TRENDS OF EXTREME TEMPERATURES IN EUROPE AND CHINA BASED ON DAILY OBSERVATIONS

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Abstract. Ten of the longest daily temperature series presently available in Europe and China are analysed, focusing on changes in extremes since pre-industrial times. We consider extremes in both a relative (with respect to the time of year) and an absolute sense. To distinguish changes in extremes from changes affecting the main part of the temperature distribution, a percentile smaller than 10 (and/or larger than 90) is recommended for defining an extreme. Three periods of changes in temperature extremes are identified: decreasing warm extremes before the late 19th century; decreasing cold extremes since then and increasing warm extremes since the 1960s. The early decreases and recent increases of warm extremes dominate in summer, while the decrease of cold extremes for winter persists throughout the whole period. There were more frequent combined (warm plus cold) extremes during the 18th century and the recent warming period since 1961 at most of the ten stations, especially for summer. Since 1961, the annual frequency of cold extremes has decreased by about 7% per century with warm extremes increasing by more than 10% per century but with large spatial variability. Compared with recent annual mean warming of about 2–3 °C/century, the coldest winter temperatures have increased at three times this rate, causing a reduced within-season range and therefore less variable winters. Changes in the warmest summer temperatures since 1961 exhibit large spatial variability, with rates of change ranging from slightly negative to 6 °C/century. More extensive station observations since 1961 indicate that the single site results are representative of larger regions, implying also that the extremes studied are the result of large-scale changes. Recent circulation changes in daily gridded pressure data, used as an indicator of wind speed changes, support the results by explaining some of the trends.

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1. Introduction

Climate can be defined as an ensemble of many weather phenomena. Climatologists often use the mean (conventionally the monthly and annual mean) of weather-related parameters to describe climate. The mean value, however, is not all the climate. Climatic changes might occur if certain aspects of the distribution of extreme values change, while the mean does not. Katz and Brown (1992), for example, show from a theoretical viewpoint that in a changing climate, extreme values are determined more by changes in variability than changes in the mean. Possible changes in extreme event frequency receive considerable attention along with the global warming, because extremes directly impact human society and the economy. For most societally sensitive extremes and related changes in their variability, an analysis based on daily data becomes necessary. This paper considers two aspects (relative and absolute values) of extreme temperatures on a daily basis. We do not consider spells of extreme days, periods which will likely have greater socio-economic and health impacts (Kalkstein et al., 1996; Wagner, 1999), than individual extreme days.

The first aspect is the frequency of extreme events in a relative sense. For each year, there are some unusually warm and cold days, defined with respect to the normal for the time of year. They reflect, in general, weather-timescale phenomena (e.g., cold air outbreaks, heat waves). To analyse such extremes, it is necessary to define a mean climatological distribution of temperature anomalies for each calendar day to judge how unusual the daily temperature anomaly is and then to count the number of extreme days there are in a given year. Jones et al. (1999) recently applied a 3-parameter-Gamma distribution to temperature anomalies for each calendar day based on the reference period 1961–1990. They defined extreme warm (cold) days as those being above the 90th (below the 10th) percentiles. The number of the extreme days each year provides a basis for studying possible changes in the frequency of extreme events. In the present paper, extreme events are defined by ranking all days and then determining appropriate threshold values according to the data's own distribution. This relates any anomalous conditions to a common reference and enables daily series from different climate regimes to be directly compared.

The second aspect is changes of absolute extremes. In this regard, we consider whether the climate distribution changes with time. The extremes of the distribution, i.e., the climate, in one period (a year or a season) may change compared with the next. This kind of change is not necessarily linked to weather-timescale disturbances. Indeed, more frequent extreme weather events do not necessarily change absolute extremes. For example, unusually cold events may occur earlier in a winter season but be no different in an absolute sense than normal. Extremes defined in a relative sense would increase but the event could just as easily be referred to as an early winter. Changes of absolute extremes will generally significantly impact society and ecology, whereas changes of relative extremes may not. For example, higher absolute winter or spring temperatures should cause an earlier start of the growing season; and for some groups of people with certain respiratory diseases, increases in the highest summer temperatures may increase mortality rates. Changes of extremes in an absolute sense may also differ substantially from any change in mean climate. For example, Yan and Yang (2000) found that the trends in the annual 10 lowest temperatures (about 3% of the annual record) in China during the last few decades were 5–10 times greater than trends in the annual mean. Conversely, trends in the 10 warmest days were opposite in some regions to those in the annual mean. It is clear, therefore, that any analysis of changes of extremes provides a more thorough description of any changes that are occurring. However, using the 10/90th percentiles for defining extremes is an arbitrary choice. In the present paper, a series of percentile limits are set to analyse changes of extremes in both a relative and an absolute sense. The results should better indicate which levels of climate extremes have been changing more significantly.

Compared with monthly or annual mean data, which are widely available globally (Jones, 1994; Hulme, 1992), daily data for climate research remain quite limited at regional scales. Comparative analysis between different regions is therefore helpful to provide a potentially more thorough view of possible recent changes. Europe and China are located at the western and eastern extremities of the Eurasian continent, with quite different climatic regimes. By comparing their changes in extremes, we may better understand if there are some typically regional or larger-scale changes occurring. Although the long-term daily data are quite limited, especially in China, the present paper reveals both some significant trends in the regional series of extreme temperatures during the instrumental era, and highlights series where additional homogeneity may be necessary.

Section 2 describes the daily data and the methods used to define the extremes. Section 3 analyses trends in the frequencies of relative and absolute daily extreme temperatures at the stations with long-term observations. Section 4 compares the patterns of changes of extreme temperatures from individual long-term stations with more spatially detailed regional networks during recent decades. Changes of extreme wind strength are also calculated, based on daily grid-point sea level pressure data, to see whether atmospheric circulation changes influence recent trends in extreme temperatures. Section 5 summarises the main findings of the study.

2. Data and Analysis Techniques

In recent years, there have been a number of efforts to collect daily data for climate research in both Europe and China. The eight longest daily temperature series in Europe and the two longest in China are analysed in this paper. Table I lists the sites and provides source details. More series giving better spatial coverage are available since the 1960s. Seven of the long-term European temperature series have been homogenized within the scope of the EU-funded IMPROVE project. An eighth, daily

Table I

The long-term station daily temperature series used in this paper

Station name	Location		Period of record	References
Uppsala	59.9° N	17.6° E	1741–1998	Bergström and Moberg, 2002
St Petersburg	60.0° N	30.3° E	1743–1996	Jones and Lister, 2002
Stockholm	59.3° N	18.1° E	1756–1998	Moberg et al., 2002
Milan	45.5° N	9.2° E	1763–1998	Maugeri et al., 2002
Central England	52.5° N	2.0° W	1772–1998	Parker et al., 1992
Padua	45.4° N	12.0° E	1774–1996	Cocheo and Camuffo, 2002
Cadiz	36.5° N	6.3° W	1821–1996	Barriendos et al., 2002
Brussels	50.8° N	4.4° E	1833–1998	Demarée et al., 2002
Shanghai	31.2° N	121.5° E	1873–1997	Yan et al., 2001a
Beijing	39.9° N	116.3° E	1915–1997	Yan et al., 2001a

Central England series has already been extensively studied (Parker et al., 1992; Jones and Hulme, 1997; Jones et al., 1999). The Beijing and Shanghai daily series have been recently homogenized (Yan et al., 2001a). The major adjustments of the Chinese series include a regional average urban bias correction based on previous studies (Portman, 1993; Wang et al., 1990) and corrections of biases induced by site changes. More extensive analyses of the series may indicate further adjustments to some of the sites used due to changes in observation times and the number of observations per day (Moberg et al., 2000; Yan et al., 2001b), particularly in the earliest years when complete station history information is often lacking.

The first step in the analysis is to define the annual temperature cycle. Using the whole period of record at each site the average temperature for each day is calculated. To produce a relatively smooth annual cycle the value for the central day is averaged with the two days either side, and then smoothed with an 11-term binomial filter. For each calendar day, the temperature anomalies (from the smoothed annual cycle) are ranked into ascending order and thresholds determined that correspond to unusually cold percentiles (3%, 5%, 10% and 20%, referred to as $\alpha\%$). Similarly, large percentiles such as 97%, 95%, 90% and 80%, noted as $\beta\%$, define the criteria for extremely warm anomalies. Figure 1 shows examples of the annual cycle of temperature for Uppsala and Beijing and the 3/97 and 10/90 percentile thresholds.

The temperature range between the α and β thresholds, beyond which the extreme anomalies are defined, is larger for Uppsala than Beijing. In the case of $\alpha/\beta = 10/90$, this range can be up to about 15 °C during winter for Uppsala, but only 8 °C for Beijing. This indicates stronger interannual and/or inter-diurnal variability of weather at Uppsala than Beijing. The larger range in winter implies greater temperature variability within the cold season. From $\alpha\beta = 10/90$ to

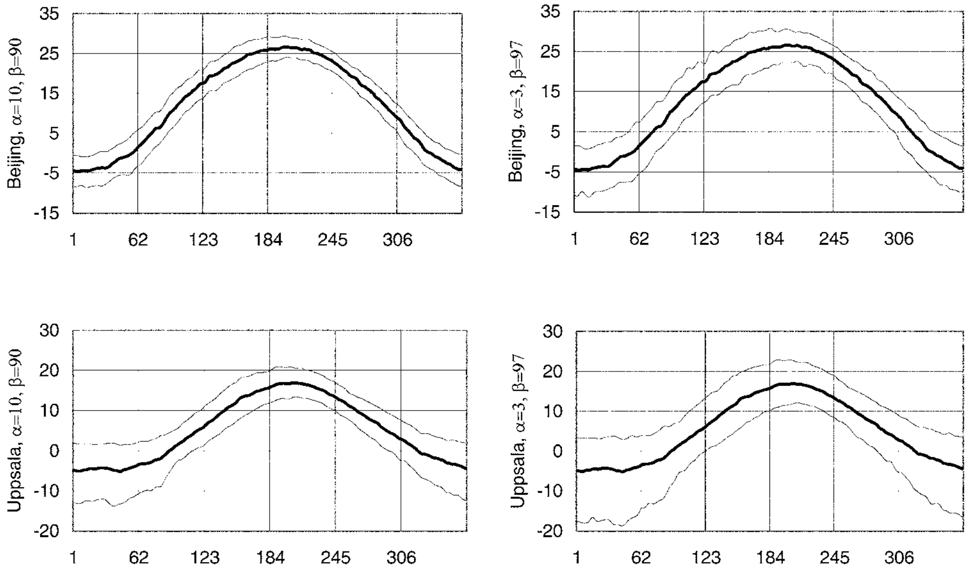

Figure 1. Annual cycle (thick) and the percentiles (thin) for defining relative extremes, based on all the available daily observations, for Uppsala (1741–1998) and Beijing (1915–1997). An 11-point binomial filter has also been applied to the percentile thresholds, which are plotted about the similarly smoothed annual cycle. Units: °C. 10/90 percentiles are on the left-hand side, with 3/97 percentiles on the right.

$\alpha\beta = 3/97$, the range is enlarged by about one third. The range between the high and low percentiles is least in autumn, implying a more stable season with lower interannual variability in both regions. Counts of the number of daily temperature values exceeding the percentile thresholds during a certain period, e.g., a year or a season, indicates the frequency of extreme events through time.

To consider changes of absolute extremes, we calculate the average of the coldest (warmest) records that occupy $\alpha\%$ $(1 - \beta\%)$ of the total records during a year or a season. The ranking this time is performed with the absolute temperatures. The absolute coldest (warmest) temperatures in a season are most likely to occur at certain times during a season particularly in the transition seasons. Analysis in the later section, therefore, concentrates on winter and summer. As Figure 1 shows, the annual cycle of temperature is larger in China (about 31 °C at Beijing) than in Europe (about 22 °C at Uppsala) so absolute values are more extreme in China. China also exhibits a sharper seasonal contrast with relatively abrupt transitions from winter to summer and vice versa. By analyzing changes of absolute extreme temperatures for different seasons, we may judge if there are some systematic changes in the annual cycle occurring in addition to longer timescale changes in the mean.

Extreme temperatures defined this way are likely to be related to changes in the atmospheric circulation. For example, decreasing extreme wind speed related to weaker winter cold outbreaks from Siberia might have led to a sharp rise of the absolute lowest temperatures in China (Yan and Yang, 2000). Wind estimates determined from pressure fields have also been shown to be closely related to changes of extreme temperatures over the British Isles (Hulme and Jones, 1991; Jones et al., 1999). While direct wind observations may be easily biased by local environmental changes, the wind indices deduced from pressure fields may better describe large-scale changes. In this paper, the U.K. Meteorological Office (UKMO) 5° latitude by 10° longitude daily grid-point sea-level pressure data series over Northern Hemisphere during 1966–1997 is used, to calculate large-scale wind strengths (Jenkinson and Collison, 1977; Hulme and Jones, 1991). Analyses of extreme wind strengths defined this way may help explain some of the extreme temperature changes.

