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## Statistical analysis of floods in Bohemia (Czech Republic) since 1825

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**Abstract** This study focuses on two main rivers of Bohemia (Czech Republic): the Vltava and the Elbe. Flows are determined for the Elbe at Děčín (discharges) and Litoměřice (water stages), and for the Vltava at Prague (discharges). Extreme flows have an important socio-economic impact; hence modelling their occurrence accurately is crucial. We identify the meteorological causes for floods: (a) the winter type due to snowmelt, ice damming, and usually rain, and (b) the summer type due to continuous heavy rains. The amplitude and frequency of floods are analysed using extreme value theory, in a non-stationary context. This allows the determination of the trends of flood features during the instrumental period and their dependence on atmospheric circulation patterns.

**Key words** Bohemia; floods; generalized extreme value theory; peak over threshold; return level; Elbe River; Vltava River

### Analyse statistique des crues en Bohême (République Tchèque) depuis 1825

**Résumé** Cette étude traite des deux rivières principales de Bohême (République Tchèque): la Rivière Vltava et la Rivière Elbe. Les mesures sont effectuées à Děčín (débits) et à Litoměřice (niveaux d'eau) pour la Rivière Elbe, et à Prague (débits) pour la Vltava. Les débits extrêmes ont un important impact socio-économique, et la prévision de leurs occurrences et ordres de grandeur est donc cruciale. Nous identifions deux causes météorologiques pour les crues: (a) celles d'hiver sont causées par la fonte des neiges, les embâcles de glace et les pluies, et (b) celles d'été sont dues à des pluies intenses et continues. L'amplitude et la fréquence de ces crues sont analysées dans le cadre de la théorie statistique des valeurs extrêmes non-stationnaire. Ceci nous a permis de détecter les tendances des caractéristiques des crues depuis le début de la période instrumentale et leur dépendance aux types de circulation atmosphérique.

**Mots clefs** Bohême; crues; inondations; théorie des valeurs extrêmes; dépassements de seuils; niveaux de retour; Rivière Elbe; Rivière Vltava

## INTRODUCTION

Since the 1990s, several extreme floods have occurred on Central European rivers (see e.g. Ulbrich & Fink, 1995; Bronstert *et al.*, 1998; Kundzewicz *et al.*, 1999; Matějčák & Hladný, 1999). The climax came in August 2002 when the Elbe and Danube rivers flooded their basins (e.g. Ulbrich *et al.*, 2003a,b). For example, in the Czech Republic, besides 19 fatalities, a rough estimate of costs for this flood alone reached around 73 billion Czech crowns (approx. US\$3.5 × 10<sup>9</sup>) (Hladný *et al.*, 2004, 2005). In several places along the Elbe River, the peak flow reached all-time records, while flood damage of this magnitude had probably never occurred in Central Europe before. Although the costs of such catastrophes are bound to increase with time, due to the spread of building and further human activities close to rivers, the frequency and magnitude of the floods themselves may not necessarily increase. Mudelsee *et al.* (2003) compiled river flow data in Central Europe for the Elbe and Oder rivers over the last millennium from various documentary sources and concluded that flood occurrences did not increase in frequency and severity during the 20th century.



**Fig. 1** Map of Bohemia (Czech Republic) with the Vltava and Elbe rivers, showing locations of Děčín, Litoměřice and Prague.

This study focuses on two important rivers in Bohemia (the western part of the Czech Republic) with heavily populated basins, namely the Elbe (Labe in Czech) and its tributary, the Vltava (Moldau in German) (Fig. 1). The Elbe River is one of the major waterways of Central Europe. It originates in the Krkonoše Mountains (Giant Mountains) in northern Bohemia and continues over Bohemia and Germany, flowing into the North Sea. Its length in the territory of the Czech Republic is 357 km, with a watershed area of 51 393 km<sup>2</sup>. The Vltava is the longest river in the Czech Republic and one of major tributaries of the Elbe. It is 433 km long and drains 28 090 km<sup>2</sup> of the territory.

Floods of the Bohemian rivers, in the instrumental as well as the pre-instrumental period, were analysed in many studies focused either on individual disastrous events (e.g. Matějčíček & Hladný, 1999; Hladný *et al.*, 2004, 2005), or on floods in a broader scope (e.g. Kakos, 1996; Brázdil *et al.*, 2004). The most comprehensive analysis was published recently by Brázdil *et al.* (2005), who studied flood series based on instrumental data and documentary evidence for five main watersheds in the Czech Republic, including the Elbe and the Vltava.

The present paper examines the possible relationships between flood magnitude, climate variables (temperatures, precipitation) and atmospheric circulation patterns. Statistical diagnostics of these events are provided in the framework of Extreme Value Theory (EVT). In particular, the trends of flood features over the past 150 years are determined.

## **FLOOD AND SEA-LEVEL PRESSURE DATA**

Analysis of floods in Bohemia is carried out for the Vltava and Elbe rivers. The period of hydrological observations on the Vltava at Prague runs from 1 January 1825 to

31 December 2003. From these measurements, the peak discharge values above a threshold of  $1090 \text{ m}^3 \text{ s}^{-1}$ , which corresponds to a return period of two years, were selected for further investigation.

