by the relationship prevents it from being used in climate predictions, the most severe heat-wave seasons generally tend to be preceded by positive values of NAOI in November to May.

The link to the atmospheric circulation is evident when Hess–Brezowsky weather types (Gerstengarbe *et al*., 1999) are considered. Most heat-wave days at Prague–Klementinum occur under three prevailing groups of GWL, which are characterized by (i) central European high, (ii) Fennoscandian or Norwegian Sea/Fennoscandian high and (iii) circulation with the inflow of warm air from southwest to southeast into central Europe. Differences in frequencies of GWLs are evident when cold and warm decades (according to heat-wave severity) are treated separately. For example, the situations with central European high or ridge were more (less) frequent during all the warm (cold) decades. The relationship between circulation conditions and heat waves is expressed particularly well for the warm 1988–97 decade, when the frequencies of anticyclonic situations over central Europe were higher at the expense of cyclonic ones, and all the groups of GWLs favourable (unfavourable) for heat waves had higher (lower) frequencies relative to their long-term means.

Moreover, the occurrence of long and severe heat waves in the 1990s may reflect an enhanced persistence of the atmospheric circulation in the summer season over Europe, since all groups of the Hess–Brezowsky weather types have considerably longer residence times in 1988–97 compared with the long-term means. The increases in frequencies of the anticyclonic circulation types at the expense of the cyclonic ones, and of situations with the southerly and easterly flows at the expense of notherly flows, resulted in the higher persistence of the atmospheric circulation in the 1990s being reflected mainly in the occurrence of positive temperature extremes in central Europe.

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