For both relative and absolute extremes our method of estimation of the percentile thresholds is determined by the data. We do not explicitly assume that the daily temperature anomaly series follows any particular distribution. Changes in extremes, however, will be caused by changes in either the mean or the variance or both, unless the series is significantly skewed (i.e., significantly non-normal). These caveats should be borne in mind when the results of the analyses are discussed in the next two sections.

3. Results

3.1. TRENDS IN FREQUENCIES OF RELATIVE EXTREME TEMPERATURES

Linear trends of the annual frequencies of cold, warm and combined (warm plus cold) extreme temperature anomalies for different periods are listed in Table II. To compare trends across periods, the frequency is expressed as the number of days per 100 days, i.e., it can be considered as a percentage. Because we have used all the available daily observations to define the percentile limits for extremes, the long-term average level of the frequency of cold (or warm) extremes can be easily anticipated as α (or $1 - \beta = \alpha$), and that of the combined extremes to be twice this (i.e., 2α). Increases (decreases) in the combined extreme total, without any change in the mean, are indicative of an increase (decrease) in the daily temperature variance. Intramonthly standard deviation is another measure of daily temperature variability. It is not discussed here, but has been assessed for some of these records by Moberg et al. (2000).

The trends for different α values are compared with the trend of annual mean temperatures. Non-zero values indicate significant trends in each time series using Mann–Kendall's test with a significance level of 0.05 (Sneyers, 1990). Insignificant trends are marked with '+' and '–'. Linear trends for the six European stations with longer series are calculated from the start of the station records (see Table I), generally all around the middle 18th century. Trends since the starting year at Shanghai

Table II

Trends of annual frequencies of cold, warm and all extremes under different α (β, $\beta = 100 - \alpha$) values compared with that of mean temperatures for the different periods. Non-zero values are significant trends. Insignificant trends are marked with '+' and '–'. Trends in frequency are calculated as days per 100 days (percentage). Units of trend are °C/century for mean temperature and percentage/century for frequencies

	Since	18th century			1873			1915			1961		
	For	Cold	Warm	All	Cold	Warm	All	Cold	Warm	All	Cold	Warm	All
Uppsala	$\alpha = 3$	–0.9	–	–1.0	–2.0	1.8	–	–	+	+	–	11	8.2
	$\alpha = 5$	–1.2	–	–1.4	–2.9	2.5	–	–	+	+	–	15	12
	$\alpha = 10$	–1.4	–	–1.8	–4.6	3.7	–	–	+	+	–	20	+
	$\alpha = 20$	–1.3	–	–2.1	–7.0	4.8	–	–	+	–	–	23	+
	Mean			0.2			0.8			+			2.9
Stockholm	$\alpha = 3$	–1.1	–	–1.2	–1.6	1.8	0	–	+	+	–	9.3	+
	$\alpha = 5$	–1.4	–	–1.6	–2.6	2.7	0	–	3.4	+	–	14	+
	$\alpha = 10$	–1.7	–	–2.1	–4.3	3.9	–	–	4.7	+	–	17	+
	$\alpha = 20$	–1.5	–	–2.3	–6.1	5.9	–	–	+	+	–	+	+
	Mean			0.2			0.7			+			+
St Petersburg	$\alpha = 3$	–1.2	1.4	+	–1.9	2.3	+	–	3.5	+	–	+	+
	$\alpha = 5$	–1.6	2.0	+	–2.7	3.5	+	–	4.4	+	–	+	+
	$\alpha = 10$	–2.5	2.9	+	–4.2	5.3	+	–	6.3	+	–	20	+
	$\alpha = 20$	–3.7	3.9	+	–6.4	7.7	+	–	+	+	–	+	+
	Mean			0.7			1.1			1.3			3.3
Central England	$\alpha = 3$	–1.1	1.0	–	–2.4	1.8	–	–2.0	+	0	–	12	9.3
	$\alpha = 5$	–1.5	1.0	–0.5	–3.6	2.6	–	–2.9	+	–	–7.3	16	+
	$\alpha = 10$	–2.3	1.4	–0.9	–5.8	4.0	–	–5.0	+	–	–	24	14
	$\alpha = 20$	–3.2	1.9	–1.3	–8.2	5.8	–	–7.5	+	–	–19	31	+
	Mean			0.3			0.7			0.6			2.4
Milan	$\alpha = 3$	–0.7	+	–	–	+	+	+	+	+	–	8.2	7.5
	$\alpha = 5$	–	0.9	+	–	2.3	+	+	+	+	–	13	+
	$\alpha = 10$	–1.5	1.6	+	–	3.5	+	–	+	+	–	19	+
	$\alpha = 20$	–2.4	3.0	+	–	5.9	3.2	–	+	+	–	31	16
	Mean			0.3			0.4			+			2.1

Table II

(Continued)

	Since	18th century			1873–			1915–			1961–		
	For	Cold	Warm	All	Cold	Warm	All	Cold	Warm	All	Cold	Warm	All
Padua	$\alpha = 3$	–1.4	–	–1.6	–2.4	–	–2.5	–2.4	–1.7	–4.1	–	+	+
	$\alpha = 5$	–2.0	–	–2.2	–3.6	+	–3.3	–3.7	–	–5.8	–	+	+
	$\alpha = 10$	–3.0	+	–2.8	–5.7	+	–4.0	–5.9	–	–7.7	–	12	+
	$\alpha = 20$	–3.7	+	–2.9	–7.5	3.6	–3.9	–7.2	–	–7.9	–	+	+
	Mean			0.2			0.5			+			1.2
Cadiz	$\alpha = 3$				0.9	1.7	2.6	1.9	+	5.0	–	12	+
	$\alpha = 5$				+	2.4	3.9	3.7	+	7.5	–	+	+
	$\alpha = 10$				+	3.3	5.2	+	+	8.0	–	+	+
	$\alpha = 20$				+	+	5.1	+	+	8.0	–	+	+
	Mean						+			+			+
Brussels	$\alpha = 3$				–2.7	3.7	+	–2.9	3.9	+	–	12	9.5
	$\alpha = 5$				–3.9	5.1	+	–3.9	5.3	+	–	16	12
	$\alpha = 10$				–6.4	7.4	+	–5.8	7.1	+	–	23	15
	$\alpha = 20$				–9.2	9.6	+	–8.4	8.8	+	–	26	+
	Mean						1.1			1.0			2.6
Shanghai	$\alpha = 3$				–1.0	1.2	+	–	+	+	–	+	+
	$\alpha = 5$				–1.4	1.8	+	–	+	+	–	+	–
	$\alpha = 10$				–2.6	3.0	+	–	+	+	–15	+	–
	$\alpha = 20$				–4.7	4.8	+	–	+	+	–29	22	–
	Mean						0.5			+			2.3
Beijing	$\alpha = 3$							–	–	–2.4	–	+	+
	$\alpha = 5$							–	–	–2.5	–	+	+
	$\alpha = 10$							–	–	–3.4	–	13	+
	$\alpha = 20$							–	+	–3.3	–	23	+
	Mean									0.5			2.1

(1873) and Beijing (1915) are also calculated for the eight European stations for comparison and to study trends over the last 100 years or so. Trends since 1961 are calculated because of recent unprecedented warming trends and to compare later with more extensive station data for Britain and northern China.

To better understand and discuss the quantitative trends in Table II, we illustrate in Figure 2 the annual mean temperatures together with the frequencies of warm, cold and combined extremes for $\alpha = 5$. When we refer here and later to α thresholds the β threshold is complementary (i.e., 5/95). In Figure 2, the frequency of cold extremes is multiplied by –1, conventionally letting decreases of cold extremes imply warming. An 11-year binomial filter is applied to highlight trends.

We begin discussing trends at Uppsala and Stockholm, due to their being only 65 km apart. Similarity of trends is to be expected given their closeness, but knowing the complexities of the homogenization procedure (Bergström and Moberg, 2002; Moberg et al., 2002) the agreement is gratifying to see. At these two sites there was only a small trend (0.2 °C/century) in annual mean temperature since the 18th century, because of some warm episodes during that century which were similar to today's levels. Significant warming of about 0.7–0.8 °C/century occurred since the late 19th century. Recent warming (since 1961) has become as large as 2.9 °C/century at Uppsala, but not significant at Stockholm due to large interannual variations. Decreasing trends of 1.0–2.3% per century prevailed in the frequencies of combined extremes since the 18th century. Decreasing trends of warm extremes became apparent during the 19th century following their large frequencies in the later decades of the 18th century. Reduction of cold extremes has occurred since the late 19th century, while warm extremes began to increase by a lesser amount. The frequency of the combined extremes decreased until the 1960s (Figure 2), when a sharp increase of warm extremes began. The large increasing trend of warm extremes during recent decades has been about 10–20% per century. For most periods, the most extreme part ($\alpha = 3$) has made the greatest contribution. For example, at Uppsala since the 18th century, the frequency of combined extremes defined by $\alpha = 3$ decreased by 1.0% per century, that between $\alpha = 3$ and 5 contributed an additional 0.4% and that between $\alpha = 10$ and 20 an additional 0.3%. At Stockholm for 1961–1998, warm extremes defined by $\alpha = 3$ increased by 9.3% per century, those between $\alpha = 3$ and 5 contributed an additional 4.7% but those between $\alpha = 10$ and 20 contributed slightly negatively. This implies that, to distinguish more clearly extreme trends from those of average temperature, a value of α smaller than 10 is necessary to define extreme events. Trends are more significant for an α value of 5 than 10.

Changes at the other European stations are qualitatively similar: slight trend during the early period, warming since the late 19th century and enhanced warming since 1961. Although Table II shows a linear trend of as large as 0.7 °C/century at St Petersburg since the 18th century, Figure 2 clearly shows that the warming trends generally began in the late 19th century, before which temperature levels were relatively constant. The warming rate since 1873 ranged from 0.4 °C/century (Milan)

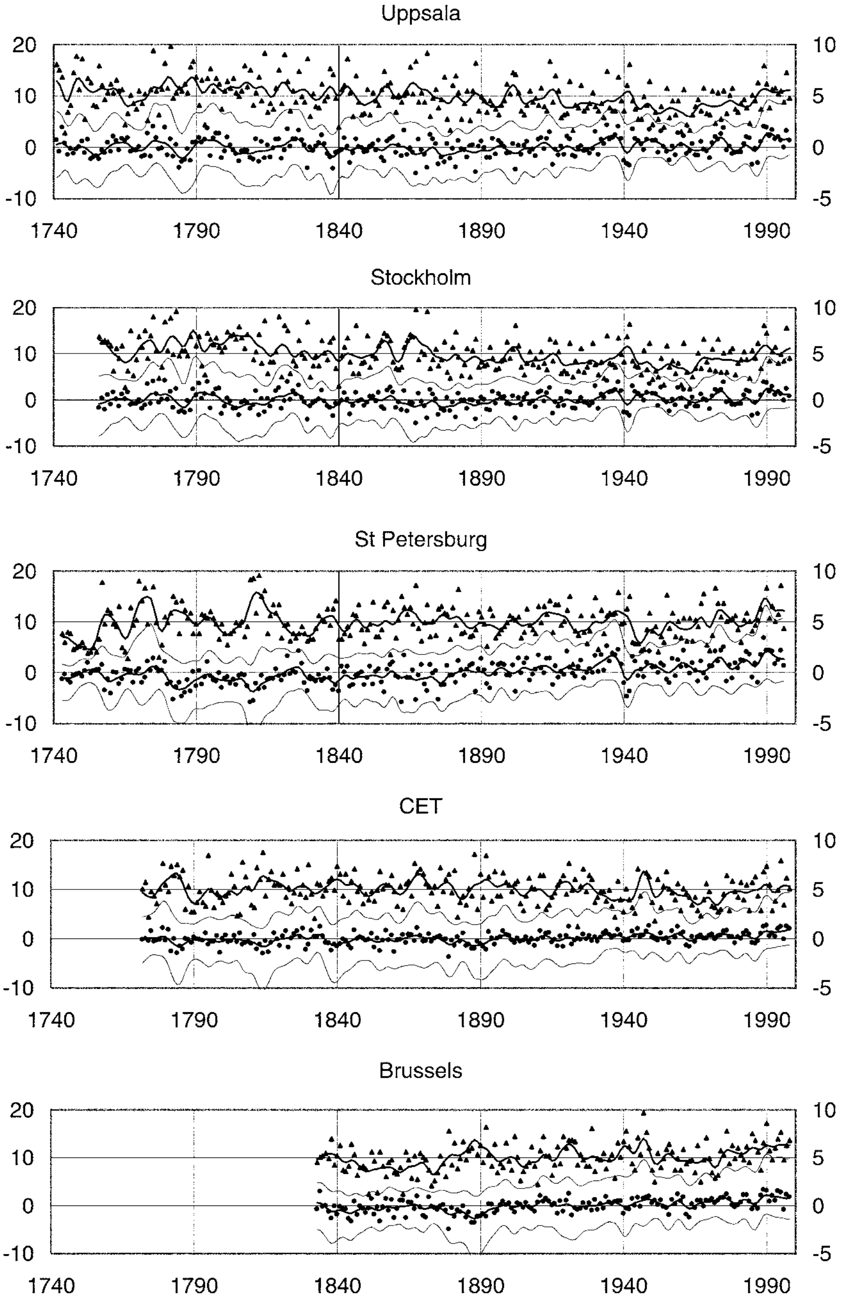
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Figure 2a.