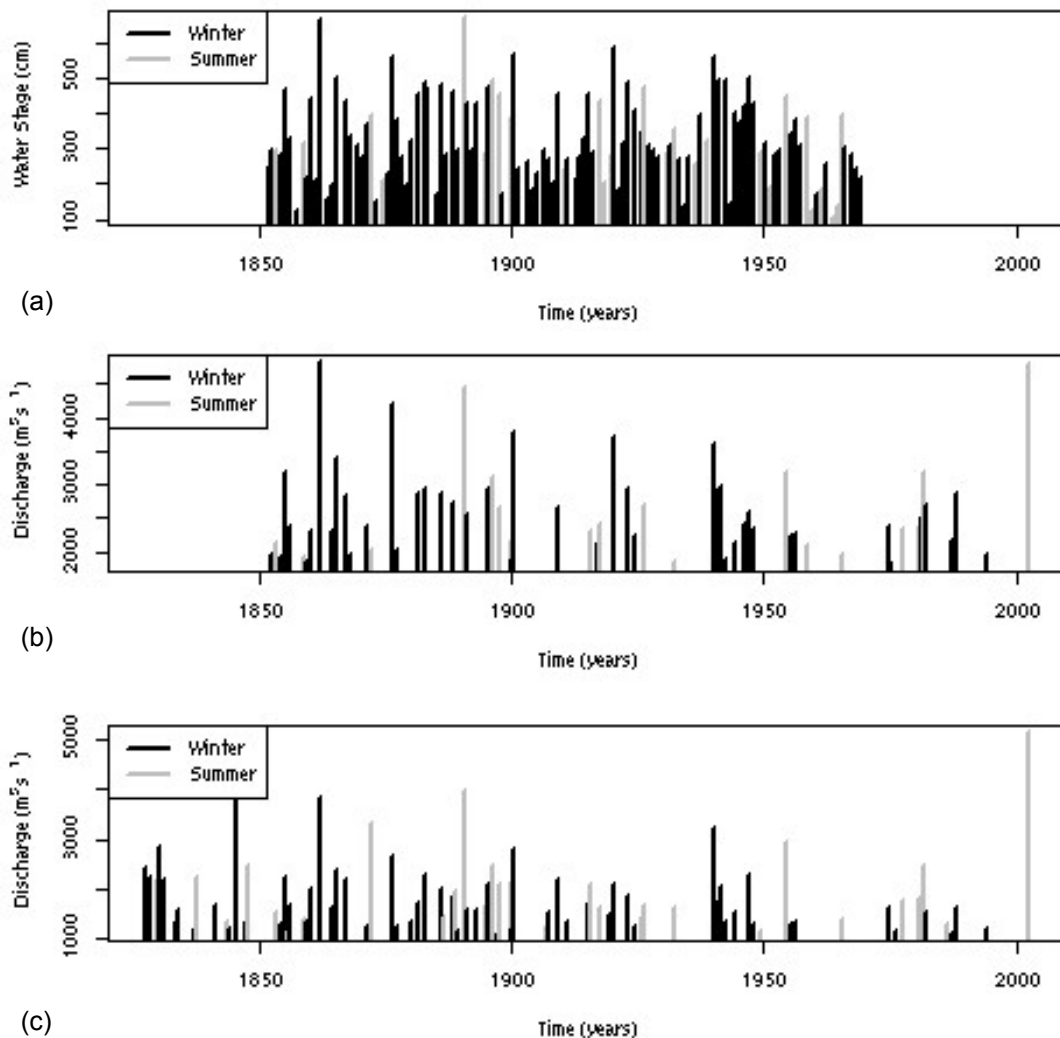
Two different data sets were used for the study of the Elbe floods. The town of Děčín is located near the border with Germany, where the Elbe leaves the Czech territory. The peak discharges above a threshold of  $1830 \text{ m}^3 \text{ s}^{-1}$ , corresponding to a return period of two years, were available for the period 1 January 1851–31 December 2003. For the town of Litoměřice, located on the Elbe not far from Děčín, there exist only series of annual peak water stages (in cm), covering the period 1 January 1851–31 December 1969, which was not re-calculated into discharge series. On the other hand, very rich documentary evidence is available on floods in the pre-instrumental period, including water levels derived from old water marks (see e.g. Brázdil *et al.*, 2005).

The hydrological regime of the River Vltava at Prague was markedly affected by the construction of a system of reservoirs (the so-called “Vltava Cascade”), mainly during the 1950s. However, the effectiveness of the Vltava Cascade in the diminution of floods in Prague drops with increasing discharges. Once its protective volume ( $172.1 \times 10^6 \text{ m}^3$  in the whole Vltava catchment) is exceeded, the effect of the cascade can be very small. To avoid this influence, all peak discharges at Prague and also on the Elbe at Děčín from 1954 were corrected to have a homogeneous series of peak discharges. Moreover, it is impossible to quantify other changes in the watersheds such as in land use, river bed, regulation of rivers, etc. (for more details see Brázdil *et al.*, 2005). The analysed time series are shown in Fig. 2.

All analysed floods were divided into two groups according to their meteorological causes:

- (a) Winter floods: floods of the winter synoptic type are related to sudden warming in Central Europe, as a consequence of warm airflow, with intense snow melting or ice jam on rivers. Synchronous occurrence of rain heightens flood intensity. These floods occur mainly from December to March, with some cases in April and November.
- (b) Summer floods: floods of the summer synoptic type occur as a consequence of heavy continuous precipitation over a few days, which can be combined with intense downpours. The trajectory and speed of cyclones with respect to the Czech territory is of key importance. These are mainly cyclones of Mediterranean origin passing along the well-known van Bebber Vb trajectory (see e.g. Štekl *et al.*, 2001; Mudelsee *et al.*, 2004). Floods of this type occur mainly from May to October, sometimes in November and April.

To study the relationships between floods and circulation patterns, the daily mean sea-level pressure (SLP) data obtained from the European and North Atlantic daily to MULTidecadal climATE variability (EMULATE) project were used. This data set (hereafter referred to as EMSLP) was produced using 86 continental and island stations distributed over the region bounded by  $70^\circ\text{W}$ – $50^\circ\text{E}$  and  $25^\circ$ – $70^\circ\text{N}$ , combined with marine data from the International Comprehensive Ocean Atmosphere Data Set (Ansell *et al.*, 2006). The EMSLP fields for 1850–1880 are based purely on observations from land stations and on board ships. From 1881, the combined land and marine fields are further combined with already available daily Northern Hemisphere fields. Complete coverage is obtained by employing reduced space optimal inter-



**Fig. 2** (a) Annual peak water stages for Elbe River at Litoměřice, and peak flood discharges for (b) the Elbe at Děčín and (c) the Vltava in Prague.

polation. Squared correlations indicate that the EMSLP data set generally captures 80–90% of daily variability represented in an existing historical SLP data set and over 90% in modern ERA-40 re-analyses over most of the region. A lack of sufficient observations over Greenland and the Middle East, however, has resulted in low quality reconstructions there. Error estimates, produced as part of the reconstruction technique, flag these as regions of low confidence. Ansell *et al.* (2006) have shown that the EMSLP daily fields and associated error estimates provide a unique opportunity to examine the circulation patterns associated with extreme events across the European–North Atlantic region.

