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Short Communication

Implications of enhanced persistence of atmospheric circulation for the occurrence and severity of temperature extremes

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Abstract:

The relationship between persistent atmospheric circulation patterns over Europe and surface air temperature anomalies is studied for the 20th century using the Hess–Brezowsky catalogue of circulation types and temperature data from Prague. Circulation types significantly conducive to heat and cold waves are detected. It is demonstrated that the persistence of the circulation patterns is linked to surface air temperature anomalies and the occurrence and severity of temperature extremes that become more pronounced under more persistent circulation. The consequences vary for warm and cold extremes, depending on features related to atmospheric dynamics (e.g. air-mass advection and fronts). The intensification of anomalies due to higher persistence of circulation patterns would likely be more important for warm temperature extremes than the cold ones. The recently observed increases in the frequency and severity of heat waves over Europe are likely related to enhanced persistence of the atmospheric circulation, and the impacts of the expected climate change on the occurrence and severity of temperature extremes may be exacerbated by more persistent circulation patterns over the European midlatitudes. Copyright © 2007 Royal Meteorological Society

KEY WORDS atmospheric circulation; persistence; temperature; Europe; climate variability

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INTRODUCTION

Several recent papers have pointed out that the persistence of the atmospheric circulation (measured by the mean residence times of circulation types) over the North Atlantic–European domain has increased from the mid-1980s, compared to previous decades, in both winter and summer seasons and for most groups of weather types (Werner *et al*., 2000; Kyselý, 2002; Domonkos *et al*., 2003; Kyselý and Domonkos, 2006). The Hess–Brezowsky catalogue of Grosswetterlagen (Hess and Brezowsky, 1952; Gerstengarbe *et al*., 1999) was utilized in most of these studies, particularly because it extends back to the late 19th century and is considered to be free of artificial biases and trends. The shift towards longer residence times of the circulation patterns over Europe in the 1980s was found to be unprecedented since the late 19th century and statistically significant according to the change point and outlier detection methods for most groups of circulation types and for all seasons (Kyselý and Domonkos, 2006).

It has also been hypothesized that the enhanced persistence of atmospheric circulation patterns may affect the occurrence of surface climatic extremes, particularly heat and cold waves (Kyselý, 2002; Domonkos *et al*., 2003) and precipitation extremes (Fowler and Kilsby, 2003). The reason for this expectation is the fact that stable atmospheric circulation conditions usually support spells of either positive or negative anomalies of surface air temperature as well as some other climatic variables. Thus, the increased frequency and severity of high-temperature extremes observed over Europe in the 1990s and early 2000s (Heino *et al*., 1999; Kyselý, 2002; Domonkos *et al*., 2003; Beniston, 2004; Moberg and Jones, 2005) may, to some extent, be related to the enhanced persistence of the atmospheric circulation patterns. Nevertheless, very little effort has been made to support these hypotheses.

The aim of this paper is to demonstrate the consequences of the changes in the mean residence times of circulation types on air surface temperature anomalies and the frequency and severity of warm and cold temperature extremes in central Europe, and also evaluate how the links vary for individual Hess–Brezowsky types and between warm and cold events.

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DATA AND METHODS

Circulation types

The Hess–Brezowsky catalogue of large-scale circulation patterns (Hess and Brezowsky, 1952; Gerstengarbe *et al.*, 1999) describes the atmospheric flow over most of Europe and is frequently utilized in studies dealing with changes in the atmospheric circulation (e.g. Bárdossy and Caspary, 1990; Werner *et al.*, 2000) or in examining links between circulation types and surface climatic variables over many parts of Europe (Buishand and Brandsma, 1997; Kyselý, 2002; Sepp and Jaagus, 2002; Pryor and Barthelmie, 2003; Domonkos *et al.*, 2003). This classification recognizes three groups of circulations (zonal, half-meridional and meridional) divided into 10 major types (Grosswettertypen) and 29 types (Grosswetterlagen); see Gerstengarbe *et al.* (1999) or Cawley (2002) for typical maps of individual types. A characteristic feature of the classification is that each occurrence of any of the types persists for at least 3 days. The mean residence times (evaluated over 1881–2000 in annual data) are between 4.3 and 5.2 days for all the types, with the exception of the zonal types WS (5.7 days) and WZ (6.2 days). Less than 1% of the days (transitions from one type to another) remain unclassified. For the description of individual types as well as for details on the classification itself, see Gerstengarbe *et al.* (1999); mean seasonal residence times and relative frequencies are given in Table I.