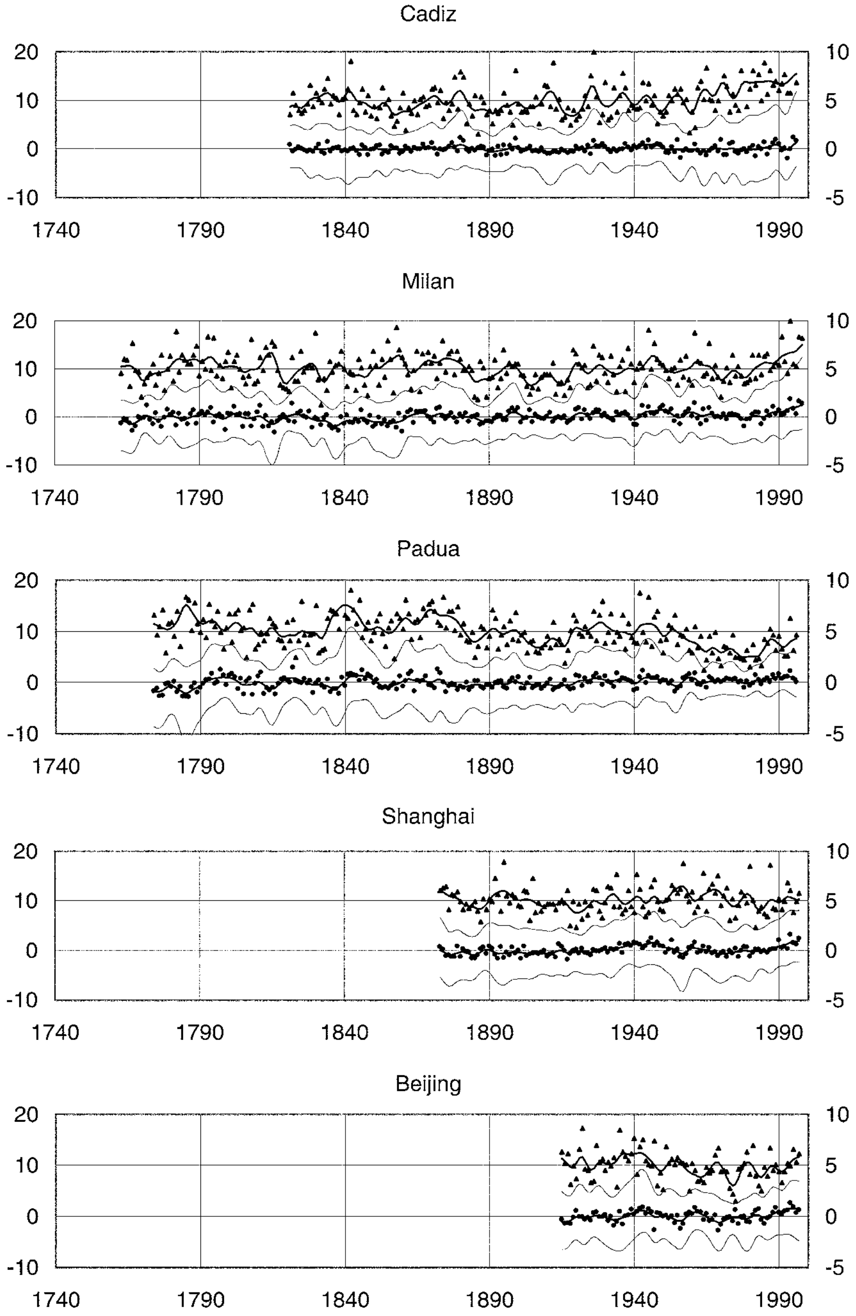


Figure 2b.

Figure 2. Smoothed annual temperature anomaly series (lower thick) compared with the frequency of cold extremes (lower thin), warm extremes (upper thin) and all extremes (upper thick) for $\alpha = 5$. The left coordinate is for frequency (days per 100 days) and the right for temperature anomaly (°C). The dots/triangles (anomalies/counts) around the thick lines are raw values. For clarity only, raw frequency counts of warm and cold extremes are not shown. The frequency of cold extremes is multiplied by –1.

to 1.1 °C/century (St Petersburg and Brussels) and that since 1961 has increased to between 1.2 °C/century (Padua) and 3.3 °C/century (St. Petersburg). The warming rate at St. Petersburg is greater, perhaps due to its more continental location. During the early period, decreasing trends of extremes were more dominant. Increasing warm and decreasing cold extremes (except Cadiz) were clear, in general, since the late 19th century. The exceptional increases of cold extremes at Cadiz since 1873 and 1915 are mainly due to large frequencies of cold extremes during the 1950s–1980s (Figure 2). For the period since 1961, increasing warm extremes became dominant. Although different stations have different details of changes in extremes, all the European stations show a sharp increase of warm extremes since 1961, with a rate about 10% per century or even larger. Recent warming in Europe has, therefore, been more due to an increase of extremely warm weather than to a decrease of extremely cold weather.

The series for Shanghai and Beijing also show warming trends which enhance recently, 0.5 °C/century for whole period and about 2 °C/century since 1961, relatively parallel to those in Europe. There is no significant trend in the frequency of combined extremes at Shanghai, because the decrease of cold and increase of warm extremes almost compensates. The decrease of cold extremes is clearer since 1961. Decreases of combined extremes of about 2.4–3.4% per century occurred at Beijing since 1915. This decreasing trend has reduced since 1961 when warm extremes increased in frequency. Large frequencies of cold extremes during the 1950s–1970s can also be found at Shanghai (Figure 2), as at Cadiz. Considering their both being in the lower-mid-latitudes, this feature may be natural. Taken together, the records from China parallel to a large extent those of Europe.

In summary, warming trends were not evident until the late 19th century. Beginning with the early cooling trend, a decreasing trend in the frequency of extremes is evident for most of the stations. The decrease of extremes continued till the 1950s, when a strong warming trend started. This latest warming trend has been accompanied by an increase of extremely warm days at most of the stations.

In order to study the seasonal details, Table III lists different seasonal values for the changes in frequencies of extremes from the 5/95 percentile limits, compared with the trends in mean temperature. Seasons are defined as usual (winter denotes December–February, etc.). Figure 3 compares the winter and summer series. Seasonal series are more variable from year to year than for annual values. Consequently, some large trends during recent decades are not significant using Mann–Kendall's test. From the seasonal series, some strange changes may be more easily considered as potentially due to inhomogeneities. For example, Cadiz exhibits very small frequencies of extremes for summer during the 1850s–1900s; Milan and Padua show totally different trends in extremes for winter during recent decades (Figure 3). We do not consider these further, but refer the reader to Barriendos et al. (2002), Maugeri et al. (2002) and Cocheo and Camuffo (2002). The results highlight the need to consider the types of analyses that will be performed on daily and monthly temperature series once they have been homogenized.

Table III

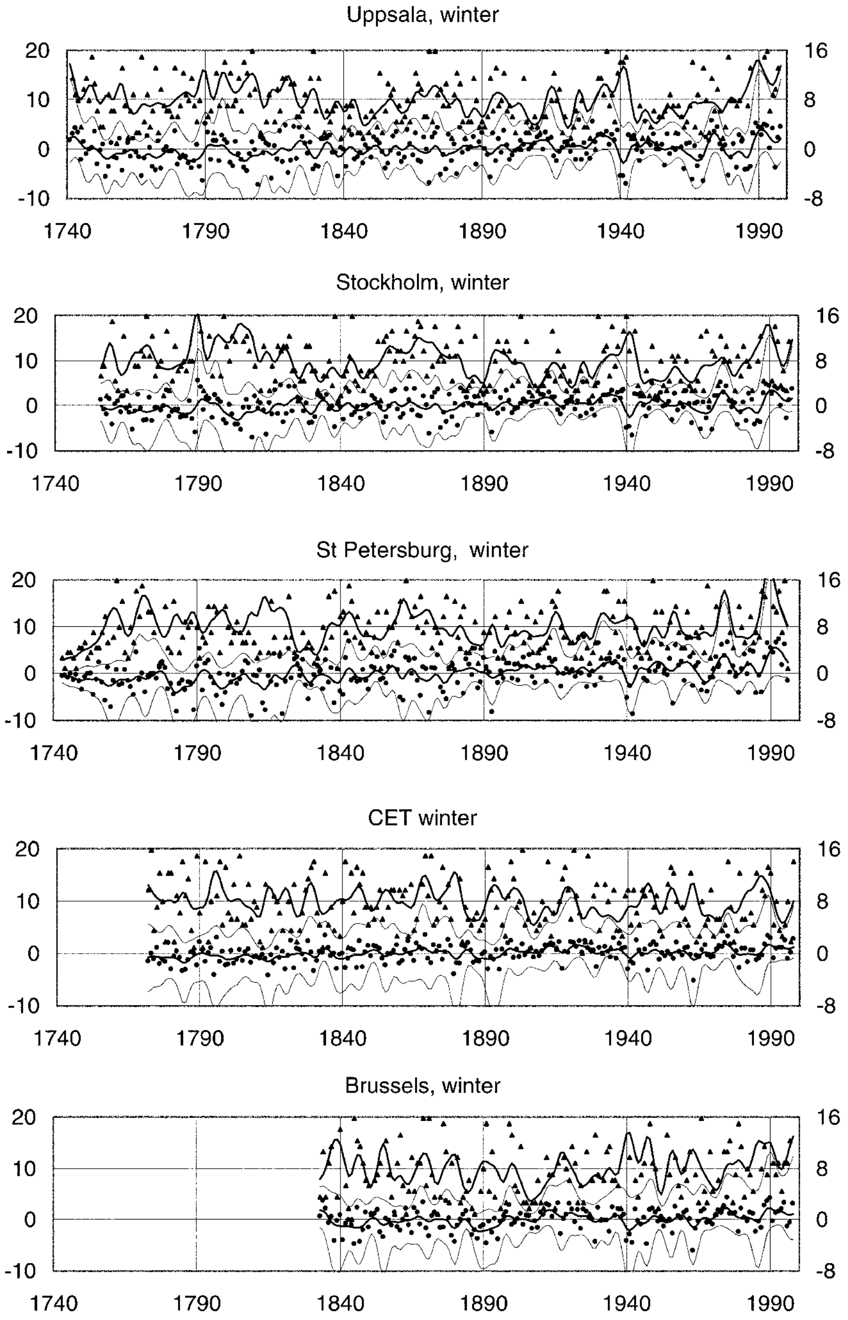
Trends in seasonal mean temperature (M) and frequencies of cold (C), warm (W) and combined (A) extremes ($\alpha = 5$, $\beta = 95$) since the years as stated. Non-zero values indicate significant trends. Insignificant trends are marked with '+' and '–'. Units are °C/century for mean and percentage/century for frequency

	Since	18th century				1873				1915				1961			
	For	C	W	A	M	C	W	A	M	C	W	A	M	C	W	A	M
Uppsala	Win	–	+	–0.4	0.5	–	+	+	+	0.9	+	+	+	–	+	+	+
	Spr	–2	+	–1.9	0.3	–	+	–	1.3	–	+	+	1.2	–	+	+	+
	Sum	0.4	–1.7	–1.3	–0.5	–	+	–	0.6	–	+	+	+	–	+	+	+
	Aut	–1.6	–0.3	–1.9	0.2	–4.2	+	–2.3	0.8		+	–	+	–	+	+	–
Stockholm	Win	–	+	–1.0	0.6	–	+	+	+	1	+	+	+	–	+	+	+
	Spr	–	+	–1.3	0.3	–	+	+	1.2	–	+	+	1.1	–	+	+	+
	Sum	0.4	–1.3	–0.9	–0.5	–	+	+	+	–	+	+	+	–	+	+	+
	Aut	–2	–1	–3.1	0.2	–	+	–2.2	0.8	–	+	–	+	–	–	–	–
St Petersburg	Win	–2.2	2.8	+	1.2	–	+	+	1.5	–	+	+	+	–	+	+	+
	Spr	–	+	+	0.9	–	6.5	+	2.1	–	11	+	2.9	–	36	29	6.3
	Sum	–	+	+	+	–	–	–	+	1.4	–3.6	–	–	–	–	–	+
	Aut	–1.7	1.8	+	0.5	–	+	–	0.8	–	+	+	+	–	-	–	–
Central England	Win	–	+	–0.7	0.5	–	+	–	+	1.4	+	+	+	–	+	+	+
	Spr	–	+	–1.3	+	–4.2	+	–1.5	0.7	–	+	–	+	–	+	+	+
	Sum	–	+	+	0	–	+	0	0.6	–	+	+	+	–	+	+	2.8
	Aut	–2	+	–	0.5	–4.9	+	–2.1	1	–	+	–	1.2	–	+	+	+
Milan	Win	–	+	–	0.7	–	+	+	0.9	–	+	+	+	–	+	+	+
	Spr	–	+	+	+	–	+	+	+	1.7	+	9	+	–	+	+	+
	Sum	0.4	0	+	0	1.6	+	+	–	1.7	+	+	+	–	+	+	3.4
	Aut	–	+	–	0.3	–	+	–	+	–	–	–	+	3.4	–	+	–