## STATISTICAL METHODS

Analysis of the distribution of extremes is an important diagnostic tool for investigating the occurrence of rare events (Leadbetter *et al.*, 1983; Coles, 2001;

Naveau *et al.*, 2005). This study is based on a standard statistical approach, which has proved to be efficient in the fields of finance (Embrechts *et al.*, 1997) and hydrology (Katz, 1999; Katz *et al.*, 2002). The general idea of the Generalized Extreme Value theory is to parameterize the tail of the distribution of climate variables, which contains information about the distribution of extremes. For instance, a Gaussian distribution has a thin tail with a “low” probability of observing large events, whereas a distribution with a heavy tail yields a relatively high probability of having large values (and has infinite higher moments). This description is preferable to (and encompasses) the study of the probability of crossing one or several standard deviations, since climate variables such as precipitation might not have a finite variance. The general properties of extreme values are summarized below.

### Generalized Extreme Value method

The three data sets are related to extremes of flows (annual peak water stages and discharges exceeding some threshold). It is thus natural to use the Generalized Extreme Value (GEV) theory to describe them. The GEV theory has been applied in hydrological sciences by many authors, to determine discharge values associated with large return periods (Katz *et al.*, 2002). In the following, the GEV is briefly described for a stationary time series.

Under general conditions, when it converges if the number of observations grows to infinity, the maximum of an independent and identically distributed (IID) sequence of random variables has to follow a GEV distribution:

$$G(z) = \exp \left[ - \left( 1 + \xi \frac{z - \mu}{\sigma} \right)^{\frac{1}{\xi}} \right] \quad (1)$$

with  $1 + \xi(z - \mu)/\sigma > 0$  and  $\sigma > 0$ . This is analogous to the Central Limit Theorem, which states that the mean of a random variable converges to a Gaussian distribution (Coles, 2001). In equation (1),  $\mu$  and  $\sigma$  represent a location parameter and a scale parameter, respectively. The shape parameter,  $\xi$  describes the weight of the distribution tail of the random variable. Hence,  $\xi < 0$  (Weibull Law) indicates a bounded distribution (and a bounded maximum);  $\xi = 0$  (Gumbel Law) accounts for an exponential-like distribution with very rare large values; and  $\xi > 0$  (Fréchet Law) can imply an unbounded maximum and frequent large values.

In this analysis, it is assumed that the annual block maxima of water stages at Litoměřice are independent from one year to the next. Hence, the GEV method without pre-processing can be applied.

### Peak-over-threshold method

The peak discharges at Prague and Děčín have values above a threshold corresponding to a two-year return period. Thus, a classical alternative to GEV, the peak-over-threshold (POT) method can be applied (Coles, 2001). The POT method describes the probability density function of a variable when it exceeds a high threshold. For an IID

random variable,  $X$ , of distribution  $F$ , a given fixed threshold  $u$  and any positive number  $y$ , the conditional probability  $F_u(y)$  that  $X$  does not exceed  $y + u$ , given that  $X$  exceeds  $u$ , is:

$$F_u(y) \equiv \Pr(X \leq u + y \mid X > u) = \frac{F(u + y) - F(u)}{1 - F(u)}. \tag{2}$$

If the sample maximum stemming from the distribution  $F$  converges to a GEV distribution with parameters  $\mu$ ,  $\sigma$  and  $\xi$ , and if the threshold  $u$  is sufficiently large, the function  $F_u(y)$  can be approximated by the generalized Pareto distribution (GPD) with parameters  $\tilde{\sigma}$  (scale parameter) and  $\xi$  (shape parameter):

$$F_u(y) \approx H(y) = 1 - \left(1 + \frac{\xi y}{\tilde{\sigma}}\right)^{-\frac{1}{\xi}} \tag{3}$$

defined for  $y > 0$  and  $1 + \xi \frac{y}{\tilde{\sigma}} > 0$ , and where  $\tilde{\sigma} = \sigma + \xi(u - \mu)$  (Coles, 2001). Thus there is a formal correspondence between the standard GEV and GPD theories, as they share the same shape parameter  $\xi$  (Leadbetter *et al.*, 1983).

For an IID process, the number of times that the threshold is exceeded during a given interval of time is classically modelled by a Poisson distribution with parameter  $\lambda$ . The parameter  $\lambda$  describes their average frequency (therefore a large  $\lambda$  implies more frequent events). Monitoring  $\lambda$  is essential to determine whether the frequency of extreme events is constant in time or not. This approach is similar to point process models (Coles, 2001).

Compared to the GEV approach, the GPD estimate also takes into account all the observations that exceed the threshold  $u$ . In contrast, only maxima are considered by the GEV. The discharges of the Vltava at Prague and the Elbe at Dčín can exceed a high threshold more than once a year. Therefore the GPD is indeed more suited to describe these two data sets.

Historically, EVT has been designed for stationary data sets (Katz *et al.*, 2002). Since we are interested in trends of extremes, we introduce time dependences in the POT scale and frequency parameters, as discussed by Nogaj *et al.* (2006). In this procedure, time dependence for  $\sigma$  and  $\lambda$  can be linear or quadratic. For example, the linear case gives:

$$\begin{cases} \sigma(t) = \sigma_0 + \sigma_1 t \\ \lambda(t) = \lambda_0 + \lambda_1 t \end{cases} \tag{4}$$

with the constraint that  $\sigma(t), \lambda(t) > 0$ . The parameters  $\sigma_0, \sigma_1, \lambda_0, \lambda_1$  are estimated by likelihood maximization, and confidence intervals are derived. We then test the constant (i.e. stationary), linear and quadratic fits of those two parameters with a likelihood ratio test which compares models with an increasing number of parameters  $\sigma_i, \lambda_i$  ( $i = 0, 1, 2$  and  $j = 0, 1, 2$ ) to determine the best polynomial model describing the data. This procedure chooses the optimum model that represents the data extremes (Nogaj *et al.*, 2006). In this way, one can assess the time variations of the scale and rate of extreme events. Nonstationarity parameters  $\sigma(t)$  and  $\lambda(t)$  are often modelled by exponential functions to ensure their positiveness (Coles, 2001). Since this can



overamplify variations near the edges of the time series, we prefer using linear forms of quadratic models, such as equation (4). We check that the values of the parameters are always positive. The results of Mudelsee *et al.* (2003, 2004) are mainly based on estimates of the Poisson parameter  $\lambda$  and its variations through time. In this paper, we treat both the scale and frequency of extreme floods.