Table I. Mean residence times and relative frequencies of circulation types (CT) in JJA (DJF) and during heat (cold) waves in Prague, 1901–2000. Efficiency coefficient, c_{ef}, is defined as the ratio between the frequency of the CT in heat (cold) wave conditions and its mean seasonal frequency; values of c_{ef} significantly higher than 1.0 at the 0.05 level are shown in bold.

Group of CT	CT	Description of CT	JJA				DJF			
			Mean residence time (d)	Mean freq. (%)	Freq. in heat waves (%)	c_{ef}	Mean residence time (d)	Mean freq. (%)	Freq. in cold waves (%)	c_{ef}
West	WZ	West cyclonic	6.22	17.4	3.6	0.21	6.43	17.5	0.8	0.05
	WA	West anticyclonic	5.16	7.9	2.7	0.34	4.81	5.0	0.5	0.11
	WW	West angular	4.64	2.1	0.4	0.21	4.45	2.9	1.4	0.47
	WS	Southern west	5.90	1.8	0.0	0	6.33	5.7	0.8	0.14
Central European high	HM	Central European high	4.52	8.1	16.6	**2.06**	5.56	9.6	13.5	1.40
	BM	Central European ridge	5.35	8.3	18.8	**2.26**	5.15	7.3	11.8	**1.61**
East	HFA	Fennoscandian high anticyclonic	4.93	2.8	6.3	**2.21**	5.28	4.2	21.4	**5.13**
	HNFA	Norwegian Sea/Fennoscandian high anticyclonic	5.19	1.3	5.4	**4.30**	5.00	1.3	6.3	**4.75**
	HFZ	Fennoscandian high cyclonic	4.67	0.9	4.5	**5.16**	4.25	1.3	3.0	2.35
	HNFZ	Norwegian Sea/Fennoscandian high cyclonic	4.81	1.1	1.8	1.63	5.07	1.6	7.7	**4.79**
South	SA	South anticyclonic	3.91	0.4	3.1	**7.60**	5.13	2.3	2.7	1.20
	SZ	South cyclonic	3.00	0.03	0.9	**27.50**	4.83	1.7	0.0	0
	TRW	Western Europe trough	4.38	4.4	7.2	1.62	4.62	1.6	0.8	0.53
	TB	British Isles low	4.93	3.3	6.3	1.92	4.26	1.6	0.3	0.18
Southwest	SWA	Southwest anticyclonic	4.68	1.6	4.0	2.48	4.91	2.9	3.0	1.04
	SWZ	Southwest cyclonic	4.85	1.3	6.3	**4.66**	5.15	3.2	0.0	0
Southeast	SEA	Southeast anticyclonic	3.62	0.5	2.7	**5.27**	4.79	2.1	2.5	1.17
	SEZ	Southeast cyclonic	3.50	0.04	1.3	**30.94**	5.35	2.7	2.7	1.00
North	NA	North anticyclonic	4.82	1.3	0.0	0	3.63	0.3	0.0	0
	NZ	North cyclonic	5.09	2.9	0.0	0	4.46	2.4	1.4	0.56
	HNA	Iceland high anticyclonic	4.60	3.8	3.6	0.96	5.18	2.2	9.6	**4.47**
	HNZ	Iceland high cyclonic	4.40	1.6	0.0	0	4.95	1.1	5.2	**4.66**
	TRM	Central European trough	4.78	3.9	0.4	0.11	4.75	3.8	1.4	0.36
	HB	British Isles high	5.33	3.1	0.0	0	4.77	2.8	0.5	0.19
Northwest	NWA	Northwest anticyclonic	4.48	5.6	1.8	0.32	4.86	2.7	0.0	0
	NWZ	Northwest cyclonic	4.86	5.1	0.0	0	4.93	5.4	0.5	0.10
Northeast	NEA	Northeast anticyclonic	5.07	3.8	1.3	0.36	4.15	0.9	0.3	0.29
	NEZ	Northeast cyclonic	4.87	2.6	0.0	0	4.07	1.2	0.0	0
Central European low	TM	Central European low	4.48	1.9	0.0	0	4.75	1.9	0.0	0