Table III

(Continued)

	Since	18th century				1873				1915				1961			
	For	C	W	A	M	C	W	A	M	C	W	A	M	C	W	A	M
Padua	Win	–	–	–2.6	0.3	–	–1	–4.8	+	–	–2.1	–9.2	+	–13	+	–	+
	Spr	–2.4	+	–2.1	0.3	–4.7	+	–3.3	0.6	–	–	–3.9	+	–	+	–	+
	Sum	–	–	–1.8	0.2	–	+	–	0.6	–	+	–	0.7	–	+	+	2.4
	Aut	–	–0.3	–2.3	+	–	–0.4	–4.7	+	–	–6.1	–9.8	+	6.1	+	+	–
Cadiz	Win					–	+	+	+	–	+	+	+	+	+	+	+
	Spr					+	+	+	+	4.1	+	+	+	+	+	+	+
	Sum					4.6	+	+	–	6.7	+	+	–	–	+	+	+
	Aut					0.8	+	+	+	4.5	+	11	–	–	+	+	+
Brussels	Win					–	5	+	1.1	–	+	+	+	–	+	+	+
	Spr					–4.8	5	+	1.1	–	+	+	+	–	+	+	+
	Sum					–4.4	6	+	1.0	–	+	+	1.3	–	25	+	3.6
	Aut					–4.7	4.2	–	1.2	–	+	–	1.3	8	+	+	–
Shanghai	Win					–	+	+	0.5	–	–	–4	+	–19	+	–15	4.4
	Spr					–	+	–	+	+	+	+	0	–	+	–	+
	Sum					–	+	+	+	2.4	+	+	0	7.1	+	+	+
	Aut					–	3.6	+	0.8	–	+	+	0.7	–	–	–	+
Beijing	Win									–	+	–	1.6	–	20	+	5.9
	Spr									–	–	–	+	–	+	+	+
	Sum									+	–4.7	–	–	9.1	–	+	–
	Aut									–	–3.5	–4.1	+	+	+	+	+


Uppsala, winter
Stockholm, winter
St Petersburg, winter
CET winter
Brussels, winter
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-8
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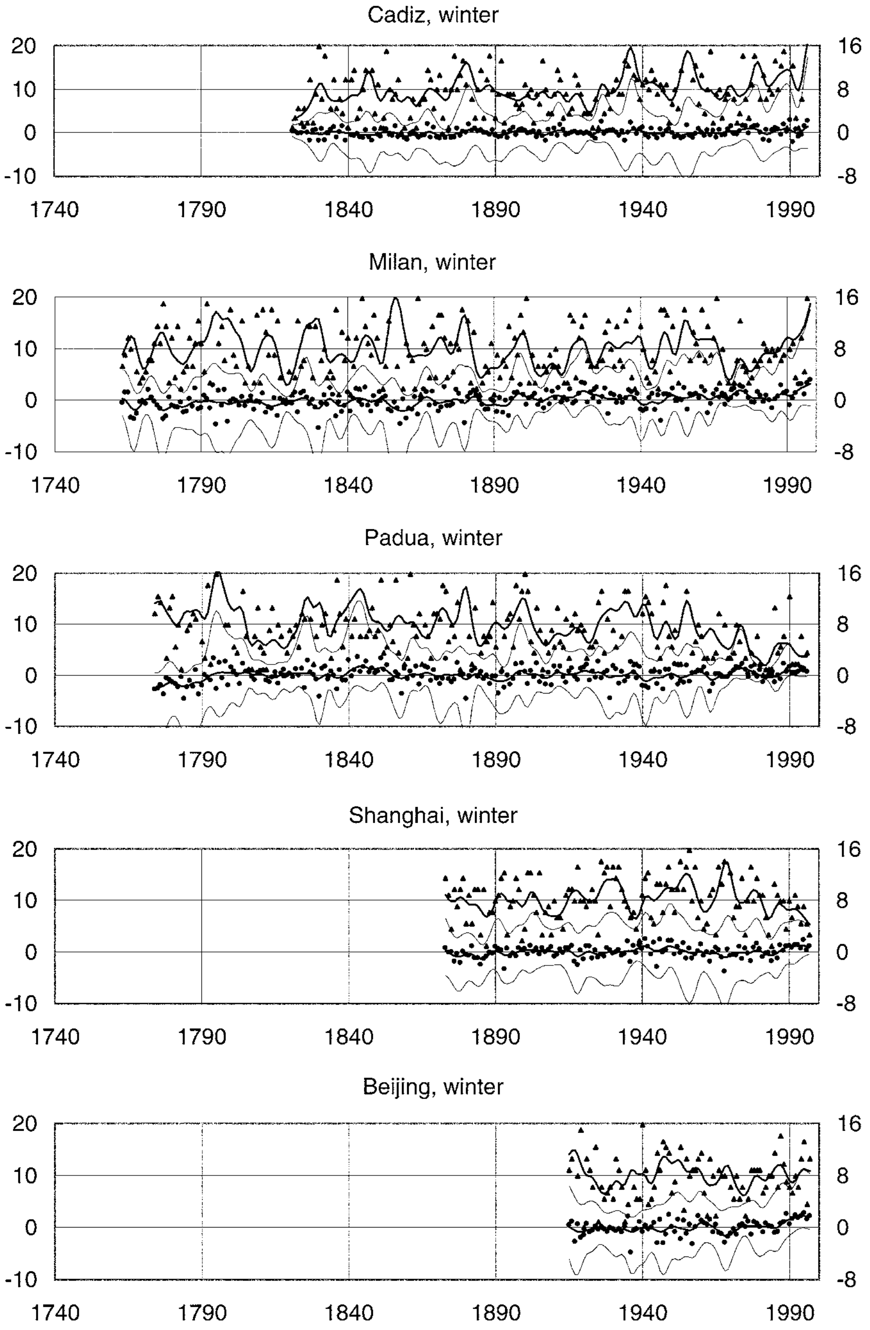
1940
1990

Figure 3a.


Cadiz, winter
Milan, winter
Padua, winter
Shanghai, winter
Beijing, winter
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16
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-8
1740
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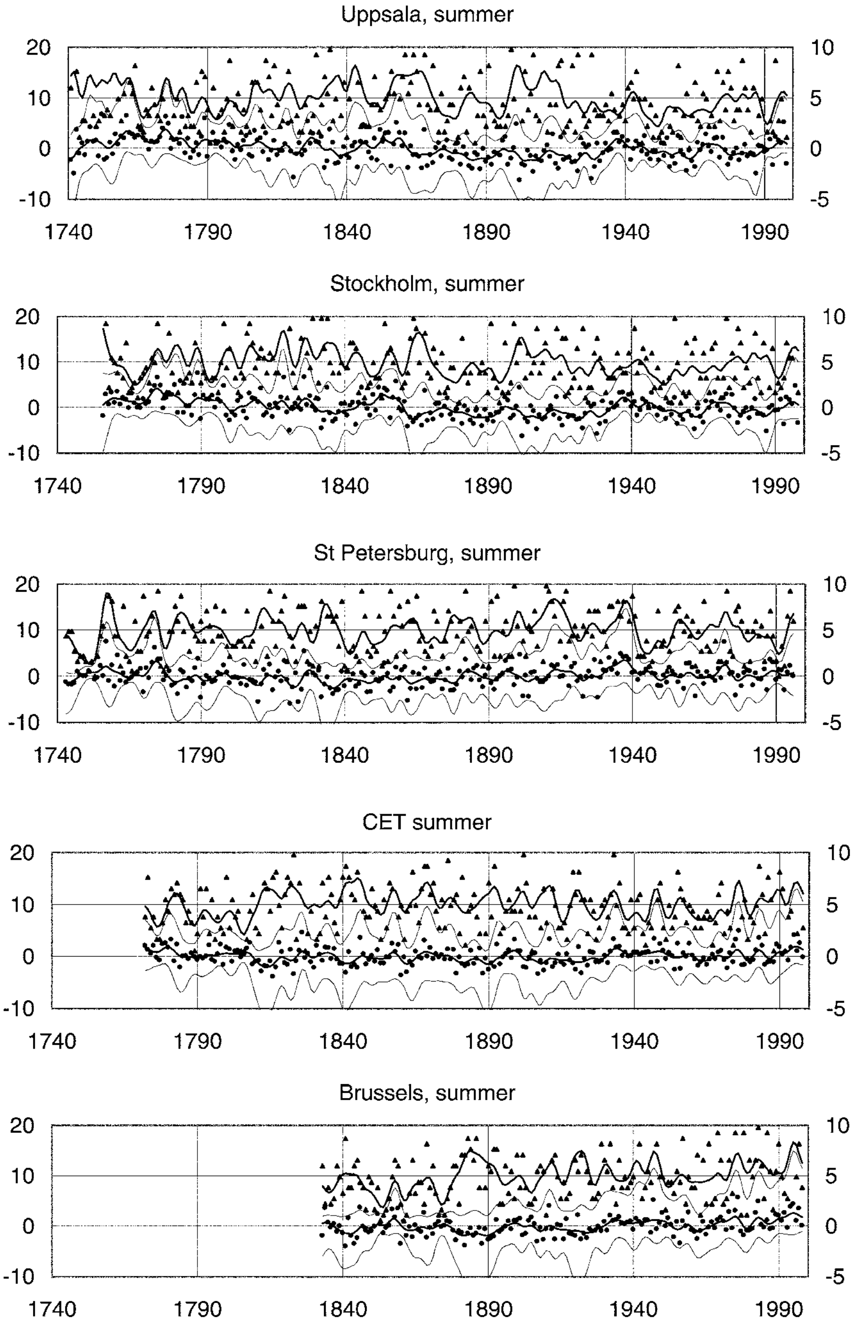
1890
1940
1990

Figure 3b.


Uppsala, summer
Stockholm, summer
St Petersburg, summer
CET summer
Brussels, summer
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5
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-5
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1790
1840
1890
1940
1990

Figure 3c.

