INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **23**: 987–1010 (2003)
DOI: 10.1002/joc.929

VARIABILITY OF EXTREME TEMPERATURE EVENTS IN SOUTH–CENTRAL EUROPE DURING THE 20TH CENTURY AND ITS RELATIONSHIP WITH LARGE-SCALE CIRCULATION

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Received 4 October 2002
Revised 14 April 2003
Accepted 25 April 2003

ABSTRACT

The variability of winter extreme low-temperature events and summer extreme high-temperature events was investigated using daily temperature series (1901–98) from 11 sites in central and southern Europe. An extreme temperature event (EXTE) is defined by various threshold values of daily temperature or daily temperature anomaly. Systematic changes in the frequencies of EXTEs are investigated by the Mann–Kendall test and a method based on the Wilcoxon test. The catalogue of macrocirculation types over central Europe (the Hess–Brezowsky classification) is applied to investigate the connections between EXTEs and large-scale circulation. Circulation classes (HBC) are defined, and mostly spatial averages of EXTEs are examined.

There were large long-term fluctuations in the frequencies of both winter extreme cold events (EXCEs) and summer extreme warm events (EXWEs) during the 20th century. The systematic changes referring to the entire period indicate a slight warming tendency, but only a few of the changes, mostly in the northernmost sites, are statistically significant. Strong connections are present between the frequencies of EXTEs and the large-scale circulation on various time scales, particularly for EXCEs. The spatial differences of EXTE fluctuations and EXTE–HBC connections are small within the study area. Northerlies and easterlies, as well as meridional and anticyclonic situations, are favourable for EXCEs, whereas southerlies and persistent anticyclonic situations are favourable for EXWE occurrences. In the latest decades, a decline in the frequency of EXCEs and a sharp increase in the frequency of EXWEs happened, and the residence times of the circulation patterns over central Europe became longer both in winter and summer.

KEY WORDS: extreme temperature event; temperature–circulation relationship; climate change detection; central Europe; southern Europe

1. INTRODUCTION

Near-surface air temperature varies over a rather wide range in most parts of the Earth, particularly over the mid and high latitudinal continental areas. It is also the case of the study area, which is the southern part of central Europe and the adjoining Mediterranean region: annual absolute maxima usually exceed 30 °C and can sometimes reach 40 °C, and minima below −25 °C may occur in some bitterly cold winters in most places of the region.

Living creatures and ecosystems, as well as the human society, are sensitive to the severity, frequency and persistence of extreme temperature events (EXTEs; Wigley, 1985). Therefore, these characteristics are often examined in climatological studies. The unusual temperature anomalies may do harm in any season of the

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year, yet a large portion of the damage is connected to some special categories of EXTE. They are: (a) winter extreme cold events (EXCEs; Flocas *et al.*, 1995; Konrad, 1996; Lana and Burgueño, 1996; Domonkos and Piotrowicz, 1998; Piotrowicz, 2001); (b) summer extreme warm events (EXWEs; Rohli and Keim, 1994; Kunkel *et al.*, 1996; Livezey and Tinker, 1996; Karl and Knight, 1997; Kyselý *et al.*, 2000); (c) frost events within the growing season (Rogers and Rohli, 1991; Cooter and Leduc, 1995; Stone *et al.*, 1996); (d) 'false start' events, i.e. too warm in late winter and/or early spring, resulting in enhanced sensitivity of plants to later cold spells (Davis, 1972; Morison and Spence, 1989; Morison and Butterfield, 1990); (e) bitter snow and ice conditions coupled with severe frost (Changnon, 1979; Assel *et al.*, 1996); (f) summer drought coupled with hot spell (Chang and Wallace, 1987; Kunkel, 1989; Lyon and Dole, 1995; Huth *et al.*, 2000; Domonkos, 2001). Sultriness and wind chill are also strongly related to occurrences of extreme temperature values. A lot of papers have analysed characteristics of extreme cold and extreme warm events together (e.g. Tarleton and Katz, 1995; Plummer, 1996; Henderson and Muller, 1997; Gershunov, 1998; Domonkos, 2001; Huth *et al.*, 2001; Kyselý, 2002b).

The studies of EXTEs include case studies, the statistical analysis of observed data series, the investigation of the connections between EXTEs and other local- and/or large-scale weather elements, as well as the extreme value analysis relying on statistical models. The theoretical estimation of the distribution function has an essential role in planning for rare (extraordinary) extreme events, but nowadays its importance is even greater in the quantification of likely changes related to the global warming (e.g. Mearns *et al.*, 1984; Katz and Brown, 1992; Hennessy and Pittock, 1995; Barrow and Hulme, 1996; Kharin and Zwiers, 2000). The influence of the large-scale circulation on the characteristics of EXTEs is also a topic commanding wide interest (Konrad, 1996; Stone *et al.*, 1996; Gershunov, 1998; Huth *et al.*, 2000; Kyselý, 2002a; Piotrowicz and Domonkos, 2002). The EXTE characteristics from observations and stochastic models are compared, for example, by Macchiato *et al.* (1993), Domonkos (1998), Huth *et al.* (2001) and Kyselý (2002c).

The statistical characteristics of EXCEs and EXWEs and their connection to the large-scale circulation patterns are investigated in this study. Central and southern European temperature series and a catalogue of European macrocirculation situations introduced by Hess and Brezowsky (1977) are used for the analysis. Although the Hess–Brezowsky classification is focused on a territory (Germany) that is situated a few hundred kilometres northwestward from the centre of the study area, the quantification of connections between macrocirculation and EXTEs might still be beneficial. The reason for using the Hess–Brezowsky classification is that it is frequently used to characterize the macrocirculation conditions in the northern and central parts of the area under study (Matyasovszky and Weidinger, 1998; Kyselý, 2002a), and no other classification comparable in effectiveness is available yet for the study area.

There are three main aims of our work:

- to describe the temporal variability and trends of selected winter cold and summer warm events;
- to evaluate the similarities and differences between the calculated characteristics at individual locations, in order to obtain information about the spatial coherence of climatic variability;
- to evaluate the relationship between EXTEs and the large-scale circulation patterns on different time scales, and to assess the role of the continental-scale circulation in temperature variability in south–central Europe.

Although large spatial differences exist between the climatic characteristics at the individual sites because of their different geographical locations, it will be demonstrated that the fluctuations detected and their connections to the large-scale circulation are often surprisingly similar.

2. DATA

Series of daily temperatures observed in the 20th century at 11 stations from six countries are used (Figure 1, Table I). All the series are provided by the national meteorological services except for Bologna, which was obtained via the Internet. Daily temperature values in all series are the arithmetic averages of daily minimum

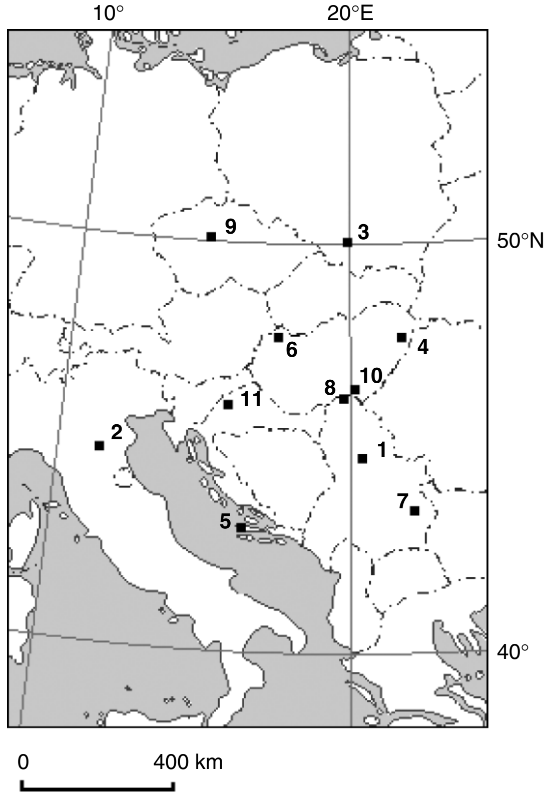

Figure 1. Location of the observing stations

Table I. Locations of the meteorological stations

No.	Station	Country	Altitude a.s.l. (m)	Period examined
1	Beograd	Serbia	132	1949–98
2	Bologna	Italy	150	1901–98
3	Cracow	Poland	220	1901–98
4	Debrecen	Hungary	120	1901–98
5	Hvar	Croatia	20	1949–98
6	Mosonmagyaróvár	Hungary	122	1901–98
7	Nis	Serbia	202	1949–98
8	Palic	Serbia	102	1949–98
9	Prague	Czech Republic	191	1901–98
10	Szeged	Hungary	80	1901–98
11	Zagreb Gric	Croatia	157	1901–98

and daily maximum temperatures, so there is no methodological difference involved in the derivation of the values.

Seven series cover the base period 1901–98; the other four are shorter, covering only the last 50 years (1949–98; Table I). All the temperature series are complete, and they have fairly good quality in general. However, it should be noted that some inhomogeneity problems have affected the data series; these problems and their likely influence on the calculated characteristics will be discussed along with the evaluation of the computational results in Section 4.1.

