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Change detection in high river flows in Europe

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Abstract Several destructive floods have occurred in the last decade in Europe, causing record high material damage. The question of detection and attribution of changes in various flood-related indices attracts increasing interest. Among the mechanisms that can impact flood risk are changes in socio-economic systems, which influence terrestrial systems, and changes in the climatic system. The atmosphere's water holding capacity, and hence the potential for intense precipitation, increases with temperature and more intense precipitation has been documented. However, a general and coherent increase in high river flows has not been detected. Results of change detection studies of 70 long time series of annual maximum daily river flow in Europe show that the overall maxima (for the 1961–2000 period) occurred more frequently in the subperiod 1981–2000 than in the subperiod 1961–1980. A sample of results of national studies is also presented. Regional changes in the timing of floods have been observed in many areas of Europe, with increasing incidence of late autumn and winter floods (caused by rain) and fewer spring snowmelt floods. Also, the number of ice-jam related inundations has gone down. On the other hand, intensive and long-lasting summer precipitation episodes have led to disastrous recent floods in Central Europe.

Key words climate change; climate variability; Europe; floods; global change; hydrological extremes; river flow

INTRODUCTION

Over several decades, extreme climate-related events, including floods have become more destructive worldwide. Floods cause material damage of the order of tens of billions of dollars per year in both developed and developing countries, and thousands of fatalities, mostly in developing countries. Since 1990, there have been over 30 flood events worldwide in each of which the material losses exceeded one billion US$ and/or the number of fatalities was greater than one thousand.

Several destructive floods have recently hit Europe. The material flood damage recorded in the European continent in 2002 was higher than in any single year previously. The floods in Central Europe in August 2002 alone (on the rivers Danube, Labe/Elbe and their tributaries) caused damage exceeding 15 billion Euro.

Therefore, the search for a climate change signature in flood records has been an area of much recent interest. It has been driven by the attempt to understand observed changes in flood damage and to set a context for the projections of increasing frequency and severity of floods in the future.

OBSERVED CHANGES IN HIGH FLOW

Is there a climate change signature in flood data? Existing projections announce an increasing frequency and severity of floods in the future, warmer world with an accelerated hydrological cycle. A question can be posed: How do these prognostications fare in the context of the evidence provided by the data already observed?

Published results of change detection in flood flows do not give a conclusive and general proof as to how climate change affects the flood behaviour, in the light of the data observed so far. The general statement that high floods are becoming more frequent is supported by several studies, while other publications do not report such evidence, or changes observed are not statistically significant. It may well be that strong natural variability overshadows weak, if any, greenhouse signature.

Kundzewicz *et al.* (2004a) studied a set of 70 long time series of annual values of maximum daily discharge in European rivers. The data consist of time series collected at 17 stations in Germany, 15 in Norway, 13 in the United Kingdom, 12 in Finland, five in Sweden, two in each of the Czech Republic and Romania. The analysis does not support the hypothesis of a general growth of annual maximum river flows. Out of 70 time series, only 20 show statistically significant changes (11 increases and nine decreases), while most (50) time series do not show any significant changes. Table 1 presents stations where significant changes (at the level of 90%) have been observed. Figure 1 presents the direction and significance of changes in annual maximum daily river flow at stations examined in Europe.

The lengths of the data series are not the same, yet 69 data sets started before 1960 and one in 1960. Hence, it is interesting to examine the number of occurrences of the highest maximum annual flow in particular decades. It turns out that, from 1990 to 2000, as many as 17 occurrences of highest maximum annual flow were noted. Fewer occurrences of highest annual maximum flows have been noted in the earlier decades (11 in 1980–1989, seven in 1970–1979, and only four in 1960–1969). In seven cases, the highest maximum annual flow occurred in the 1950s (there were five of 54 series starting in 1950 or earlier). In 25 cases, the highest maximum flow occurred before 1950, and in several cases of long time series, in the 19th century (cf. Fig. 2).