### Return levels

Rather than looking only at the scale and shape parameters of the EVT distributions, it is often more practical to compute return levels associated with a return period. We define a return level (RL)  $z_T$  corresponding to a return period  $T$  by the expectation of the event “to exceed the RL” to be equal to one. For instance, let  $X_t$  ( $t = 1, \dots, P$ ) be the annual maximum discharge series over  $P$  years. The number of times  $N_t$  that  $X_t$  is larger than a value  $z_T$  during a period  $T$  is given by:

$$N_t = \sum_{t=1}^T \mathbf{I}(X_t > z_T) \quad (5)$$

where  $\mathbf{I}(x)$  is the indicator function ( $\mathbf{I}(x) = 1$  if  $x$  is true, otherwise  $\mathbf{I}(x) = 0$ ). The return level  $z_T$  associated with a period  $T$  can be written as the solution of the general equation:

$$\mathbf{E}(N_t) = \sum_{t=1}^T \mathbf{E}(\mathbf{I}(X_t > z_T)) = 1 \quad (6)$$

where  $\mathbf{E}(x)$  is the mathematical expectancy of  $x$ . We derive that:

$$\mathbf{E}(N_t) = \sum_{t=1}^T \Pr(X_t > z_T). \quad (7)$$

Assuming that the data are stationary, applying EVT gives:

$$\sum_{t=1}^T \Pr(X_t > z_T) = \sum_{t=1}^T (1 - G(z_T)) = T(1 - G(z_T)) = 1. \quad (8)$$

Here,  $G(z)$  is defined by equation (1). Thus, in this case, the return level  $z_T$  associated with return period  $T$  is obtained by inverting that equation:

$$z_T = \mu + \frac{\sigma}{\xi} \left( 1 - \left( -\log \left[ 1 - \frac{1}{T} \right] \right)^{-\xi} \right). \quad (9)$$

Equation (9) has a different expression when  $\xi = 0$ , but it is derived in the same way (Coles, 2001). The relationship between  $z_T$  and  $T$  is increasing, but the derivative of the variation depends on the sign of  $\xi$ , i.e. the type of extreme distribution. This formulation can be extrapolated outside the range of the data. Thus, one can estimate return levels associated with return periods that are longer than the observational period with the caveat of large confidence intervals. For instance, one could obtain 200-year return levels of water stages with only 150 years of data. Confidence intervals for the RL are determined from the covariance matrix of the GEV parameters, assuming they follow a Gaussian distribution approximately, which is generally achieved for long time series (for details, see Coles, 2001, Sec. 3.3.3).

When taking the POT method with a threshold  $u$ , arguments similar to the ones used to derive equation (9) lead to an estimate of  $z_T$  in the stationary case:

$$z_T = u + \frac{\sigma}{\xi} \left[ (n_y T \zeta_u)^\xi - 1 \right] \quad (10)$$

where  $n_y$  is the number of observations per year and  $\zeta_u$  is the probability of an individual observation to exceed the threshold  $u$ .

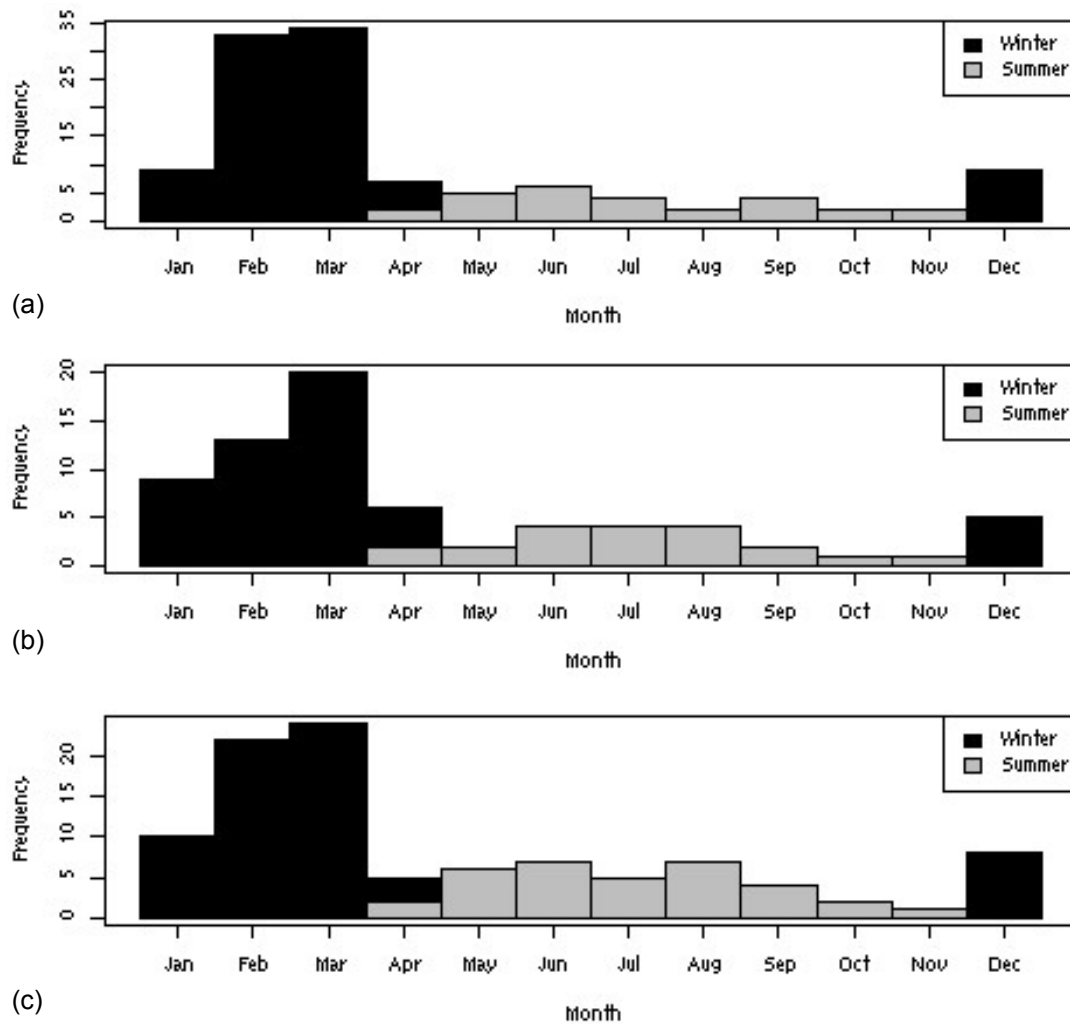
In the nonstationary case, we define a RL by a value that is exceeded once during a period,  $T$ , during which the extreme parameters can vary. Hence the RL formulation becomes more complex, because EVT parameters are not constant in equation (6). In such a case, equation (6) has to be inverted numerically to obtain the RL  $z_T$ . This computation is done for the peak flow data of the Elbe at Děčín and the Vltava at Prague. There is no simple way of obtaining confidence intervals for nonstationary RLs; therefore, the RL variations should be interpreted with caution.

