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Could global warming have caused the most recent floods on the Tisza River?

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Abstract The Hungarian part of the Tisza River has experienced the highest ever flood peaks during the last four years, higher than any in the 100-year series of observations. The purpose of this paper is to analyse the possible causes of these floods and establish methodologies for the assessment of design floods. The first task is to identify the common meteorological features occurring prior to floods. Large-scale atmospheric circulation patterns are considered for this purpose. The time series of these variables shows non-stationary behaviour. The time series of circulation patterns is investigated for the frequencies of the patterns and their duration. The relationship between the circulation patterns and discharge changes helps identification of the amount to which climate change or climate fluctuations are responsible for the unusual behaviour of the Tisza River.

Key words climate change; circulation pattern; flood; Tisza River, Hungary

INTRODUCTION

During the last few years several parts of the world experienced extreme floods. The recent floods in Central Europe (Rhine: 1993, 1995; Oder: 1997; Elbe and Danube: 2002) were related to extreme precipitation amounts preceding the events. The water system of the River Tisza has two main typical properties: its system is forked and has several subsidiary streams, and when the river reaches the plain area the slope of the riverbed reduces to a few centimetres per kilometre. The watercourses forming a fan up against the east–northeastern crags of the Carpathians collect precipitation water from fronts coming from the south and west. A large number of extreme situations is conceivable, because each cyclone affects each part of the basins differently. The Hungarian part of the Tisza River has experienced the highest ever flood peaks during the last four years, higher than any in the 100-year series of observations. Figure 1

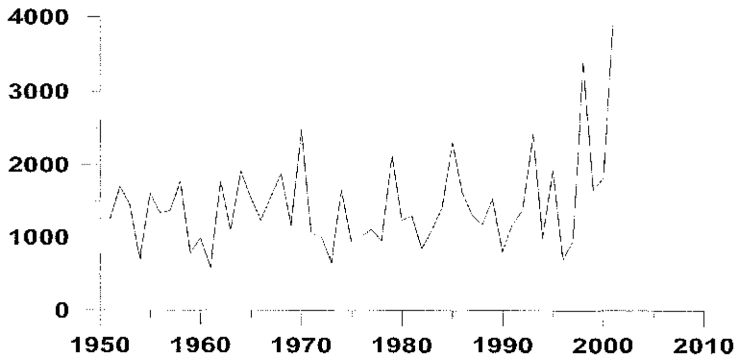

Fig. 1 Time series of annual peak discharges of Tisza River at Tivadar.

shows the time series of the annual maxima for the upper part of the Tisza River at Tivadar. Possible causes for the increase of extremes might be: (a) changes in land cover in the catchments; (b) unusual weather conditions either corresponding to normal climate variability, or partly due to climate change.

Land-use changes in the region during the last 30 years were mostly due to afforestation, In contrast to deforestation processes between 1950 and 1970. As an increase of the forested area generally leads some decrease of peak discharges, changes in the climate might be responsible for the recent floods.

The purpose of this paper is to identify critical weather patterns leading to floods, and to investigate the time series of the frequency of these patterns.

METHODOLOGY

The purpose of this section is to investigate the link between circulation patterns (CP) and floods, and to develop a methodology for the identification of flood producing CPs from daily sea level pressure (SLP) fields. A better understanding of the meteorological causes of floods might explain changes in flood frequencies in time and lead to better design flood estimation.

It is obvious that there is a close relationship between large-scale atmospheric conditions and local climatic variables. This has been investigated by different authors for more than 40 years (Bürger, 1958; Lamb, 1977). Recently, the regional forecasting of the effects of climate change has led to the development of a large number of methods for downscaling. There are several methods which quantitatively link surface weather variables (precipitation, temperature) to large scale atmospheric variables such as SLP, or geopotential elevations, or other derived indices (vorticity, flow direction). Wilby *et al.* (1998b) give a good overview of different techniques.

In contrast, there are only a few investigations of the direct relationship of large-scale atmospheric features and river discharge. The only exception are the studies investigating the relationship between ENSO or NAO and floods (Waylen, 1989; Arnell, 1999). These studies are not based on daily observations but relate anomalous discharges, mostly floods in a selected season, to the El Niño or La Niña events, or NAO anomalies.

On the daily time scale the relationship between large-scale features and discharge is difficult to find. The main reasons for this are: (a) the delayed reaction of basin runoff related to the concentration time; (b) the other influencing factors related to the state of the basin such as previous rainfall, state of the vegetation cover; and (c) high discharges occur both on the rising and on the falling limb of the discharge curve.

A possible advantage of considering discharge is that it integrates the precipitation falling over a large area, and is thus less influenced by local differences. In Duckstein *et al.* (1993) the authors investigated the occurrence of daily circulation patterns prior to floods in Arizona. They concluded that there were CPs which occur statistically significantly more frequently before floods than on arbitrary other days. Caspary (1995) investigated the link between the occurrence of floods in southwest Germany and westerly circulations. He found that in selected regions all winter floods were related to zonal circulation.

