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Is the Frequency and Intensity of Flooding Changing in Europe?

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Introduction

Floods have recently become more destructive and projections show that this tendency may become even more pronounced. The Intergovernmental Panel on Climate Change (IPCC, 2001a) reports that the costs of extreme weather events have exhibited a rapid upward trend. From the 1950s to the 1990s, yearly economic losses from weather extremes increased tenfold (in inflation-adjusted dollars). A part of this trend is linked to socio-economic factors, such as population increase and accumulation of wealth in vulnerable areas, another part is probably linked to increased reporting. However, these factors alone cannot explain the whole observed growth, and possibly a portion of it is linked to climate.

Hydrological variables, such as precipitation, river flow, soil moisture and groundwater levels, display strong spatial and temporal variability. From time to time they take on extremely high values, exerting considerable impacts on ecosystems and human society. Floods have been a major concern since the dawn of human civilization and continue to hit every generation of human beings. In fact, flood losses worldwide continue to rise. According to the global data compiled by the Red Cross for 1971 – 1995, in an average year floods killed nearly 13 thousand people worldwide and made over three million homeless, affecting more than 60 million people, and the mean annual flood damage exceeded 40 billion USD. From the global data compiled by Berz (2001), one may conclude that the number of great flood disasters in the nine years 1990 – 1998 was higher than in earlier three-and-half decades, 1950 – 1985, together. Most flood fatalities, 140 thousand, resulted from a storm surge in Bangladesh in April 1991 (Munich Re 1997), while the highest material damage (exceeding 30 billion dollars) has been caused by floods in China in summer of 1998 (Kundzewicz & Takeuchi 1999). Since 1990, there have been over 30 floods worldwide in each of which the material losses exceeded one billion USD and/or the number of fatalities was greater than one thousand. The majority of recent large floods have occurred in Asia, but indeed only few countries worldwide are free of the flood danger. Destructive floods have also occurred in arid and semiarid regions.

Increase in the total national flood damage, adjusted for inflation, with the rate of 2.92 % per year was found by Pielke & Downton (2000) for the data from the USA, covering the period 1932 – 1997. This rise has been related to both climate factors (increasing precipitation) and socio-economic factors (increasing population and wealth).

Several destructive floods have been experienced in the last decade in Europe. It is estimated that the material flood damage recorded in the European continent in 2002 has been higher than in any single year before. The floods in Central Europe in August 2002 alone (on the rivers Danube, Labe/Elbe and their tributaries) caused damage exceeding 15 billion Euro, therein 9.2 in Germany, 3 each in Austria and in the Czech Republic. A little later, during severe storms and floods on 8 – 9 September 2002, 23 people were killed in southern France (Rhone valley), while the total losses went up to 1.2 billion USD.

Has there been a climate track in the apparent rise of flood and drought hazard? Is it likely to manifest itself in the future? The present paper reviews various aspects of these issues.

Observed variability of intense precipitation and projections for the 21st century

The mean global land precipitation has increased in the warming world. Moreover, according to the Clausius-Clapeyron law, the atmosphere´s water holding capacity, and hence the potential for intense precipitation, increases with temperature. Since evaporation grows with temperature rise, this means that the actual atmospheric moisture increases, favouring stronger rainfall events and increasing the risk of flooding (Trenberth 1998, 1999). Trenberth (1999) presented a physically-based conceptual framework for changes in hydrological extremes with climate change.

Higher and more intense precipitation has been already observed. As stated in IPCC (2001), it is very likely "that in regions where total precipitation has increased … there have been even more pronounced increases in heavy and extreme precipitation events". Moreover, increases in intense precipitation have also been documented in some regions where the total precipitation has remained constant or even decreased. That is, the number of days with precipitation may have decreased more strongly than the total precipitation volume.

Over the latter half of the 20th century it is likely that there has been a 2 to 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. The area affected by most intense daily rainfall is increasing and significant increases have been observed in both the proportion of mean annual total precipitation in the upper five percentiles and in the annual maximum consecutive 5-day precipitation total. The latter statistic has increased for the global data in the period 1961 – 1990 by 4 % (IPCC, 2001).

Some recent rainfall events in Europe have exceeded all-time records. On 12 – 13 August 2002, a new German record of one-day precipitation (from 6.00 a.m. 6.00 a.m.) of 312 mm was measured at the gauge Zinnwald-Georgenfeld, while in the category of 24-hour precipitation (from 5.00 a.m. to 5.00 a.m.) 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), cf. Rudolf & Rapp (2003).

However, projections of extreme events for future climate are highly uncertain. There are large quantitative differences between scenarios and models. Yet, based on global model simulations and for a wide range of scenarios, global average water vapour concentration and precipitation are expected to increase further during the 21st century, while precipitation extremes are projected to increase more than the mean, with consequence for the flood risk. The frequency of extreme precipitation events is projected to increase almost everywhere (IPCC 2001).

