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

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Summary

For the analysis of trends in weather extremes, we introduce a diagnostic 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. Application to daily meteorological records from Potsdam (1893–2005) and Prague (1775–2004) reveals that extremely cold winters occurred only until mid-20th century, whereas warm winters show upward trends. These were significant changes in higher moments of the temperature distribution. In contrast, trends in summer temperature extremes (e.g., 2003 European heatwave), can be explained by linear changes in mean or standard deviation. While precipitation at Potsdam does not exhibit pronounced trends, dew point displays an enigmatic change from maximum extremes during the 1960s to minimum extremes during the 1970s.

Zusammenfassung

Zur Untersuchung von Trends von Wetterextremen wird ein neuartiges „Wirkungsmaß” eingeführt, das Produkt der Extremwertübertreffung, welches die beiden Aspekte „Stärke” und „Häufigkeit” miteinander verbindet. Es werden Trends in höheren Momenten von Trends in Mittelwert und Standardabweichung getrennt sowie Bootstrap-Verfahren angewendet, um die statistische Signifikanz auszuwerten. Bei der Verwendung von meteorologischen Daten in täglicher Auflösung von Potsdam (1893–2005) und Prag (1775–2004) zeigt sich, dass extrem kalte Winter nur bis Mitte des 20. Jahrhundert auftraten, wohingegen warme Winter einen Aufwärtstrend aufweisen, welche signifikante Änderungen in höheren

Momenten der Temperaturverteilung darstellen. Im Gegensatz dazu kann der Trend von Sommer-Temperaturextremen (z.B. die Hitzewelle im Jahr 2003 in Europa) durch Änderungen in Mittelwert und Standardabweichung erklärt werden. Während der Niederschlag in Potsdam keine ausgeprägte Trends zeigt, weist der Taupunkt einen rätselhaften Übergang von Maximumextremen in den 1960ern zu Minimumextremen in den 1970ern auf.

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 previous work summarized in the Third IPCC Assessment Report [*Houghton et al.*, 2001]. Not only increases 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), also higher moments of distributions of weather variables may 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 record (past 220 years) evolved differently from their means. Higher moments describe the tails of a distribution, where the extremes sit: their quantification is socio-economically relevant.

Schär et al. [2004] found negative correlations between temperature and precipitation anomalies in records from Switzerland (1864–2003); 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 statistical properties: (1) intensity and (2) duration (related to empirical frequency) a threshold is exceeded. Several criterions can therefore be used to define a heatwave [*Beniston*, 2004; *Meehl and Tebaldi*, 2004]. 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 Hulme*, 2002; *Mudelsee et al.*, 2003], a variable with distributions substantially different from a normal shape.

The present paper studies trends in extreme weather and separates between changes of higher moments and changes of mean and variance. We introduce a new diagnostic variable, the “exceedance product”, to combine the intensity with the frequency aspect. We analyze besides temperature and precipitation also 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 extreme events is an inherent difficult methodical task [*Frei and Schär*, 2001], especially when, as here, a seasonal differentiation is sought. Consequently, we study long, daily-resolved, continuous instrumental records from two European stations, Potsdam and Prague.

2 Data

The records from Potsdam, Germany comprise maximum temperature, minimum temperature, dew point at 13.08 UTC (i.e., 14.00 local time), and 24 h precipitation and cover the interval from 1 January 1893 to 31 December 2005 in daily resolution; those from Prague-Klementinun, Czech Republic comprise maximum and minimum temperature and cover the interval from 1 January 1775 to 31 December 2004 in daily resolution.

The Potsdam series have a remarkable homogeneity [*Lehmann and Kalb*, 1993; *Körber*, 1993]: neither the measurement settings nor the observation times 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 records from Prague exhibit a strengthening of the urban heat island effect (for the period 1922–1995, see *Brázdil and Budíková* [1999]). The Prague records serve here to augment the Potsdam data. In the analysis, the above mentioned effect in the Prague records is taken into account.

3 Method

Let $x(i,j)$ be the value of a record 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, $i = 1, \ldots, n_i$ (Potsdam, $n_i = 113$) and days.

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

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

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 29 February value is omitted.)