Since all the series, analysed by Kundzewicz *et al.* (2004a), commence no later than 1960, the year 1961 can be taken as the starting point for a 40-year common period for all data and then this common period can be divided into two 20-year subperiods. It was found that the overall maxima (for the whole 1961–2000 period) occurred more frequently (46 times) in the later subperiod, 1981–2000, than in the earlier subperiod, 1961–1980 (24 times). This was despite the fact that not all time series lasted until the year 2000. Series at 15 stations end in 1999 and at six stations end in 1998. Hence, it may well be that even more maxima fall into the subperiod 1981–2000.

Svensson *et al.* (2004) studied changes in flood data for six European rivers, using a number of indices, such as: annual maximum daily mean river flow, peak-over-threshold (POT) indices, POT1 and POT3 set in such a way that, on average, one or three POTs were selected per year. The POT indices were used for both magnitude and frequency of floods. For each of the six European river stations, changes in five indices

Fig. 1 Trends in annual maximum flows (source: Kundzewicz *et al.*, 2004a).

Table 1 Significant changes in annual maximum flow in European rivers.

Station No.	River, station, country	Data period	Significance level
Significant increases			
6335100	Rhine River, Kaub, (DE)	1931-2002	97.52
6335125	Kinzig, Schwaibach, (DE)	1921-2000	98.71
6335350	Lahn, Leun (Neu), (DE)	1936-2001	91.58
6607650	Thames, Kingston, (GB)	1883-2000	93.38
6608200	Teifi, Glan Teifi, (GB)	1960-2000	91.83
6609400	Avon, Evesham, (GB)	1937-1999	92.57
6731165	Gaular, Viksvatn, (NO)	1903-2000	98.68
6731200	Vosso, Bulken, (NO)	1892-2000	99.3
6731610	Fusta, Fustvatn, (NO)	1909-2000	90.95
6854600	Iijoki, Raasakka (near the mouth), (FI)	1911-2001	98.6
6855500	Karjaanjoki, Lohjanjarvi-Peltokoski, (FI)	1938-2001	98.38
Significant decreases			
6335301	Main, Schweinfurt, (DE)	1845–2000	99.51
6335500	Main, Wuerzburg, (DE)	1824–2001	99.35
6337400	Weser, Hann.-Muenden, (DE)	1831–2000	99.96
6545200	Krka, Podbocje, (SI)	1933–1999	94.92
6609500	Severn, Bewdley, (GB)	1922–2001	96.46
6731160	Nausta, Nausta, (NO)	1909–2000	95.94
6731280	Austena, Austena, (NO)	1925–2000	97.0
6731300	Etna, Etna, (NO)	1920–2000	99.2
6731455	Otta, Lalm, (NO)	1914–2000	92.93

