Theor Appl Climatol (2009) 98:187–195
DOI 10.1007/s00704-008-0094-5

ORIGINAL PAPER

# Trends in extremes of temperature, dew point, and precipitation from long instrumental series from central Europe

**K. Kürbis · M. Mudelsee · G. Tetzlaff · R. Brázdil**

Received: 30 June 2008 / Accepted: 5 December 2008 / Published online: 7 February 2009


**Abstract** For the analysis of trends in weather extremes, we introduce a diagnostic index variable, the exceedance product, which combines intensity and frequency of extremes. We separate trends in higher moments from trends in mean or standard deviation and use bootstrap resampling to evaluate statistical significances. The application of the concept of the exceedance product to daily meteorological time series from Potsdam (1893 to 2005) and Prague–Klementinum (1775 to 2004) reveals that extremely cold winters occurred only until the mid-20th century, whereas warm winters show upward trends. These changes were significant in higher moments of the temperature distribution. In contrast, trends in summer temperature extremes (e.g., the 2003 European heatwave) can be explained by linear changes in mean or standard deviation. While precipitation at Potsdam does not show pronounced trends, dew point does exhibit a change from maximum extremes during the 1960s to minimum extremes during the 1970s.

## 1 Introduction

The European summer heat in 2003 led to intensive efforts to quantify and understand past and recent trends regarding weather extremes and to project them into the future, thereby extending the previous work summarized in the Third IPCC Assessment Report (Houghton et al. 2001) and finding entrance into the Fourth IPCC Report (Solomon et al. 2007). Increases not only in the mean value of temperature, but also of the second moment variance have to be invoked to explain the 2003 heat with a realistic chance of occurrence (Schär et al. 2004). Besides mean and variance (or standard deviation), higher moments of distributions of weather variables may also change with climate (Nogaj et al. 2006). For example, Brabson and Palutikof (2002) showed that both cold winters and hot summers in the central England temperature series (past 220 years) evolved differently from their means. Higher moments describe the tails of a distribution, where the extremes are located: their quantification is socio-economically relevant.

Schär et al. (2004) found negative correlations between temperature and precipitation anomalies in records from Switzerland (1864–2003), and recent papers (Diffenbaugh et al. 2007; Vautard et al. 2007) elaborated the role of the Mediterranean region in land–atmosphere coupling under climate change (Seneviratne et al. 2006): hot European summers are preceded by winter rainfall deficits over southern Europe.

Weather extremes such as the 2003 heatwave have two properties: (1) intensity and (2) duration (related to empirical frequency) of the period a threshold is exceeded. Several criterions can therefore be used to define a heatwave (Beniston 2004; Meehl and Tebaldi 2004). The selection of a suitable criterion is important because it influences the accuracy of the statistical estimation and, hence, the detectability of (climatically induced) trends in the occurrence of weather extremes. This concerns not only extreme temperature but also precipitation (Osborn and

K. Kürbis · G. Tetzlaff
Institute of Meteorology, University of Leipzig,
Leipzig, Germany

M. Mudelsee (✉)
Climate Risk Analysis,
Schneiderberg 26, 30167 Hanover, Germany
e-mail: mudelsee@mudelsee.com

R. Brázdil
Institute of Geography, Masaryk University Brno,
61137 Brno, Czech Republic

Hulme 2002; Mudelsee et al. 2003), a variable with distributions substantially different from a normal shape.

The index variables previously employed to measure longer-lasting extremes such as heatwaves (Table 1) focused either on intensity or on duration, and the indices have either temperature (K) or time units (days). There may exist situations where those indices do not work well. For example, the first index in Table 1 (the average of temperatures of three consecutive warmest nights) may be unsuitable in capturing the size of extremes lasting longer than 3 days. As another example, the WSDI index (the annual count of 6 or more consecutive days when daily maximum temperature exceeds the 90th percentile) is independent of the intensity as long as the 90th percentile is exceeded. A second deficit is the degree of arbitrariness in the definition of the indices. Take the 97.5th, 95th, or the 90th percentile, set a duration threshold for 3, 6, or another count of days?

We believe that for most situations those indices yield meaningful results, and we also acknowledge that the arbitrariness can be reduced by means of sensitivity studies or by introducing more flexible tools, such as the $k$-day heatwave (Table 1). On the other hand, this should not hinder the development of new methods that (1) combine intensity more intimately with duration and (2) reduce further the degree of arbitrariness.

This paper studies trends in extreme weather. It separates between changes of mean and variance and changes of higher moments. It introduces a new diagnostic index, the “exceedance product”, to combine the intensity with the frequency aspect. Besides the selection of seasons, the new index is free of arbitrariness. Apart from temperature and precipitation, we also analyze dew point because this meteorological variable contains information about precipitation with less variability in the spatial and temporal domains. Since (1) the data distributions differ from the normal shape, and (2) no error bars for a complex quantity such as the exceedance product can be analytically derived, we perform bootstrap simulations to determine the statistical significance of the exceedance product. Trend detection in series of extreme events is an intrinsically difficult methodical task (Frei and Schär 2001), especially when, as here, a seasonal differentiation is sought. Consequently, we study long, daily-resolved, continuous instrumental series from two European stations, Potsdam and Prague–Klementinum.

## 2 Data

The time series from Potsdam, Germany, (Fig. 1) comprises maximum and minimum temperatures, 24-h precipitation, and dew point at 14.00 of mean local time; they cover the interval from January 1, 1893 to December 31, 2005 in daily resolution; those from Prague–Klementinum, Czech Republic, (Fig. 1) comprise maximum and minimum temperature and cover the interval from January 1, 1775 to December 31, 2004 in daily resolution.