## RESULTS OF STATISTICAL ANALYSES

### Correlations with climate variables

The floods observed in Bohemia obviously have meteorological causes (e.g. excess of rain and/or ice damming), but, once they occur, the relationship between their amplitude and climate variables such as temperature or precipitation is not very clear. As can be seen from the annual distribution of floods for the Elbe and Vltava, winter floods occur mainly in February and March, and summer floods primarily between May and August (Fig. 3). The magnitude of winter and summer floods is comparable in both rivers, although winter floods are much more frequent. Before performing a detailed description of the extremes of discharge data, it is helpful to assess the correlations between local temperature and precipitation rates and discharge data. In this study, we used the Prague observations of daily mean temperature and precipitation total from the European Climate Assessment (ECA) data set (Klein Tank *et al.*, 2002). Spearman (rank) correlation was used to assess the correlation coefficients between flood and climate variables (von Storch & Zwiers, 2002). This choice was motivated by the highly non-Gaussian nature of the flood and precipitation variables.

Correlations between Elbe and Vltava discharges and precipitation totals or mean temperatures in Prague during the three days preceding the floods are very small and barely significant (Table 1). We find marginally significant positive correlations of summer discharges with precipitation total, and a negative correlation of summer floods with mean temperatures. Since the occurrence of floods is clearly caused by meteorological conditions, our results suggest that precipitation and temperature in the Prague area are not the only parameters controlling the intensity of floods around Prague, especially in the winter, and that other parts of the watersheds as well as other characteristics (e.g. antecedent soil moisture) have to be taken into account. Attempts at modelling the influence of precipitation on flood trends on other rivers have shown that such a relationship is necessarily complex (Bronstert, 1995; Bates & De Roo, 2000; De Roo *et al.*, 2001), which explains the low correlations found in this study.



**Fig. 3** Histograms of (a) frequencies of maximum water stages of the Elbe River at Litoměřice; and peak water discharges of the Elbe (b) at Děčín; and (c) at Prague.

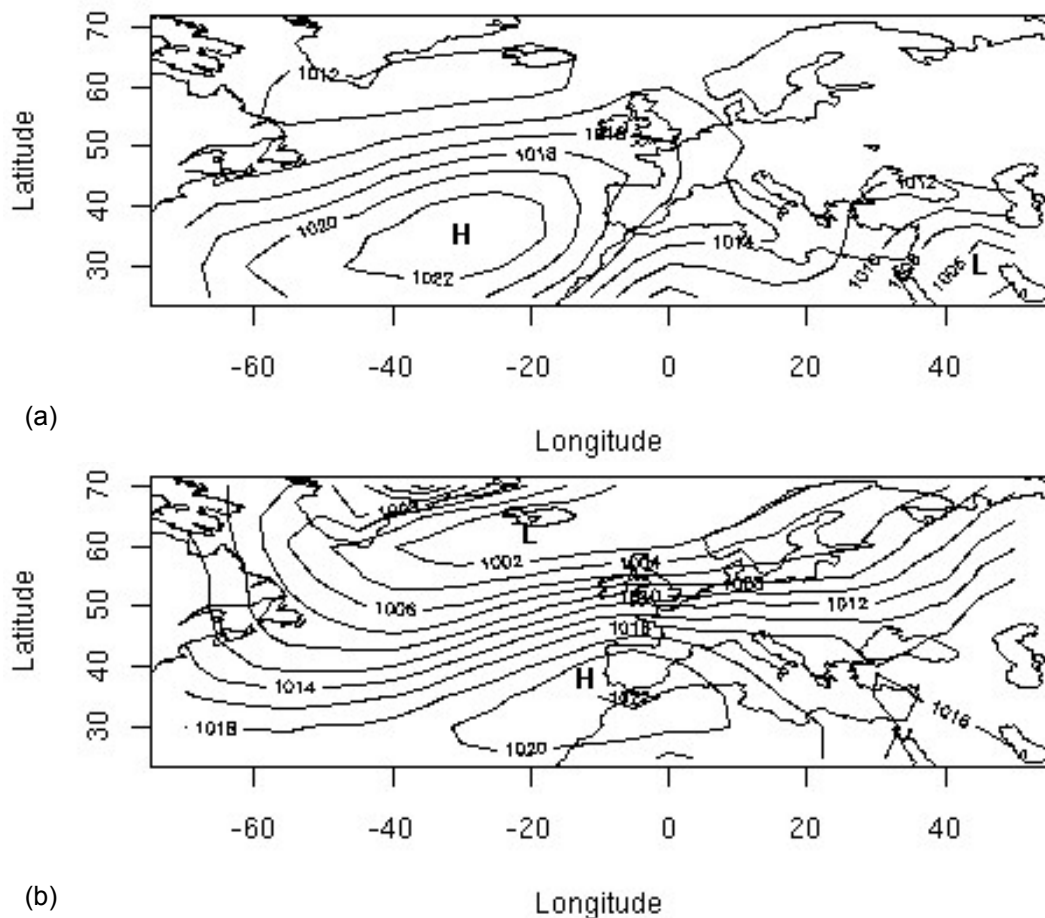
**Table 1** Spearman (rank) correlation coefficients between Vltava discharges at Prague, and mean temperatures as well as precipitation totals observed at Prague during the three days preceding a flood. The correlations were computed between 1827 and 2002 (i.e., the first and last recorded floods).