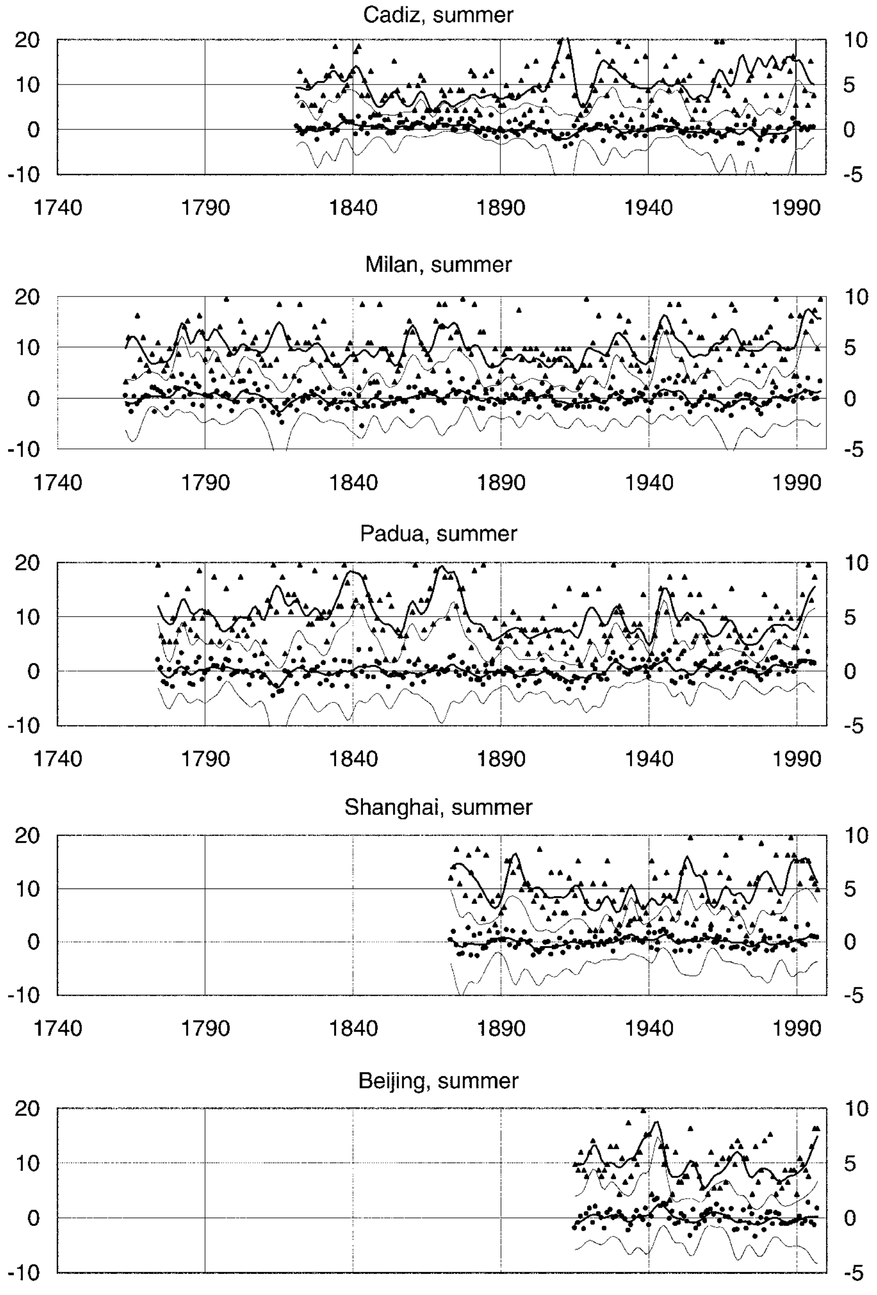


Figure 3d.

Figure 3. As Figure 2 but for the winter and summer seasons.

Despite these issues, we recognize some general trends that are potentially large scale in character. While warming trends dominate for most cases, cooling trends of about 0.5 °C/century since the middle of the 18th century occurred during summer for Scandinavia. As Figure 3 shows, this summer cooling trend persisted until the early part of the 20th century. For other seasonal and regional cases, the early cooling trends appear weak partly because the recent warming dominates the trend for the whole series. Decreasing trends of extremes since the 18th century have prevailed more than increasing trends. We infer that cooling trends (especially in summer) and decreasing extremes might form some natural background level prior to the warming of the 20th century.

Since the late 19th century, warming trends, larger than 0.5 °C/century, prevailed almost everywhere for all seasons. These warming trends have tended to be accompanied by decreases of cold extremes and increases of warm extremes, for almost all seasons and regions. Exceptions are St Petersburg which shows a decrease of warm extremes for summer, Padua exhibiting decreases of warm extremes for autumn and winter, Milan having an increase of cold extremes for summer and Cadiz showing increases of cold extremes through spring to autumn. The Cadiz case probably indicates inhomogeneities of some form in the daily data.

Since 1961, seasonal warming dominates over cooling, but significant rates, ranging between 2 and 7 °C/century, only occur at St Petersburg for spring, Central England, Milan, Padua and Brussels for summer and Shanghai and Beijing for winter. European sites exhibit slight cooling during autumn except Central England and Cadiz. During winter and spring, warm extremes increase more sharply than cold extremes decrease at most stations, resulting in an increase of combined extremes. However, Padua and Shanghai show more notable decreases of cold extremes in winter and spring, implying that the warming in these southern regions during cold seasons is more due to decreasing or weaker cold outbreaks from northern areas. For summer, Beijing and Shanghai show significant increases of cold extremes. For autumn, Milan, Padua and Brussels show significant increases of cold extremes. This may imply that the warm seasons have become more variable at these sites during recent decades (see also Yan et al., 2001b). For most of the seasonal cases, however, trends in frequencies of extremes are insignificant due to large interannual variations.

In summary, there were warm episodes and more frequent extremes during the 18th century, which led to decreasing trends in mean temperature (especially for summer) as well as a reduction in the frequency of extremes in the 19th century. Similar trends are apparent at all five sites, giving us confidence that they are climatic and not due to instrumental or site problems. Warming dominates since the late 19th century, while the frequency of combined extremes continued to decrease up to as late as the 1960s. The large warming since 1961 has been accompanied by increasing frequencies of warm extremes at most sites for winter and spring, except for the southern locations such as Shanghai and Padua, where decreases of cold extremes are more notable than increases of warm extremes for both winter and spring. A number of the sites including Beijing, Shanghai, St Petersburg, Milan, Padua and Brussels also show increasing cold extremes for summer and/or autumn since 1961.

3.2. TRENDS IN SEASONAL ABSOLUTE EXTREME TEMPERATURES

For each season, the lowest (highest) temperature in an absolute sense is expressed here as the mean of the $\alpha\%$ lowest (highest) records chosen from the complete records of each season. Linear trends in these seasonal absolute extreme temperatures are listed in Tables IV and V. To make the tables succinct, we mark with + (–) the insignificant positive (negative) trends. Non-zero values indicate significant trends under Mann–Kendall's test with a significance level of 0.05. The case for $\alpha = 20$ is not included in these tables because, as mentioned previously, this large percentile is less suitable for defining extremes. Figure 4 shows the time series for winter and summer at each location.

We discuss the lowest seasonal temperatures first. For the whole period back to the 18th century, all six series with data exhibit significant increasing trends (ranging between 0.4 and 2.3 °C/century) in the lowest seasonal temperatures, except for summer. Cold winters in the late 18th to early 19th century have led to an overall rise of the lowest temperature in Europe, although the earliest records in the mid-18th century at Uppsala and St Petersburg show earlier milder winters (Figure 4), nearly comparable to recent levels. For summer, cooling trends (about –0.3 to –0.5 °C/century) prevail, except for Padua and St Petersburg where slight positive trends are evident due to recent warmer records.

Between the late 19th century and the present, increases of the seasonal lowest temperatures became more prevalent even for summer. Exceptions include Milan still exhibiting strong cooling and Cadiz with slight cooling trends for summer. Trends became less significant in the later, shorter periods principally due to large interannual and interdecadal variations.

Since 1961, some unprecedented trends have occurred. For example, the trend in the lowest spring temperature at St Petersburg reaches values as large as 15 °C/century. This is partly due to the short time window over which the linear trend is calculated. However, warming trends in the lowest temperature have prevailed during winter and spring, though only significant at St Petersburg, Central England, Brussels and Beijing for spring and at Padua, Shanghai and Beijing for winter. The large warming rates for the lowest winter and spring temperatures at Beijing and Shanghai (about 6–7 °C/century) imply milder Siberian High airmasses in cold seasons during recent times. Cold air outbreaks from Siberia principally control the lowest cold season temperatures in surrounding areas such as northern China and eastern Europe.

In contrast, during the same recent decades, slight decreases in the lowest summer and/or autumn temperatures occur for Scandinavia, Central England, Milan, Padua and Beijing. Only Shanghai exhibits a significant increase in the lowest

Table IV

Trends in seasonal lowest temperatures (°C/century). Non-zero values indicate significant trends

	Since	18th century			1873			1915			1961		
	For $\alpha =$	3	5	10	3	5	10	3	5	10	3	5	10
Uppsala	Win	1.9	1.7	1.4	+	+	+	+	+	+	+	+	+
	Spr	1.5	1.3	1.2	2.9	2.8	2.5	+	3.3	3.0	+	+	+
	Sum	–	–0.3	–0.3	1.4	1.2	1.0	2.4	2.1	+	–	–	–
	Aut	1.0	0.9	0.7	2.2	2.0	1.6	+	+	+	+	+	+
Stockholm	Win	1.9	1.8	1.6	+	+	+	+	+	+	+	+	+
	Spr	1.6	1.4	1.2	2.7	2.5	2.2	+	2.9	+	+	+	+
	Sum	–0.4	–0.4	–0.4	1.0	0.9	+	1.9	+	+	–	–	–
	Aut	1.0	0.9	0.8	1.6	1.5	1.3	+	+	+	+	+	+
St Petersburg	Win	2.3	2.2	2.1	+	+	+	+	+	+	+	+	+
	Spr	1.9	1.7	1.5	3.4	3.4	3.3	6.5	6.5	6.1	+	15.0	13.0
	Sum	0.3	0.2	+	+	+	+	+	+	+	+	+	+
	Aut	1.2	1.0	0.8	+	+	+	–	–	+	+	+	+
Central England	Win	0.8	0.7	0.7	+	+	+	–	–	–	+	+	+
	Spr	0.5	0.5	0.5	1.2	1.1	1.0	+	+	1.3	6.2	5.8	5.1
	Sum	–	–	–	+	+	+	–	0	+	–	–	–
	Aut	0.7	0.6	0.6	1.0	1.0	1.0	+	+	+	+	+	+
Milan	Win	1.1	1.1	1.0	+	+	0.9	+	+	+	+	+	+
	Spr	0.5	0.5	0.5	+	+	+	+	+	+	+	+	+
	Sum	–0.5	–0.4	–0.3	–1.1	–1.0	–0.8	–1.7	–1.4	–	+	+	+
	Aut	0.5	0.5	0.5	1.2	1.2	1.1	+	+	+	–	–	–

Table IV

(Continued)

	Since	18th century			1873			1915			1961		
	For $\alpha =$	3	5	10	3	5	10	3	5	10	3	5	10
Padua	Win	0.8	0.8	0.7	1.1	1.1	1.1	2.4	2.2	2.0	+	5.1	5.1
	Spr	0.8	0.8	0.7	1.3	1.3	1.1	+	+	+	+	+	+
	Sum	+	+	0.2	+	+	+	–	–	–	–	–	0
	Aut	+	0.5	0.4	1.4	1.3	1.2	+	+	+	–	–	–
Cadiz	Win				+	+	+	+	+	+	+	+	+
	Spr				+	+	+	+	+	+	+	+	+
	Sum				–	–	–	–	–	–	+	+	+
	Aut				+	+	+	+	+	+	+	+	+
Brussels	Win				+	+	+	+	+	+	+	+	+
	Spr				1.5	1.5	1.4	1.8	+	+	6.5	6.3	5.6
	Sum				0.5	0.6	0.6	+	+	+	+	+	+
	Aut				1.7	1.5	1.2	1.7	+	1.8	+	+	+
Shanghai	Win				+	+	0.7	2.1	2.0	1.6	6.0	6.1	6.5
	Spr				+	+	0.7	+	+	+	+	+	+
	Sum				0	+	+	–	–	–	3.1	2.9	2.4
	Aut				+	+	1.0	–	–	+	+	+	+
Beijing	Win							3.3	3.1	2.8	7.3	6.6	6.5
	Spr							2.6	2.5	2.0	6.8	7.1	6.6
	Sum							+	+	+	–	–	–
	Aut							+	+	+	–	–	–