As the relationship between the SLP fields and surface climatic variables or discharge is highly nonlinear, an explicit functional relationship can hardly be found. In contrast, a classification method can easily cope with the nonlinearity. The classification method used is the modified version of the fuzzy-rule based classification presented in Bárdossy *et al.* (2002). It is based on the concept of fuzzy sets (Zadeh, 1965) which enables the ability to deal with imprecise statements. The CPs are based on sea level pressure data observed over Europe and the Eastern Atlantic. The grid resolution is 5° × 5°. Every CP is defined with the help of a fuzzy rule giving the locations of high and low normalized pressure values (anomalies). The rules are identified using an optimization algorithm.

The task of the optimization based on discharge observations is to achieve such a set of CPs, which explain the increase of discharge as much as possible. It means that the discharge series have to be transformed into new series by subtracting discharges on consecutive days:

$$\Delta Q(t) = Q(t) - Q(t-1) \tag{1}$$

In this way, positive increments are obtained for the rising limb of hydrograph and negative for the falling limb. Because critical weather causes an increase of the discharge we are only interested in positive increments. However, on mesoscale basins one-day's weather might cause an increase of discharge on the following days. This is why, in order to find the appropriate cause of an increase, more subsequent increments have to be considered.

After this transformation, the objective function can be defined as follows:

$$O = \frac{1}{T}\sum_{t=1}^{T}\sum_{k=0}^{K}\left|\ln\left(1 - \frac{\Delta Q^{+}(CP(t-k))}{\overline{\Delta Q}}\right)\right| \tag{2}$$

where T is the number of days, $\Delta Q^{+}(CP(t))$ is the average positive increment conditioned to CP occurrence and $\overline{\Delta Q}^{+}$ is the unconditioned average positive increment. In order to take into account the delay time between the meteorological conditions and the discharge response, K previous days were also considered in equation (1). During the optimization the objective function is maximized. For maximizing the objective functions a simulated annealing algorithm was used. A detailed description of the algorithm can be found in Bardossy *et al.* (2002). Large

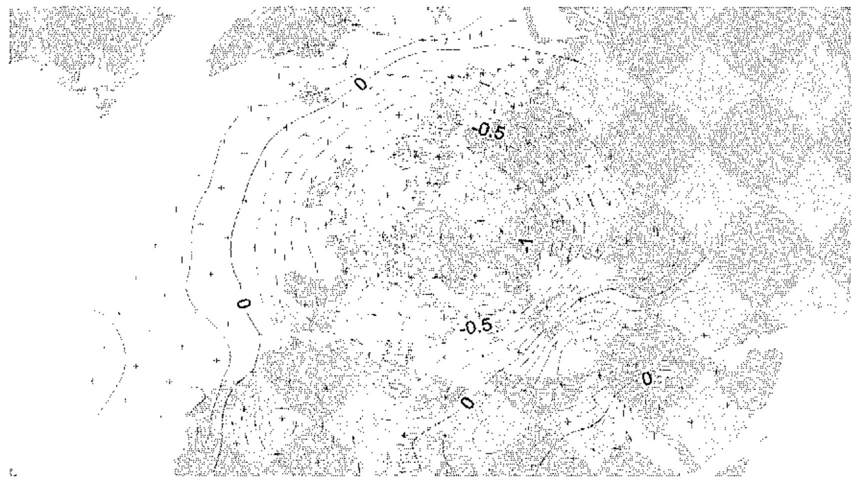

Fig. 2 Normalized SLP anomalies corresponding to CP01 for the Tisza at Vásárosnamény (------ negative anomalies, —— positive anomalies).

values of *O* indicate that the classification explains the meteorological conditions that lead to floods very well.

APPLICATION

The above-described methodology was applied to two nested sub-basins of the Tisza River. The first upstream from Tivadar has an area of 12 540 km^2; the second upstream from Vásárosnamény has an area of 29 057 km^2. Using the simulated annealing algorithm, ten CPs were identified for each sub-basin. For Tivadar the increase of two consecutive days was considered; for Vásárosnamény, four days were taken into account. For both basins two critical flood producing CPs could be identified. For both Tivadar and Vásárosnamény the most critical CP caused more than four-times higher discharge increments than a normal day on average. The CPs obtained differ only slightly—with low pressure centres more to the east for the upper subcatchment (Tivadar). Figure 2 shows the map of the anomalies corresponding to CP01—the most flood relevant CP for Vásárosnamény.

The anomalies are well structured and show that a low pressure centre southeast of Poland is related to strong precipitation and subsequent possible floods in the upper Tisza basin. The occurrence of these patterns does not necessarily cause floods, but conversely most of the floods were caused by these patterns. Figure 3 shows the 100 biggest floods at Vásárosnamény for the period 1900–1999. The CPs occurring on the days before the peak, which are responsible for the increase of the discharge, were identified. Three classes were formed, CPs caused by CP01, CP05 and others. It is seen from Fig. 3 that most of the floods were caused by CP01, some by CP05. The biggest flood, which does not correspond to CP01 or CP05, ranks 10 among the observed floods.