River (flood type)	Temperature	Precipitation
Vltava – Prague (summer)	-0.27 ( $p = 0.12$ )	0.28 ( $p = 0.11$ )
Vltava – Prague (winter)	0.05 ( $p = 0.65$ )	0.18 ( $p = 0.14$ )

The mean SLP patterns during the week preceding a flood on the Elbe and the Vltava between 1850 and 2003, separated for the winter and summer types of floods, are shown in Fig. 4. The SLP patterns preceding summer floods are coherent for the 18 recorded floods between the months of April and September. Their average is shown in Fig. 4(a). The SLP pattern exhibits a high-pressure zone on the Atlantic coast of Western Europe and a low-pressure zone centred on Turkey. Floods occurring in October yield a rather different SLP pattern and hence cannot be associated with the majority of summer flood circulations. A principal component analysis of sea level

pressure data (Brázdil *et al.*, 2005) indicates that a zone of cyclonic activity moves from the southeastern Mediterranean to Central Europe during three days before flood peak discharge. This pattern is obtained from the first principal component of pressure data during Prague summer floods in the period 1881–2000 and explains 28–30% of SLP variability in the Atlantic–European region.

The SLP patterns preceding winter floods are coherent with each other for the 48 recorded floods between November and March, as shown in Fig. 4(b). This SLP pattern is similar to the positive phase of the North Atlantic Oscillation (NAO; Hurrell *et al.*, 2003), with a high pressure near the Azores and a low pressure over Iceland. Such a SLP regime leads to generally warmer conditions in Central Europe that contribute to possible ice damming and snow melting. It can also be accompanied by rains. Brázdil *et al.* (2005) found a similar positive NAO pattern from the first principal component of SLP (explaining 32–39% of SLP variance) during the five days preceding the Prague winter floods in the period 1881–2000. The SLP patterns of floods in Bohemia (Fig. 4) are, as expected, reminiscent of those found by Mudelsee *et al.* (2003) in their study of the Elbe (German part) and Oder floods, although EMSLP data used in this paper are probably more accurate.



**Fig. 4** Mean SLP patterns in the Atlantic–European area during the week preceding the Elbe floods at Děčín for (a) summer and (b) winter.

## Statistics of extremes

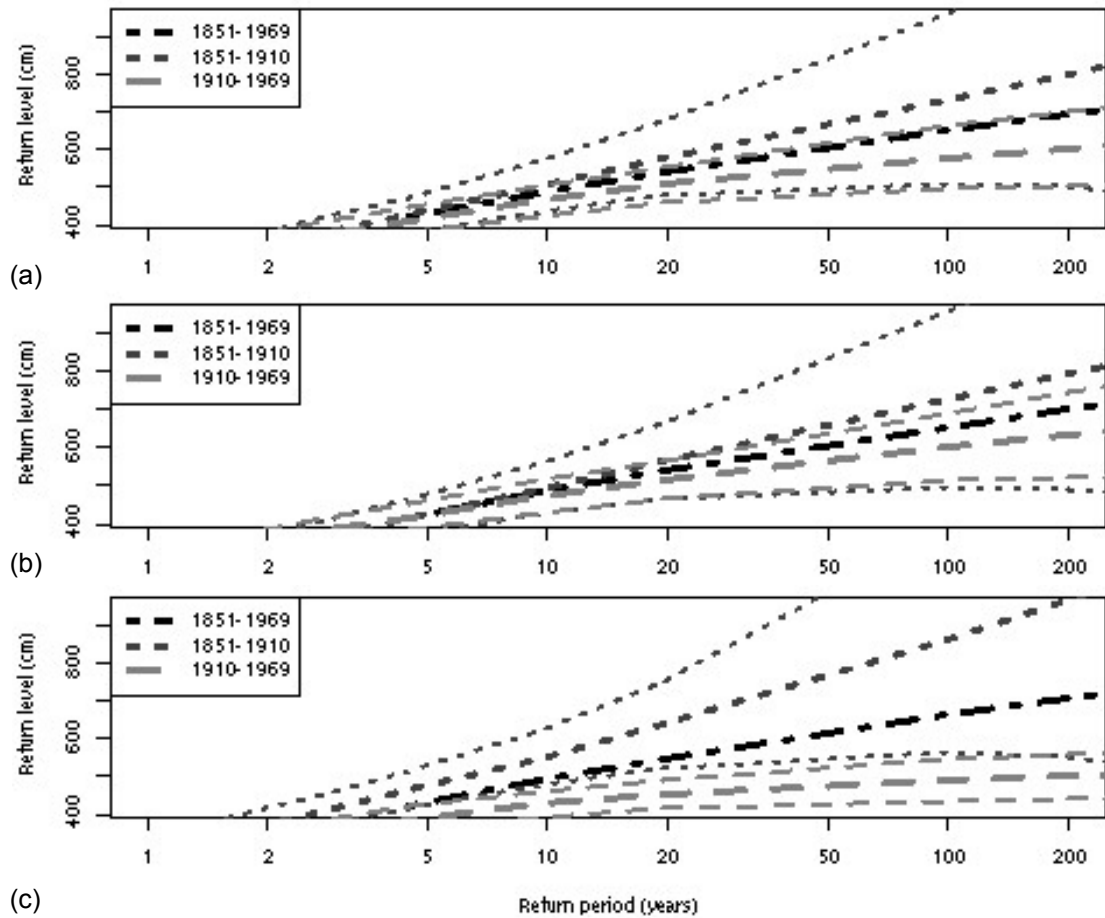
The GEV parameters – location ( $\mu$ ), scale ( $\sigma$ ) and shape ( $\xi$ ) – for the Elbe annual peak water stages at Litoměřice are  $\mu = 275 \pm 11$  (cm),  $\sigma = 105 \pm 8$  (cm) and  $\xi = -0.11 \pm 0.07$  (the values after  $\pm$  are the standard errors of the EVT parameters). Differentiating winter and summer cases does not change the GEV parameters outside the confidence intervals. The data set ends in 1969 and hence does not cover the disastrous flood of August 2002.