Above definitions apply to maxima or positive extremes. This is the case when x is the highest of the daily maximum temperature (abbreviated as TX_{high}), the highest minimum temperature (warmest night, TN_{high}), the highest dew point (DP_{high}), or the highest precipitation amount (RR_{high}). Analogous definitions (e.g., y is minimum) are used for negative extremes, when x is the lowest maximum temperature (coldest day, TX_{low}), the lowest minimum temperature (TN_{low}), or the lowest dew point (DP_{low}).

The resulting curves of the exceedance product, $P(i)$, form the basis for evaluating trends in the occurrence of extreme events. Next is bias correction. The bias comes from the fact that with increasing 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 (Figures 1 to 4). If an observed $P(i)$ curve (gray bars in Figures 1 to 4) lies above the confidence limit at year i, we consider this as a significant extreme in P. Figure 5 illustrates the estimation of trend parameters, the subdivision of year into five periods (seasonal variations), the non-normal distribution of residuals, and their autocorrelation. Robust regression is performed for trend estimation of the 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 (Figure 5c). The residuals are drawn block-wise to preserve autocorrelation. For example, for the residuals plotted in auxiliary material Figure 5d, 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 n_k their number. Under the null hypothesis "no trend in occurrence of extremes", the statistic $u = [\sum_k T(k)/n_k - (t_2 - t_1)/2]/[(t_2 - t_1)/(12n_k)^{1/2}]$ is approximately standard-normally distributed. (Example: In Figure 1b, t_1 = 1924, t_2 = 2006, $n_k = 5$, and the $T(k)$ are labelled. 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 temperature records more robust against inhomogeneity effects.