The Potsdam series have a remarkable homogeneity (Körber 1993; Lehmann and Kalb 1993): neither the measurement settings nor the observation times have

**Table 1** Heatwave definitions according to the literature; d, days; K, Kelvin; n.n., “not named”

| Index | Definition | Units | Reference |
|---|---|---|---|
| n.n. | Average of temperatures of three consecutive warmest nights | K | Meehl and Tebaldi (2004) |
| $k$-day heatwave | Largest average (within a year) over $k$ consecutive days of daily maximum temperature | K | Khaliq et al. (2005) |
| TS30 | Cumulative daily maximum temperature in excess of 30°C over a period satisfying the conditions that (1) daily maximum temperature exceeds 30°C for at least 3 days, (2) average of daily maximum temperature over the entire period exceeds 30°C, (3) daily maximum temperature exceeds 25°C for every day within the period | K | Kyselý (2002) |
| n.n. | Longest period of consecutive days satisfying the conditions that (1) daily maximum temperature exceeds 97.5th percentile for at least 3 days, (2) average daily maximum temperature exceeds 97.5th percentile for entire period, (3) daily maximum temperature exceeds 81st percentile for every day within the period | d | Meehl and Tebaldi (2004) |
| WSDI | Annual count of days with at least six consecutive days when daily maximum temperature exceeds the 90th percentile | d | Alexander et al. (2006) |
| HW-DSMT | Maximum number of consecutive days when daily summer (JJA) maximum temperature exceeds the 95th percentile | d | Della-Marta et al. (2007) |
| $P$ | Exceedance product, given by exceedance in daily maximum temperature multiplied by the number of days when the previous record value is exceeded within a summer season (JJA) | d·K | This work |

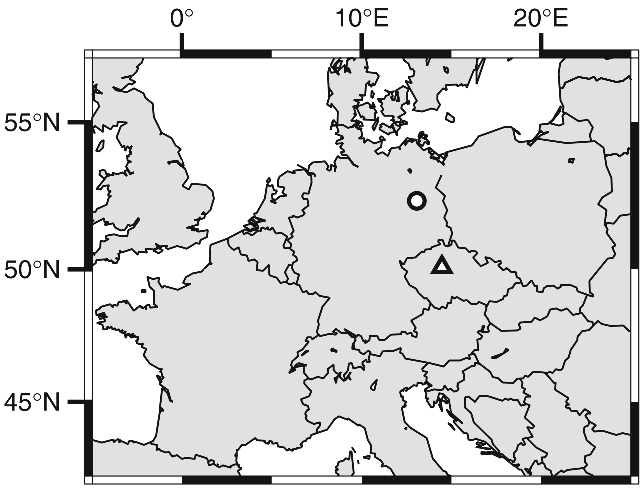


**Fig. 1** Map of central Europe, with the locations of the stations Potsdam, Germany, (*circle*) and Prague–Klementinum, Czech Republic, (*triangle*)

changed at least since 1893. External influences from urbanization such as the heat island effect are small owing to the location of the Potsdam station within a forest (Klein Tank et al. 2002).

Station Prague–Klementinum was established in a vast complex of buildings of the College of St. Clement in the Old Town of Prague. This series is among the longest from Europe and often used in the analysis of air temperature fluctuations and for the calibration of proxy data (Brázdil and Budíková 1999). The time series from Prague–Klementinum exhibits a strengthening of the urban heat island effect (for the period 1922–1995, see Brázdil and Budíková (1999)). The Prague– Klementinum series serve here to augment the Potsdam data. In the analysis, the above-mentioned effect in the Prague–Klementinum series is taken into account.

## 3 Method

Let $x(i,j)$ be the value of a series at day $j$ of year $i$. Let further $y(j)$ be the maximum at day $j$ of $x(i,j)$ over the same and all preceding years ($\leq i$). The data from the first year (Potsdam, 1893) initialize the reference extremes $y$ as $y(j) = x(1,j)$. To define the exceedance, $\beta(i,j)$, for day $j$ of year $i$, the values $x$ are compared with the reference extremes $y$: if $x(i,j) > y(j)$, then

$$\beta(i,j) = |x(i,j) - y(j)| \tag{1}$$

and the reference extreme is updated, $y(j) = x(i,j)$. This procedure is carried out for all years, $i$=1,...,$n_i$ (Potsdam, $n_i$=113) and days.

The exceedance captures the intensity aspect of climate extremes. To also include the frequency aspect, we multiply the exceedance, $\beta$, with the number of days, $N$, a reference extreme is exceeded; the product, $P$, is then the diagnostic index variable for extremes in the instrumental series:

$$P(i) = \sum_{j=K}^{L} [\beta(i,j)] \cdot N(i). \tag{2}$$

The units of $P$ are the units of $x$ multiplied by the units of time (days). By selecting the bounds $K$ and $L$, it is possible to focus on seasons. We study summer extremes (June to August, JJA) by setting $K$=152 and $L$=243, and winter extremes (December to February, DJF). (The February 29 value is omitted.)

The definitions above apply to maxima or positive extremes. This is the case when $x$ is the highest daily maximum temperature (abbreviated as $TX_{\mathrm{high}}$), the highest minimum temperature (i.e., warmest night, $TN_{\mathrm{high}}$), the highest dew point ($DF_{\mathrm{high}}$) or the highest precipitation total ($RR_{\mathrm{high}}$). Analogous definitions (e.g., $y$ is minimum) are used for negative extremes, when $x$ is the lowest maximum temperature (coldest day, $TX_{\mathrm{low}}$), the lowest minimum temperature ($TN_{\mathrm{low}}$) or the lowest dew point ($DF_{\mathrm{low}}$).