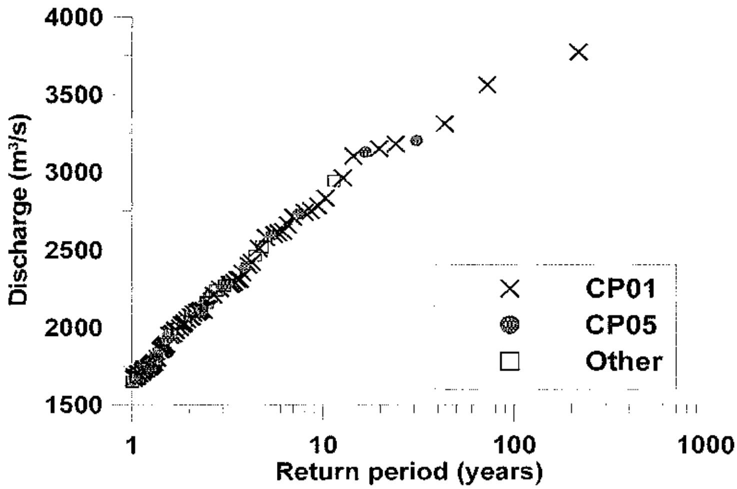

Fig. 3 The 100 largest observed floods on the Tisza at Vásárosnamény for the time period 1900–1999, with the corresponding CPs.

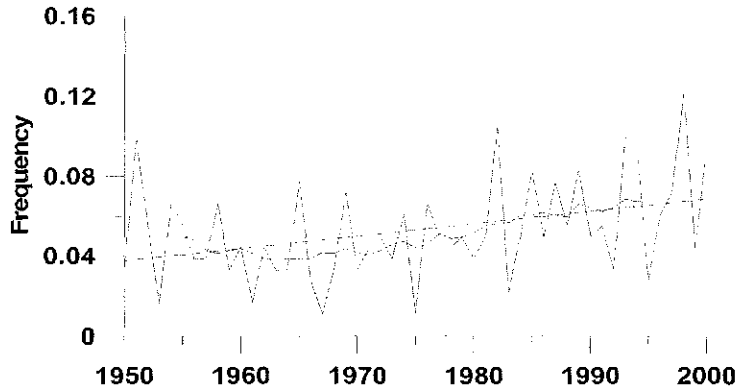

Fig. 4 Annual frequencies of CP10 for the Tisza at Tivadar.

In order to investigate possible changes in the occurrence and magnitude of the floods the frequency of the critical CPs was calculated for the observation periods. Figure 4 shows the frequencies of CP10 for Tivadar. A slight increase of the occurrence of this pattern can be seen on the figure.

For Vásárosnamény a longer series could be constructed. Figure 5 shows the frequencies of CP01 in the months November to May. This time period was chosen as most of the floods occurred during these months, and CP01 was seldom related to floods in summer and autumn. The increase of the frequencies is significant for these patterns.

Different statistical tests, as suggested in WMO (2000), were applied to investigate the stationarity of this series. All of them rejected the hypothesis of stationarity. The changes of the frequencies of the patterns could be a possible explanation for the increase of floods in the Tisza basin.

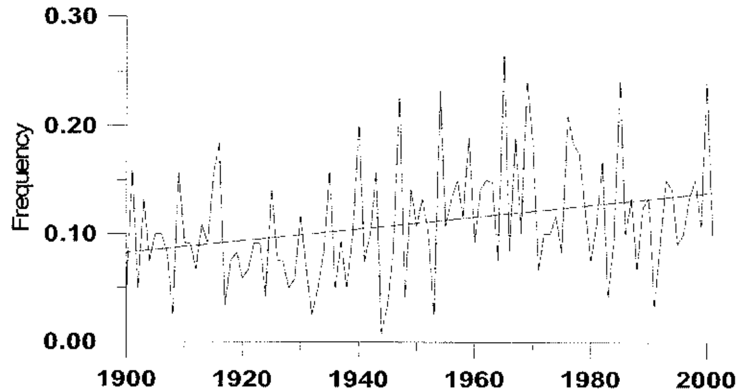

Fig. 5 Annual frequencies of CP01 for the Tisza at Vásárosnamény.

DISCUSSION AND CONCLUSIONS

In this paper we have shown that the increase of discharge can be used for the identification of flood producing circulation patterns. The occurrence of these patterns does not automatically lead to a major flood, but conversely most of the floods that occurred typically have an atmospheric origin. Further investigation of the influence of the duration of the patterns on floods is necessary. The link between CPs and floods can be used to explain recent changes in flood occurrence. On the other hand, changes of the occurrence of flood producing CPs can, at the moment, not be directly related to climate change caused by the increase of CO_2 in the atmosphere. The methodology described can, however, be used in connection with GCM outputs to assess future trends in flood occurrences and magnitudes.

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