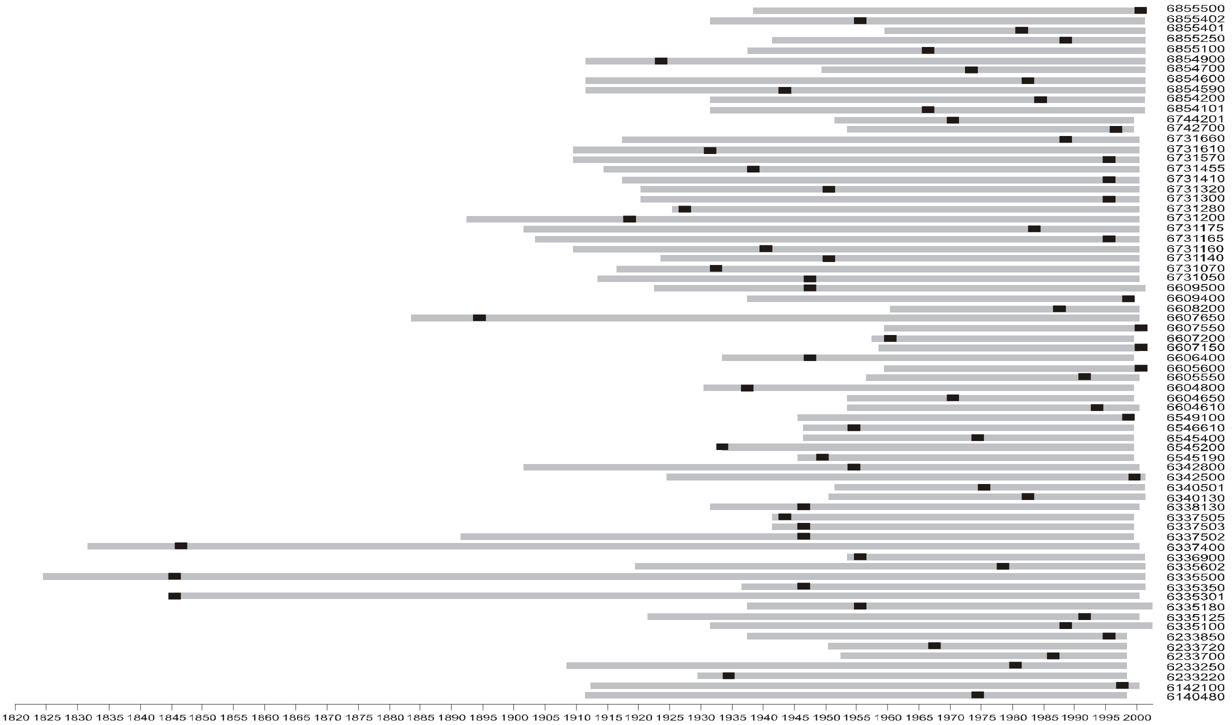

Fig. 2 Years of occurrence of maximum flows in European rivers (source: Kundzewicz *et al.*, 2004a).

were evaluated, with the help of two methods for each (linear regression and the Mann-Kendall test with significance levels obtained by block bootstrapping). For two of the six cases, i.e. the Morava at Moravicany and Vantaanjoki at Oulunkyla, none of the tests found a significant change for any of the indices. For two stations, Kinzig at Schweibach and Avon at Evesham, growing trends were detected in some indices by one or two methods (with only one case of a significant change in POT frequency). For Krka at Podbocje and Etna at Etna, some indices show significant decreases. At the former station, both the POT frequency indices show significant decreases according to both methods.

Milly *et al.* (2002) demonstrated an increase in the frequency of severe floods (exceeding 100-year levels) in 16 extratropical basins worldwide during the 20th century. They examined long series of monthly river flow data and concluded that seven out of eight 100-year floods (on a monthly scale) occurred in the second (more recent) half of the records.

There have been a number of trend detection studies for European flood data, mostly at the national level (cf. Table 2). There has been a plethora of studies of time series at single streamgauges reporting trend detection and this has encouraged researchers to extend the analysis into a truly spatial domain. However, spatial patterns are problematic. Only some series show a significant trend and out of those only some feature an increasing trend, while others exhibit decreasing trends. It is not uncommon that neighbouring gauges behave in a different way, possibly due to non-climatic factors, which are not necessarily in tune with gross climate-related drivers.

It is difficult to disentangle the climatic component in the flood data which are subject to strong natural variability and influenced by man-made environmental

Table 2 A sample of findings on trends in existing flow data reported in literature.

Country	River	Time interval	Principal findings	Source
UK	~600 stream gauges in the UK	Records of length 15 to over 100 years	Significant non-stationarity in annual maxima and peak-over-threshold (POT) variables was detected. Some regional features were visible in the results. More increases than decreases of flooding, particularly in Scotland and in South East of England, were noted.	Robson & Reed (1996)
	Tay in Scotland	1988/9 *vs* 1996/7	Number of flood-induced embankment failures has grown nearly fivefold.	Gilvear & Black (1999)
Sweden	61 stations	1807–2002, and parts thereof	Substantial recent increase in both annual discharge and flood magnitude was found, but it is not exceptional in the context of high flows experienced earlier.*	Lindström & Bergström (2004)
Germany	Elbe and Oder	Instrumental and documentary data	No upward trends in the occurrence of extreme summer floods were detected but downward trends for winter floods were found.	Mudelsee *et al.* (2003)
	Elbe	20th *vs* 19th century	Decrease in discharge rates corresponding to a range of recurrence intervals (from 2 to 200-year) was noted.	Bronstert (2003)
	Four rivers in Germany	Long time series	Marked recent increase in the amplitude of floods. The 100-year-flood determined from the older data corresponds to much lower return periods (between 5 and 30-year-flood) for the more recent data.	Caspary (2000)
	Rhine at Cologne	1890 to 2000	Growing trend in annual maxima was observed.	Engel (1997)
Austria	441 stations in Austria	1952–1991 and parts of this period	Only in a portion of cases (from 4.3% to 31.5 %), a significant trend was detected, therein more examples of positive trend (64.3%) than of negative trend (35.7%). Analysis of the full 40-year period results in detection of a positive trend in 66.3% of the cases with significant trend.	Nobilis & Lorenz (1997)

