

INTENSE PRECIPITATION AND HIGH RIVER FLOWS IN EUROPE – OBSERVATIONS AND PROJECTIONS

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A b s t r a c t

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 potential for intense precipitation) increases with temperature and more intense precipitation has been documented in the warming world. However, a general and coherent increase in high river flows has not been detected. Results of change detection studies of 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. Regional changes in the timing of floods have been reported 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 decreased. On the other hand, intensive and long-lasting summer precipitation episodes have led to disastrous floods in Central Europe (cf. the 1997 Odra/Oder flood, the 2001 Vistula flood, and the most destructive 2002 deluge on the Labe/Elbe), and river flooding has been recently recognized as a major hazard in the region. Significant differences between future projections and the reference period, indicating the likelihood of increasing flood hazard, have been identified in both intense precipitation and high flows.

Key words: climate change, climate variability, floods, global change, hydrological extremes, river flow.

1. INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC, 2001b) 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. In an average year, floods cause material damage of the order of tens of billions of dollars globally, in both developed and less developed countries, and more than ten thousand fatalities, mostly in less developed countries.

Several destructive floods have recently hit Europe. In Poland, the nation-wide toll for both the Odra and the Vistula floods of summer 1997 was an all-time high as far as the economic damages are concerned. It was also the most extreme event on record in hydrological terms (peak stage, flow, inundated area). The flood during July 1997 caused large damage also in two other riparian countries of the Odra/Oder, i.e. Czech Republic and Germany. Even higher was the material flood damage (above 20 billion Euro) recorded in the European continent in 2002, considerably exceeding records for 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 (Munich Re, 2003).

The three most recent floods in Central and Eastern Europe; 1997 (Odra/Oder, Vistula, and their tributaries), 2001 (Vistula and its tributaries), and 2002 (Labe/Elbe and its tributaries) have several commonalities. All these flood events occurred in summer and were caused by similar atmospheric drivers – *Vb* atmospheric circulation type. The floods were generated by intensive precipitation during a longer wet spell, which covered vast areas. Very fast, violent flash floods occurred in small and medium catchments of mountainous tributaries of large rivers and in the upper reaches of the main rivers. Subsequently, huge masses of water propagated downstream the main rivers, causing dyke failures, and inundating urban areas, therein large towns. Since levees were broken and vast, mostly agricultural areas were inundated, this weakened the impetus of the flood wave. The flood waves flattened as part of them was trapped in a temporary storage. The return period of flood flow decreased downstreams, from very rare events in headwaters to more common events in lowland courses.

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

Indeed, some recent rainfall events in Europe have exceeded all-time records. According to Czech sources (Kubát *et al.*, 2003), in four precipitation observing stations, the 24-hour precipitation in August 2002 has qualified into the ten highest observations ever recorded in the Czech territory. In Zinnwald-Georgenfeld (Saxony, Germany), 312 mm of one-day precipitation was also recorded from 12 Aug., 6 a.m. to 13 Aug. 2002, 6 a.m. (usual time interval for measuring one-day precipitation), matching the observation at a nearby Czech station in Cinovec, and beating all-time German national record. The maximum 24-hour precipitation recorded in Zinnwald-Georgenfeld from 12 Aug., 3 a.m. to 13 Aug. 2002, 3 a.m. was even higher and reached 352.7 mm (Rudolf and Rapp, 2003). The list of all-time extreme precipitation totals, in several rainfall duration classes, observed in Germany contains several entries from the last ten years. From the viewpoint of areal extent of precipitation, its intensity and duration (a wave of two wet spells), the August 2002 event was exceptional.

The 2002 flood peak level in Prague exceeded all the events recorded in the last 175 years (Kubát *et al.*, 2003). This was the only time when the flow rate of 5000 m³/s was exceeded, while between 1941 and 2001 Vltava flow never reached 2500 m³/s. The water level of the Elbe in the profile Dresden on 17 August 2002, i.e. 940 cm, has considerably (by 63 cm) exceeded the former historical record. In the past, stages in excess of 800 cm were observed in Dresden five times during less than a century – from 1785 to 1879 (four out of five times – in February or March), but this level was never reached in 1880–2001. However, such a long period of lower annual maxima has not been uncommon in the historical data. For instance, between 1502 and 1783, i.e. 281 years, the level of 800 cm was exceeded only once.

The 2002 deluge resembled historical events from remote past. For example, on 21 July 1342, a St. Magdalene's flood, caused by intensive rain, devastated large areas of Europe, causing thousands fatalities and immense destruction. Yet, apart from the record set in Dresden, the all-times historical flood records on the river Mulde in Döbeln (1897) and Grimma (1573) were exceeded in August 2002 by 126 and 136 cm respectively (Becker and Grünwald, 2003). The two types of disastrous floods occurring in the past were: summer floods in June-July-August, caused by intense precipitation, and winter floods caused by snowmelt, ice-advances and ice-blocking.

2. OBSERVED CHANGES IN INTENSE PRECIPITATION

Even if the changes of global land precipitation over the 20th century were statistically significant, they were neither spatially nor temporally uniform. Instrumental records of land surface precipitation show an increase of 0.5 to 1% per decade over much of mid- and high latitudes of the Northern Hemisphere (IPCC, 2001a). Precipitation increase in the 20th century was of the order of 7-12% for the zones 30 to 85°N (IPCC, 2001a). Marked increase in precipitation in the later part of the 20th century over several

regions, such as Northern Europe (New *et al.*, 1999; IPCC, 2001a) have been observed. A general increase in precipitation in the Northern Hemisphere mid- and high-latitudes was particularly pronounced in autumn and winter (IPCC, 2001b).