Table II. Allocation of sites into subregions

Subregion	Site
Northern	Cracow, Mosonmagyaróvár, Prague
Mid	Debrecen, Palic, Szeged, Zagreb
Mid–southern	Bologna, Debrecen, Szeged, Zagreb
Southern	Beograd, Bologna, Hvar, Nis
Overall	Bologna, Cracow, Debrecen, Mosonmagyaróvár, Prague, Szeged, Zagreb

Table III. HBC types

Circulation class (HBC)	Circulation type
Zonal	WA, WZ, WS, WW
Mixed	SWA, SWZ, NWA, NWZ, HM, BM, TM
Meridional	All types that do not belong to zonal and mixed, except for U
Westerly	WA, WZ, WS, WW, SWA, SWZ, NWA, NWZ
Northerly	NA, NZ, HNA, HNZ, HB, NEA, NEZ, HFA, HFZ, HNFA, HNFZ, NWA, NWZ
Easterly	NEA, NEZ, HFA, HFZ, HNFA, HNFZ, SEA, SEZ
Southerly	SA, SZ, TB, TRW, SEA, SEZ, SWA, SWZ
Anticyclonic	HM, BM, HFA, HNFA, SA, SEA, SWA, WA, NA, NEA, NWA, HNA
Cyclonic	HFZ, HNFZ, SZ, SEZ, SWZ, TRW, WZ, NZ, NEZ, NWZ, HNZ, TM, TRM

Spatial averages of the EXTE occurrences for subregions (Table II) and the entire region investigated are used to obtain brief summaries of the results. Although some climatic characteristics show a zonal gradient over south–central Europe, the cardinal spatial differences are linked to quasi-meridional gradients. Sorting the sites into subregions reflects these differences, as well as the necessity of using long (98 years long) series for some purposes. The EXTE characteristics calculated for the mid and southern subregions may not refer to a longer than 50 year period, since their derivation includes local data series with a length of just 50 years. Therefore, a 'mid–southern' subregion was also introduced to produce the average EXTE occurrences for the 1901–98 period over that territory.

The Grosswetterlagen Catalogue (Hess and Brezowsky, 1977; Gerstengarbe *et al.*, 1999) for the period 1901–98 is used to analyse the statistical connections between the characteristics of EXTEs and atmospheric macrocirculation. The circulation types are sorted into nine (not disjunct) Hess–Brezowsky circulation classes (HBCs) according to their degree of zonality, direction of the prevailing flow and cyclonicity–anticyclonicity (Table III).

3. METHODS

3.1. Definition of thresholds for EXTEs

There are several ways to define an EXTE. Domonkos and Piotrowicz (1998) give a brief summary of the options, as well as of the advantages and limitations related to practical application. Two thresholds are introduced here for both EXCEs and EXWEs. One is absolute threshold, namely −5.0 °C daily temperature for an EXCE (in December–February), and 23 °C for an EXWE (in June–August). Further thresholds are derived from the empirical distribution function of temperature anomalies; the lowest decile of the distribution is applied for an EXCE and the highest decile for an EXWE:

$$a < a_L \quad \text{and} \quad a > a_H$$

respectively, where a is the daily temperature anomaly, a_L is the threshold value for the lower decile of anomalies and a_H is the threshold value for the upper decile of anomalies. The base period for the calculation of the anomalies is 1949–98. The values of the a_L and a_H thresholds change along with the seasonal cycle of the anomaly distribution. See further details of the calculation method in Domonkos and Piotrowicz (1998). If no other determination is given in the text, then EXCE and EXWE denote extreme events derived from the anomaly thresholds.

The application of different types of extreme event definition herein provides an opportunity to make several kinds of comparison between climatic characteristics, and reap the various advantages of the different methods.

3.2. Calculation of trends and fluctuations

Fluctuations and trends in the frequencies of specified EXTEs are investigated both for the unstratified data and the data stratified by HBCs. Long-term fluctuations are illustrated using a 15-point Gauss filter.

Systematic changes in the seasonal mean temperatures are calculated by linear trend analysis. However, as the frequency distributions of EXTEs are usually far from a normal distribution, other tools are applied to reveal the statistically significant systematic changes in the frequencies of EXTEs. These tools are the Mann–Kendall test and a procedure based on the Wilcoxon test. For the latter, some threshold event for the number of seasonal EXTE occurrences must be introduced. Let S_i mark the number of seasonal EXTE occurrences (of a specified sign) in the ith year of the period investigated, $i = 1, 2, \ldots, n$ ($n = 98$ in this study). Let S_T be a threshold value above which the frequency is considered to be extremely high and $\mathbf{k}$ a vector containing the information of threshold event occurrences:

$$\text{if } S_i > S_T \text{ then } k_i = 1$$
$$\text{else } k_i = 0, i = 1, 2, \ldots, 98$$

A rank statistic r can be calculated as follows:

$$r = \sum_{i=1}^{98} i k_i$$

Following the rules of the Wilcoxon test, a test statistic y with the standard normal distribution for the null hypothesis that there is no trend can be calculated relying purely on r, the length of the sample n, and the number of $k_i = 1$ events (m) in the sample:

$$y = \frac{12[r - 0.5\, m(n + 1)]}{\sqrt{m(n - m)(n - 1)}}$$

This test was also applied by Szinell *et al.* (1998) with a more detailed explanation of the method. Hereafter, it will be referred to as the Wilcoxon test. Two kinds of threshold value (S_{T1} and S_{T2}) are applied in this paper, namely 130% and 150% of the mean frequency for the period 1949–98:

$$S_{Ti} = c_i S_{\text{mean}} \quad \text{where } i = \{1, 2\}, c_1 = 1.3 \text{ and } c_2 = 1.5$$

3.3. Calculation of statistical connections

To reveal the statistical connections between the frequency of EXTEs and HBC occurrences, the conditional frequencies of EXTEs under specific HBCs and correlation coefficients are calculated. Correlations of EXTE–HBC variable pairs are examined both for the seasonal and decadal occurrences of specified events. (Decadal occurrence means the total number of events in ten succeeding seasons.) As decadal mean frequencies are calculated using overlapping periods with one year step only, they have rather high positive autocorrelations. Therefore, following Slonosky *et al.* (2000), the effective sample size is computed for each significance investigation of the correlation coefficients between decadal characteristics:

$$n_{\mathrm{eff}} = n\frac{1 - R(f)R(g)}{1 + R(f)R(g)}$$

where f and g represent variables, n is the original sample size and n_{eff} the effective sample size. R denotes one year lag autocorrelation.

4. RESULTS

A trend in conditional frequencies of EXTEs (of a specified sign) may be a consequence of an alteration linked definitely to the variable pair investigated (i.e. to the relationship between the specified HBC and EXTE) or only to one of the variables, or even only (or mainly) to the systematic change in the mean temperature. Therefore, changes in the mean seasonal temperatures, as well as those of the frequencies of HBCs, should be kept in mind during the evaluation of the results. Hence, the systematic changes of the mean temperatures and HBCs are calculated as well. The organization of this section is as follows: trends in the mean seasonal temperatures are examined first, then EXCE and EXWE characteristics are described and some general characteristics of HBC occurrences are presented. Finally, the connections between EXTEs and HBCs are analysed.

4.1. Systematic changes in mean seasonal temperatures

A slight warming is detected in almost all of the seasonal mean temperature series investigated (Table IV). The rates of the warming differ considerably. Whereas there is a mean rate of more than 1.5 °C/100 years for the whole 98 year period and more than 4 °C/100 years for the last 50 years (not shown) in the winter mean temperature series at the northern sites, a slight decrease is detected in the summer mean temperatures in Szeged. Relying on the values shown in Table IV, the warming during the 20th century was more pronounced in the northern sites than in other parts of the study area; it was slightly higher in winter than in summer, and usually higher in the last 50 years than during the first half of the century. The mean systematic changes for the whole period are mostly not significant at the 0.05 level, with few exceptions. The linear trend analysis and the Mann–Kendall test gave the same statistical significance in all cases illustrated in Table IV.

The relatively high warming rates detected in the northern sites (Cracow and Prague) are caused partly by the increasing urban heat island effect (Brázdil and Budíková, 1999; Piotrowicz and Domonkos, 2002), although real climatic differences likely play a substantial role in the observed spatial variability as well. The temperature series of Szeged and Debrecen were affected by station moves in 1951, and the negative trend

Table IV. Linear trend in the seasonal mean temperatures in 1901–98. **P** (**N**): significant positive (negative) change at the 0.05 level

Site	Winter (°C/decade)	Significance	Summer (°C/decade)	Significance
Bologna	0.07	—	0.04	—
Cracow	0.17	**P**	0.16	**P**
Debrecen	0.14	—	0.06	—
Mosonmagyaróvár	0.05	—	0.03	—
Prague	0.14	—	0.13	**P**
Szeged	0.01	—	−0.08	**N**
Zagreb	0.10	—	0.04	—

detected in Szeged is very likely due to this inhomogeneity effect. The influences of the local inhomogeneity effects and real macroclimatic differences can hardly be separated in other cases.

The calculated trends for Bologna, Mosonmagyaróvár and Zagreb are rather similar, and they are in accord with the results of other studies (e.g. Brázdil *et al.*, 1996; Wanner *et al.*, 1997; Domonkos and Zoboki, 2000). Thus, these sites appear to have the most reliable temperature series, representing well the temperature variability during the 20th century in most of the study area.

4.2. Trends and fluctuations in the frequency of EXTEs

4.2.1. Long-term changes of EXCEs. The severity of winters varies in a large range from year to year in the area investigated. Whereas at the Mediterranean sites (Bologna and Hvar) the absolute annual minimum of daily mean temperatures ranges between −4 and −11 °C, around or below −20 °C daily mean temperatures have been recorded in the continental area. The lowest value was recorded in Cracow (−28.4 °C, in February 1929). The occurrence of temperatures close to the record minimum is very rare, and even the frequency of temperatures below −5 °C is rather low, particularly in the southern stations (Figure 2). In spite of the fact that the annual mean frequency has great spatial variation, the main features of the low-frequency changes are similar at all sites (except for Bologna, where the frequency is permanently very low to make temporal comparisons). However, a notable difference appears in the trends: in Mosonmagyaróvár the mean frequency of below −5 °C events was similar at the beginning and at the end of the study period, whereas it was definitely the lowest in the latest two decades in Cracow and Zagreb.