[*] Although Linström & Bergström (2004) concluded, based on their study of trends in 61 river flow series in Sweden, that flood magnitude increased substantially between 1970 and 2002, they have weakened this corollary in a number of ways. Firstly, they stated that occurrence of such floods is not exceptional as similar conditions were experienced there in the 1920s. Furthermore, flood peaks in old data are probably underestimated, while the largest flow increase was found in less reliable data series. It is therefore difficult to conclude that flood levels are increasing in a statistically significant way.

changes. Highly skewed distributions render change detection in annual maxima of daily river flows difficult. Kundzewicz *et al.* (2004a) showed that it is not uncommon that the highest recorded annual maximum daily flow at a given station is considerably (several times) higher than the second highest value in the long time series of records. As noted by Radziejewski & Kundzewicz (2004), tests are not able to detect a weak trend or change that has not lasted sufficiently long, but this cannot be interpreted as a demonstration of the absence of change. With the enhanced climate change, the changes of hydrological processes may be stronger and last longer, so that the likelihood of change detection may grow.

Important changes have been observed in river flow regimes, i.e. temporal distributions of flow. Regional changes in the timing of floods have been observed in many areas, with increasing incidence of late autumn and winter floods (caused by rain) and fewer snowmelt floods in Europe. In much of Europe high flows now come earlier in the year due to earlier snowmelt (sometimes in winter rather than spring) and less snow cover may reduce the severity of spring snowmelt floods. During warmer and wetter winters with less water storage in snow, increased flows are observed. It seems that, where the rivers still freeze, milder winters lead generally to thinner ice cover and shorten the persistence and reduce the severity of ice jams. The number of inundations caused by ice jams has gone down as a result of warming (more rivers do not freeze at all) and better human capacity to cope with ice-based obstructions of flow. Looking at the data assembled by Mudelsee *et al.* (2003), in the last 150-year time series of maximum daily flow on the Elbe (Dresden gauge), one can see that the discharge of 3000 $m^3 s^{-1}$ was exceeded 11 times: eight times in winter (1862, 1865, 1876, 1881, 1895, 1900, 1920, and 1940), and only three times in summer (1896, 1890, and 2002); the last discharge being the highest. This illustrates that floods have not been common in the 20th century and that severe winter floods, frequent in the days of yore, have not occurred on the Elbe for the last 64 years.

Intensified extreme hydrological events have been associated with observed changes in climatic variability (e.g. oscillations in the ocean–atmosphere system. Unprecedented increase of the frequency, persistence, and intensity of El Niño (warm phase of ENSO) has been observed since the mid 1970s (IPCC, 2001), accompanied by a higher probability of occurrence of wetter-than-usual conditions, and high river flow, in several regions. Also the NAO index has been high during the last two decades, with a possible link to high river flows in Europe.

On the other hand, intensive and long-lasting summer precipitation episodes (in particular, related to the Vb cyclone track (cf. Kundzewicz *et al*., 2004) have led to several disastrous recent floods in Europe, e.g. the Odra/Oder deluge in 1997 (cf. Kundzewicz *et al.*, 1999), the 2001 inundation in the Vistula basin and the 2002 flooding on the Elbe and its tributaries. Not only were historic records of material losses exceeded, but also records of hydrological variables, such as stage and discharge. The maximum stage of the River Elbe at Dresden (940 cm in August 2002) was far above the former record (877 cm in 1845) and the peak discharge at Raciborz-Miedonia on the Odra in July 1997 was twice as high as the second highest on record.