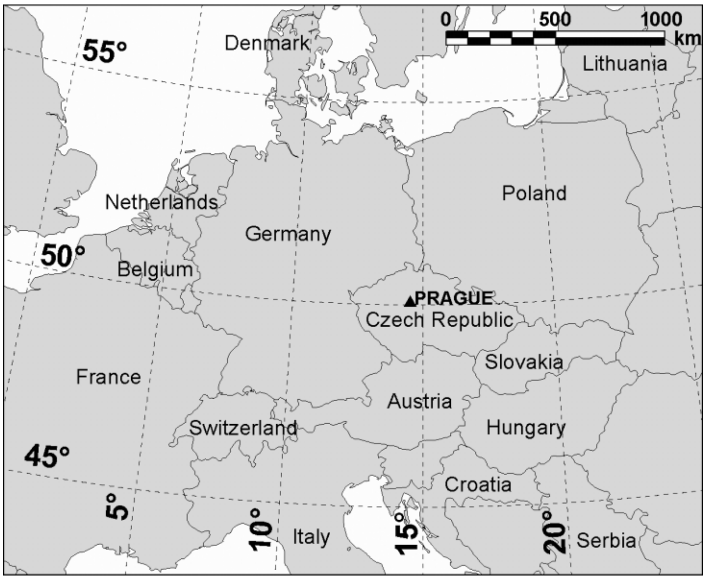

Figure 1. Location of the Prague station.

Individual circulation types (hereafter denoted as CT) are merged into 10 groups corresponding to the major types of the original Hess–Brezowsky classification (Table I). The analysis is performed for the winter (DJF) and summer (JJA) seasons and covers the period 1901–2000.

Surface air temperature measurements

The analysis is carried out for the Prague-Klementinum station (latitude 50°05′ N, longitude 14°25′ E, altitude 197 m a.s.l.), particularly because of its location close to the center of the area on which the Hess–Brezowsky classification focuses (Figure 1). It is situated in the vast complex of buildings in the campus of St. Clement College in Prague. The daily series recording of air temperature is uninterrupted since 1775, and the location of the thermometer has not changed since 1889. Changes in the instrumentation have not affected the homogeneity of the temperature series because simultaneous observations were carried out in such instances, and the required corrections were made. Structural changes in the courtyard have also not influenced the homogeneity of measurements (Hlaváč, 1937; Pejml, 1975). Reliability of the temperature series was evaluated recently by Štěpánek (2005), who found no significant inhomogeneities (except for a trend connected with the heat island effect) in the period from the beginning of the 20th century. The history of measurements is described in more detail in Hlaváč (1937) and Brázdil and Budíková (1999).

Anomalies of daily mean temperature (TAVG) from the mean annual cycle (smoothed by 7-day running means) were computed and examined further.