The curves of the exceedance product, $P(i)$, are the basis for evaluating trends in the occurrence of extreme events. Next is bias correction. The bias comes from the fact that with every additional year, $i$, it becomes less likely for a value $x$ to lie above (positive extreme) the reference extreme because the data set to define the reference extreme grows with $i$. Another effect is that under global climate change, we expect upward trends in the mean and standard deviation, which lead to more extremes, as was shown for the 2003 summer heatwave (Schär et al. 2004). We correct also for this effect to study higher-order moments.

The bootstrap simulation approach (Efron and Tibshirani 1993) is used to assess the statistical significance and to correct for bias and effects of trends in mean and standard deviation on the $P(i)$ curves. Artificial curves, $P^*(i)$, of the exceedance product are generated by simulating artificial climate time series, $x^*(i,j)$. This assumes (1) linear trends in day-wise mean and standard deviation of $x(i,j)$ over years $i$, (2) seasonally varying distributions of trend residuals, and (3) seasonally varying autocorrelation (memory) of trend residuals. A high number (200,000) of simulations is employed to accurately determine the upper percentile confidence limits (99.9%, 99%, and 95%) of the simulated $P^*(i)$ curves (Figs. 2 and 4). If an observed $P(i)$ curve (grey bars in Figs. 2 and 4) lies above the confidence limit at year $i$, we consider this as a significant extreme in $P$. Figure 3 illustrates the estimation of trend parameters, the subdivision of the year into five periods (seasonal variations), the non-normal distribution of residuals and their autocorrelation. Robust regression is performed for trend estimation of the

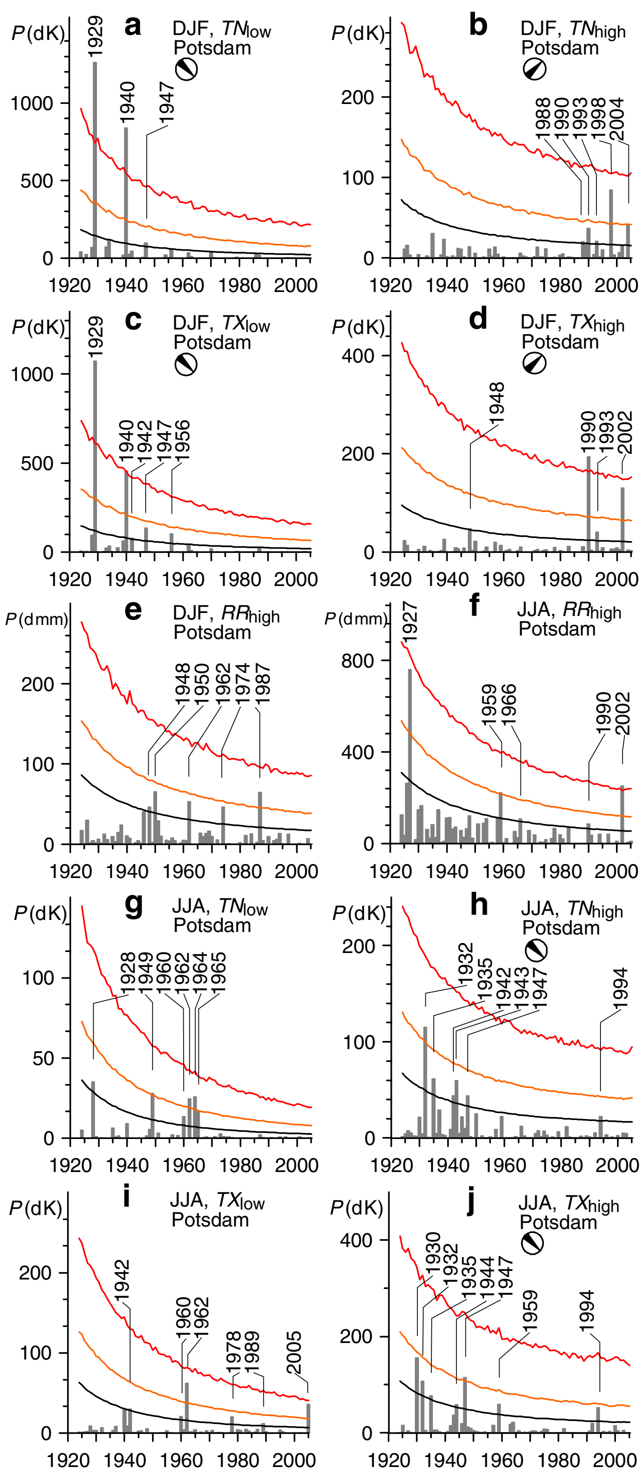


**Fig. 2** Extreme temperature (*TN* , *TX*) and precipitation (*RR*) events in Potsdam: each panel shows exceedance product *P* (*grey bars*) and its confidence limits (99.9% level, *red/upper line*; 99%, *orange/middle line*; 95%, *black/lower line*); significant events are labeled. *Arrows* (up/down) mark acceptance in statistical tests (90% level) of the hypothesis "there is a trend (upward/downward) in occurrence of significant *P* events"

precipitation series, least-squares regression for the other data. Simulated series are generated by adding residuals drawn randomly from the empirical distribution to the estimated trends; this takes into account deviations from the normal shape (Fig. 3c). The residuals are drawn block-wise to preserve autocorrelation. For example, for the residuals plotted in Fig. 3d, the block length is 14 (days); a memory for minimum temperature beyond this length is unlikely. See Künsch (1989) for details of this block bootstrap approach.