Table V

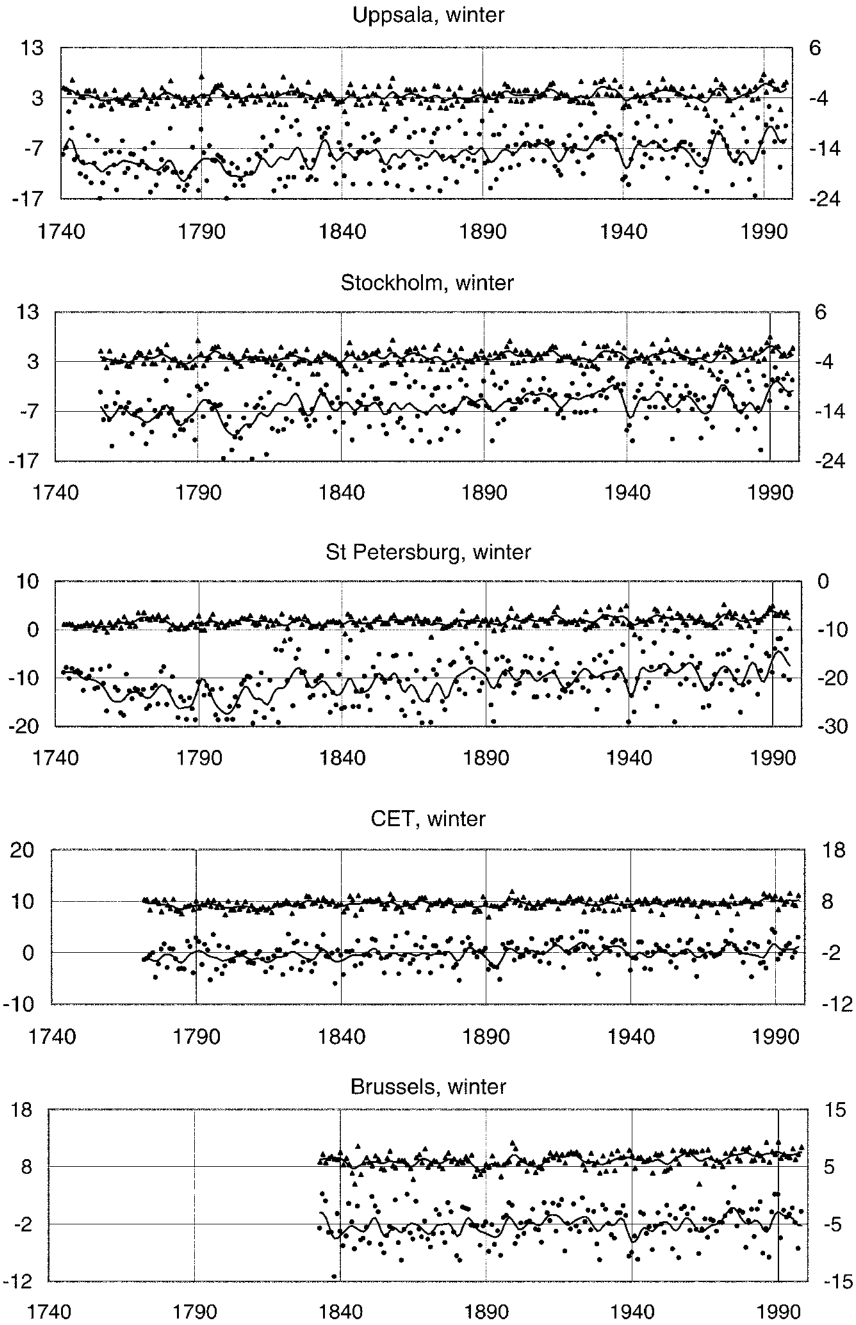
As Table IV but for seasonal highest temperatures

	Since	18th century			1873			1915			1961		
	For $\alpha =$	3	5	10	3	5	10	3	5	10	3	5	10
Uppsala	Win	0.4	0.3	0.3	0.8	0.8	+	+	+	+	6.2	6.2	6.0
	Spr	‘0	0	0	+	+	+	+	+	+	+	6.6	+
	Sum	–0.5	–0.5	–0.5	+	+	+	–	+	+	+	+	+
	Aut	–0.3	–	–	+	+	+	+	+	0	–	–	–
Stockholm	Win	0.4	0.4	0.3	+	+	+	+	+	+	+	+	+
	Spr	+	0	0	+	+	1.1	+	+	+	6.3	6.1	+
	Sum	–0.4	–0.5	–0.5	+	+	0.9	–	+	+	+	+	+
	Aut	–	–0.3	–0.3	+	+	+	+	+	+	–	–	–
St Petersburg	Win	0.5	0.5	0.5	1.0	0.9	0.9	+	+	+	+	+	+
	Spr	1.0	0.9	0.9	+	+	+	+	+	+	+	+	+
	Sum	+	+	+	–	–	–	–1.9	–1.7	–1.5	–	–	+
	Aut	+	+	+	+	+	+	+	+	+	–	–	–
Central England	Win	0.3	0.3	0.3	0.5	+	+	+	+	+	4.2	3.7	3.3
	Spr	0	0	0	+	+	+	–	–	–	+	4.5	4.4
	Sum	+	+	+	+	+	+	+	+	+	5.8	5.7	5.5
	Aut	+	+	0.2	+	+	+	–	–	–	+	+	+
Milan	Win	+	+	0.4	+	+	+	+	+	+	+	+	+
	Spr	–0.4	–0.4	–	–	–	+	–	–	–	+	+	+
	Sum	–	0	+	+	+	+	+	+	+	+	+	+
	Aut	+	+	+	–	–	–	–	–	–	+	+	+

Table V

(Continued)

	Since	18th century			1873			1915			1961		
	For $\alpha =$	3	5	10	3	5	10	3	5	10	3	5	10
Padua	Win	0	0	0	–	–	–	–	–	‘–	+	+	+
	Spr	0	0	0	0	+	+	–	–	–	+	+	+
	Sum	0	+	+	0.5	0.5	0.6	+	0.7	0.9	+	+	+
	Aut	0	+	+	–	–	–	–	–	–	+	–	–
Cadiz	Win				+	+	+	+	+	+	4.5	4.1	+
	Spr				–	–	–	–	–	–	–	–	–
	Sum				+	+	+	0	0	–	5.5	5.1	4.4
	Aut				+	+	+	–	–	–	+	+	+
Brussels	Win				1.3	1.3	1.4	1.5	1.5	1.5	+	+	+
	Spr				1.1	1.2	1.2	–	–	–	+	+	5.8
	Sum				1.8	1.7	1.6	1.6	1.8	1.9	6.6	6.5	6.2
	Aut				+	+	+	–	–	–	–	–	–
Shanghai	Win				+	+	+	+	+	0	+	5.0	+
	Spr				+	+	+	+	+	+	4.1	4.1	4.0
	Sum				+	+	+	1.1	1.0	0.9	+	+	+
	Aut				+	+	+	+	+	+	+	+	–
Beijing	Win							1.8	1.7	1.5	6.4	5.8	5.4
	Spr							–	+	+	–	–	–
	Sum							–1.2	–1.2	–1.1	–	–	–
	Aut							–	–	–	+	+	+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3
-7
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-14
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1940
1990
Stockholm, winter
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3
-7
-17
6
-4
-14
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1890
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1990
St Petersburg, winter
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-20
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-10
-20
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1890
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CET, winter
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1890
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Brussels, winter
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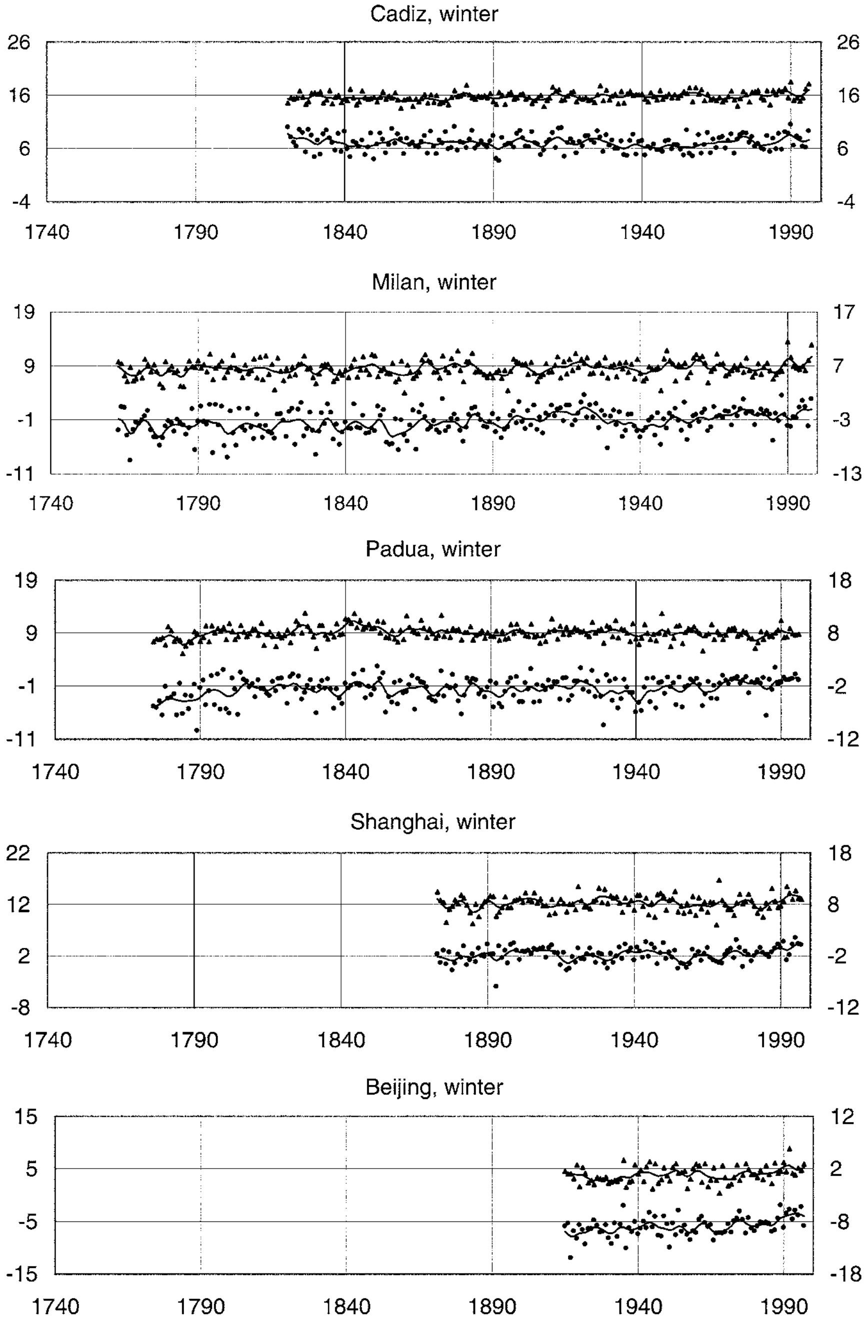
Figure 4a.


Cadiz, winter
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Milan, winter
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-1
-11
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-3
-13
Padua, winter
18
8
-2
-12
Shanghai, winter
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Beijing, winter
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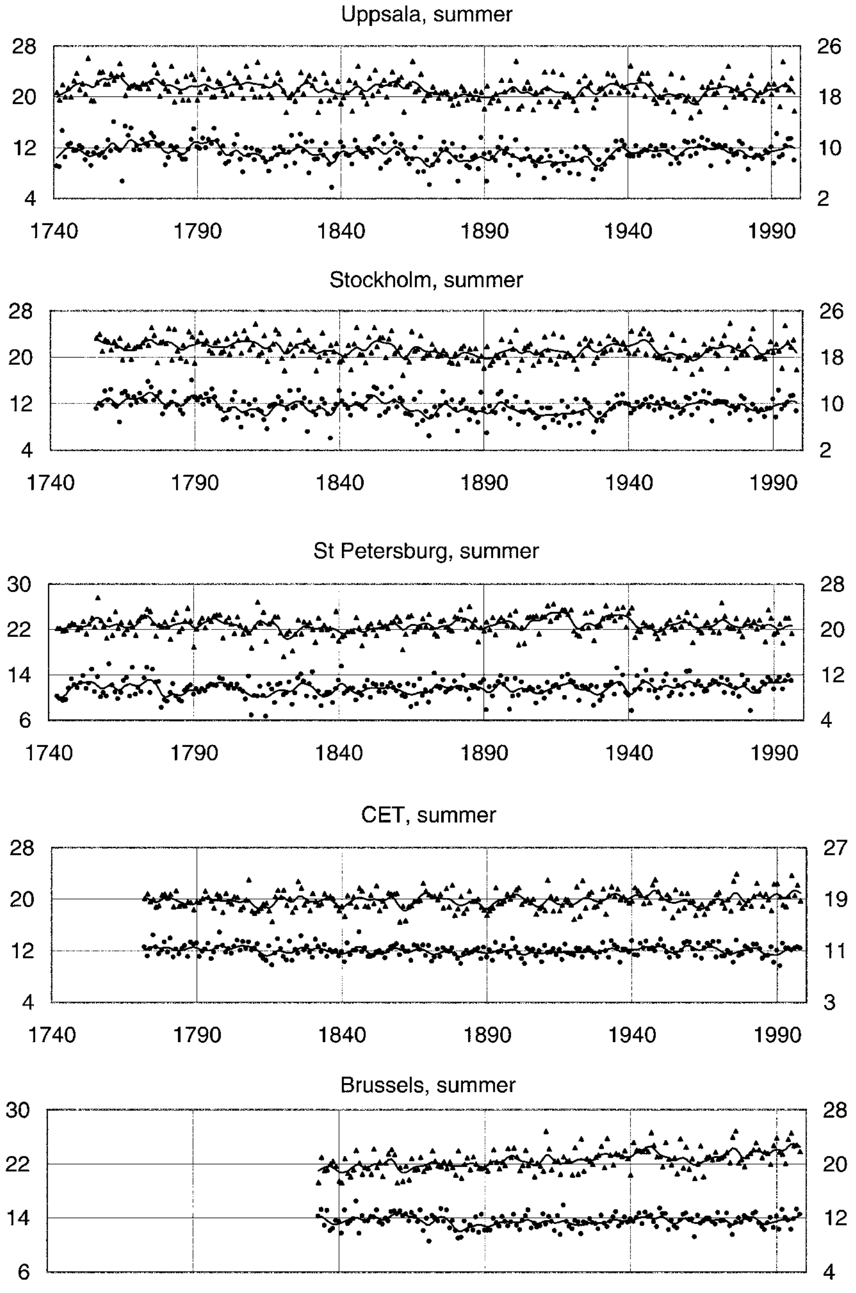
Figure 4b.