Statistical testing for differences in means

To depict the influence of persistent circulation patterns on air temperature, average anomalies from the mean annual cycle of daily mean temperature have been examined on days 1–5 and >5 of sequences classified with the same CT, separately for each CT and for summer and winter seasons. Note that ‘days 1–5’ involves all days of short spells (lasting 3–5 days) and early stages of longer spells (lasting >5 days) classified with the same CT, while ‘days >5’ includes late stages of spells lasting >5 days. The Wilcoxon–Mann–Whitney rank-sum test (e.g. Wilks, 1995) is utilized for testing the differences between the means of air temperature anomalies on days 1–5 and >5 (over all occurrences of a given CT), and is evaluated at the 0.05 significance level against the null hypothesis that there is no difference between the means.

The same tests are carried out for other possible thresholds (4 and 6 days instead of 5 days) that may distinguish between short spells and early stages of longer spells on the one hand, and late stages of persistent occurrences of a CT on the other.

Heat and cold waves

Since the relationship to circulation patterns is more direct for temperature anomalies than raw data (due to the annual cycle of temperature), and because the standard deviation of temperature anomalies is varying seasonally (being larger in winter than in summer in central Europe), definitions of heat and cold waves based on percentiles of temperature anomalies are employed.

Heat (cold) waves are defined in terms of deviations of daily mean temperature (TAVG) from the mean annual cycle ($M_{TAVG,d}$) as periods of at least 3 successive days with $TAVG\text{-}M_{TAVG,d} \geq P95_{TAVG,d}$ ($TAVG\text{-}M_{TAVG,d} \leq P05_{TAVG,d}$), where $P95_{TAVG,d}$ ($P05_{TAVG,d}$) stands for the 95th (5th) percentile of the empirical distribution function of $TAVG\text{-}M_{TAVG,d}$ on day d ($d = 1, \ldots 365$). Values of $P95_{TAVG,d}$ and $P05_{TAVG,d}$ were set for each day d from the empirical distribution function of $TAVG\text{-}M_{TAVG,d}$ over a 61-day interval $<d - 30, d + 30>$. (Samples containing 61 (days) × 100 (years) = 6100 observations were used to determine the percentiles.) The choice of the length of the interval in which empirical distribution functions are considered to estimate the percentiles has little effect on the percentile values, and has a negligible effect on heat and cold wave characteristics. A similar definition of heat and cold waves has been utilized in Kyselý and Dubrovský (2005).

Although this definition may be applied for any period of the year or to annual data, heat waves are examined in summer (JJA) and cold waves in winter (DJF) in this study, not only because of the enormous impacts of these extreme events on the environment and society, including negative effects on ecosystems (e.g. Parmesan *et al.*, 2000), energy consumption (Colombo *et al.*, 1999) and mortality and morbidity (e.g. Laschewski and Jendritzky, 2002; Kyselý, 2004), but also because of seasonally varying links to the atmospheric circulation for hot and cold events.

Relationship between atmospheric circulation and heat and cold waves

The link between a circulation type and heat (cold) waves is evaluated in terms of an efficiency coefficient calculated as a ratio of a relative frequency of a given CT in heat (cold) waves to its long-term mean seasonal frequency (in JJA for heat waves and DJF for cold waves). A value of the efficiency coefficient higher than 1.0 indicates that the CT is conducive to heat/cold waves. The ratios were tested for their statistical significance using a block resampling method, in which sequences of days classified with one CT in a given season (JJA for heat waves and DJF for cold waves) were taken as blocks. The null hypothesis was that the efficiency coefficient is not higher than 1.0; the tests were evaluated at the 0.05 significance level utilizing 1000 artificial series of CT.

RESULTS

Relative frequencies of circulation types in heat and cold waves in Prague and values of the efficiency coefficients are shown in Table I. In summer, the patterns significantly conducive to heat waves are the central European high (HM, BM), east types (HFA, HNFA, HFZ), south types (SA, SZ), southwest types SWZ and southeast types (SEA, SEZ); they comprise 66% of all heat wave days. Although the critical values of the efficiency coefficients obtained from the resampling test depend on climatological frequencies of CT, they do not lead to dynamically contradictory findings. For all the types conducive to heat waves, prevailing positive radiative balances due to inhibited cloudiness under the influence of a dominant high-pressure system and/or warm air-mass advection from southwest to east is typical. Note that the long-term frequencies of occurrence of some of the types conducive to heat waves are extremely low (smaller than 0.5%; see Table I), which prevents the temperature differences on days 1–5 and >5 of sequences classified with these types from being evaluated; this is why the SA, SZ, SEA and SEZ types are omitted from further analysis in summer.