Although the application of absolute thresholds is a useful tool to show the spatial differences in severity, the use of an anomaly threshold is the best way to demonstrate the resemblance and differences in the low-frequency changes of EXTEs. Figure 3 shows the smoothed seasonal frequencies of the $a < a_L$ events for all the sites investigated in the three subregions. The amplitude of the fluctuations is very large again, as the maximum frequency is three to four times higher than the lowest values (in spite of the smoothing). The similarity is spectacular not only within the subregions, but also between any two curves presented in Figure 3(a), (b) and (c). The maximum frequency occurred in the early 1940s and the second highest peak in the early 1960s in all the temperature series. Perhaps the only notable difference is that a decreasing tendency in the EXCE frequency in the latest decades is more evident in the southern sites than in the northern subregion.

The Wilcoxon test indicates that (with both the thresholds applied) the frequency decline during the entire 98 year period is significant at the 0.05 level for the mid–southern subregion and for the overall spatial average

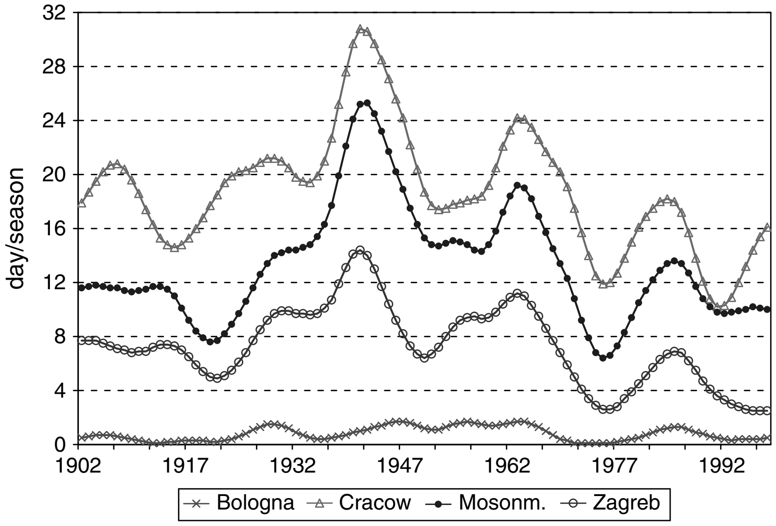

Figure 2. Smoothed time series of the annual occurrence frequencies of winter EXCEs with $t < -5\,^{\circ}\mathrm{C}$

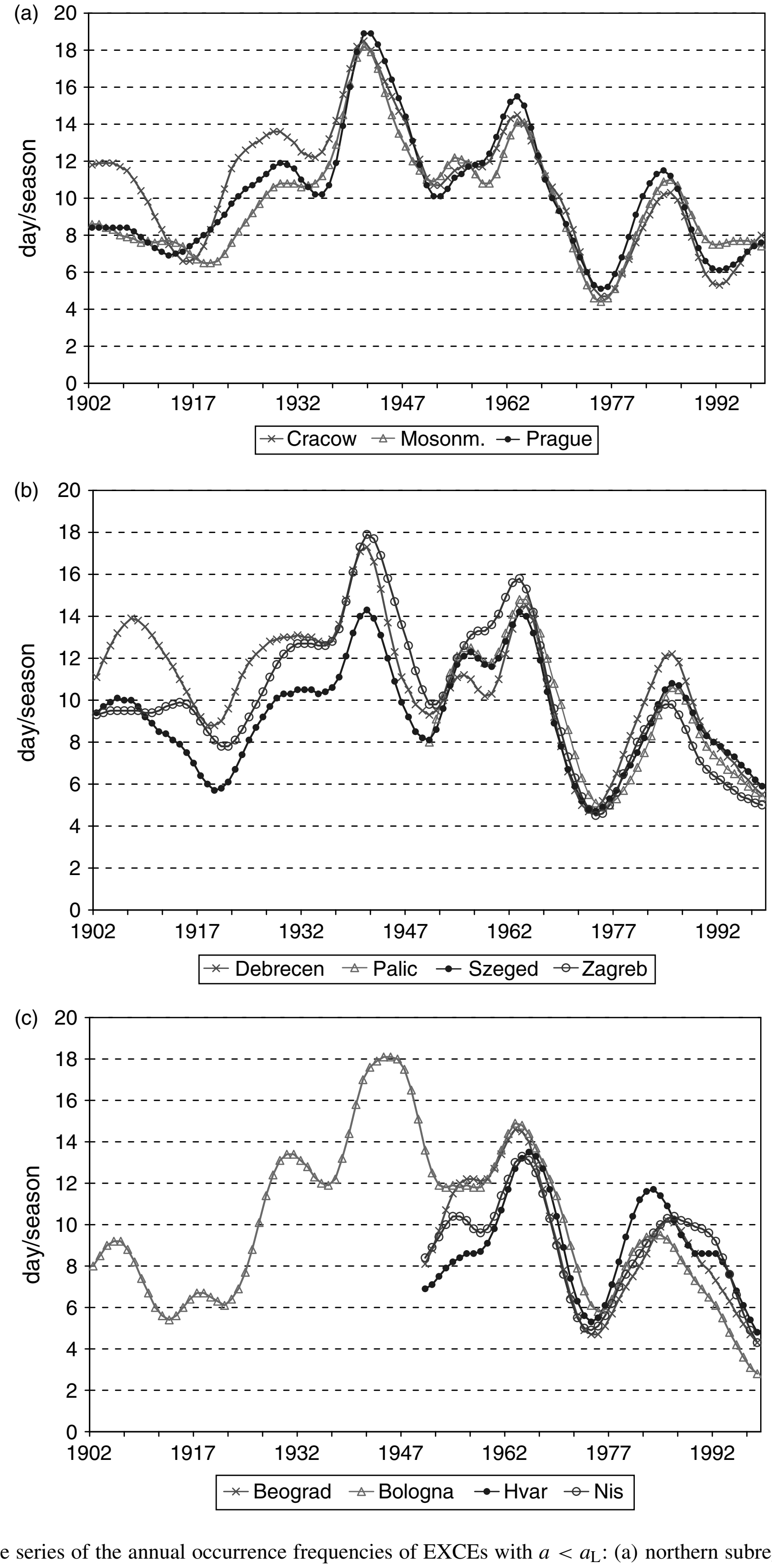

Figure 3. Smoothed time series of the annual occurrence frequencies of EXCEs with $a < a_L$: (a) northern subregion; (b) mid subregion; (c) southern subregion

series. Considering the local data series, the Wilcoxon test application (at least one of the two versions) also indicates the significant frequency decrease of EXCEs for Debrecen, Szeged and Zagreb. On the contrary, the Mann–Kendall test does not indicate any significant trend in the EXCE frequency. This difference between the test results indicates that the frequency decrease of extremely severe winters is more enhanced than that of the moderately cold winters.

An interesting point is that whereas a significant increase in the winter mean temperature was detected only in one of the northernmost sites (Cracow), the decrease of the EXCE frequency is the greatest and statistically significant in the Carpathian Basin.

4.2.2. Long-term changes of EXWEs. The spatial differences in the absolute maximum daily mean temperatures are much smaller than those in the absolute minimum temperatures. These are ranged between 30 and 34 °C at all the sites. The highest values, 33.7 °C and 33.6 °C, were measured in Nis and Bologna respectively.

Although the absolute threshold applied for EXWE (23 °C) is closer to the absolute maxima than the EXCE threshold is to the absolute minima, the mean frequency of EXWEs with the absolute threshold application is generally higher than that of EXCEs. The smoothed values for the seasonal occurrences of above 23 °C events (Figure 4) vary between 2 and 35 in the northern and mid subregions, but in Bologna two-thirds of the summer days belongs to this category. (This means that above 23 °C events cannot be considered real 'extreme' events in the Mediterranean).

The low-frequency fluctuations in Figure 4 seem to be slightly smaller than those of the EXCE frequency, but they are still large. The main features of the fluctuations have great spatial similarity again. The highest frequencies occurred around 1930, in the late 1940s and in the latest decade, whereas the lowest frequency was in the 1910s and around the late 1970s (see also Kyselý (2002a)). It should be noted that the spatial differences in the long-term fluctuations of the EXWE frequencies are larger than those for EXCEs. For example, a general increasing tendency during the 20th century without clear peaks around 1930 and 1950 is typical in Cracow.

Figure 5 shows the smoothed curves of the seasonal occurrences for the $a > a_H$ events. The long-term mean is around eight to ten in all subregions (from the definition). The curves for the sites within subregions are fairly similar, except for Szeged. Some unique features in the curve for Szeged are likely caused by the mentioned inhomogeneity effect of the station moving in 1951. Notwithstanding this, the main features of the EXWE frequency fluctuations in Szeged are still very similar to the fluctuations in other sites.