In order to check the temporal stability of the GEV parameters, the series of maxima was split into two equal parts – before 1910 and after 1910 – and the GEV parameters were assumed to be constant over those two sub-periods. The decade around 1910 also coincides with a period of low maximum water stages, as well as very few peaks over the threshold of the Elbe flow at Děčín. A decrease in the shape parameter (from  $-0.02$  to  $-0.22$ ) indicates a change in the behaviour of extremes after 1910. The return levels associated with these two intervals are shown in Fig. 5. The RLs with high return periods tend to decrease during the second part of the 20th century, although with overlapping confidence intervals. When separating the winter and summer maxima, the RL analysis shows that their decrease is accentuated in the summer (Fig. 5(b)–(c)). The decrease in RL values in the winter is barely meaningful because of the overlapping 95% confidence intervals.

Peak-over-threshold analyses of discharges at Prague and Děčín were conducted, using a methodology described by Nogaj *et al.* (2006). A threshold corresponding to the two-year return flood discharges was fixed for the two studied discharge series. The estimates of the Pareto parameters  $\sigma$  and  $\xi$ , as well as the Poisson parameter  $\lambda$ , are summarized in Table 2, in which the summer and winter types of floods are separated. For both seasons and all rivers the shape parameter  $\xi$  estimates are very close to zero, and the corresponding confidence intervals contain the zero value.

If all years (including 2002) and floods are considered, the scale parameter is constant, which could be anticipated from a visual inspection of Fig. 2. The flood rate  $\lambda$  is also best modelled by a decreasing function for the two rivers. Winter floods are the most frequent, as seen in Fig. 3. This is also reflected by a relatively high  $\lambda$  for both rivers. The scale and frequency of the winter floods diminish with time, while mean temperatures increase and precipitation totals in the winter do not exhibit any trend. This suggests that warmer winters are not favourable for forming of deep snow cover and they hinder the formation of ice jams as well, i.e. reducing the probability of significant winter floods (see e.g. Kakos, 1996; Brázdil *et al.*, 2005). In the summer, a constant  $\lambda$  is obtained, with one large flood every 5–7 years. The scale of the summer floods is either constant (the Vltava) or increasing (the Elbe).

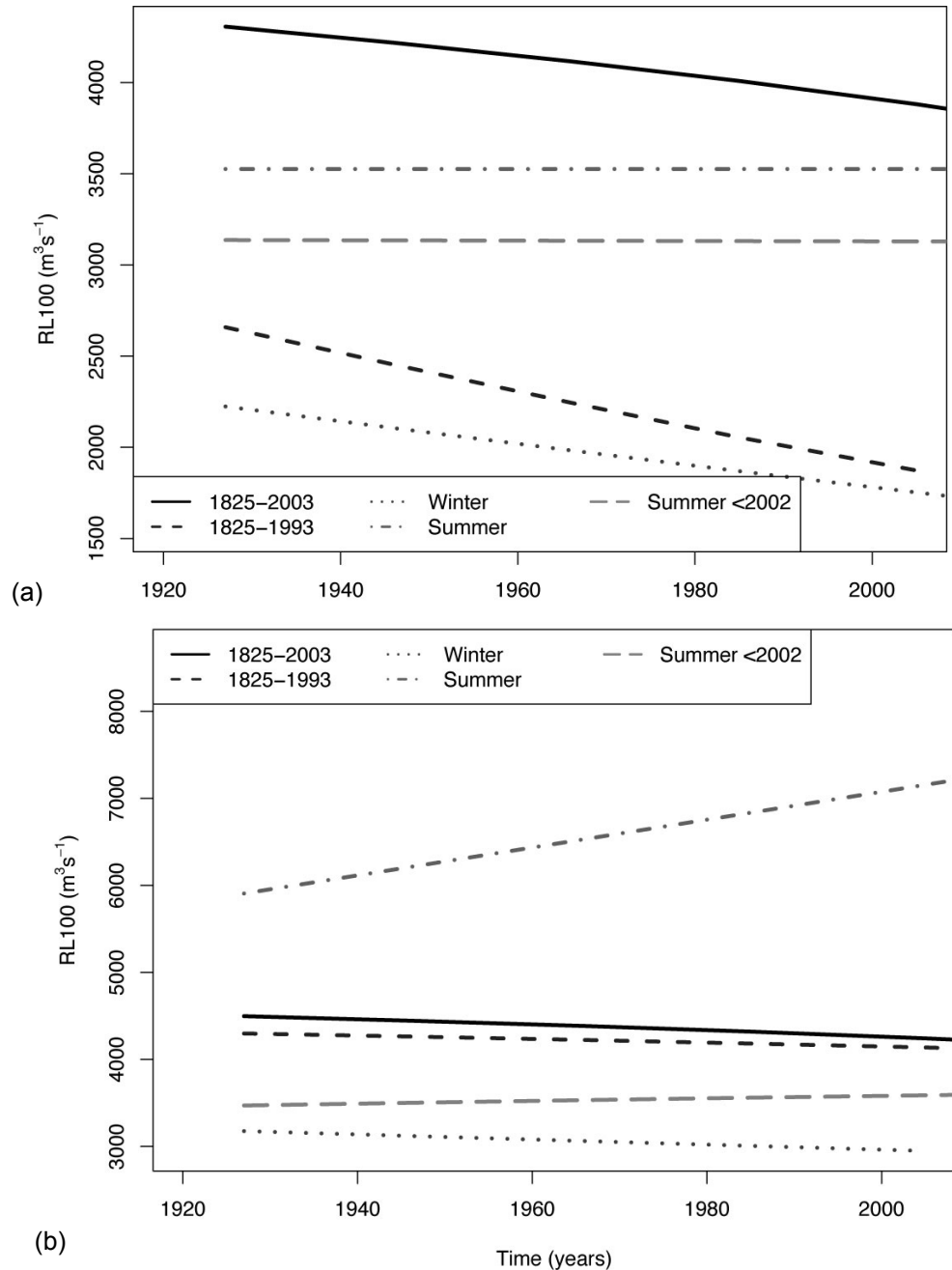
If only floods before the year 2002 are included in the analysis, the estimates of scales and frequencies of extreme discharges decrease, albeit with a small slope. Since the year 2002 is close to the absolute record for the river discharges, considering this event inevitably pulls all the extreme parameters towards a stationary sequence of extremes. Thus, when the flood of 2002 is not taken into account, the scale parameter  $\sigma$  yields a decreasing trend, but considering this flood leads to a constant and larger value of  $\sigma$ . However, the  $\lambda$  parameter for the Elbe summer floods at Děčín, which was increasing during the 20th century, is constant when the 2002 flood is included in the analysis. This is explained by the fact that the penultimate flood was in 1993, while the average frequency of summer floods before 1993 was one every seven years, and nine