4 Results and Discussion

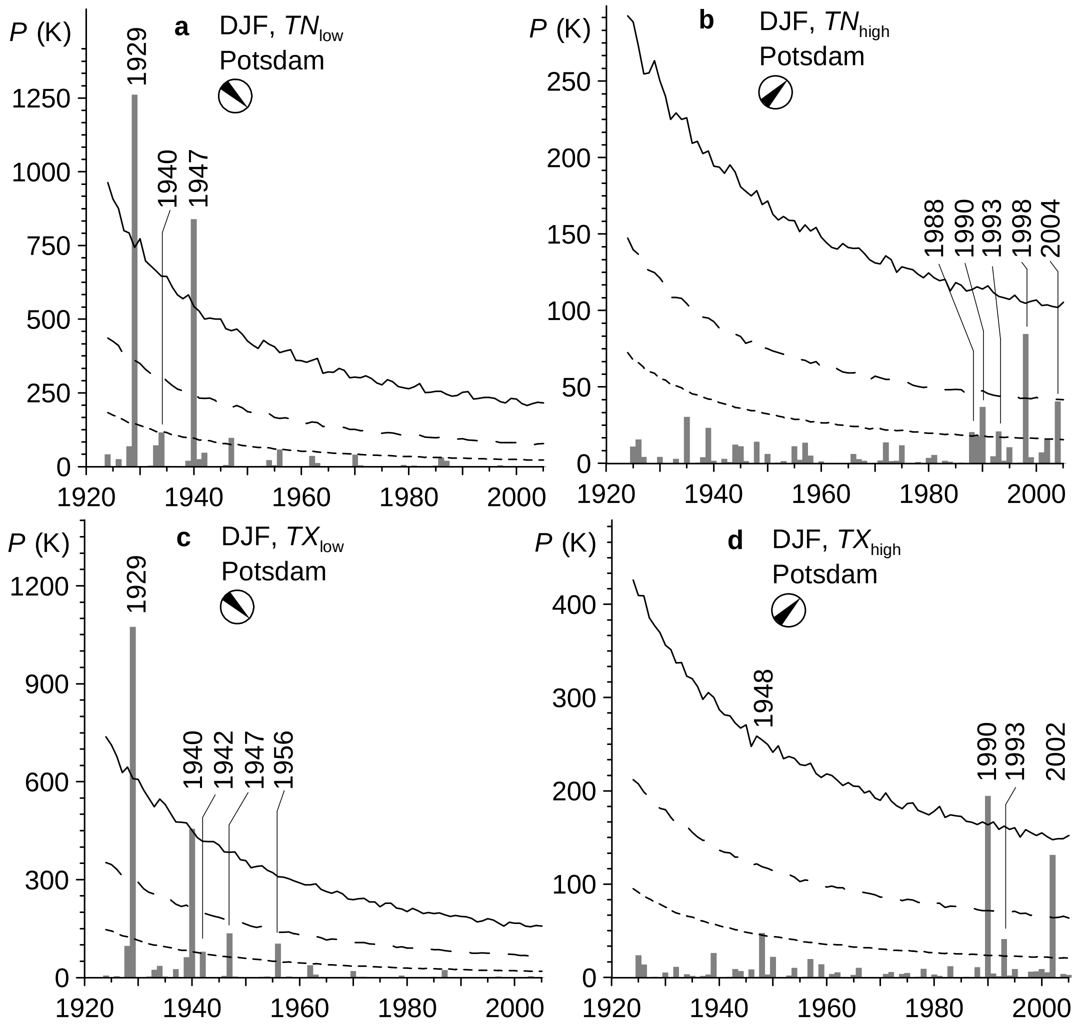

***Figure 1**: Extreme temperature (TN, TX) events in Potsdam in winter (DJF): each panel shows exceedance product P (gray bars) and its confidence limits (99.9% level, solid line; 99%, long–dashed; 95%, short–dashed); significant events are labelled. Arrows (up/down) mark acceptance in statistical tests (90% level) of the hypothesis "there is a trend (upward/downward) in occurrence of significant P events."*

The results (Figure 1) reveal that the Potsdam winters had cold extremes (TN_{low}, TX_{low}) only until the mid-20th century (Figures 1a and 1c). The winters 1940, 1942, and 1947 led also to ice-jam enhanced spring floods in rivers Elbe and Oder [*Mudelsee et al.*, 2003]. February 1929 was the coldest month (−10.9 °C average) ever recorded at Potsdam.

The downward trends in occurrence of extreme cold winters in Potsdam, confirmed by the hypothesis test, are mirrored by upward trends for warm winters, which set in 1988 (Figures 1b and 1d). Noticeable are the years 1990 (TX_{high}) and 1998 (TN_{high}), but also 1903 (not shown in Figure 1 because of large scatter of $P(i)$ curves in the early decades) had high TN_{high} values.

Extremely warm winters (TX_{high}) became more frequent from the 1990s not only in Potsdam but also in Prague (Figure 3a). 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 1834 (discussed below).