Finally, we study trends in the occurrence of significant $P(i)$ extremes using the following hypothesis test (Cox and Lewis 1966; Mudelsee et al. 2003). Let $[t_1;t_2]$ be the test interval; $T(k),k=1,\ldots,n_k$ the dates of the $P(i)$ extremes; and

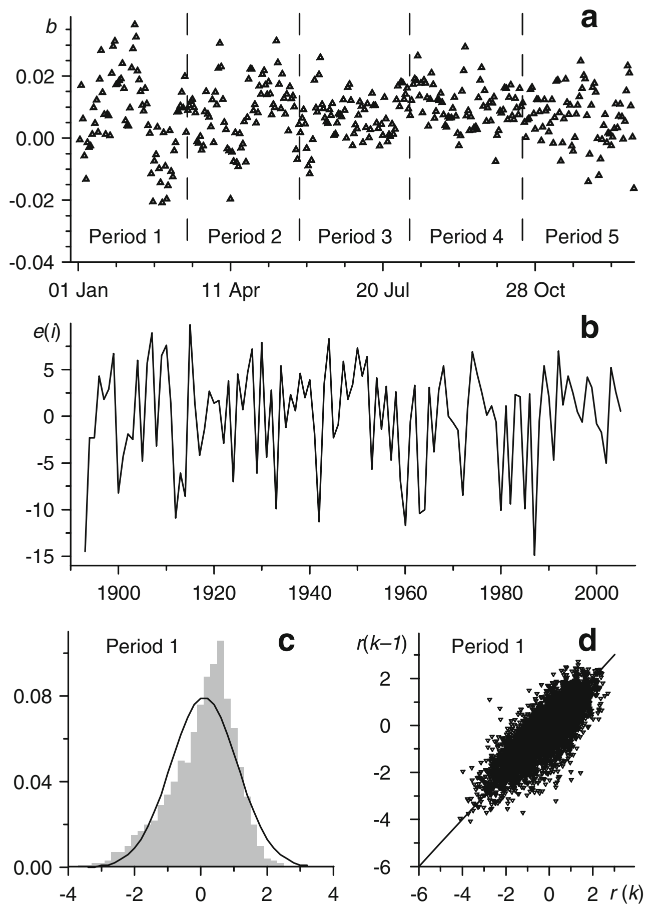


**Fig. 3** **a** Slopes, *b*, of day-wise linear regression to minimum temperature over 1893–2005, Potsdam. Also shown is sub-division of year into five periods of equal length, 73 days. **b** Regression residuals, $e(i)$, for 15 January. (The $e(i)$ are calculated as $x(i, j)$ minus fitted regression.) **c** Normalized histogram of scaled residuals, $r = e(i)/STD$, for all days within period 1. Normal distribution with the same mean and standard deviation is also shown. The total number of scaled residuals is $n_r = 73 \cdot n_i = 73 \cdot 113 = 8249$. **d** Lag-1 scatterplot of $r(k)$, $k=1, \ldots, n_r$, for period 1. The autocorrelation coefficient, $\Phi$, is 0.82 (other periods: 2, $\Phi$=0.68; 3, $\Phi$=0.62; 4, $\Phi$=0.61; 5, $\Phi$=0.75)

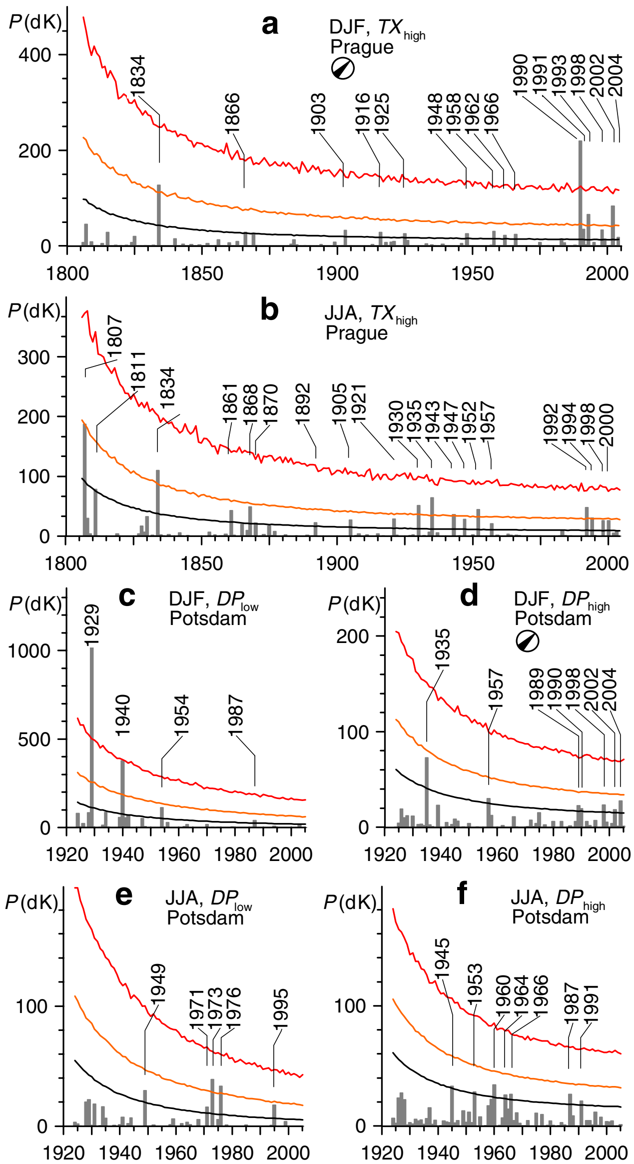


**Fig. 4** Extreme temperature events at Prague–Klementinum and extreme dew point events in Potsdam (for explanation see Fig. 2)

$n_k$ their number. Under the null hypothesis "no trend in occurrence of extremes", the statistic

$$u = \frac{\sum_k T(k)/n_k - (t_2 - t_1)/2}{(t_2 - t_1)/(12n_k)^{1/2}} \tag{3}$$

is approximately standard-normally distributed. (Consider the following example. In Fig. 2b, $t_1$=1924, $t_2$=2006, $n_k$=5 and the $T(k)$ are labeled. The $u$-value of +2.8 is significantly different from zero at the 99% level, and the null hypothesis is rejected against the alternative "upward trend".)