REASONS FOR CHANGE

Destructive floods observed in the 1990s all over the world have led to record highs of material damage. The immediate question emerges, as to the extent to which this measured increase of flood hazard and vulnerability can be linked to climate variability and change.

One can identify three groups of factors which control the river flow process: changes in climate, changes in terrestrial systems, and changes in socio-economic systems. Flood hazard and vulnerability change over many areas due to a range of factors whose relative order of importance is site-specific. It would be enlightening to study longer time series of records pertaining to flood-related variables. Yet, this is possible only to a limited extent, since long time series are only available for a few variables, and then only in a very limited number of locations (Kundzewicz & Schellnhuber, 2004).

The Intergovernmental Panel on Climate Change (IPCC, 2001a) reports that the costs of extreme weather events have exhibited a rapid upward trend; yearly economic losses from weather extremes increased tenfold (in inflation-adjusted dollars) between the 1950s and the 1990s. The insured portion of these losses has grown even stronger.

A part of this trend is linked to socio-economic factors, such as population increase and accumulation of wealth in vulnerable areas. However, these factors alone cannot explain the whole observed growth, and a portion of it is linked to climate.

Climatic factors

Changes in climate and atmospheric systems refer to: total precipitation, intense precipitation events, temperature (controlling snowmelt and ice-jam), seasonality and climate variability (e.g. ENSO, NAO, PDO, IPO).

It is generally difficult to find a gradual, low-frequency change (e.g. related to climatic impacts) in the behaviour of the extremes of river flow, amidst overwhelming natural variability. In order to detect a weak, if any, climate change component, it is necessary to eliminate other influences, e.g. by using data from baseline river basins.

According to IPCC (2001), the increase of global land precipitation over the 20th century was statistically significant, but neither spatially nor temporally uniform. Precipitation increase was of the order of 7–12% for the zones 30°N to 85°N. Marked increase in precipitation in the later part of the 20th century over Northern Europe (New *et al*., 1999; IPCC, 2001) has been observed. A general increase in precipitation in the Northern Hemisphere mid- and high latitudes, is particularly pronounced in autumn and winter (IPCC, 2001a).

As the atmosphere's water holding capacity, and thus its absolute potential water content, increase with temperature according to the Clausius-Clapeyron law, the potential for intensive precipitation also increases. More pronounced increases in heavy and extreme precipitation events have been observed, arising from a number of causes, e.g. changes in atmospheric moisture and large-scale storm activity. Increased atmospheric moisture contents favours more intensive precipitation events thus increasing the risk of flooding. Over the latter half of the 20th century it is likely that there has been a 2–4% increase in the frequency of heavy precipitation events reported by the available observing stations in the mid- and high latitudes of the Northern Hemisphere (IPCC, 2001). For instance, there is evidence that the frequency of extreme rainfall has increased in the UK (IPCC, 2001a) and a greater proportion of precipitation is currently falling in large events than in earlier decades (Osborn *et al.*, 2000), at the expense of moderate events.

In their studies of *Grosswetterlagen* (synoptic-scale weather patterns), Bárdossy & Caspary (1990) noted a rise of frequency and persistence (measured by the time intervals of occurrence) of some "wet" patterns (in particular Wz, i.e. West cyclonic) in catchments in Southwest Germany during the autumn. A similar tendency of precipitation was detected by Engel (1997), who compared climatological standard normals of precipitation over the intervals 1931–1960 and 1961–1990 in the Rhine basin up to Cologne, Germany. He found increased precipitation during the fall (November–January) and spring (March–June).

Some recent rainfall events in Europe have exceeded all-time records. On 12–13 August 2002, a new German record of one-day precipitation (06:00–06:00 h) of 312 mm was measured at the Zinnwald-Georgenfeld gauge (matching the observation at a nearby Czech station in Cinovec), while in the category of 24-h precipitation

(05:00 to 05.00 h) the record went up to 352 mm. The list of all-time extreme precipitation totals observed in Germany contains several entries from the last ten years (in several rainfall duration classes).