The differences in the EXWE frequency fluctuations between different subregions are much higher than for EXCEs. In the northern subregion the amplitude of the low-frequency changes is relatively small, and a

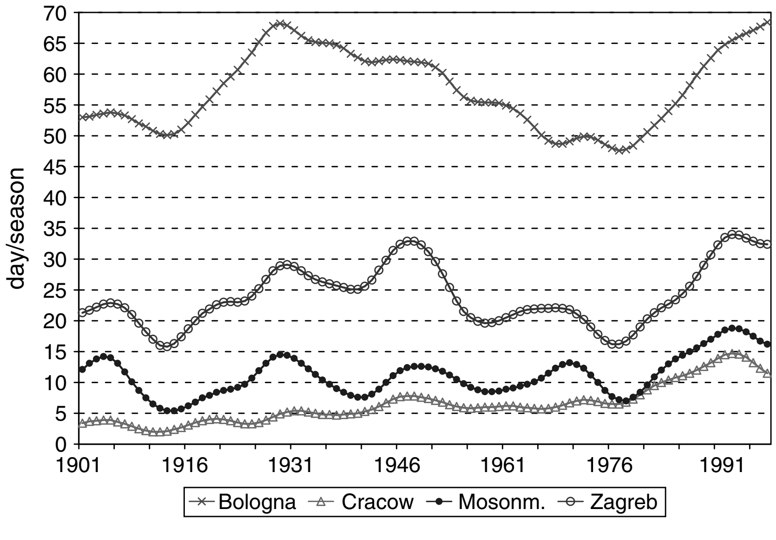

Figure 4. Smoothed time series of the annual occurrence frequencies of summer EXWEs with $t \geq 23\,^{\circ}\mathrm{C}$

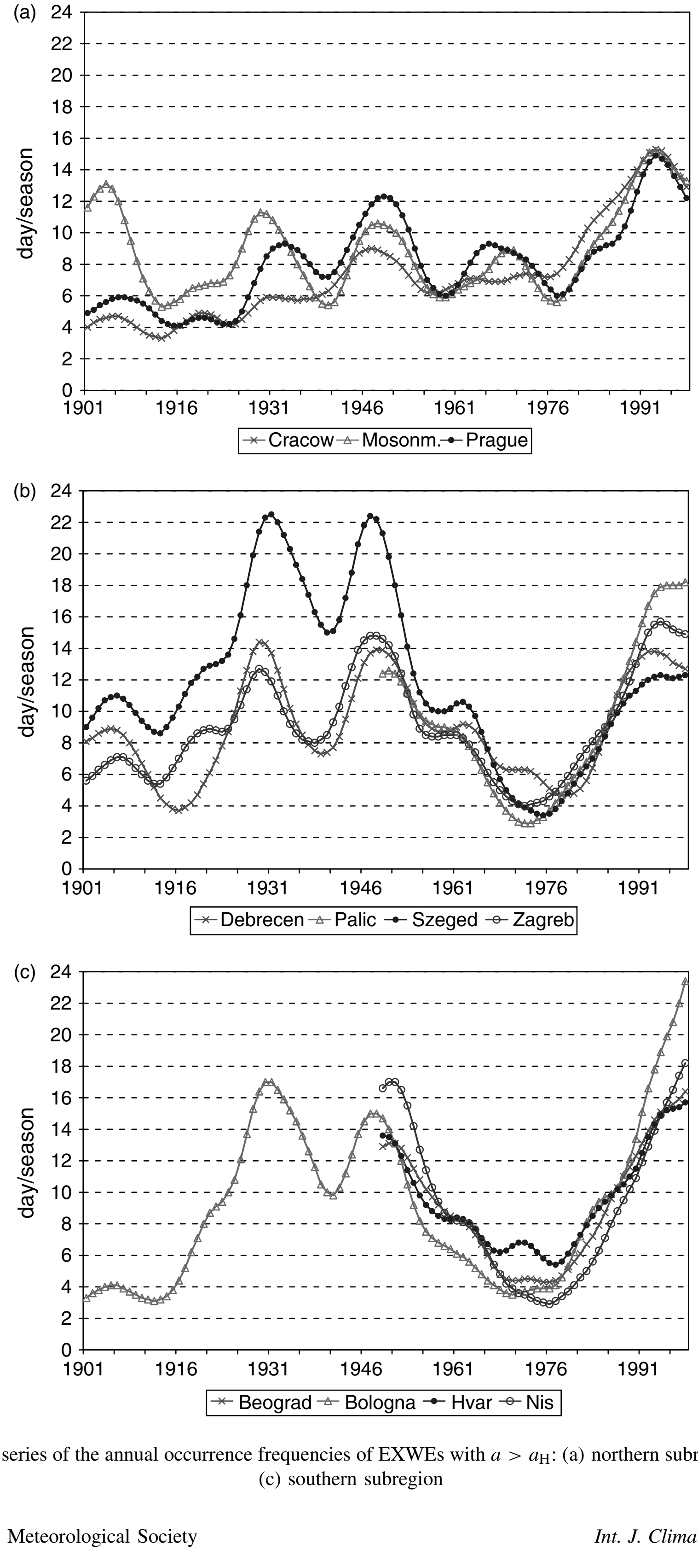

Figure 5. Smoothed time series of the annual occurrence frequencies of EXWEs with $a > a_{\mathrm{H}}$: (a) northern subregion; (b) mid subregion; (c) southern subregion

slight increasing trend seems evident throughout the century, except for Mosonmagyaróvár. In the mid and southern subregions the general warming tendency still appears, but the markedly large irregular fluctuations with high peaks around 1930, in the late 1940s and at the end of the century are the most dominant features. The amplitude of the fluctuations in Figure 5(b) and (c) usually exceeds that of the $a < a_L$ events.

Tests indicate a significant increase of the EXWE frequency in the northernmost sites (Cracow and Prague). This result coincides with the spatial distribution of the trends detected in the mean summer temperatures.

Some indications of a quasi-50-year oscillation appear in Figure 5(b) and (c). Although the data series used are obviously too short to evaluate such a long-term oscillation of the variables investigated, we note that spectrum analysis indicates a statistically significant mode at a 50 year wavelength for a 98 year series of mean summer temperatures in Hungary (Domonkos and Tar, in press).

4.3. General statistical characteristics of HBC occurrences

In this subsection, some general statistical characteristics and the systematic frequency changes of HBC occurrences are described (Table V).

A meridional flow is slightly more frequent than a zonal flow, both in winter and summer over central Europe, but the difference is not large: all the rates for zonal, mixed and meridional circulation classes are close to 30%. Both the anticyclonic and cyclonic situations have a share of 40%, whereas some 20% of the days do not belong to either of these situations. The distribution of flow directions is not so symmetric. The westerly is the most frequent flow, with 40% share both in winter and summer, followed by the northerly with 25% in winter and 33% in summer. Easterly and southerly winds are much rarer, particularly in summer.

Concerning the mean systematic changes of the HBC frequencies during the winters of the 20th century, the frequency of cyclonic situations significantly increased at the expense of anticyclonic situations, but there were no substantial changes in the rate of flow directions. On the contrary, significant changes in the summer rates of flow directions are present. The frequency of southerlies increased spectacularly in summer at the expense of northerly and westerly flows. These changes may influence the calculation results referring to the connections between EXTEs and HBCs (Section 4.4).

With regard to the frequencies of HBCs in selected subperiods of the 20th century or some other statistical characteristics of HBCs (e.g. the residence time — the mean duration of uninterrupted sequences of macrocirculation types), it should be noted that several significant changes can be found in the time series of the characteristics. One of these, an increase in the frequency of zonal flow after the 1960s, is related to the recent change of the winter circulation and climate in Europe, which has been intensively investigated (e.g. Stefanicki *et al.*, 1998; Slonosky *et al.*, 2000; Werner *et al.*, 2000; Domonkos and Tar, in press). Although

Table V. Mean seasonal occurrences and systematic changes in the frequency of circulation classes. **P** (**N**): significant positive (negative) trend at the 0.05 level

Circulation class (HBC)	Winter			Summer		
	Mean seasonal occurrence (days/season)	Mean systematic change (days/decade)	Linear trend significance	Mean seasonal occurrence (days/season)	Mean systematic change (days/decade)	Linear trend significance
Zonal	27.5	0.59	—	26.9	−0.52	—
Mixed	29.8	−0.50	—	30.0	−0.20	—
Meridional	32.5	−0.18	—	34.2	0.67	—
Westerly	40.0	0.57	—	39.8	−1.02	**N**
Northerly	25.1	−0.11	—	32.9	−1.37	**N**
Easterly	14.1	−0.16	—	11.9	0.50	—
Southerly	16.5	0.00	—	10.5	1.17	**P**
Anticyclonic	37.2	−1.16	**N**	41.9	−0.57	—
Cyclonic	40.8	1.53	**P**	39.9	0.52	—

the catalogue of Hess–Brezowsky types has been revised recently and found homogeneous (Bárdossy and Caspary, 1990; Gerstengarbe *et al.*, 1999), the clarification of the causes of some rapid changes in the statistical characteristics of HBCs needs further analysis.

4.4. Connections between EXTEs and the large-scale circulation

4.4.1. EXCE and EXWE frequencies under specified HBCs. The mean frequency and the significance of its systematic change during the period 1901–98 were calculated for the $a < a_L$ EXCE as well as for the $a > a_H$ EXWEs under specified circulation classes (HBC). The results are summarized in Table VI.

EXCEs are substantially more frequent with the meridional situations than with the zonal ones, and their occurrence is more typical under anticyclonic than cyclonic situations over central Europe. Almost half of the EXCEs are coupled with the northerly flow and, considering the relatively low climatic frequency of the easterly situations, the rate of EXCEs under this HBC is also relatively high. On the contrary, EXCEs are rare under westerly and southerly flows. The distributions of EXCEs conditioned by the HBCs under which they occur show rather large, spatially similar differences in all subregions. These differences are slightly higher in the northern subregion than in the other parts of the area investigated, indicating that the connections between HBCs and winter weather are the strongest there. Only very few of the century-scale changes in the conditional EXCE frequencies were proven to be significant at the 0.95 level.