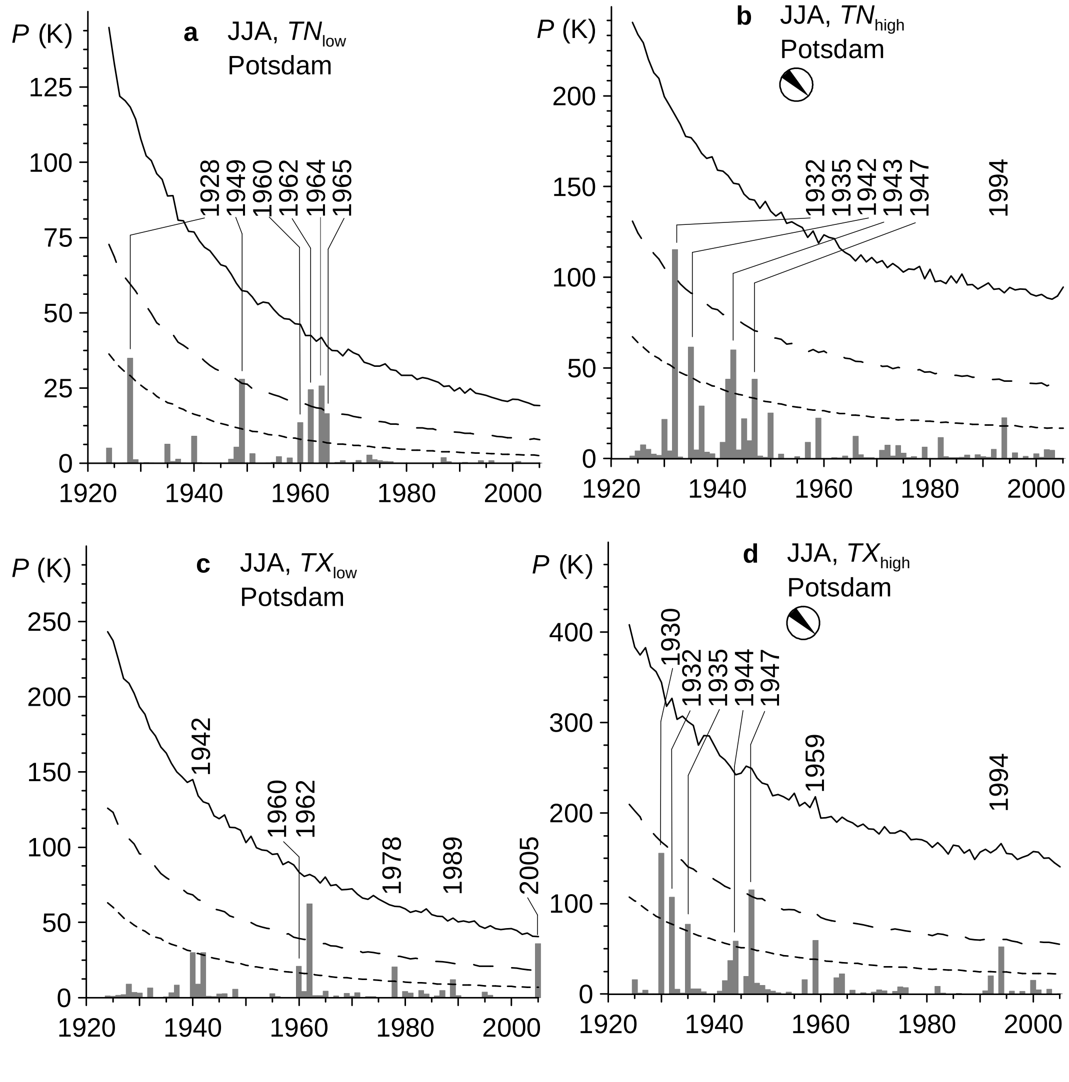

***Figure 2**: Extreme temperature (TN, TX) events in Potsdam in summer (JJA) (cf. Figure 1)*

The various winters indices (Figures 1a to 1d, Figure 3a) display coherently a tendency of fewer cold and more warm extremes with time, in broad agreement with previous findings for many regions and larger spatial scales [*Houghton et al.*, 2001]. Also the summer indices (Figures 2a to 2d, Figure 3b) show a coherent picture, however, not one of cold extremes becoming less and warm extremes becoming more frequent. The warm nights in Potsdam summer (TN_{high}, Figure 2b) occurred mainly in the 1930s and 1940s, then none until the single event 1994. The hypothesis test confirms this downward trend. Likewise, the warm days in Potsdam summer (TX_{high}, Figure 2d) occurred between 1930 and 1947, and then in 1959 and 1994. Extreme cold summer nights (TN_{low}, Figure 2a) or days (TX_{low}, Figure 2c) in Potsdam occurred intermittently.

The summer 2003 was recorded also in Potsdam as very hot (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 2003. In that summer, the heat was focused on France, Switzerland, and south-western 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 1947 or 1994 at Prague [*Kyselý*, 2002].