According to the material compiled in (IPCC 2001a), wetter winters are projected throughout Europe, with the two regions of highest increase being the Northeast of the continent and the northwestern Mediterranean coast. This is of direct importance for flood hazard.

Palmer & Räisänen (2002) analyzed the modelled differences between the control run with 20th century levels of carbon dioxide and an ensemble with transient increase to doubled CO_2 concentration (61 – 80 years from present). They found a considerable increase of the risk of a very wet winter in Europe. The modelling results indicate that the probability of total boreal winter precipitation exceeding two standard deviations above normal will considerably increase over large areas of Europe. For example, an over five-fold increase is projected over Scotland, Ireland and much of the Baltic Sea basin, and even over seven-fold increase for parts of the Russian Federation.

The Modeling the Impact of Climate Extremes (MICE) project within the 5th Framework Programme of the European Union examines changes in precipitation between the control period, 1961 – 1990 and the 2070 – 2099 period, using climate models, HadCM3 and HadRM3. Based on the results of the climate models, it is projected that in most of Europe intense precipitation will increase, even over vast areas where decrease of mean precipitation is expected. This is shown in analyses performed within the MICE project for extremes simulated by HadRM3, between the control period in the 20th century, 1961-1990, and the period of interest in the 21st century, 2070 – 2099 (cf. Kundzewicz et al., 2005). These results agree qualitatively with the findings of Christensen & Christensen (2003), based on a different model.

Increase in intense precipitation over many areas in the future (IPCC; 2001a) will have multiple adverse consequences, such as: increased risk of such damaging events as flood, landslide, avalanche, and mudslide; increased soil erosion; increased pressure on government and private flood insurance systems and on disaster relief.

Floods

Observed changes in extreme river flow

Where data are available, changes in annual streamflow usually relate well to changes in total precipitation (IPCC 2001). However, published results of change detection in flood flows show no uniform greenhouse signature. The statement that severe floods are becoming significantly more frequent and intense is supported by several studies, while other publications do not report such evidence. This deserves a closer look, and possibly consideration of different flood-generation mechanisms.

In a comprehensive study of US river flow records by Lins & Slack (1999), all, but the highest quantiles of discharge were found to increase across broad areas. However, no general dominating tendency of increase or decrease in the 90th and 100th percentiles of daily streamflow could be detected, despite the documented increase in extreme precipitation events (e.g. Easterling et al. 2000).

Regional changes in timing of floods have been observed in many areas, with increasing late autumn and winter floods (caused by rain) and less snowmelt floods, e.g. in Europe. Also the number of inundations caused by ice jams goes down in effect of warming (more rivers do not freeze at all) and human capacity to cope with ice-based obstructions of flow. This has been a robust result. Looking at the data assembled by Mudelsee et al. (2003), in the last 150-year time series of maximum daily flow on the Elbe (gauge Dresden), the level of 3000 m^3/s was exceeded 11 times: eight times in winter (1862, 1865, 1876, 1881, 1895, 1900, 1920, and 1940), and only three times in summer (May 1896, September 1890, and August 2002); the last discharge being highest. This illustrates that severe winter floods, frequent in the days of yore, have not occurred for 63 years now.

On the other hand, intensive and long-lasting summer precipitation episodes (in particular, related to the Vb cyclone track after van Bebber, cf. Kundzewicz et al. 2005) have led to disastrous recent flooding in Europe, e.g., the Odra / Oder deluge in 1997 (cf. Kundzewicz et al. 1999), and the 2002 flooding on the Elbe and its tributaries, the Danube, and other rivers. Not only historic records of material losses were exceeded, but also records of hydrological variables, such as stage or 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.

Kundzewicz et al. (2004) studied a set of 195 world-wide hydrological time series of maximum daily river flow, for every year, from holdings of the Global Runoff Data Centre (GRDC) in Koblenz, Germany. The analysis does not support the hypothesis of general growth of annual maximum river flows worldwide. Even if 27 cases of strong, statistically significant increase have been identified with the help of the Mann-Kendall test, there are 31 significant decreases as well, and most (137) time series do not show any significant changes.

However, highly skewed distributions render detecting changes in annual maxima of daily river flows difficult. As shown by Kundzewicz et al. (2004), it is not uncommon that the highest recorded annual maximum daily flow at a given station is considerably (even by the factor of 4.07 and 3.97) 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 a change, which 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.

Kundzewicz et al. (2004) studied 70 long time series of annual maximum daily river flow from Europe, covering different periods. Since all analysed series start no later than in 1960, one can take the year 1961 as the starting point for a fourty-year common period for all data and then divide this common period into two twenty-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 last until the year 2000 (series at 15 stations end in 1999 and at 6 end in 1998). Hence, it may well be that even more maxima fall into the subperiod 1981-2000. *Figure 1* presents direction and significance of changes in annual maximum daily river flow at examined stations in Europe.