Regarding the urbanization influence, we note that the detrending, originally meant to remove linear global climate trends and thereby extract trends in higher moments, also removes the linear portion of the urban heat island effect. That means detrending makes the results from the Prague–Klementinum temperature series more robust against inhomogeneity effects.

A careful reviewer kindly directed our attention to previous work. Galambos (1978: Sects. 6.3 and 6.4 therein) studied the asymptotic distributions of the $y(j)$, which he called "records", and of the $N(i)$, which counted his "record times". However, Galambos (1978) assumed stationarity, that is, processes with time-constant properties. Subsequently, Redner and Petersen (2006) studied the statistics of record-breaking temperatures, and in Sect. VI of their paper they allowed for linear changes (a form of nonstationarity) in the mean of day-wise temperature. This makes their study relevant in the context of climate changes and their influence on the occurrence of extremes. The assumption of linear changes in the mean and either exponentially or normally distributed random components allowed Redner and Petersen (2006) to derive analytically the distribution of temperature extremes. Redner and Petersen (2006) corroborated the analytical results by means of Monte Carlo simulations and applied their methodology to a 126-year daily temperature time series from Philadelphia, Pennsylvania, United States of America.

It seems to us that we have not re-invented the methodology of Redner and Petersen (2006) or of previous workers, but with the exceedance product, $P(i)$, we introduce a new functional that combines intensity with frequency. The derivation of the time-dependent distribution (confidence limits) of $P(i)$ under realistic assumptions may be analytically intractable; therefore we resort to block bootstrap resampling. The realistic assumptions for the analysis of temperature, dew point and precipitation time series regard (1) deviations from normal or exponential distributional shapes, (2) systematic trends not only in the first moment (mean) but also in higher moments and (3) autocorrelation of the data generating process.

It may further be possible to embed the study of the distribution of functionals like $P(i)$ within the context of multivariate extremes. This theory (Beirlant et al. 2004: Chaps. 8 and 9 therein) can also be applied to our univariate process, written as $X(i,j)$, by considering a function of values:

$$f(X(i,K), X(i,K+1), ..., X(i,L)). \tag{4}$$

The function, $f$, can be designed to take various aspects of heatwaves (Table 1) into account. Smith et al. (1997) list designs to describe, for example, (1) the number of exceedances of a threshold, (2) the number of local maxima within a cluster, or (3) the cumulative total of all excesses over a threshold. The distribution of $f$ can be studied theoretically and by means of Monte Carlo simulations. Also, the serial dependence of the process $X(i,j)$ can be explored. Smith et al. (1997) analyzed daily minimum temperature at Wooster, Ohio, United States of America, during the interval from 1893 to 1987. They studied various functionals as, for example, the length of a cluster of cold extremes. We conclude that multivariate extreme value theory is a powerful tool. It has, however, yet to be utilized—and it is unclear whether this can be done—to study distributional properties and confidence limits of the newly introduced exceedance product, $P(i)$.

## 4 Results and discussion

The results (Fig. 2) reveal that the Potsdam winters had cold extremes ($TN_{low}$, $TX_{low}$) only until the mid-20th century (Fig. 2a and c). In the winters of 1940, 1942, and 1947 ice jam enhanced spring floods in central European rivers (Mudelsee et al. 2003; Brázdil et al. 2005). February 1929 was the coldest month ever recorded in Potsdam (−10.9°C average) and also Prague–Klementinum (−11.0°C).

The downward trends in the occurrence of extremely cold winters in Potsdam, confirmed by the hypothesis test, are mirrored by upward trends for warm winters, which started in 1988 (Fig. 2b and d). Noticeable are the years 1990 ($TX_{high}$) and 1998 ($TN_{high}$), but also 1903 had high $TN_{high}$ values (not shown in Fig. 2 because of the large scatter of $P(i)$ curves in the early decades).

Extremely warm winters ($TX_{high}$) became more frequent from the 1990s onwards, not only in Potsdam but also in Prague–Klementinum (Fig. 4a). Outstanding here is the year 1990, which is clearly above the 99.9% confidence limit. Back through the 19th century, minor extremes occurred sporadically, with the exception of the warm winter of 1834 (discussed below).

The various winter indices (Figs. 2a–d and 4a) display a coherent tendency of fewer cold and more warm extremes with time, in broad agreement with previous findings for many regions and larger spatial scales (Alexander et al. 2006; Moberg et al. 2006; Solomon et al. 2007). Also the summer indices (Figs. 2g–j and 4b) show a coherent picture, however, not one of cold extremes becoming less and warm extremes becoming more frequent. The warm nights in the Potsdam summer ($TN_{high}$, Fig. 2h) occurred mainly in the 1930s and 1940s, then none until the single event in 1994. The hypothesis test confirms this downward trend. Likewise, the warm days in Potsdam summer ($TX_{high}$, Fig. 2j) occurred between 1930 and 1947, and then in 1959 and 1994. Extremely cold summer nights ($TN_{low}$, Fig. 2g) or days ($TX_{low}$, Fig. 2i) in Potsdam occurred intermittently.