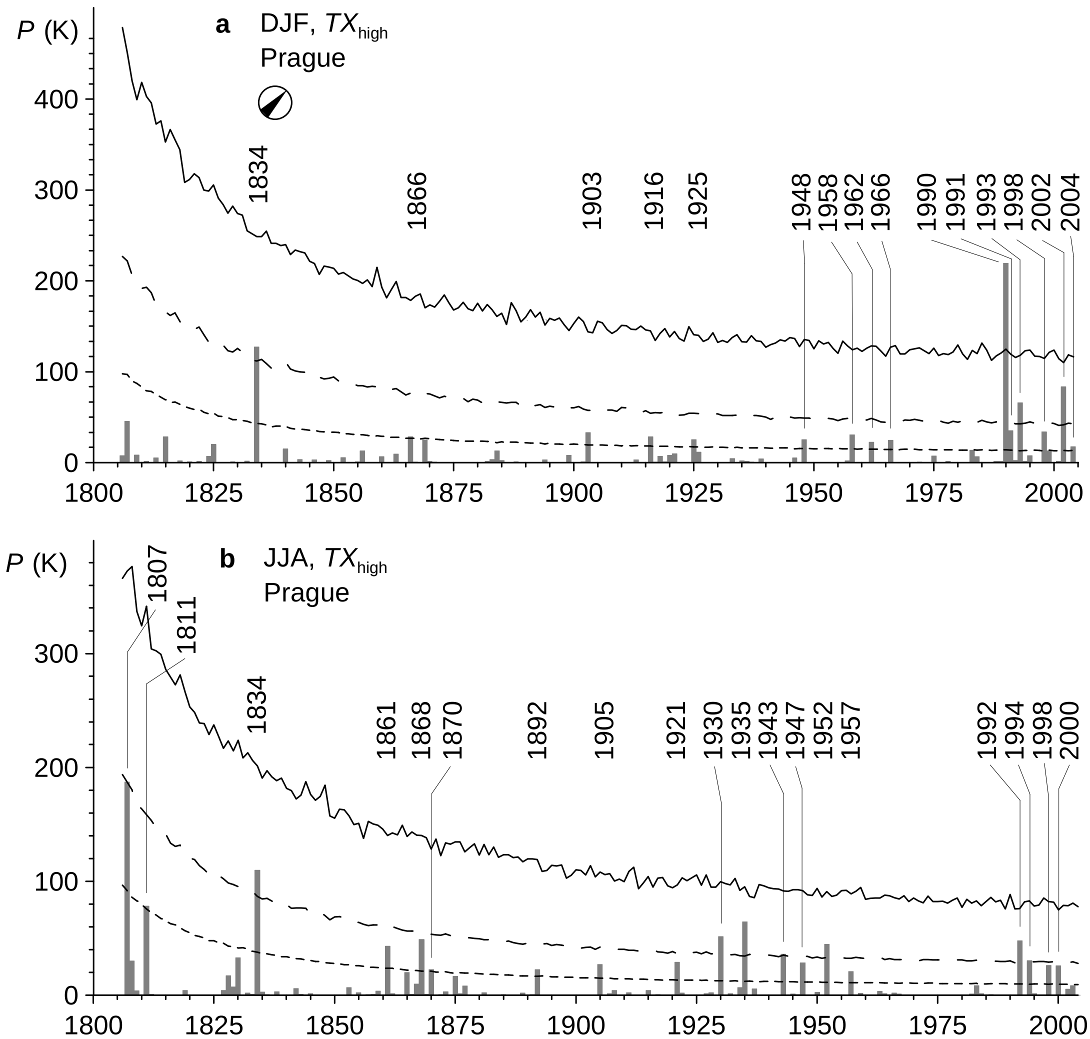

***Figure 3**: Extreme temperature events in Prague in winter (DJF) and summer (JJA), (cf. Figure 1).*

Regarding Prague-Klementinum, there is agreement with Potsdam in the occurrence of hot summer days (TX_{high}, Figure 3b) during the 1930s and 1940s, examples are the years 1935 and (above 99%) 1947, but also in 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. Documentary evidence from Bohemia [*Robek*, 1978; *Katzerowsky*, 1895] confirms the warm winter 1833/34 and the warm summer 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 (Figures 4a and 4b) are less pronounced than those of temperatures: they are neither