The global average sea level rose by 10–20 cm during the 20th century, partly due to the thermal expansion of ocean water (steric rise) and the widespread loss of land ice associated with the 20th century warming. The average rate of the sea-level rise in the 20th century was an order of magnitude larger than the average rate over the last 3000 years (IPCC, 2001). The rise of the mean state of the sea level clearly impacts on extremes. Increased frequency of flooding in Venice accompanied 30 cm relative sea-level rise in the 20th century (IPCC, 2001a).

Non-climatic factors

The economic development of flood-prone areas, with a general increase in population and wealth, has led to increasing exposure to flood and exacerbated flood losses. It is a well-established fact that flood risk has been aggravated by locational decisions in flood-prone areas (flood plains, coast). Anthropopressure and shortage of land cause the tendency of encroaching onto flood plains, and investing in infrastructure there. Consequently, much of the natural flood storage volume is lost, ecosystems are devastated and riparian wetlands destroyed. Development of flood-endangered areas, in which growing wealth accumulates, increases the flood damage potential.

An important factor influencing the flood hazard is an unjustified belief in the absolute security of structural defenses. However, even an over-dimensioned and perfectly maintained dike does not guarantee complete protection—it can be over-topped by an extreme flood. When a dike breaks, the damage may be greater than it would have been in a levee-free case.

Land-use changes, which induce land-cover changes, cause changes of hydrological systems and control the rainfall–runoff relations, hence impacting on flood risk. Deforestation, reduction of wetlands, and rising urbanization have adversely influenced flood hazard in many watersheds by reduction of the available water storage capacity, increase in the portion of impervious area (roofs, yards, roads, pavements, parking lots, etc.) and in the runoff coefficient. This leads to growth in the amplitude and reduction in the time-to-peak of a flood triggered by a “typical” intense precipitation (which may also have changed due to climatic reasons, becoming more intense). On average, 2% of agricultural land has been lost to urbanization per decade in the EU. As noted by Bronstert (1996), direct urbanization effects are particularly visible in small or middle size floods, which often constitute a substantial contribution to flood losses in the longer term. Van der Ploog *et al.* (2002) attributed the increase in flood hazard in Germany to climate (wetter winters), engineering modifications, but also to intensification of agriculture, large-scale farm consolidation, subsoil compaction, and urbanization. The urbanized area in West Germany more than doubled from 6% in 1950 to approximately 13% in 1995.

Timing of river conveyance may have been considerably (sometimes, adversely) altered by river regulation (channel straightening and shortening, construction of embankments).

CONCLUSIONS

Globally, no uniform increasing trend in flood flows has been detected. The conclusive and general statement that severe floods are becoming more frequent is supported by a portion of the available studies, while other publications report contradictory evidence. Climate-related changes in flood frequency are complex, depending on the flood-generating mechanism (rainfall *vs* snowmelt). Higher and more intense precipitation has been already observed, hence flood magnitudes typically increase with warming if high flows result from heavy rainfall, but decrease where they are generated by spring snowmelt (IPCC, 2001). Flood risk has changed due to changes in socio-economic and terrestrial systems.

Regional changes in the timing of floods have been observed in many areas, with increasing late autumn and winter floods (caused by rain) and snowmelt floods coming earlier.

Floods have been identified by the IPCC TAR (2001a) as one regional reason of concern. Yet, quantification of flood statistics is subject to high uncertainty. It is difficult to disentangle the climatic component in the flood data which are also subject to strong natural variability and influenced by man-made environmental changes: urbanization, deforestation, human occupation of hazardous areas, reduction in storage capacity and increase in runoff coefficient. According to IPCC (2001), "[t]he analysis of extreme events in both observations and coupled models is underdeveloped" and "the changes in frequency of extreme events cannot be generally attributed to the human influence on global climate." The latter statement may seem somewhat conservative and is likely to be revised in the forthcoming new report. Change detection in flood data remains an exciting scientific challenge.

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