Uppsala, summer
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Stockholm, summer
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1940
1990
St Petersburg, summer
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1990
CET, summer
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1840
1890
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Brussels, summer
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Figure 4c.

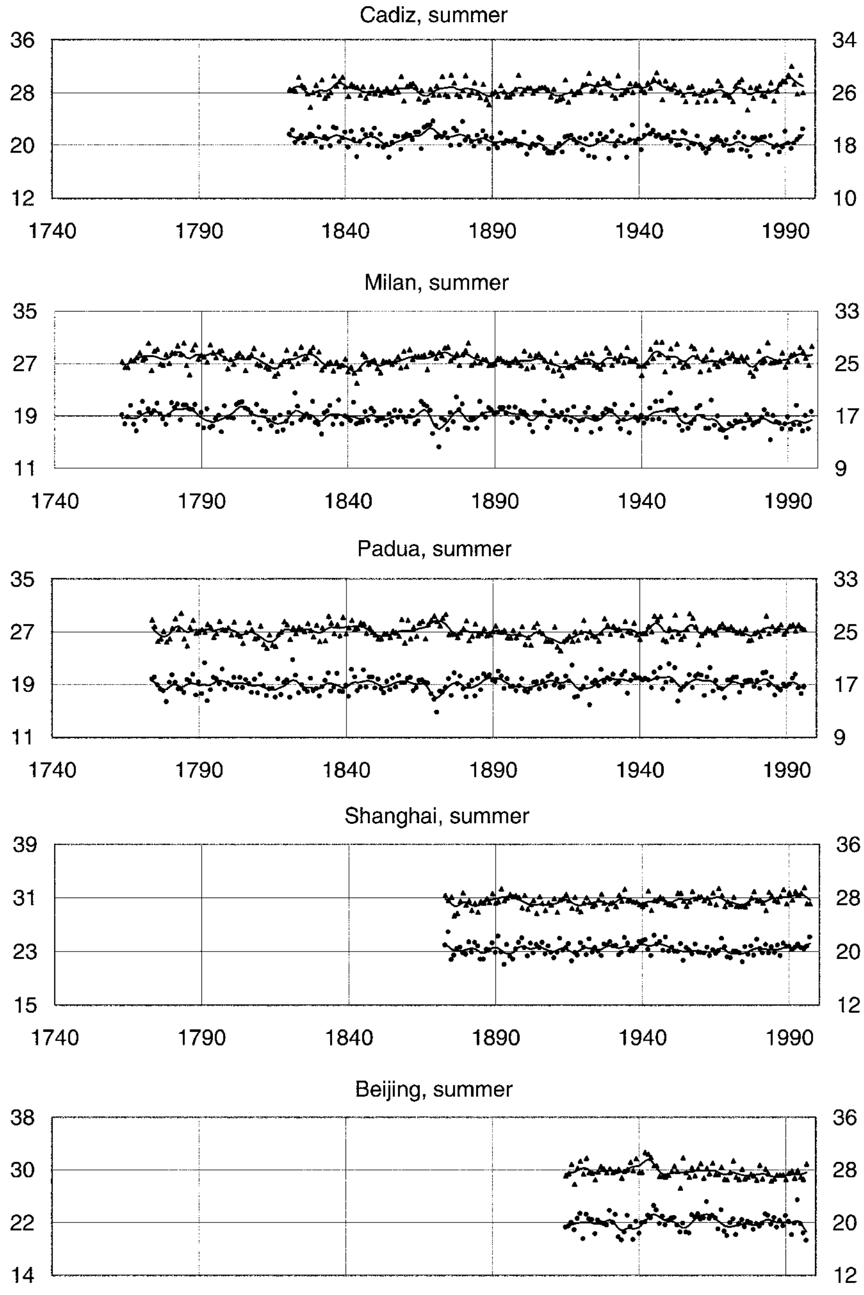

Figure 4d.

Figure 4. Absolute values and 11-year-binomial smoothing (lines) series of the highest (dots) and lowest (triangles) temperatures ($\alpha = 5$) for winter and summer. The left axis is for the highest temperature and the right for the lowest temperature (units: °C).

summer temperatures, which are essentially related to the Meiyu events in June with intermittent drizzle and heavy clouds. The increase of the lowest summer temperature at Shanghai may therefore imply a weakening of the Meiyu phenomenon and/or greater dominance of the western Pacific Subtropical High over the region during June. The widespread reduction of the lowest summer temperatures for most of the northern regions may imply that summer starts later or ends earlier than usual.

Now we comparatively discuss the highest seasonal temperatures (Table V). For the whole period from the 18th century to the present, warming trends are much weaker than those of the lowest temperatures. Scandinavia, St Petersburg and Central England exhibit slight warming trends in the highest winter temperatures (about 0.3–0.5 °C/century). St Petersburg also exhibits a warming trend of about 1.0 °C/century for spring. Decreasing trends in the highest summer and autumn temperatures (0.3–0.5 °C/century) are evident for Scandinavia. Milan exhibits a cooling in the highest spring temperatures.

Since 1873 and 1915, significant trends have been fewer, but Brussels exceptionally exhibits strong increases in the highest temperatures for both winter and summer. These trends probably indicate that Brussels records are biased by the effects of urbanization as the trends are greater than for Central England.

Since 1961, increases of the highest winter temperatures (about 4–6 °C/century) still prevail, but are weaker than those of the lowest temperatures at most sites, though they are more significant in Scandinavia and Central England. In contrast to the lowest summer temperatures, the highest summer temperatures have increased for more regions, with significant rates of about 4–7 °C/century for Central England, Cadiz and Brussels. Therefore, the within-season difference has become smaller for winter but larger for summer since 1961, while the whole annual cycle has become weaker.

As Figure 4 shows, for winters, interannual variability is generally stronger in the lowest than the highest temperatures. For summer, the highest temperatures become as variable and sometimes more so than the lowest values (e.g., Central England and Brussels). This is because these annually extreme temperatures are likely linked with the strongest short-term weather phenomena, e.g., cold outbreaks in winter and strong anticyclones in summer, which are variable from year to year. The trends in these extreme temperatures and the within-season temperature ranges discussed earlier, therefore, imply that weather variability might have become weaker during winter but stronger during summer at most sites (see also Yan et al., 2001b).

Variations of the lowest summer and highest winter temperatures could be related to changes in the phase of the seasonal cycle. For example, in Scandinavia, the decrease of the lowest summer and highest autumn temperatures in recent decades might imply an earlier start to autumn. At Shanghai, as another example, the increase of the lowest summer and highest spring temperatures implies an earlier start to summer. There is clear scope to investigate these aspects further.

In summary, for cold seasons, the lowest temperatures are more sensitive and have risen significantly for 2 centuries. Conversely, for warm seasons, the highest temperatures are more sensitive and have also increased considerably during the last decades. Comparing the recent temperature levels with the earlier warmth recorded at Uppsala and St Petersburg, however, we might infer a similar level even for the lowest winter temperatures. Analyses of proxy data also suggested warmer conditions in China during the 18th century (Zhang, 1981; Wang, 1990). This implies that the recent strong warming may not be beyond the scope of natural variability on centennial timescales, though it seems highly unusual in the context of the last century.

4. Regional Patterns of Recent Climate Change

Since 1961, more spatially extensive data are available enabling us to investigate whether the trends at single stations represent those over larger areas. Furthermore, daily sea-level pressure data can be used to consider whether the temperature trends might be related to changes in large-scale circulation fields rather than local non-climatic factors.

First we make a simple comparison of changes in the seasonal cycle between Beijing and a number of surrounding stations. From the 62-station daily data set (Yan and Yang, 2000), we choose 14 stations covering a large part of northern China, where Beijing is located. Most of the 14 stations are located in cities, however, so a regional average urban bias (Portman, 1993; Yan et al., 2001a) is subtracted before any comparison. The correlation coefficient between the mean of these stations and Beijing reaches 0.99 for the daily temperature series and 0.76 for the anomaly series during 1961–1997. Figure 5 shows the mean annual cycle at Beijing during 1981–1997 and 1961–1980, compared with the regional (14 stations) mean for northern China. The 5/95 percentile criteria defining the frequencies of cold/warm extremes are also compared between the two periods. The Beijing record represents the regional mean well even at the intramonthly timescale, e.g., the strong warming at the beginning of February and the lowering of the extreme criterion near the end of November. Beijing, therefore, clearly represents a much larger region with respect to extremes than might have been expected. In general, the winters and springs during 1981–1997 are much warmer than in 1961–1980.

A similar comparison between the Central England series and British Isles regional average is also shown in Figure 5. The daily temperature of each station is calculated as the average of the daily maximum and minimum. The mean of 36 stations, with less than 1% missing rate during 1961–1995, also shows excellent agreement with Central England. While autumn remains at a stable level, the other seasons show warming with large intramonthly variability. The intramonthly variations of the 5/95 percentile extremes over the British Isles are vividly recorded by

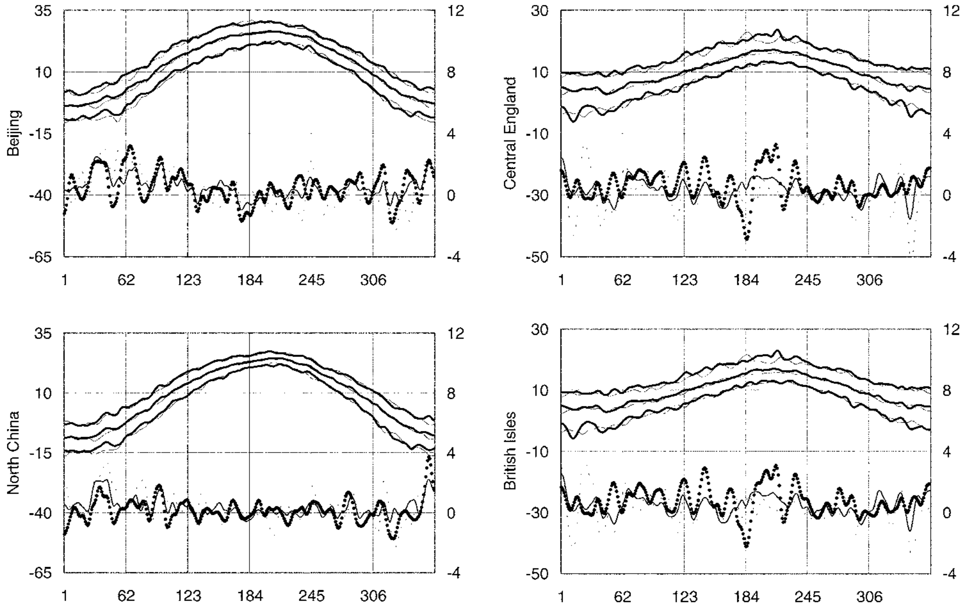

Figure 5. Changes in the annual cycle and 5/95 percentile criteria of extremes from 1961–1980 (thin lines) to 1981–1997 (thick lines) at Beijing and to 1981–1995 for Central England, compared to means from surrounding stations (noted as North China and British Isles), (°C, left axis). The series in the lower half of the panels show the differences between the two periods (later minus earlier); line for mean temperature, thick dotted for warm extreme criterion and thin dashed for cold extreme criterion (°C, right axis).

the Central England series. This implies that changes of extremes are not unduly influenced by local factors and the large-scale dominates. The comparisons here also suggest that the results from the long-term daily observations analyzed in this paper represent real climate changes over larger areas.

Possible causes of the changes in extremes might relate to recent circulation changes. We calculate daily geostrophic wind strengths at each grid point from the UKMO Northern Hemisphere sea-level pressure data set for 1966–1997. Before 1965, there were some time periods with different methods of analysis, making the grid-point series potentially inhomogeneous (Hulme and Jones, 1991; Jones et al., 1999). As earlier, we divide the period into two parts, 1966–1980 and 1981–1997, and map the differences between the periods to see whether any changes have occurred. Changes in both the absolute extreme wind speed and the frequency of extremes are calculated with the results for both measures being similar. Figure 6 shows the changes in the extreme wind speeds, i.e., the average of the largest 5% of the record, for winter and summer over the Eurasian continent.