With the exception of the SWZ type, which is cyclonic over central Europe, and thus mostly linked to approaching/increasing frontal and prefrontal cloudiness and decreasing air temperature (note that a similar pattern appears for other CT with the ratios insignificantly higher than 1.0, which are predominantly cyclonic over central Europe, namely, TRW, TB and HNFZ), all other CT conducive to heat waves are warmer on days >5 than days 1–5, i.e. higher average temperature anomalies are typical on days >5 (Table II, Figure 2). The differences in average temperature anomalies between days >5 and 1–5 are statistically significant for the HM (3.6 °C), HNFA (1.9 °C), HFA (1.3 °C) and BM types (0.9 °C); these four CT comprise nearly half of the heat wave days in Prague. The 'mean effect' of a gradual increase in temperature under these CT stems from both radiative and advective warming. It is obvious that in summer a more persistent atmospheric circulation supports more severe and longer heat waves.

In winter, circulation patterns significantly conducive to cold waves in Prague are north types (HNA, HNZ),

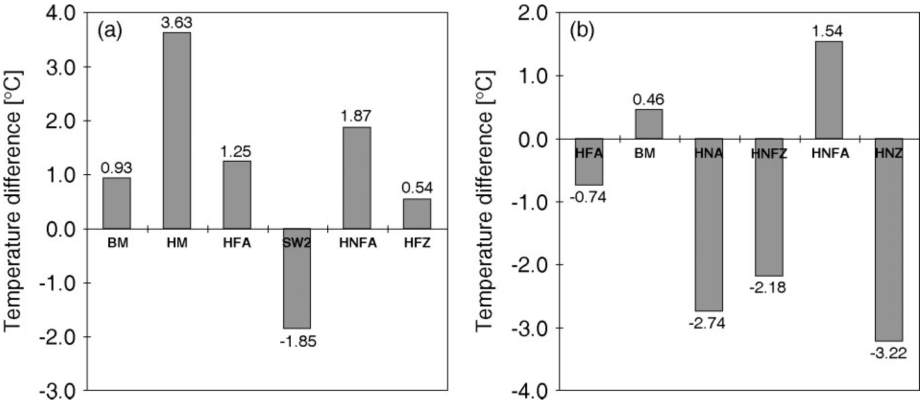

Figure 2. Differences of average anomalies from the mean annual cycle of daily mean temperature in Prague on days >5 and 1–5 of sequences classified with the same circulation type (CT). (a) for CT conducive to heat waves, (b) for CT conducive to cold waves. CT are ranked with respect to their relative frequencies of occurrence in heat (a) and cold waves (b). CT with a mean seasonal frequency of occurrence ≤0.5% were omitted.

Table II. Average anomalies from the mean annual cycle of daily mean temperature in Prague on days 1–5 and >5 of sequences classified with the same circulation type (CT). Data for types conducive to heat waves in summer and cold waves in winter are shown in bold. Symbol * denotes average temperature anomalies on days >5 of a given CT significantly different at the 0.05 level from those on days 1–5.