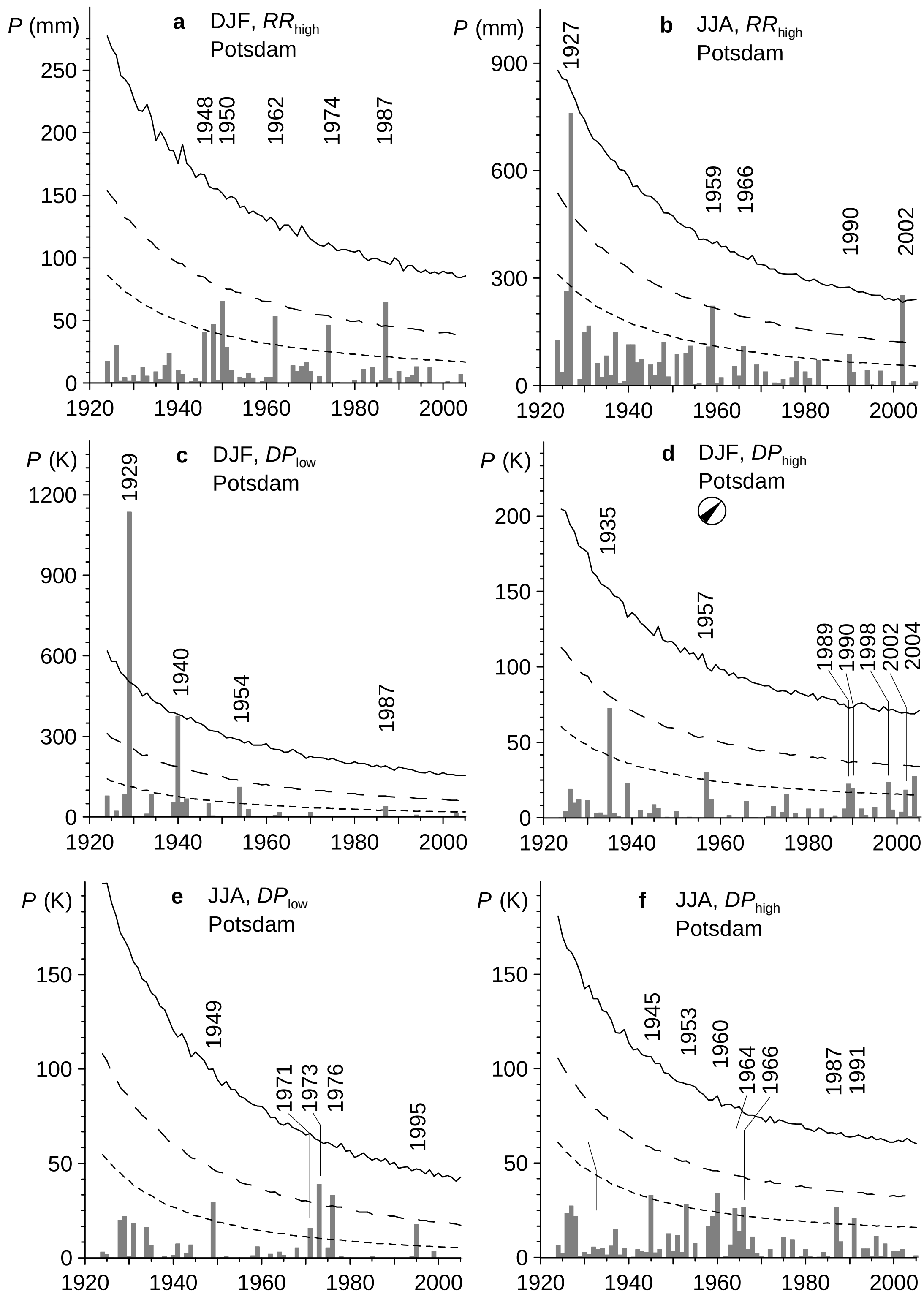

Figure 4*: Extreme precipitation (RR) and dew point (DP) events in Potsdam in winter (DJF) and summer (JJA) (cf. Figure 1)*

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} (Figure 4b), namely the summers 1927 and 2002. Both years saw also devastating flood events in the low-mountainous region (Erzgebirge) 100 to 200 km south of Potsdam. The July 1927 event (99% confidence limit) brought a flash flood afflicting the small rivers Gottleuba and Müglitz [*Fickert*, 1934]. However, the August 2002 event (99.9%) was clearly stronger. It influenced a much larger region than the Erzgebirge, and led to a flood in the river Elbe with a return period of more than 100 years [*Mudelsee et al.*, 2003]. In contrast to the 1927 event [*Scherhag*, 1948, pp. 294–295 therein], the 2002 summer flood was associated with a Vb weather situtation [*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.

The $P(i)$ curves for dew point at Potsdam (Figures 4c and 4d) reflect to a high degree what is found for temperature (TN_{low}, Figure 1a), such as the prominence of the cold winters in 1929 and 1940. An exception is the winter 1954, which had an extreme event in dew point (Figure 4c) but not in temperature (Figure 1a). 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 south-eastern parts of Europe [*Gerstengarbe and Werner*, 2005]. Analogously, the $P(i)$ curves for DP_{high} in winter (Figure 4d) follow the curves for TN_{high} (Figure 1b) 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 the summer at Potsdam. Minimum extremes occurred mainly during the 1970s (DP_{low}, Figure 4e), while maximum extremes (DP_{high}, Figure 4f), occurred during the 1960s (and other decades, but not the 1970s). This change of patterns is unreflected by the temperature extremes.

The absence of clear trends in extreme precipitation (Figures 4e and 4f) could reflect that one record 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 records would be preferable, but we doubt that many such records, long and without missing values, and with the same degree of homogeneity as Potsdam, do exist. An exception may be the network of stations from Switzerland, for which *Schmidli and Frei* [2005] detected upward trends of heavy winter precipitation in the 20th century.