The summer of 2003 was recorded as very hot also in Potsdam (JJA average 20.1°C, anomaly +2.7 K with respect to interval 1893–2005). However, the exceedance product had no high value for $TX_{high}$ in Potsdam in 2003. In that summer, the heat was focused on France, Switzerland, and the southwestern parts of Germany (Schär et al. 2004). In Potsdam, however, although temperatures from June to August 2003 were generally high, they did not often break records. The heat in Potsdam was more evenly distributed over the three months than, for example, during the summers of 1947 or 1994 at Prague–Klementinum (Kyselý 2002).

Prague–Klementinum is in agreement with Potsdam regarding the occurrence of hot summer days ($TX_{high}$, Fig. 4b) during the 1930s and 1940s, examples are the years 1935 and (above 99%) 1947, but also 1994. Going further back in time, the climate of the year 1834 was exceptional: an extremely warm winter followed by an extremely hot summer. Both events are above the 99% confidence level in $P(i)$, a coincidence that is unique in the 230-year-long time series of Prague–Klementinum. Documentary evidence from Bohemia (Katzerowsky 1895; Robek 1978) confirms the warm winter of 1833/34 and the warm summer of 1834. For example, frost occurred in the night, but during the day it was warm and did not snow during the whole month of January 1834 (Robek 1978).

The trends in the occurrence of precipitation extremes at Potsdam (Fig. 2e–f) are less pronounced than those of temperatures: they are neither significantly up-/downward, nor do they exhibit clustering in certain decades. This observation applies to both winter and summer extremes. Two strong rainfall events can be identified in the $P(i)$ curves for $RR_{high}$ (Fig. 2f), namely the summers of 1927 and 2002. Both years saw also devastating flood events in the low-mountainous region 100 to 200 km south of Potsdam. (We refer to these German/Czech mountains henceforth as “Erzgebirge”, noting that the Czech expression is “Krušné hory”.) The July 1927 event (99% confidence limit) brought a flash flood afflicting the small rivers Gottleuba and Müglitz (Fickert 1934; Alt and Fickert 1936). Several stations in that region measured daily precipitation totals of more than 100 mm on July 8, 1927. Station Adolfov, 750 m a.s.l., had 209 mm. Extreme precipitation was related to a small-scale cyclone over this region (Štekl et al. 2001). However, the event in August 2002 (99.9%) was clearly stronger. Heavy precipitation (station Zinnwald, 882 m a.s.l., had 312 mm on 13 August) influenced a much larger region than the Erzgebirge, and led to a flood in the Elbe catchment with a return period of more than 100 years at station Dresden (Mudelsee et al. 2003). On the river Vltava, at station Prague–Chuchle, peak runoff reached the level of a 500-year return period, and for many places in Bohemia it had been the largest flood for several centuries (Brázdil et al. 2005). In contrast to the 1927 event (Scherhag 1948: pp 294–295 therein), the 2002 summer flood was associated with a Vb weather situation (Ulbrich et al. 2003a, 2003b; Mudelsee et al. 2004), where atmospheric lows take up warm, moist air over the Adriatic region and move in northeast direction, which may lead to orographic intensification of precipitation in the Elbe basin (van Bebber 1898).

The $P(i)$ curves for dew point at Potsdam (Fig. 4c–d) reflect to a high degree what is found for temperature ($TN_{low}$, Fig. 2a), such as the prominence of the cold winters in 1929 and 1940. An exception is the winter of 1954, which had an extreme event in dew point (Fig. 2c) but not in temperature (Fig. 2a). The weather in this winter, only moderately cool (DJF anomaly −2.4°C), was dominated by dry air masses centered in the northern, eastern, and southeastern parts of Europe (Gerstengarbe and Werner 2005). Analogously, the resulting $P(i)$ curves for $DF_{high}$ in winter (Fig. 4d) follow the curves for $TN_{high}$ (Fig. 2b) because with increased inflow of warm, maritime air from the Atlantic Ocean also the humidity increased. Intriguing are the patterns of dew point extremes in Potsdam in that summer. Minimum extremes occurred mainly during the 1970s ($DF_{low}$, Fig. 4e), while maximum extremes ($DF_{high}$, Fig. 4f), occurred during the 1960s (and in other decades, but not in the 1970s). This change of patterns is not reflected by the temperature extremes.

The absence of clear trends in extreme precipitation (Fig. 2e,f) could reflect that one series of point measurements (Potsdam), albeit of high quality, is insufficient to capture trends in the presence of high temporal and spatial variabilities. A dense network of stations with point time series would be preferable, but we doubt that many such series, long and without missing values, and with the same degree of homogeneity as the one from Potsdam, do exist. An exception may be the network of stations from Switzerland, by means of which Schmidli and Frei (2005) detected upward trends of heavy winter precipitation in the 20th century.

Other methods, such as quantile regression (Koenker and Hallock 2001) or fitting time-dependent generalized extreme value (GEV) distributions (Nogaj et al. 2006), do not seem to be directly adaptable to the analysis of the exceedance product, $P$, because the latter variable already combines the duration (time) with the intensity aspect. The multivariate view (see end of Sect. 3) confirms that quantile regression or time-dependent GEV parameter fitting does not work well for analyzing heatwaves because these concepts are from univariate statistics.

There is yet no agreed upon optimum way to study trends in the occurrence of extreme values of meteorological variables, and it is therefore beneficial to have a set of methods to study the different aspects associated with such (climatically induced) changes.

## 5 Conclusions

The time-dependent exceedance product, $P$, an index variable introduced in this paper, combines intensity with frequency to diagnose trends in extreme weather events. Trends in higher moments can be separated from trends in first (mean) or second-order (standard deviation). Bootstrap simulations produce confidence bands for the $P$ curves, which allow to assess the statistical significance of observed trends. The method can also be used for time series influenced by effects from autocorrelation, non-normal shape and inhomogeneities.