The spatial differences between the distributions of conditional EXTE frequencies are usually moderate, except for EXCEs under western and eastern flows: an EXCE in the north is very sparse under western flows, but is more frequent in the mid–south subregion. EXCE frequencies with eastern flows show the opposite spatial difference. Whereas the EXCE frequency is more than three times higher with easterlies than with westerlies in the north, the difference is lower than 50% (but still with the lead of easterlies) in the mid–south.

Considering the summer mean frequencies of the individual HBCs, southerlies are favourable for EXWEs and northerlies are unfavourable. EXWEs with zonal circulation or westerlies are slightly rarer in the northern subregion than in the southern subregion, and the unconditional EXWE frequency in the entire area. The conditional EXWE frequencies in the northern subregion mostly show significant increases, but there is no trend in the conditional EXWE frequency for the unfavourable HBCs (northerly, zonal, westerly). In contrast with this, in the mid–southern subregion, only the EXWEs under southerlies show a significant increase. However, one must be careful when evaluating the detected significant increase in the EXWEs under the southerly circulation class, since the frequency of southerly flow in summer substantially increased during the 20th century (Table V).

4.4.2. Relationships between frequencies of EXCEs and HBCs. Correlation coefficients were calculated between the total number of EXTEs ($a < a_L$ and $a > a_H$ events) and HBC occurrences for one season and ten-season long subperiods in the period 1901–98. The results are presented in Table VII. The correlation coefficients between the mean residence time of anticyclonic and cyclonic types on the one hand and EXTE frequencies on the other hand are also presented there. These characteristics show the statistical connection between the persistence of synoptic situations and the frequency of EXTEs.

Concerning the seasonal occurrences, HBCs that are favourable for EXCEs (northerly, easterly, meridional and anticyclonic ones) show significant positive correlation with the frequency of EXCEs, whereas the westerly and zonal circulation classes have significant negative correlations with EXCEs. The results for the northern and mid–southern subregions are very similar. The absolute values of the empirical correlation coefficients are often rather high, exceeding 0.5 both for seasonal and decadal characteristics. The absolute values of the correlation coefficients for decadal mean frequencies are usually similar or slightly higher than those for seasonal frequencies, but, because of the high autocorrelation in the sample of the decadal characteristics, the frequency of northerlies and that of EXCEs is the only one of the decadal variable pairs whose correlation is significant at the 0.95 level. In this case the correlation coefficients are surprisingly high (0.86–0.88). Although there is no statistically significant correlation between the persistence of circulation conditions and the EXCE frequency, it should be noted that all the calculated values for this type of relationship indicate negative connection, particularly for the cyclonic types and decadal characteristics.

Table VI. Mean seasonal occurrences of EXCEs and EXWEs (both for occurrences conditioned by HBCs and unstratified occurrences), trends of the occurrence frequencies and their significances, 1901–98. **P** (**N**): significant positive (negative) trend at the 0.05 level

Circulation class (HBC)	Northern					Mid–southern					Overall				
	Mean seasonal occurrence (days)	Mean systematic change (days/100 years)	Significance of alteration			Mean seasonal occurrence (days)	Mean systematic change (days/100 years)	Significance of alteration			Mean seasonal occurrence (days)	Mean systematic change (days/100 years)	Significance of alteration		
			Mann–Kendall test	Wilcoxon test threshold				Mann–Kendall test	Wilcoxon test threshold				Mann–Kendall test	Wilcoxon test threshold	
				130% long-term mean	150% long-term mean				130% long-term mean	150% long-term mean				130% long-term mean	150% long-term mean
Winter EXCEs															
Zonal	0.7	−0.3	**N**	**N**	—	1.1	−1.0	—	—	—	0.9	−0.7	—	—	—
Mixed	3.1	−2.2	—	—	—	3.4	−2.2	—	—	—	3.2	−2.2	—	—	—
Meridional	6.3	0.2	—	—	—	5.5	0.0	—	—	—	5.9	0.0	—	—	—
Westerly	1.2	−0.8	—	—	—	2.0	−1.6	—	—	—	1.6	−1.3	—	—	—
Northerly	5.0	0.8	—	—	—	4.7	0.2	—	—	—	4.8	0.5	—	—	—
Easterly	3.8	−1.3	—	—	—	2.9	−0.8	—	—	—	3.3	−1.0	—	—	—
Southerly	1.6	−1.2	—	—	—	1.5	−0.8	—	—	—	1.5	−1.0	—	—	—
Anticyclonic	6.6	−3.3	—	—	—	6.0	−3.6	—	—	**N**	6.3	−3.5	—	—	**N**
Cyclonic	2.6	1.1	—	—	—	3.0	0.9	—	—	—	2.8	1.0	—	—	—
All	10.2	−2.1	—	—	—	10.1	−3.0	—	**N**	**N**	10.2	−2.6	—	**N**	**N**
Summer EXWEs															
Zonal	1.9	0.0	—	—	—	2.8	−1.0	—	—	—	2.4	−0.5	—	—	—
Mixed	3.0	3.3	**P**	**P**	**P**	3.5	1.2	—	—	—	3.2	2.1	—	—	**P**
Meridional	3.1	3.0	**P**	**P**	**P**	3.5	1.4	—	—	—	3.3	2.1	**P**	**P**	—
Westerly	3.0	1.6	—	—	—	4.2	−0.2	—	—	—	3.7	0.6	—	—	—
Northerly	1.7	0.6	—	—	—	2.2	−1.2	—	—	—	2.0	−0.4	—	—	—
Easterly	1.0	1.3	**P**	**P**	**P**	0.9	0.4	—	—	—	0.9	0.8	—	—	**P**
Southerly	2.3	4.3	**P**	**P**	**P**	2.3	3.7	**P**	**P**	**P**	2.3	4.0	**P**	**P**	**P**
Anticyclonic	3.9	3.9	**P**	**P**	**P**	4.5	1.2	—	—	—	4.2	2.4	—	—	—
Cyclonic	3.4	2.3	**P**	—	—	4.4	0.6	—	—	—	3.9	1.3	—	—	—
All	8.1	6.3	**P**	**P**	—	9.9	1.5	—	—	—	9.1	3.6	—	—	—

Table VII. Correlation coefficients between the seasonal and decadal mean frequencies of the circulation class occurrences, and those of the EXCEs and EXWEs for the period 1901–98. **P** (**N**): significant positive (negative) correlation at the 0.05 level

Circulation class (HBC)	Northern subregion				Mid-southern subregion				Overall			
	Season		Decade		Season		Decade		Season		Decade	
Winter EXCEs												
Zonal	−0.45	**N**	−0.60	—	−0.43	**N**	−0.61	—	−0.45	**N**	−0.61	—
Mixed	−0.17	—	−0.22	—	−0.10	—	−0.10	—	−0.13	—	−0.16	—
Meridional	0.52	**P**	0.58	—	0.44	**P**	0.54	—	0.48	**P**	0.56	—
Westerly	−0.51	**N**	−0.54	—	−0.49	**N**	−0.54	—	−0.51	**N**	−0.55	—
Northerly	0.59	**P**	0.88	**P**	0.58	**P**	0.86	**P**	0.60	**P**	0.87	**P**
Easterly	0.60	**P**	0.60	—	0.47	**P**	0.48	—	0.54	**P**	0.54	—
Southerly	−0.01	—	−0.25	—	−0.10	—	−0.27	—	−0.06	—	−0.26	—
Anticyclonic	0.31	**P**	0.04	—	0.33	**P**	0.06	—	0.33	**P**	0.05	—
Cyclonic	−0.21	—	−0.14	—	−0.26	**N**	−0.18	—	−0.25	—	−0.17	—
Anticyclonic types residence time	−0.08	—	−0.35	—	−0.08	—	−0.35	—	−0.08	—	−0.35	—
Cyclonic types residence time	−0.19	—	−0.44	—	−0.21	—	−0.45	—	−0.21	—	−0.45	—
Summer EXWEs												
Zonal	−0.04	—	−0.13	—	0.17	—	0.53	—	0.10	—	0.36	—
Mixed	0.04	—	0.16	—	0.10	—	0.66	—	0.09	—	0.57	—
Meridional	0.00	—	−0.03	—	−0.23	—	−0.75	—	−0.17	—	−0.59	—
Westerly	−0.14	—	−0.35	—	0.12	—	0.38	—	0.03	—	0.17	—
Northerly	−0.23	—	−0.75	—	−0.34	**N**	−0.53	—	−0.33	**N**	−0.67	—
Easterly	0.02	—	−0.09	—	−0.27	**N**	−0.61	—	−0.18	—	−0.50	—
Southerly	0.27	**P**	0.59	—	0.21	—	−0.08	—	0.25	**P**	0.15	—
Anticyclonic	0.19	—	0.12	—	0.09	—	0.44	—	0.14	—	0.38	—
Cyclonic	−0.14	—	−0.02	—	−0.10	—	−0.39	—	−0.12	—	−0.31	—
Anticyclonic types residence time	0.33	**P**	0.74	—	0.19	—	0.21	—	0.26	**P**	0.43	—
Cyclonic types residence time	0.17	—	0.77	—	0.07	—	0.30	—	0.11	—	0.51	—

Figure 6 illustrates the great resemblance between the long-term changes in the EXCE frequencies and the northerlies, easterlies and meridional circulation class occurrences. There is a general strong similarity between all variable pairs until 1960, as well as for the entire period concerning the northerly–EXCE relationship. The resemblance is weaker in the last third of the century. In the 1970s and 1980s there was a sharp decline in the frequency of the meridional circulation class and the easterly flow occurrences, but not in the frequency of EXCEs and northerlies. In the latest decade the frequencies of HBCs favourable for EXCEs increased, but the frequencies of EXCEs did not. Anticyclonic circulation is also an HBC that is favourable for EXCEs; the long-term changes of its frequency, however, differ substantially from those of the other favourable HBCs and EXCEs. The correlation between the decadal mean frequency of anticyclonic situations and that of EXCEs is as low as 0.05 (Table VII), and the prevailing tendencies of the two variables were just the opposite in the last third of the 20th century (Figure 7). The smoothed time series of the residence times of circulation types in winter are also presented in Figure 7, showing a substantial increase in the latest decades. This change indicates that the circulation changes in the last few decades were not restricted to the frequency changes of HBCs, and some of them might have affected the HBC frequency–EXCE frequency relationships.