Group of CT	CT	JJA		DJF	
		ΔTAVG, days 1–5 [°C]	ΔTAVG, days >5 [°C]	ΔTAVG, days 1–5 [°C]	ΔTAVG, days >5 [°C]
West (W)	WZ	−0.46	−0.48	3.37	4.51*
	WA	0.54	1.34*	2.29	4.09*
	WW	0.44	0.39	0.72	3.35*
	WS	−1.28	−1.05	1.21	1.47
Central European high (HM)	HM	**1.09**	**4.72***	−1.68	−1.31
	BM	**1.19**	**2.12***	**−1.98**	**−1.52**
East (E)	HFA	**1.72**	**2.97***	**−5.29**	**−6.03**
	HNFA	**2.31**	**4.18***	**−5.85**	**−4.31**
	HFZ	**1.36**	**1.90**	−3.49	−4.14
	HNFZ	0.70	−1.14*	**−4.42**	**−6.60***
South (S)	SA	**2.88**	**6.11**	−1.41	−2.23
	SZ	**6.04**	–	−0.32	1.67*
	TRW	1.84	1.31	1.03	2.27
	TB	1.08	0.61	1.35	2.45
Southwest (SW)	SWA	2.95	3.17	0.76	2.30*
	SWZ	**3.32**	**1.47***	3.16	4.14
Southeast (SE)	SEA	**2.76**	**0.93**	−3.44	−1.60*
	SEZ	**6.69**	–	−1.03	−0.28*
North (N)	NA	−1.97	−2.74	−2.42	–
	NZ	−3.12	−4.40*	−1.21	−5.19*
	HNA	−0.07	−0.10	**−4.55**	**−7.29***
	HNZ	−0.77	−2.78*	**−3.14**	**−6.36***
	TRM	−2.08	−2.68	−0.44	−1.24
	HB	−1.59	−1.04	−1.56	−3.06*
Northwest (NW)	NWA	−1.54	−1.58	0.77	2.14*
	NWZ	−2.26	−3.33*	1.74	0.73*
Northeast (NE)	NEA	−0.21	0.45	−2.92	−4.65
	NEZ	−1.00	0.30*	−1.65	−5.44*
Central European low (TM)	TM	−1.02	−2.80	−0.44	−1.19

central European ridge (BM) and east types (HFA, HNFA, HNFZ). For all these CT, a negative radiation balance under a dominant high-pressure system and/or cold advection of air from the north to east is typical. Note that some of the types conducive to cold waves in winter are favorable to heat waves in summer, namely, the central European high and east types, and that the BM and HFA types are among the four most frequently occurring CT in both heat and cold waves.

The differences between winter average temperature anomalies on days 1–5 and >5 of sequences classified with the same CT are significant for the north types, with days >5 being considerably cooler (by 2.7 and 3.2 °C on average; Table II). The opposite pattern (days >5 being warmer by about 0.5 °C), but much less pronounced and insignificant, appears for the central European high types since warm advection is typical during the late stages of these CT. For east types conducive to cold waves, the differences between the average temperature anomalies on days 1–5 and >5 attain both signs and are insignificant except for HNFZ. The days >5 are colder for HNFZ and HFA while they are warmer for HNFA. A likely explanation for this takes into account the counterbalancing effects of warm advection and radiative cooling during late stages of these CT. The influence of increased persistence of the atmospheric circulation on cold waves in winter is thus less clear than on heat waves in summer. For north types, the more persistent conditions would lead to more severe and longer cold waves, while for other CT conducive to cold waves, the likely consequence is longer cold waves but with slightly less pronounced negative temperature anomalies. Nevertheless, the increased persistence of CT may have contributed to the fact that a decrease in the severity of cold waves has not been observed, or has been weaker than the recent increase in the occurrence of heat waves, over most of Europe (Klein Tank *et al.*, 2002; Klein Tank and Koennen, 2003).