Other methods like quantile regression [*Koenker and Hallock*, 2001] or fitting Generalized Extreme Value distributions with time-dependent parameters

[*Nogaj et al.*, 2006], seem not to be straightforwardly adaptable to the analysis of the exceedance product, P, because the latter variable already combines the duration (time) with the intensity aspect. There is yet no agreed optimum way to study trends in the occurrence of extreme weather events, and it is therefore benefitial to have a set of methods to study the different aspects associated with such (climatically induced) changes.

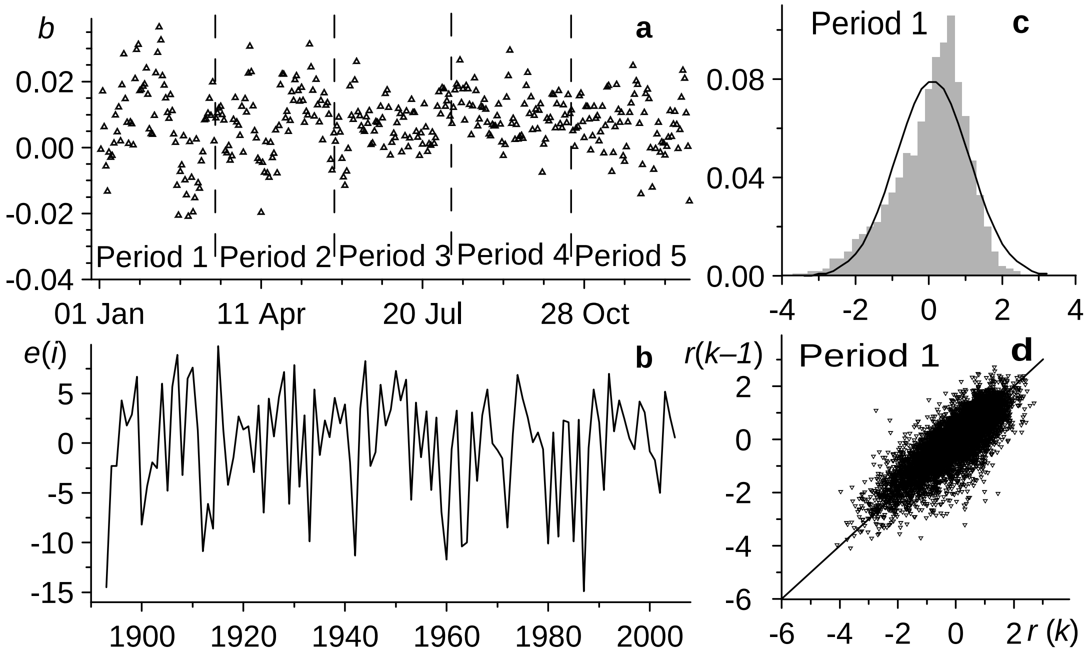

***Figure 5**: (a) Slopes of day-wise linear regression to minimum temperature over 1893–2005, Potsdam. Also shown is sub-division of year into five periods of equal length, 73 days. (b) Regression residuals, $e(i)$, for 15 January. (The $e(i)$ are calculated as $x(i,j)$ minus fitted regression.) (c)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

5 Conclusion

The newly introduced time-dependent exceedance product, P, 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 yield confidence bands for the P curves, which allow to assess the statistical significance of observed trends. The method can also be used for records influenced by effects from autocorrelation, non-normal shape, and inhomogeneties.

The application to long instrumental records from Potsdam and Prague reveal that the downward (upward) trends during the 20th century in the occurrence of extremely cold winters (warm winters) 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 1834 at Prague was extremely warm in terms of higher moments. The trends in the extremes parallel those for the mean (Potsdam, auxiliary material Figure 3a) in the case of winter.

On the other hand, in the case of summer temperature extremes at Potsdam and Prague, extremely warm days and nights occurred mainly during the 1930s and 1940s. The summer 2003 was hot also in Potsdam and Prague, 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 finding of Elbe flood analyses [*Mudelsee et al.*, 2003]. Dew point records from Potsdam reflect partly what is found for extreme temperatures. Surplus information about an extreme dry, but not cold winter is found for the year 1954.

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