4.4.3. Relationships between frequencies of EXWEs and HBCs. The relationships between the seasonal and decadal frequencies of EXWEs and those of HBC occurrences are much weaker than for EXCEs (Table VII).

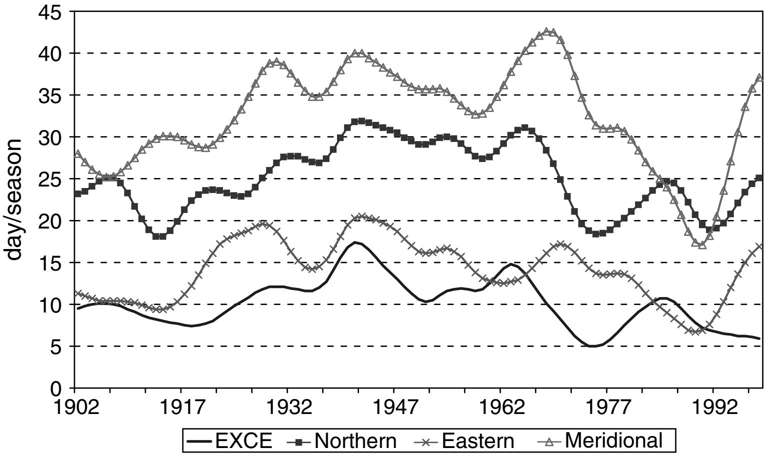

Figure 6. Smoothed time series of the annual occurrence frequencies of EXCEs and of HBC occurrences in winter

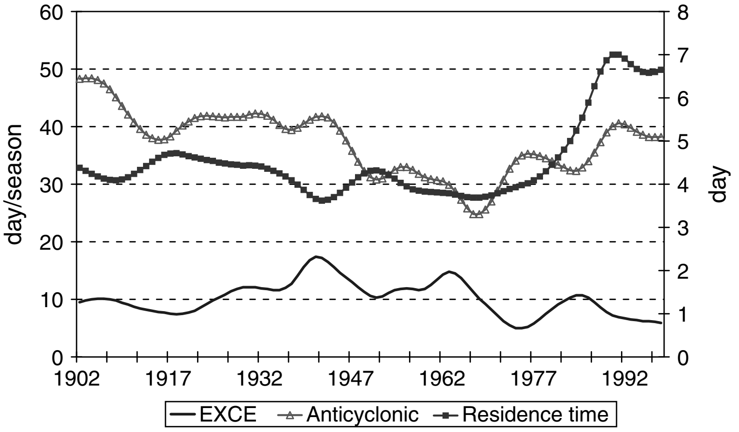

Figure 7. Smoothed time series of the annual occurrence frequencies of EXCEs, of anticyclonic class occurrences and the mean residence times of HBC types in winter

Notwithstanding this, there are still significant statistical connections for some HBCs: considering the seasonal occurrences, the southerlies have positive and the northerlies negative significant correlation coefficients with EXWEs. The residence time of the anticyclonic types has a significant positive correlation with the frequency of EXWEs. The spatial differences between the correlation coefficients for the northern and the mid–southern subregions are higher than for EXCEs. Although the meridional and easterly classes have no statistical connection with the EXWE frequency in the northern subregion, these situations are clearly unfavourable for EXWEs in the mid–southern subregion. Here, the correlation value for the easterlies–EXWE relationship is significant (negative) for the seasonal mean frequencies at the 0.05 level, and the absolute values of the correlation coefficients for decadal frequencies are quite high (although not significant at the 0.05 level). A similar spatial difference, but with the opposite gradient, can be found for the zonal and westerly circulation classes. In the northern subregion, rather high (0.74–0.77) positive correlations exist between the residence time of circulation types and the decadal mean frequency of EXWEs. A negative connection with the northerlies is also the strongest here for the decadal variables. Figure 8 illustrates the negative connection between the long-term changes of EXWEs and northerlies (for the whole region). In spite of the fact that the proportion of the situations with northerlies is not higher than 25–45% in summers, peaks of one curve tend to coincide with depressions of the other.

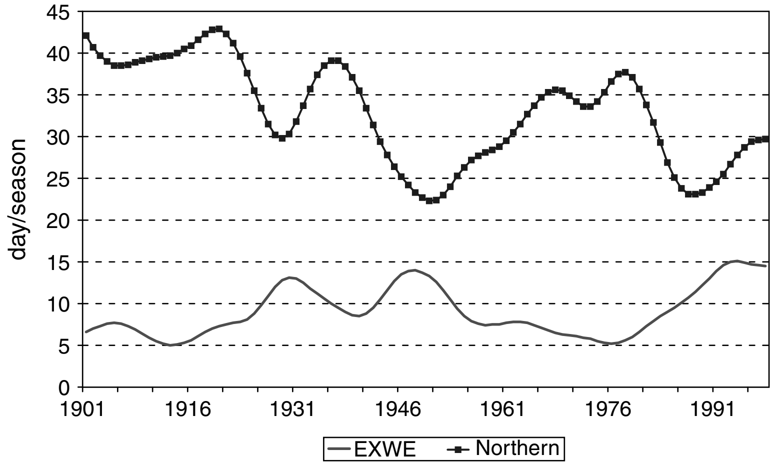

Figure 8. Smoothed time series of the annual occurrence frequencies of EXWEs and the frequencies of northerlies in summer

For the seasonal frequencies, and even more so for the decadal frequencies in the mid–southern region, the zonal and mixed classes have positive correlations with EXWEs, whereas the meridional class has a negative connection with them. However, these connections are not confirmed by the values in Table VI (35% of the EXWEs occurred under meridional situations in the mid–southern region, which is almost the same rate as in the northern region). This indicates that the zonality–meridionality influence on the EXWE frequency depends not only on the geographical location, but also on the time scale of the comparison.

In the last decades of the period investigated a sharp increase was found in the EXWE frequency (Section 4.2.2; Figure 5). Therefore, the mean seasonal occurrences of EXWEs under HBCs and the significance of systematic changes were also calculated for the last 25 years of the study period (1974–98). The results are presented in Table VIII in the same form as for the results for the entire period shown in Table VI. One can see that significant increases in the frequency of EXWEs under various HBCs occurred in the last 25 years. The increase seems to be greatest in the southern subregion. The distribution of the mean seasonal occurrences among the HBCs resembles the values in Table VI, although the rates of the anticyclonic, meridional and mixed classes are slightly higher for the last 25 years than for the entire period.

The frequency of EXWEs under the zonal and mixed classes increased significantly in the last 25 years according to all the test results in Table VIII. This tends to indicate that the long-term fluctuation of EXWEs under zonal circulation is even larger than the fluctuation of all EXWEs. Figure 9 illustrates the long-term changes in the ratio of $\sum(\text{EXWE} \cap \text{zonality})/\sum \text{EXWE}$ in percentages for the northern and mid–southern subregions along with the seasonal frequency of EXWEs for the whole region. Ratio values tend to follow the long-term fluctuations of all EXWEs in decadal time scale, although the trends for the whole period are substantially different.

4.4.4. Increase in the residence time of circulation types in the latest decades. It was shown in Figure 7 that although the mean residence time did not change too much in most parts of the century, a sharp increase occurred in the 1980s. The significant increase in the residence times of the HBC types was demonstrated first by Werner *et al.* (2000) for the zonal circulation in winter and Kyselý (2000, 2002a) for all circulation types in summer. Figure 10 confirms these results and illustrates that, in the 1980s, a sudden increase of the residence times happened in both the anticyclonic and cyclonic situations and both in winter and summer. As the unchanged or slightly variable circulation conditions lasting for relatively long periods support the anomalies of air temperature in one direction, this change may have a strong influence on the frequencies of EXTEs (Kyselý, 2002a; for more details, see Section 5.4).