The application to long instrumental meteorological series from Potsdam and Prague–Klementinum reveal that the downward (upward) trends in the occurrence of extremely cold winters (warm winters) during the 20th century reflect a change in the higher moments, beyond mean and variance. Noticeable are the 1990s, especially the year 1990, with warm winter extremes in both locations. Also the winter of 1834 at Prague–Klementinum was extremely warm in terms of higher moments. The trends in the extremes parallel those for the mean (Potsdam, Fig. 3a) in the case of winter.

On the other hand, in the case of summer temperature extremes at Potsdam and Prague–Klementinum, extremely warm days and nights occurred mainly during the 1930s and 1940s. The summer of 2003 was hot also in Potsdam and Prague–Klementinum; however, changes in mean and variance are sufficient to describe this phenomenon statistically (Schär et al. 2004). This means, trends in summer extremes did not parallel trends in summer mean temperature.

No clear trends or clustering of extreme precipitation events were detected for Potsdam. This is in agreement with previous findings of Elbe flood analyses (Mudelsee et al. 2003). Dew-point time series from Potsdam reflect partly what is found for extreme temperatures. Surplus information about an extremely dry (but not cold) winter is found for the year 1954.

**Acknowledgements** We gratefully acknowledge the profound review comments on the theory of multivariate extremes and on previous work. We thank Friedrich-Wilhelm Gerstengarbe and Peter Werner for comments on a previous version of the manuscript. We are grateful to Andrea Bleyer for proofreading. Financial support by the Deutsche Forschungsgemeinschaft (TE 51/25) is acknowledged. Rudolf Brázdil was supported by research project MŠM0021622412 (INCHEMBIOL). A software version of the exceedance product method is available from www.mudelsee.com.

## References

Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Klein Tank AMG, Haylock M, Collins D, Trewin B, Rahimzadeh F, Tagipour A, Rupa Kumar K, Revadekar J, Griffiths G, Vincent L, Stephenson DB, Burn J, Aguilar E, Brunet M, Taylor M, New M, Zhai P, Rusticucci M, Vazquez-Aguirre JL (2006) Global observed changes in daily climate extremes of temperature and precipitation. J Geophys Res 111:D05109. doi:10.1029/2005JD006290

Alt E, Fickert R (1936) Die Hochwasserkatastrophe im östlichen Erzgebirge am 8. bis 9. Juli 1927. Springer, Berlin, p 15

Beirlant J, Goegebeur Y, Teugels J, Segers J (2004) Statistics of extremes: theory and applications. Wiley, Chichester, p 490

Beniston M (2004) The 2003 heat wave in Europe: a shape of things to come? An analysis based on Swiss climatological data and model simulations. Geophys Res Lett 31:L02202. doi:10.1029/2003GL018857

Brabson BB, Palutikof JP (2002) The evolution of extreme temperatures in the central England temperature record. Geophys Res Lett 29:2163. doi:10.1029/2002GL015964

Brázdil R, Budíková M (1999) An urban bias in air temperature fluctuations at the Klementinum, Prague, The Czech Republic. Atmos Environ 33:4211–4217

Brázdil R, Dobrovolný P, Elleder L, Kakos V, Kotyza O, Květoň V, Macková J, Müller M, Štekl J, Tolasz R, Valášek H (2005) Historické a současné povodně v České republice (Historical and recent floods in the Czech Republic). Masarykova univerzita, Český hydrometeorologický ústav, Brno, Praha, p 369

Cox DR, Lewis PAW (1966) The statistical analysis of series of events. Methuen, London, p 285

Della-Marta PM, Haylock MR, Luterbacher J, Wanner H (2007) Doubled length of western European summer heat waves since 1880. J Geophys Res 112:D15103. doi:10.1029/2007JD008510

Diffenbaugh NS, Pal JS, Giorgi F, Gao X (2007) Heat stress intensification in the Mediterranean climate change hotspot. Geophys Res Lett 34:L11706. doi:10.1029/2007GL030000

Efron B, Tibshirani RJ (1993) An introduction to the bootstrap. Chapman and Hall, London, p 436

Fickert R (1934) Das Katastrophenhochwasser im Osterzgebirge im Juli 1927. Wilhelm und Berta von Baensch Stiftung, Dresden, p 92

Frei C, Schär C (2001) Detection probability of trends in rare events: theory and application to heavy precipitation in the Alpine region. J Climate 14:1568–1584

Galambos J (1978) The asymptotic theory of extreme order statistics. Wiley, New York, p 352

Gerstengarbe FW, Werner PC (2005) Katalog der Großwetterlagen Europas (1881–2004). Potsdam Institute for Climate Impact Research, Potsdam, p 148

Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (eds) (2001) Climate change 2001: the scientific basis. Contribution of Working Group I to the third assessment report of the Intergovernmental Panel on Climate Change. Cambridge Univ Press, Cambridge, p 881

Katzerowsky W (1895) Meteorologische Nachrichten aus den Archiven der Stadt Leitmeritz (1454–1865). Published oneself, Leitmeritz, p 30

Khaliq MN, St-Hilaire A, Ouarda TBMJ, Bobée B (2005) Frequency analysis and temporal pattern of occurrences of southern Quebec heatwaves. Int J Climatol 25:485–504