**Fig. 5** Return levels for varying return periods of the maximum annual levels of water stages for the Elbe at Litoměřice: (a) for the whole year; (b) for winter levels and (c) for summer levels. Dark grey (dotted lines): 1851–1910; light grey (dashed lines): 1910–1961; black (dash-dotted line): 1851–1961. Confidence intervals (95%) for each RL variation are shown as thinner corresponding lines.

**Table 2** Pareto parameters ( $\sigma$ ,  $\xi$ ) and Poisson parameter ( $\lambda$ ) for the Vltava (Prague) and Elbe (Děčín) peak flood discharges. The parameters were computed for the different types of floods, including and excluding the August 2002 flood. Time  $t$  is expressed in fraction of years since the first date of the record. For example,  $t$  varies from 1 to 176 for the Prague data set. The shape parameter  $\xi$  values are very small and can be considered as zero within 95% confidence intervals.  $T < 2002$  indicates analyses without the year 2002.

River (station)	Period	Threshold, $u$ ( $m^3 s^{-1}$ )	Pareto $\sigma$ ( $m^3 s^{-1}$ )	Pareto $\xi$	Poisson $\lambda$ (number of events/decade)
Vltava (Prague)	All years (1827–2002)	1090	606	0.10	$8.8 - 3.4 \times 10^{-3}t$
	$T < 2002$		$475 - 2.4t$	-0.01	$8.5 - 2.9 \times 10^{-2}t$
	Winter		$332 - 1.4t$	0.03	$5.8 - 8.6 \times 10^{-3}t$
	Summer		768	0.05	1.9
	Summer $T < 2002$		793	-0.11	$2.1 - 3.6 \times 10^{-4}t$
Elbe (Děčín)	All years (1852–2002)	1830	765	-0.07	$6.7 - 2.5 \times 10^{-2}t$
	$T < 2002$		733	-0.09	$6.5 - 1.9 \times 10^{-2}t$
	Winter		$642 - 2.0t$	-0.29	$4.7 - 5.5 \times 10^{-3}t$
	Summer		$1110 + 5.5t$	0.10	1.3
	Summer $T < 2002$		601	0.03	$1.2 + 3.5 \times 10^{-3}t$



**Fig. 6** Variations of 100-year return levels (RL) of peak discharge values for (a) the Vltava at Prague and (b) the Elbe at Děčín. RLs are computed over the 1825–2003 period. RLs for whole years, summer and winter floods are indicated. The line description is given in the panel legends.

years separate the last two summer floods. Return levels associated with a return period of 100 years were computed for each of the five sets of POT parameters identified in Table 2, for the Vltava and the Elbe. The resulting variations are shown in Fig. 6. They show a general decrease in RLs, with the decrease in POT parameters.

As expected, if the 70 highest values of Vltava discharges at Prague are taken into account, four of them have a peak discharge at Děčín on the same day, 34 the day

after, 19 two days after, and one four days after. Only 12 of them are not accompanied by floods on the Elbe at Děčín. This can provide a crude precursor (1 day ahead) of the Elbe floods. Indeed, the Vltava is the main tributary of the Elbe in Bohemia, and, at the confluence with the Elbe, it has even higher average discharge.

## CONCLUSIONS

A statistical analysis of floods for the Vltava and Elbe rivers in Bohemia showed that their occurrence and intensity have generally decreased over the 20th century, although precipitation totals in Bohemia do not show such trends. The decrease in winter is slightly correlated with the mean temperature increase, although there are also some changes in watershed features (mainly in land use, building of water reservoirs, etc.). On the other hand, the second part of the 19th century (covered in both rivers by instrumental records) was characterized by the highest frequency and severity of floods. This period, as well as the whole 19th century, has no analogue during the past millennium (Brázdil *et al.*, 2005). Interestingly, the 2002 summer flood alters the trend estimates of the diagnostics of floods for the Elbe and Vltava rivers. This flood was provoked by excessive precipitation totals, with which mitigating actions (such as river management) were not designed to cope.

General decreasing trend in flood occurrences and intensity during the instrumental period in Bohemia is consistent with the analysis of Mudelsee *et al.* (2003, 2004) for extreme floods in the Elbe in Germany and the Oder for the past 80–150 years. A similar tendency (with the exception of a disastrous flood in July 1997) is detectable also in the eastern part of the Czech Republic for the Morava and Oder rivers (see Brázdil *et al.*, 2005). Also, no increased frequency of floods with a return period of 10 years and more was discovered for rivers in Sweden (Lindström & Bergström, 2004). Kundzewicz *et al.* (2005), analysing annual maximum flow of 70 European rivers, found a statistically significant decrease for only nine stations and an increase for 11 stations. These studies still do not confirm the expected increase in flood frequency in connection with the global warming related to manmade influences on the atmosphere (McCarthy *et al.*, 2001). On the other hand, the disastrous floods of July 1997 and August 2002 in Central Europe may be the first signs of extreme flooding due to increasingly heavy rains. Such behaviour has been predicted by climate model calculations (see e.g. May *et al.*, 2002; Milly *et al.*, 2002; Christensen & Christensen, 2003), with the caveat that climate models do not easily capture realistic regional precipitation patterns.

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