In both summer and winter, the main findings are insensitive to the particular delimitation of ‘long’ CT, since very similar results are achieved if the temperature differences between days 1–6 and >6, or days 1–4

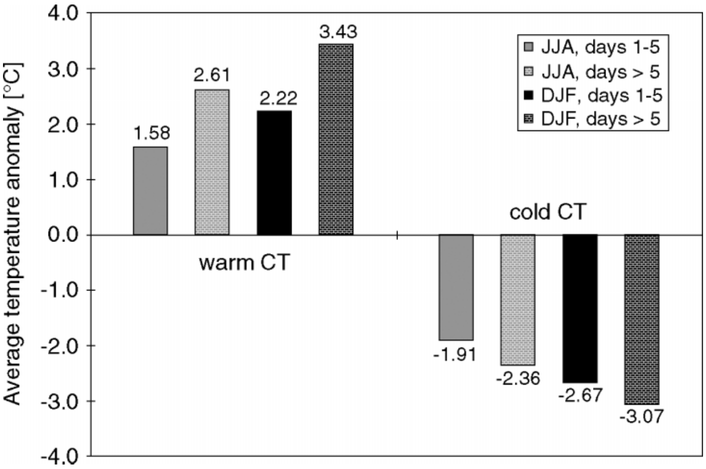

Figure 3. Average temperature anomalies in Prague on days 1–5 and >5 in warm and cold circulation types (CT) in summer and winter. Warm (cold) CT are defined as types with temperature anomalies averaged over all the days of their occurrence ≥1.0 °C (≤ − 1.0 °C).

and >4 of sequences classified with the same CT are examined.

Figure 3 demonstrates the overall tendency of 'warm' CT (defined here as types with temperature anomalies averaged over all days of their occurrence ≥1.0 °C) to be warmer on days >5 than 1–5, and of 'cold' CT (with average temperature anomalies ≤ − 1.0 °C) to be colder on days >5. The mean difference between days >5 and 1–5 exceeds 1.0 °C for warm CT both in summer and winter, and is smaller (about 0.4 °C) for cold CT in both seasons. Again, the results are not very sensitive to the particular delimitation of warm and cold CT and the same pattern is obtained if alternative thresholds of 0.5 °C/−0.5 °C, or 1.5 °C/−1.5 °C instead of 1.0 °C/−1.0 °C are utilized. This result also supports the finding that changes in the persistence of CT would likely affect more positive than negative temperature extremes in central Europe, and that the general tendency would be towards an increase in the severity of both under more persistent weather conditions.

DISCUSSION AND CONCLUSIONS

It is demonstrated that surface air temperature anomalies and the occurrence and severity of temperature extremes are linked to the persistence of atmospheric circulation patterns. Under a more persistent circulation, extreme temperature events tend to be more pronounced. Because of dynamical reasons, the consequences are more severe for warm than cold extremes. Further research should investigate the relationships between persistent circulation conditions and extreme temperature events in a more comprehensive way, involving temperature records from other sites over Europe and for all seasons.

In midlatitudes, changes in the atmospheric circulation are the main drivers of both short-term and long-term fluctuations of many surface climatic variables, including air temperature and extreme temperature events (e.g. Domonkos *et al*., 2003; Yiou and Nogaj, 2004). When evaluating links between the atmospheric circulation and surface climate, the persistence of the circulation types should be taken into account together with their frequency. Average anomalies of the surface climatic variables observed in the late stages of persistent occurrences of a particular circulation type may be significantly different from those in the early stages and in less persistent occurrences. This is shown to be the case here for surface air temperature, but it may be the case with other variables too.

Over central Europe, the intensification due to a higher persistence of circulation patterns would likely be more important for warm than cold temperature extremes. It is very likely that the recently observed increases in the frequency and severity of heat waves over Europe (Beniston, 2004) are partly linked to the enhanced persistence of the atmospheric circulation. This point deserves further investigation, particularly within the 'global warming' perspective. If climate change leads to a decrease in the baroclinicity of the troposphere over the midlatitudes and a northward shift of the North Atlantic–European storm tracks (Schubert *et al*., 1998; Knippertz *et al*., 2000; Geng and Sugi, 2003; Zhang *et al*., 2004), which are likely to support more persistent circulation patterns over central Europe, its impacts on the occurrence and severity of temperature extremes may be exacerbated.

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