Klein Tank AMG, Wijngaard JB, Können GP, Böhm R, Demarée G, Gocheva A, Mileta M, Pashiardis S, Hejkrlik L, Kern-Hansen C, Heino R, Bessemoulin P, Müller-Westermeier G, Tzanakou M, Szalai S, Pálsdóttir T, Fitzgerald D, Rubin S, Capaldo M, Maugeri M, Leitass A, Bukantis A, Aberfeld R, van Engelen AFV, Forland E, Mietus M, Coelho F, Mares C, Razuvaev V, Nieplova E, Cegnar T, López JA, Dahlström B, Moberg A, Kirchhofer W, Ceylan A, Pachaliuk O, Alexander LV, Petrovic P (2002) Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment. Int J Climatol 22:1441–1453

Koenker R, Hallock KF (2001) Quantile regression. J Econ Perspect 15:143–156

Körber HG (1993) Die Geschichte des Meteorologischen Observatoriums Potsdam. Deutscher Wetterdienst, Offenbach am Main, p 129

Künsch HR (1989) The jackknife and the bootstrap for general stationary observations. Ann Statist 17:1217–1241

Kyselý J (2002) Temporal fluctuations in heat waves at Prague–Klementinum, the Czech Republic, from 1901–97, and their relationship to atmospheric circulation. Int J Climatol 22:33–50

Lehmann A, Kalb M (1993) 100 Jahre meteorologische Beobachtungen an der Säkularstation Potsdam: 1893–1992. Deutscher Wetterdienst, Offenbach am Main, p 32

Meehl GA, Tebaldi C (2004) More intense, more frequent, and longer lasting heat waves in the 21st century. Science 305:994–997

Moberg A, Jones PD, Lister D, Walther A, Brunet M, Jacobeit J, Alexander LV, Della-Marta PM, Luterbacher J, Yiou P, Chen D, Klein Tank AMG, Saladié O, Sigró J, Aguilar E, Alexandersson H, Almarza C, Auer I, Barriendos M, Begert M, Bergström H, Böhm R, Butler CJ, Caesar J, Drebs A, Founda D, Gerstengarbe F-W, Micela G, Maugeri M, Österle H, Pandzic K, Petrakis M, Srnec L, Tolasz R, Tuomenvirta H, Werner PC, Linderholm H, Philipp A, Wanner H, Xoplaki E (2006) Indices for daily temperature and precipitation extremes in Europe analyzed for the period 1901–2000. J Geophys Res 111:D22106. doi:10.1029/2006JD007103

Mudelsee M, Börngen M, Tetzlaff G, Grünewald U (2003) No upward trends in the occurrence of extreme floods in central Europe. Nature 425:166–169

Mudelsee M, Börngen M, Tetzlaff G, Grünewald U (2004) Extreme floods in central Europe over the past 500 years: role of cyclone pathway "Zugstrasse Vb". J Geophys Res 109:D23101. doi:10.1029/2004JD005034

Nogaj M, Yiou P, Parey S, Malek F, Naveau P (2006) Amplitude and frequency of temperature extremes over the North Atlantic region. Geophys Res Lett 33:L10801. doi:10.1029/2005GL024251

Osborn TJ, Hulme M (2002) Evidence for trends in heavy rainfall events over the UK. Phil Trans R Soc Lond A 360:1313–1325

Redner S, Petersen MR (2006) Role of global warming on the statistics of record-breaking temperatures. Phys Rev E 74:061114. doi:10.1103/PhysRevE.74.061114

Robek A (1978) Městské lidové kronikářství na Rychnovsku II, Edice lidových kronikářských textů. Československá akademie věd, Praha, p 208

Schär C, Vidale PL, Lüthi D, Frei C, Häberli C, Liniger MA, Appenzeller C (2004) The role of increasing temperature variability in European summer heatwaves. Nature 427:332–336

Scherhag R (1948) Neue Methoden der Wetteranalyse und Wetterprognose. Springer, Berlin, p 424

Schmidli J, Frei C (2005) Trends of heavy precipitation and wet and dry spells in Switzerland during the 20th century. Int J Climatol 25:753–771

Seneviratne SI, Lüthi D, Litschi M, Schär C (2006) Land–atmosphere coupling and climate change in Europe. Nature 443:205–209

Smith RL, Tawn JA, Coles SG (1997) Markov chain models for threshold exceedances. Biometrika 84:249–268

Solomon S, Qin D, Manning M, Marquis M, Averyt K, Tignor MMB, Miller HL Jr, Chen Z (eds) (2007) Climate Change 2007: the physical science basis. Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge Univ Press, Cambridge, p 996

Štekl J, Brázdil R, Kakos V, Jež J, Tolasz R, Sokol Z (2001) Extrémní denní srážkové úhrny na území ČR v období 1879–2000 a jejich synoptické příčiny (Extreme daily precipitation on the territory of the Czech Republic in the period 1879–2000 and their synoptic causes). Národní klimatický program Česká republika, Praha, p 140

Ulbrich U, Brücher T, Fink AH, Leckebusch GC, Krüger A, Pinto JG (2003a) The central European floods of August 2002: Part 1 – rainfall periods and flood development. Weather 58:371–377

Ulbrich U, Brücher T, Fink AH, Leckebusch GC, Krüger A, Pinto JG (2003b) The central European floods of August 2002: Part 2 – Synoptic causes and considerations with respect to climatic change. Weather 58:434–442

van Bebber WJ (1898) Die Wettervorhersage, 2nd edn. Enke, Stuttgart, p 219

Vautard R, Yiou P, D'Andrea F, de Noblet N, Viovy N, Cassou C, Polcher J, Ciais P, Kageyama M, Fan Y (2007) Summertime European heat and drought waves induced by wintertime Mediterranean rainfall deficit. Geophys Res Lett 34:L07711. doi:10.1029/2006GL028001