In a national-scale study (61 stations over a century) carried out for Sweden, Lindström & Bergström (2004) found a substantial recent increase in both annual discharge and flood magnitude, but it is not exceptional in the context of high flows experienced earlier.

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

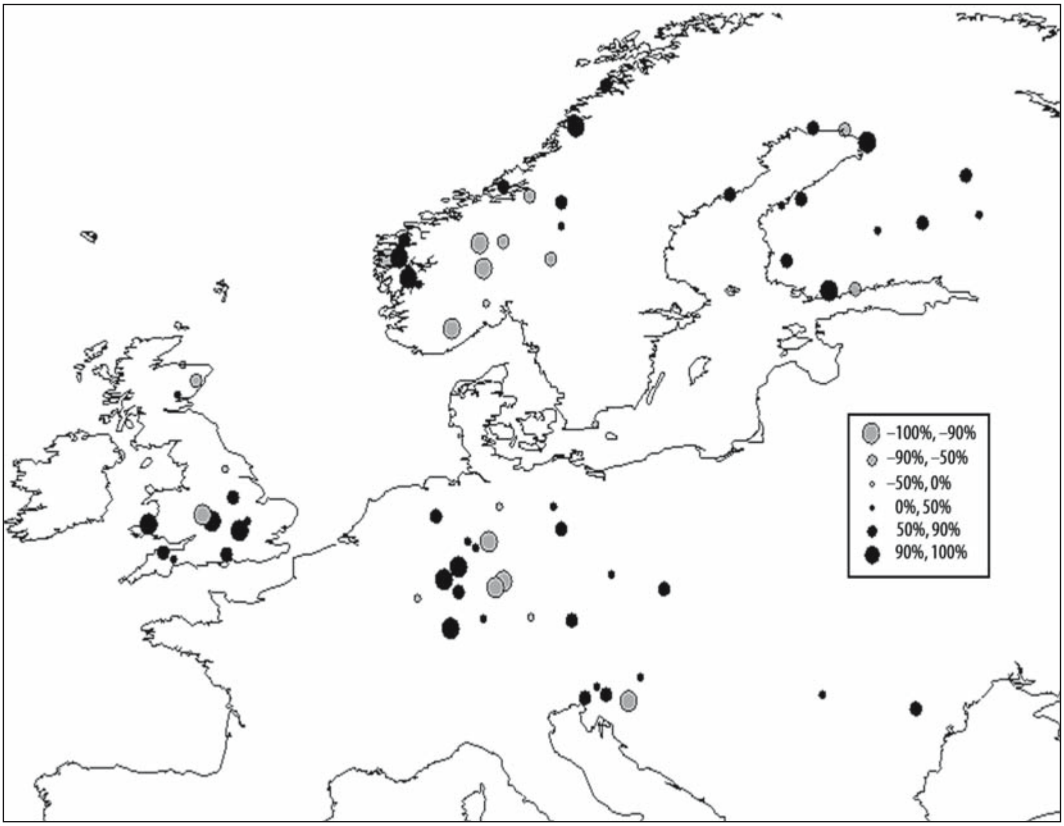
It is clear that the river flow process is controlled by several factors, climate being just one of them. Flood hazard and vulnerability tend to increase over many areas, due to a range of climatic and non-climatic impacts. The latter include impacts of changes in terrestrial systems (hydrological systems and ecosystems), and economic and social systems. Land-use changes, which induce land-cover changes, control the rainfall-runoff relation. Deforestation, urbanization, and reduction of wetlands empoverish the available water storage capacity in the catchment and increase the runoff coefficient, leading to growth in amplitude and reduction of the time-to-peak of a flood triggered by a "typical" intense precipitation (as indicated earlier, the nature of a "typical" intense precipitation event has also changed, becoming more intense). Urbanization has adversely influenced flood hazard in many watersheds by increase in the portion of impervious area. On average, 2 % of agricultural land has been lost to urbanization per decade in the EU. The timing of river conveyance may also have been altered by river regulation.

Van der Ploog et al. (2002) noted the increase in flood hazard in Germany. They attributed it to climate (wetter winters), engineering modifications, but also intensification of agriculture, large-scale farm consolidation, subsoil compaction, and urbanization. The urbanized area in the former West Germany has grown from 7.4 % in 1951 to 12.2 % in 1989.

Humans have been encroaching into unsafe areas thereby increasing the damage potential. This holds not only for informal settlements on flood plains around mega-cities in the developing world but also for human encroaching into flood-endangered areas in developed countries. An important factor influencing the flood hazard is an unjustified belief in absolute safety of structural defences. Even an over-dimensioned and well maintained dike does not guarantee complete protection. It can be overtopped when an extreme flood occurs. When a dike breaks, the damage may be higher than it would have been in a levee-free case.