Table VIII. As for Table VI, except for EXWEs in 1974–98 only

Circulation class (HBC)	Northern subregion					Mid subregion				
	Mean seasonal occurrence (days)	Mean systematic change (days/100 years)	Significance of alteration			Mean seasonal occurrence (days)	Mean systematic change (days/100 years)	Significance of alteration		
			Mann–Kendall test	Wilcoxon test threshold				Mann–Kendall test	Wilcoxon test threshold	
				130% long-term mean	150% long-term mean				130% long-term mean	150% long-term mean
Zonal	1.8	12.2	**P**	**P**	**P**	1.9	16.6	**P**	**P**	**P**
Mixed	4.2	25.1	**P**	**P**	**P**	3.5	29.2	**P**	**P**	**P**
Meridional	4.5	5.5	—	—	—	4.1	10.1	—	—	—
Westerly	3.3	22.0	—	**P**	**P**	3.4	29.0	**P**	**P**	**P**
Northerly	2.1	1.1	—	—	—	1.6	0.9	—	—	—
Easterly	1.6	−3.1	—	—	—	1.0	−5.6	—	—	—
Southerly	3.8	13.4	—	—	—	3.6	19.2	**P**	—	—
Anticyclonic	6.0	30.1	**P**	—	—	4.5	30.2	**P**	—	—
Cyclonic	3.9	10.0	—	—	—	4.1	23.8	**P**	—	—
All	10.6	43.1	**P**	**P**	—	9.5	55.5	**P**	**P**	**P**

Circulation class (HBC)	Southern subregion					Overall				
	Mean seasonal occurrence (days)	Mean systematic change (days/100 years)	Significance of alteration			Mean seasonal occurrence (days)	Mean systematic change (days/100 years)	Significance of alteration		
			Mann–Kendall test	Wilcoxon test threshold				Mann–Kendall test	Wilcoxon test threshold	
				130% long-term mean	150% long-term mean				130% long-term mean	150% long-term mean
Zonal	2.5	27.4	**P**	**P**	**P**	2.0	17.5	**P**	**P**	**P**
Mixed	3.7	31.4	**P**	**P**	**P**	4.0	27.5	**P**	**P**	**P**
Meridional	4.1	18.6	**P**	—	—	4.2	9.4	—	—	—
Westerly	4.0	41.8	**P**	—	**P**	3.6	29.0	**P**	**P**	**P**
Northerly	1.8	10.6	—	—	**P**	1.9	3.2	—	—	—
Easterly	0.9	−0.0	—	—	—	1.3	−3.3	—	—	—
Southerly	3.3	19.6	**P**	—	**P**	3.6	16.4	—	—	—
Anticyclonic	4.9	37.0	**P**	—	**P**	5.5	31.9	**P**	—	—
Cyclonic	4.6	36.4	**P**	**P**	**P**	3.9	19.0	—	—	—
All	10.4	77.5	**P**	**P**	**P**	10.2	54.2	**P**	**P**	**P**

5. DISCUSSION

The content of this section is organized about the following subtopics: long-term fluctuations of EXTEs showing large spatial resemblances are discussed in Section 5.1; spatial resemblances and differences in the EXTE–HBC connections are highlighted is Section 5.2, as is the fact that EXCE–HBC connections are stronger than EXWE–HBC connections; Section 5.3 discusses the influence of zonality–meridionality of

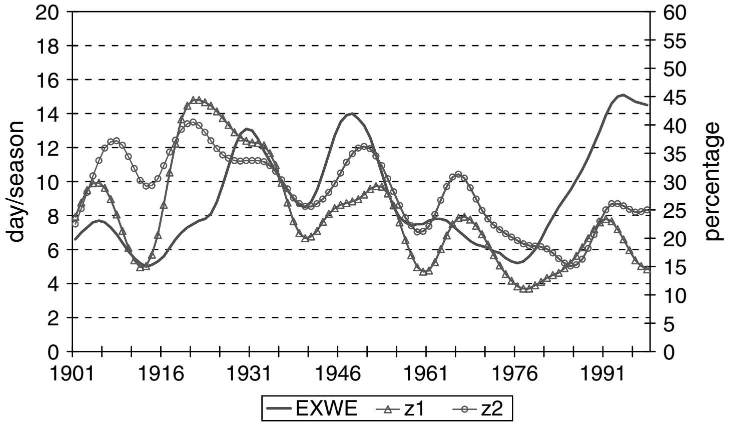

Figure 9. Smoothed time series of the annual occurrence frequencies of EXWEs and of the ratio of EXWEs occurring under zonal circulation types to all EXWEs. z1: northern subregion, z2: mid-southern subregion

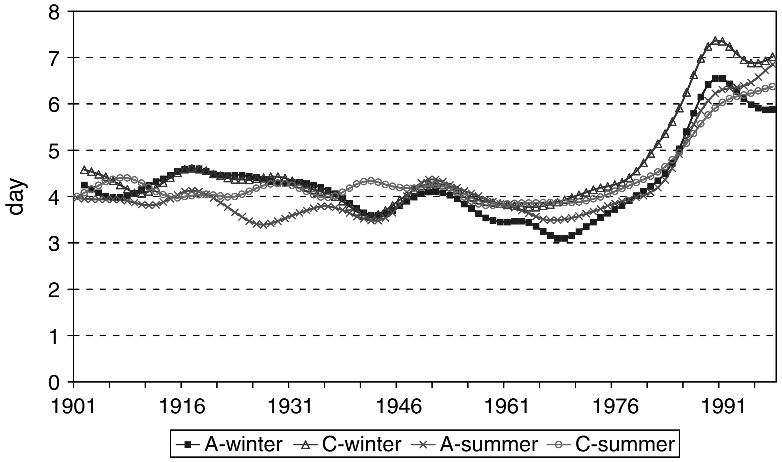

Figure 10. Smoothed time series of annual mean residence time for circulation types in specified HBCs

circulation on the EXWE frequency; Section 5.4 highlights the role of the persistence of synoptic situations; significant correlation coefficients between the decadal frequency of EXTEs and HBC occurrences are discussed in Section 5.5; Section 5.6. discusses the long-term fluctuations, and whether they are the result interference of oscillations or are a random walk; Section 5.7 discusses the frequency changes noted in EXCEs and EXWEs in the last decades.

5.1. Long-term fluctuations of EXTEs show large spatial resemblances

Large long-term fluctuations were found in the frequencies of both EXCEs and EXWEs. Applying the anomaly threshold method for delimiting EXTEs, the shapes of the fluctuations for local time series are very similar spatially. The similarity is greater for EXCEs than for EXWEs, and is usually more pronounced within the subregions than between sites located in different subregions. This similarity is an indication of a spatial coherence in the climatic variability over south–central Europe, and a justification of the adequacy of the data quality as well. This means that although some local inhomogeneity effects have influenced the data used and, hence, also the local characteristics investigated, this influence was too weak to obscure the common signs of climatic variability in the region. Moreover, these common signs are usually stronger than any of the individual features. Perhaps the only exception is the EXWE fluctuation in Szeged, which is strongly influenced by the station moving in 1951. It should be noted that the characteristics describing systematic changes are more sensitive to the inhomogeneity effects, especially when the changes are close to the significance threshold, and this is often the case of the temperature characteristics for the 20th century. For instance, a higher warming rate was detected, both in the mean seasonal temperatures and frequencies of EXTEs, in Cracow and Prague than in the other parts of the study area. It cannot be assessed from the data how many of the spatial differences are caused by the local inhomogeneity effects relative to the gradients of real macroclimatic differences. Notwithstanding this, the main findings of the paper are not affected by this uncertainty.

5.2. Spatial resemblances and differences in the EXTE–HBC connections; EXCE–HBC connections are stronger than EXWE–HBC connections

The connections detected between EXTEs and HBCs confirm several known theses of synoptic climatology over Europe. In winters, cyclones and anticyclones are usually better developed than in summers, and their mean life time is the highest in winter (Wallén, 1977). Mean horizontal temperature gradients are also larger in winter than in summer, and advection may transport airmasses with very different thermal characteristics mainly in winter. Therefore, the role of synoptic patterns in the development of EXTEs is higher in winter than in summer. This finding contrasts with results of statistical downscaling studies for daily temperatures in central Europe, which show a higher percentage of variance explained in summer than in winter (e.g. Huth, 1997) and a lower skill in the reproduction of extremes in winter compared with summer (Huth *et al.*, 2001; Kyselý, 2002b). However, temperature trends for a few decades-long period (1949–80) show much stronger connections to the circulation changes in winter than in summer (Huth, 2001).

The main features of the EXTE frequency–circulation relationship are similar in central and southern Europe in winter, but in summer the Mediterranean area often remains unaffected by the synoptic-scale perturbations in northern and central Europe. This feature of the summer climate is reflected by the relatively large spatial differences of EXWE–circulation relationship in summer.

5.3. Influence of zonality–meridionality of circulation on the EXWE frequency

The zonal circulation promotes the transport of cool air from the Atlantic Ocean to the continent in summer, but this influences mainly the northern half of Europe. Usually, at the same time the Mediterranean area enjoys calm, anticyclonic weather with descending warm air. A meridional situation may be thought to be more favourable for EXWE occurrences than a zonal one, since the meridionality blocks the cool air over the ocean from flowing towards the continental areas. However, the real processes are more complicated: in the eastern side of high-pressure systems, cool air usually flows southwards. Thus, in summers with above-normal frequency of the meridional circulation class occurrences, EXWEs are not too frequent in the southern half of the study area.

An interesting finding is that the fluctuations of the ratio of the EXWEs under the zonal circulation to all EXWEs tend to follow the fluctuations of all EXWEs on a decadal time scale. This means that whereas in relatively cool summers the few EXWEs of the season mostly occur under meridional or mixed types, in warm summers the frequencies of the zonal and meridional class occurrences with EXWE are similar. A hypothetical explanation is that the dynamical base of a summer with a large number of EXWEs in south–central Europe is an expansion of the Mediterranean-like circulation northwards; thus, the frontal activity and intensity of airmass-exchange is relatively weak in this part of Europe, even under zonal circulation class occurrences.