For winter the very large increase in wind speed around 35° N, 100° E is almost certainly due to topographic problems with the pressure field over the Tibetan Plateau. Apart from this, most of eastern Asia has experienced decreasing winter

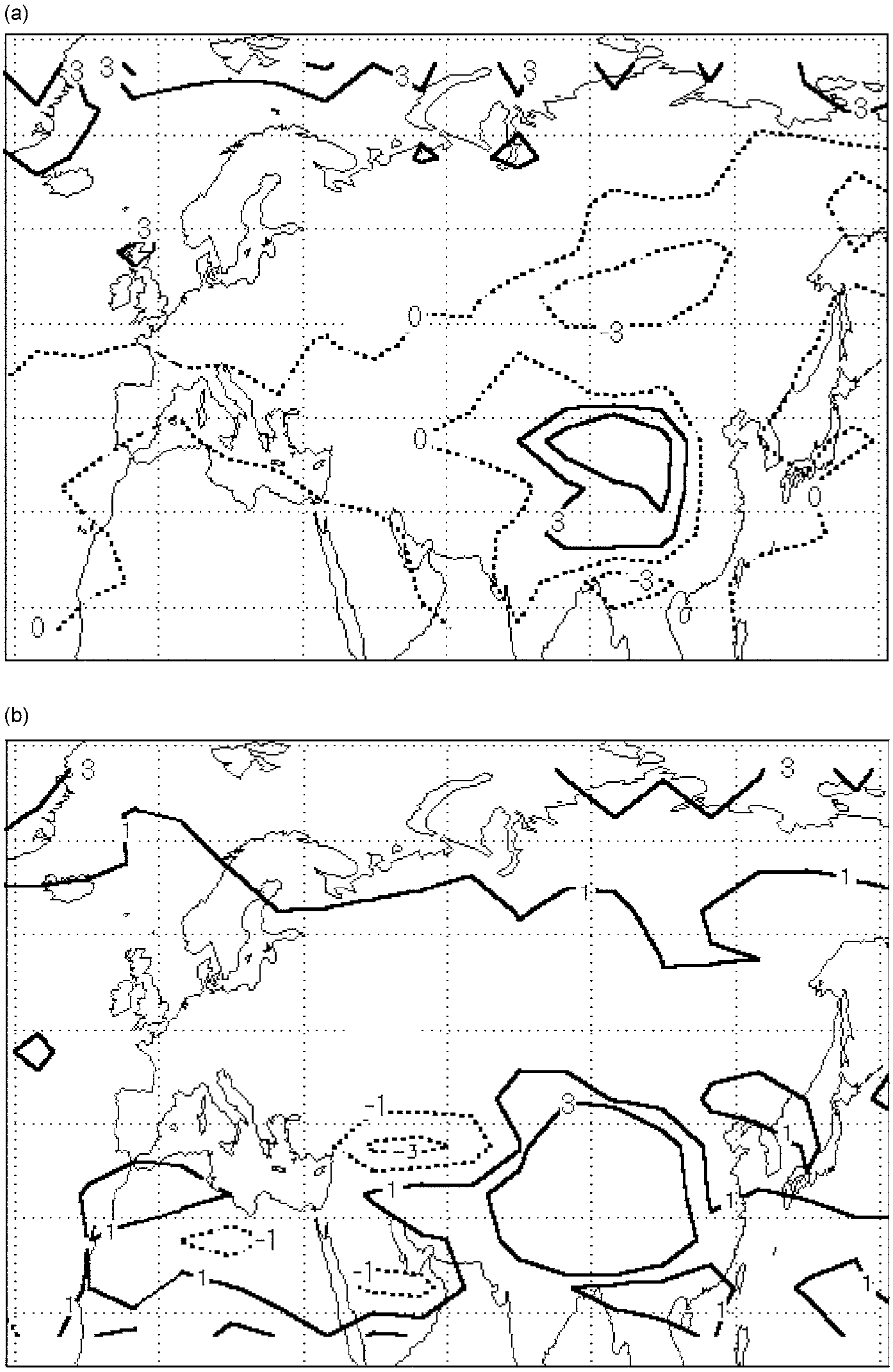

Figure 6. Change in winter (upper) and summer (lower) extreme geostrophic wind speed (mean of 5% strongest daily wind speeds of each seasonal record, unit: m/s) over Eurasia from 1966–1980 to 1981–1997.

extreme wind speeds. The decreases are up to 3 m/s in northern China. This coincides well with the result of Yan and Yang (2000). They used daily station wind observations in China since the 1950s and find decreases in annual maximum wind speeds as large as 3 m/s. Decreasing extreme winds over northern Asia imply that cold air outbreaks from Siberia have weakened. This is part of the reason for the much milder recent winters at Beijing and Shanghai (Table IV). The zone of weakening winter extreme wind speeds, but with a smaller magnitude, is also evident in the Mediterranean, implying weaker cold outbreaks from the east as well. This might explain the more significant winter warming in extremely low temperatures and decreasing cold extremes at Padua than at the northwestern European sites (Tables III and IV), although the differing trends between Padua and Milan during recent decades might imply data problems. Comparatively, northwestern Europe has experienced slightly increasing extreme wind speeds in winter. As this region is controlled by storm tracks in winter, this implies strengthening winter storms. This is clearly related to the increase in the North Atlantic Oscillation (NAO) values from the 1960s to the 1990s (Hurrell, 1995). Cyclonic storms may bring warmer airmasses from lower latitude parts of the Atlantic into northwestern Europe, but with large intramonthly variability. This may explain the winter warming in extreme temperatures at European sites, which is quite large despite being statistically insignificant in some cases (Tables IV and V and Figures 3 and 4). We say, *may*, as the NAO was nearly as positive during winters in the 1900s and 1910s (Jones et al., 1997), but extremes were not as warm.

For summer, the large change around the Tibetan Plateau remains as evidence of problems with the pressure field over high elevations. Elsewhere, there is little change in summer extreme winds for northern China and western Europe. Figure 6 shows some strengthening of extreme geostrophic winds along the Chinese coast. Our calculation also indicates increasing frequency of extreme winds for summer in this area. Enhanced large-scale pressure gradients often correspond to cloud and rainfall, leading to lower daily temperature. This may be part of the reason for the increase of cold extremes during summers at Shanghai and Beijing since 1961 (Table III). There is a slight strengthening of extreme winds over the northern Atlantic and Europe. Analysis of the UKMO pressure data shows that this corresponds to enhanced subtropical High pressure ridges extending over western Europe in summer, which sharpen the pressure gradient to the north. These enhanced subtropical ridges may also partly explain the increase of the highest seasonal temperatures and of the frequency of warm extremes at some European locations, especially Central England (Tables III and V).

5. Summary and Conclusions

We have analysed the longest observational daily temperature series that are presently available in Europe and China, focussing on extreme climate changes over the last 200–250 years. Here, we itemize the important findings.

1. The earliest European instrumental observations appear to have captured part of an earlier warm epoch in the 18th century. This was followed by a cooling trend and a decrease of warm extremes, especially for summer. Most of the long-term station series recorded these early trends, especially the reduction of extremes. Since the late 19th century, reductions in cold extremes have become more important and annual temperatures began to increase significantly by about 0.5–1.0 °C/century. Since 1961, a strong warming, together with increasing warm extremes, has occurred at most of the sites studied. Three stages of change in extremes can be recognized: decreasing warm extremes up to the late 19th century; decreasing cold extremes since then and increasing warm extremes since 1961.

   The relatively large frequency of extremes in the 18th century and the recent trends potentially imply that extreme temperature fluctuations may be more frequent during warm periods. Although the daily observational series in China are not long enough to record the earlier epoch, proxy data analyses have noted a warm period during the 18th century (Wang, 1990; Zhang, 1981). Yan (1994) analyzed annual drought/flood indices in China since the 15th century, which describe unusual hydrological conditions, mainly for summer. After separating different time-scale variations, he found that the interannual (short-term) fluctuations were stronger during long-term warmer periods. Zeng and Yan (1993) analyzed different timescale variations in cloudiness over China during recent decades. They found that the ENSO-scale signal was stronger in the warm 1950s, weakened during the cool 1960s–1970s and was enhanced again during the warm 1980s. If stronger short-term climate fluctuations can be related to stronger weather phenomena, these studies may further support the possibility that weather variability and hence, the frequency of extremes could be expected to be greater during warm periods in some regions such as China, especially for summer. However, the reduction of cold extremes during warming periods for winter indicates the opposite. More systematic analyses are necessary before a better understanding of any relationship between changes in the frequency of extremes and mean temperature can be made.
2. Absolute extreme temperatures clearly show different trends between winter and summer. Although there are more complex regional differences, we have identified a general feature that the lowest temperature is more variable than the highest for winter, but in general the highest temperature changes vary considerably more than the lowest for summer. Since 1961, the lowest winter temperature has increased more sharply than the highest, causing a smaller

within-season range at most of the sites. Comparatively, the highest summer temperatures have increased more than the lowest at most of the sites, causing a larger within-season temperature range. Therefore, while the whole seasonal cycle has become weaker due to larger warming in winter, winters have become less variable but summers more.

A more sophisticated analysis of the daily observations using wavelet techniques, reaches a comparable result that weather variability has been weaker for cold seasons almost everywhere but opposite trends tend to prevail for warm seasons (Yan et al., 2001b).

3. Strong increases of warm extremes and decreases of cold extremes have accompanied the strong warming since 1961. This is a clear difference between the present warm epoch and that in the 18th century, when cold extremes were more frequent. The increases of warm extremes since the 1960s have been more evident in western Europe, perhaps due to enhanced ridges extending from the subtropical Atlantic High in summer and strengthened storms in winter. The reductions of cold extremes are more evident at the southern sites such as Shanghai, Beijing and Padua, possibly due to weaker winter outbreaks from cooler higher latitudinal continental areas. The analysis of atmospheric circulation changes based on daily sea-level pressure data shows results that are physically consistent with those of the temperature changes.

   The sharp increase of warm extremes since 1961 may partly result from an imperfect analysis technique. It could be argued that if temperature anomalies are generally normally distributed and the extreme thresholds fixed, a warming of the mean will cause an increase of warm extremes more than a decrease of cold extremes. However, the more evident reduction of cold extremes at some sites during the warming period, the comparative analysis of wind extremes and our recent study with a more sophisticated method (Yan et al., 2001b) suggest that the changes of climate extremes are not statistical artifacts.
4. By comparisons of records for Central England and Beijing with averages from a number of surrounding stations covering a larger area since 1961, we have shown that for mean temperature and also for changes of extreme temperatures the long-term individual station analyses represent much wider spatial regions. Changes of extremes are not significantly affected by local factors, and the large-scale dominates. The single sites should, therefore, be considered representative for the full length of their records for larger regions. We do not have more spatially extensive data, however, to judge the single sites for earlier periods, when inhomogeneities are more likely. The analyses discussing the earliest periods may contain larger uncertainties, although our main conclusions are based on multi-site comparisons instead of any single station time series.
5. Quantitative estimates of changes of extremes depend on the definition. The present analysis suggests that, in order to effectively separate changes of extremes from changes in the remainder of the daily temperature distribution, a

percentile smaller than 10 (and/or larger than 90) should be used when defining extremes.

6. Using the 5/95 (%) criterion for defining cold/warm extremes, we can contrast changes of extremes from changes in the mean. For the most recent annual mean warming since the 1960s of about 2–3 °C/century, the coldest winter temperatures show increasing trends larger than 5 °C/century at most of the sites. Trends in the warmest summer temperatures show more geographical diversity, ranging from insignificant cooling to significant warming of up to 6 °C/century. Analysis of recent relative extremes indicates that unusually cold days decrease at a rate about 7%/century or larger and warm extremes increase at a rate larger than 10%/century (both with large spatial variability). Although such large trends are partly due to the short time periods, they indicate that extreme temperatures are more sensitive to change than mean temperatures.
7. Spatial patterns of changes in extreme geostrophic wind speeds (calculated from gridded daily sea-level pressure data) correspond well to changes in extreme temperatures. Weaker winds due to a weakened Siberian High cause less cold surges in winter in China. This can be linked to warming trends in extreme temperatures during recent decades. Increases in the pressure gradient over the northern Atlantic and Europe (corresponding to a more enhanced NAO) have caused increases in warm extremes over Europe in recent decades. These correspondences reinforce our analyses of the daily temperature data and imply that changes in extremes are closely related to large-scale circulation changes.
8. The analysis of extremes has provided more details of recent climate changes. Moreover, it may also have helped to identify additional inhomogeneities in the daily temperature observations. For example, Cadiz does not indicate anything unusual in seasonal mean temperature series, but our analysis indicates a period of unusually low frequency of extremes for summer around the late 19th century. The recent trends of extremes at Padua and Milan contrast strikingly with one another. Although the bulk of our conclusions are quite robust as discussed in the previous sections, inhomogeneities in some of the data series may bias some calculations. Further study of homogeneity on the daily data may be necessary to obtain greater detail concerning recent trends in extremes. Some new methods to homogenize variance as well as the mean, discussed by Allen and DeGaetano (2000) and Yan et al. (2001b), may prove very useful. It is clear that homogenization, particularly for the daily timescale, cannot be considered in isolation from the sorts of statistical techniques that will be used to analyse each daily series.

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