Recently, a paper by Mudelsee et al. (2003) reported "no upward trends in the occurrence of extreme floods in Central Europe", hence demonstrating the lack of continuity between the observations of no increase (Mudelsee et al. 2003) and model projections for the future (Christensen & Christensen 2003),

Fig. 1



Direction and significance of changes in annual maximum daily river flow in Europe, based on a set of data provided by GRDC.

where increase in intense precipitation was demonstrated. The conclusions by Mudelsee et al. (2003) corroborate results of Bronstert (2003), who found that discharge rates of the Elbe river, corresponding to a range of recurrence intervals (from 2 to 200-year) in 20th century have been lower than in the 19th century.

Vulnerability to floods can be regarded as a function of exposure, sensitivity and adaptive capacity. Since, in many areas, exposure grows faster than adaptive capacity, the vulnerability increases too. Counter-intuitively, vulnerability of societies may grow even as they become wealthier, because technology helps populate and develop "difficult" areas, and societies become more exposed. High investment into maladaptation does not reduce the vulnerability!

It is estimated that 17 % of all the urban land in the USA, and 7 % of the total area of the conterminous US are located in the 100-year flood zone. About 10 % of the population of the USA and of the UK live in the 100-year flood zone. In Japan, half the total population and about 70 % of the total assets are located on floodplains, which cover only 10 % of the total country area. The percentage of flood-prone area is much higher in Bangladesh, and inundation of more than half of the country area is not rare (e.g. over two thirds of area of Bangladesh were inundated by the 1998 flood).

Projections of changes in extreme river flow for the 21st century

Climate change is likely to cause an increase of the risk of riverine flooding across much of Europe. However, changes in future flood frequency are complex, depending on the generating mechanism. Increasing flood magnitudes are projected where floods result of heavy rainfall and flood magnitudes generated by spring snowmelt may decrease (IPCC 2001a). Where snowmelt is the principal flood-generating mechanism, the time of greatest flood risk would shift from spring towards winter. Winter flood hazard is likely to rise for many catchments under many scenarios.

Menzel et al. (2005) examined flood frequency of the river Mosel at Cochem, comparing two thirty-year periods: 1961 – 1990 and 2061 – 2090. For the control period, they analysed observed discharge data (and fitted frequency curve) and modelled discharge series with three different input data sets: (1) observation records and (2 – 3) downscaled climate information from two GCMs: ECHAM4 and HadCM3. They also made calculations for the modelled future, using a hydrological model and downscaled climate information. For a specific discharge, the return interval is considerably lower in future climate, hence floods may become more frequent.

Milly et al. (2002) demonstrated changes in the risk of great floods (exceeding 100-year levels). For all (but one) large basins analysed, the control 100-year flood (100-year annual maximum monthly discharge) is exceeded more frequently as a result of CO_2 quadrupling. Probability of what has been a 100-year "flood" (quotation marks are used because maximum monthly discharge is not the most meaningful flood descriptor) is projected to increase drastically in the CO_2-quadrupling world. In some northern rivers, what was a 100-year "flood" in the control run, is projected to become much more frequent, even occurring every 2 to 5 years.

The risk from storm surge also appears to be changing. The global average sea level, which rose by 10 to 20 cm during the 20th century, is projected to continue to rise (IPCC 2001), with substantial adverse effects on low-lying lands and river deltas in flood prone areas: increased probability of storm surges and tidal flooding. Needless to say, that the sea-level rise itself is a dangerous occurrence, jeopardizing low-lying coastal areas, which may cause permanent inundations, resulting in massive relocation of people. Global warming has the potential to trigger large-scale singular events, such as the disintegration of the West Antarctic and Greenland ice sheets, in a time scale of multiple centuries, which would cause a significant sea-level rise (of the order of meters), and permanent inundation of large, now densely populated, areas. The probability of such developments in the near future is low, but should not be ignored given the severity of consequences. However, coastal flooding is beyond the scope of this article.

Conclusions

Higher and more intense precipitation has been already observed and this trend is expected to strengthen in the future, warmer world, directly impacting on flood risk. However, snowmelt and ice-jam related floods have been decreasing over much of Europe. These statements respond to the question posed in the title of the present paper. The impact of climate forcing on flood risk is complex, depending on the generating mechanism (rainfall vs snowmelt). In many places flood risk is likely to have grown and further growth is projected.

Floods have been identified by IPCC TAR (2001a) among regional reasons of concern. Yet, there is still a great deal of uncertainty in findings about climate change impacts on water-related extreme events. Only in some areas, the projected direction of change is consistent across different models and scenarios. As stated in 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." It is difficult to disentagle the climatic component in hydrological extremes from strong natural variability and man-made environmental changes. This remains an exciting scientific challenge.

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