Owing to the long-term persistence in summer weather, EXWE occurrences early in the summer predict a warmer than normal summer in central Europe (Gerstengarbe, 1992; Domonkos, 2001). Relying on the above discussion, an early appearance of EXWE(s) with zonality may be an enhanced sign of a warmer than normal summer in this region. A quick examination between the frequencies of June EXWEs and EXWEs in the following July–August period, over the mid–south subregion, resulted 0.20 correlation for all events and 0.34 correlation if the June events are restricted to EXWEs with zonal class occurrences. (In the northern region the correlations are practically equal to zero.) Although the 0.34 value is statistically significant at the

0.01 level, it explains only 11.5% of the variability. Nevertheless, the evaluation of the predictability potential of the June temperature and circulation fields needs further investigation.

5.4. Role of the persistence of synoptic situations

The residence time of anticyclonic types has a significant positive correlation with the frequency of EXWEs (especially in the northernmost sites). It is obvious, since anticyclonic situations in summer are favourable for the development of unusually high temperatures. However, it should be noted that the positive connection between a temperature anomaly and residence time appears for both cyclonic and anticyclonic circulation types. For instance, the residence time of cyclonic types in summer has a positive correlation with EXWE (albeit the seasonal value is lower than the same type characteristic for the anticyclonic types, and not statistically significant). The increasing residence time may be an explanation for the increasing frequency of EXWEs in the latest decades.

The residence time of circulation types in winter has negative (though not significant statistically) connection with the frequency of EXCEs. A possible explanation is that the movement and changes of high-pressure systems with a warm airmass in the mid and upper troposphere are sluggish, and the extent of this type of pattern influences the life time of both the anticyclonic and cyclonic situations over central Europe. Although there is no immediate connection between surface temperature and upper-air temperature in winter, the persistent presence of warm airmass in the upper levels tends to prevent the development of EXCEs. On examining the results presented in Figures 6 and 7, one explanation for the recent change of winter weather is that, in the 1990s, the frequency of meridional circulation rose substantially, but with the extension of persistent, warm anticyclones, and thus the frequency of EXCEs did not rise in the same period.

An increasing dominance of warm anticyclones may also explain the increase of residence time throughout the year. A larger than normal extent of subtropical anticyclones is a favourable condition for the development of persistent anticyclonic situations and occurrences of summer EXWEs, but not for cold air outbreaks and EXCEs (Wallén, 1977). On the other hand, the recent abrupt increase of the persistence of Hess–Brezowsky circulation types and its reliability needs further investigation.

5.5. Significant correlation coefficients between the decadal frequency of EXTEs and HBC occurrences

It was found that the absolute values of the correlation coefficients between the decadal frequencies of HBCs often accompanied by EXTEs and decadal frequencies of EXTEs are usually higher than between the same type variables for one season. Many values exceed 0.5, and the highest ones reach 0.86–0.88 (for EXCE–northerly flow connection). In most cases, statistical significance has not been proven because of the small effective sample size. However, as this finding appears repeatedly in the results (though with some exceptions) it is likely to be non-random. The strong statistical connections between the long-term changes of EXTEs and the frequency of HBCs tend to show that the large long-term fluctuations of EXTEs in south–central Europe during the 20th century were governed by long-term changes in some characteristics of the large-scale atmospheric circulation.

According to some other studies, the connection between long-term changes of temperature and large-scale circulation is relatively weak. Yarnal (1985; Pacific northwest coast) and Huth (2001; central Europe) examined the relationship between 500 hPa field changes and temperature variability, and they found a moderate connection in the long time scale. Hanssen-Bauer and Forland (2000; Norway) found a poor connection for variations before 1940, but a much stronger one for the later part of the temperature series. Beyond real spatial and temporal differences, the results likely depend on the number and type of variables, and the quality of the time series. Tomozeiu *et al.* (2002) carried out a thorough investigation of the variability in the seasonal means of maximum daily temperature in Romania, and examined the connections to several variables of the large-scale circulation. They concluded that most of the long-term temperature variability is related to some specific changes of the circulation regime. Our results also show that randomness in the atmospheric processes under a constant state of the climate-influencing factors is of secondary importance in the formation of the long-term changes of EXTE characteristics.

5.6. Long-term fluctuations: interference of oscillations or random walk?

There is some evidence in the literature to indicate the presence of both regular or quasi-regular oscillations and irregular fluctuations in the time series of environmental elements. Unfortunately, the proportion of regular oscillations in the entire variability is difficult to estimate using purely statistical tools. If the hypothesis in Section 5.5 is correct, and the low-frequency changes of the large-scale circulation govern the fluctuations in the local climatic characteristics, oscillations with the same frequencies should be detectable in the time series of different environmental variables. This concurrent presence is true for the oscillation with a cycle of 50–70 years detected in the air–sea relationship over the Atlantic (Schlesinger and Ramankutty, 1994; Tourre *et al*., 1999), in the North Atlantic oscillation index (Paeth *et al*., 1999; Pozo-Vázquez *et al*., 2000), in the global mean temperatures (Mann *et al*., 1995) and also in the summer mean temperatures in Hungary (Domonkos and Tar, in press). In spite of the substantial coherence between these changes, the regularity is doubtful, since all the reliable data series are too short to clarify the regularity of an oscillation-like signal with such a long cycle.

5.7. Frequency of EXCEs decreased and that of EXWEs increased significantly in the last decades

In the 1990s, the EXCE frequency reached or approached its minimum, and the EXWE frequency reached or approached its maximum. An important question arises, as to whether a general warming tendency can be realized from the calculated characteristics or not. We do not want to answer with a simple ‘yes’ or ‘no’, because both could be misleading. There are several signs of a general warming in the last few decades of the 20th century. However, only a few tests prove statistically significant trends for the whole century (mainly at the northernmost sites). The frequencies of EXCEs rose in the first four decades of the 20th century, and the decreasing trend (still with large fluctuations) began only around the middle of the century. A general increase in the EXWE frequencies is even more doubtful; in the 1970s, a deep depression (the deepest in some sites) of this variable occurred, and a sharp increase began only afterwards. The EXTE frequency values around the end of the period investigated tend to indicate that a substantial warming has happened recently. However, whether the changes in the latest decades can be considered the starting phase of an accelerated warming tendency or whether they are a temporary change caused by oscillations and irregular fluctuations of climate is still a subject of uncertainty. Likely, the origin of the observed warming in the latest decades is mixed, being a combination of internally and externally forced natural variability and anthropogenic sources (Barnett *et al*., 1999; Bertrand and van Ypersele, 2002).

6. CONCLUSIONS

The long-term fluctuations, systematic changes and connections with macrocirculation conditions over central Europe during the 20th century were investigated for the winter EXCEs and summer EXWEs in the daily temperature series (1901–98) at 11 sites in central and southern Europe. The daily catalogue of circulation types by Hess and Brezowsky (1977) was used to describe the circulation conditions. The main findings of the study are as follows:

- There were large long-term fluctuations in the frequency of both EXCEs and EXWEs during the 20th century. The fluctuations at individual sites show great spatial similarity. These fluctuations are basically irregular, although some signs of regular oscillations also appear in them. Likely, a quasi- 50 year oscillation influences the EXWE frequency, but the regularity of the oscillation-like variation in the data series cannot be proven.
- There are several signs of a general, slight warming tendency during the period investigated (1901–98), though only few of the tests, mostly for the northernmost sites of the study area, showed significant systematic alterations.
- Several strong statistical connections were found between the frequencies of EXTEs and those of circulation class (HBC) occurrences. The characteristics for this connection usually have great spatial resemblances

again, though some substantial differences were also revealed between the characteristics for the northern and southern subregions.

- The EXCE–HBC connections are usually stronger than the EXWE–HBC connections. Northerlies, easterlies, and meridional and anticyclonic situations are the favourable HBCs for EXCE occurrences, whereas southerly flow and persistent anticyclonic situations are favourable for EXWEs. The spatial similarity of the characteristics for EXTE HBC connections is greater for EXCEs than for EXWEs.
- Zonal circulation is relatively rare during EXWEs in the northern subregion, but is normally frequent in the mid and southern subregions. The correlations between the seasonal numbers of zonal circulation class occurrences and those of EXWEs indicate a positive connection in the south and no connection in the north. The long-term fluctuations of EXWEs under zonal circulation are larger than those of all EXWEs. The ratio of the EXWE occurrences under zonal circulation to all EXWEs tends to follow the decadal fluctuations of all EXWEs. Therefore, the appearance of EXWEs under zonal circulation might be a special indicator of hot summers in south–central Europe.
- The mean residence time of individual circulation types has a positive correlation with the frequency of EXWEs and a negative correlation with the frequency of EXCEs. This relationship is significant at the 0.95 level in the case of the anticyclonic situations–EXWE variable pair. In the latest decades the frequency of EXCEs decreased, that of EXWEs increased sharply, and the residence time of synoptic patterns (both of the cyclonic and anticyclonic types) increased substantially, both in winter and summer.
- The quality and strength of the EXTE–HBC connections in longer time scales (season, decade) are usually similar to that of the individual events, though some exceptions occur (e.g. EXCE–anticyclonic class). The absolute values of the correlation coefficients between the frequency of EXTEs and of HBCs that are favourable for the EXTE occurrences are often even higher for the decadal than the seasonal characteristics. This result tends to show that large long-term fluctuations of EXTEs in south–central Europe during the 20th century were governed by the long-term changes in some characteristics of the large-scale circulation. Temporal accumulations of EXTE occurrences in some periods of the last century are likely the result of these circulation changes, and the randomness of the atmospheric processes within circulation classes has a secondary importance only.

ACKNOWLEDGEMENTS

The research was supported by the Hungarian Research Foundation (T-029374), the Grant Agency of Academy of Sciences CR (B3042004) and the Grant Agency of the Czech Republic (205/01/D040). The authors thank the national meteorological services for providing the temperature data series in appropriate form and quality.

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