Heavy and extreme precipitation events have increased even stronger than the mean values (IPCC, 2001a). Moreover, increases in “heavy and extreme precipitation” have also been documented (IPCC, 2001a) in some regions where the total precipitation has decreased or remained constant. 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. For instance, there is evidence that the frequency of extreme rainfall has increased in the UK (IPCC, 2001b) 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. The area affected by most intense daily rainfall is growing 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, 2001a). The number of stations reflecting a locally significant increase in the proportion of total annual precipitation occurring in the upper five percentiles of daily precipitation totals outweighs the number of stations with significantly decreasing trends by more than 3 to 1 (IPCC, 2001a).

Changes in the frequency of heavy precipitation events can arise from several causes, e.g., changes in atmospheric moisture or circulation. 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. Increased atmospheric moisture contents favours more intensive precipitation events thus increasing the risk of flooding.

In their studies of *Grosswetterlagen* (synoptic-scale weather patterns), Bárdossy and 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 to January) and spring (March to June).

3. OBSERVED CHANGES IN HIGH FLOW

Where data are available, changes in annual streamflow usually relate well to changes in total precipitation (IPCC, 2001a). Yet, this does not directly translate to changes in

flood flows. In general, published results of change detection in flood flows show no uniform greenhouse signature (Kundzewicz, 2005). The general statement that severe floods are becoming significantly more frequent (a 100-year-flood determined for older data may therefore correspond to a significantly lower return period for more recent data) and more intense is supported by several studies, while other publications report contradictory evidence, where either a non-stationary behaviour of flood series could not be detected, or a decrease of amplitude was found.

There have been a number of trend detection studies for European flood data, mostly at the national level. There exist a plethora of studies of time series at single stream gauges reporting trend detection and this has encouraged researchers to extend the analysis into a truly spatial domain. However, spatial patterns are problematic (cf. Mitosek, 2005; Kundzewicz *et al.*, 2004; 2005b). Only some series show a significant trend and only some of those with significant trend feature an upward tendency. 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.

For example, Robson and Reed (1996) analyzed about 600 stream gauges in the UK records of length of 15 to over 100 years, finding significant non-stationarity in annual maxima and peak-over-threshold (POT) variables. Some regional features were visible in the results. More increases than decreases of flooding, particularly in Scotland and in the South East of England, were noted. Lindström and Bergström (2004) analyzed 61 long time series of records (some of which were very long, e.g. from 1807 to 2002) for stations in Sweden. 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. Although Lindström and Bergström (2004) concluded that flood magnitude increased substantially in the Swedish rivers between 1970 and 2002, they have weakened this corollary in a number of ways. Firstly, they stated that occurrence of such floods was not exceptional as similar conditions had been experienced there in the 1920s. Furthermore, they considered flood peaks in old data to be 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. Nobilis and Lorenz (1997) studied 441 stations in Austria. 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 (1952–1991) resulted in detection of a positive trend in 66.3% of the cases with significant trend.

Mudelsee *et al.* (2003) detected no upward trends in the occurrence of extreme summer floods but found downward trends for winter floods in instrumental and documentary data on the Elbe and the Oder. In their considerations, they included such factors as reservoirs and deforestation, and found that they had minor effect on flood

frequency. The instrumental database used in their study was extended by concatenation of the historical database. In the observation records, a decrease in winter flood occurrence over the last century was observed, with fewer events of strong freezing. For 1920–2002, and for 1852–2002, decreasing numbers of winter floods were observed for the Oder and the Elbe, respectively. This finding is consistent with Bronstert (2003) who compared floods on the Elbe in the 20th and 19th centuries. Decrease in discharge rates corresponding to a range of recurrence intervals (from 2 to 200-year) was noted.

Regional changes in timing of floods have been observed in many areas, with increase in late autumn and winter floods (caused by rain) and reduction in ice-jam-related floods, e.g., in Europe. This has been a robust result. Yet intensive and long-lasting precipitation episodes happening in summer have also 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.

Kundzewicz *et al.* (2004; 2005b) studied a set of 195 long time series of annual values of maximum daily discharge worldwide, therein 70 series for European rivers, from the GRDC holdings. The European data consist of time series collected at 17

Table 1

Statistically significant changes in annual maximum flow
in rivers in Germany and Norway

Station no.	River, station, country code	Data period	Significance level
Significant increases			
6335100	Rhine River, Kaub, D	1931–2002	2.48
6335125	Kinzig, Schwaibach, D	1921–2000	1.29
6335350	Lahn, Leun (Neu), D	1936–2001	8.42
6731165	Gaular, Viksvatn, N	1903–2000	1.32
6731200	Vosso, Bulken, N	1892–2000	0.70
6731610	Fusta, Fustvatn, N	1909–2000	9.05
Significant decreases			
6335301	Main, Schweinfurt, D	1845–2000	0.49
6335500	Main, Wuerzburg, D	1824–2001	0.65
6337400	Weser, Hann.-Muenden, D	1831–2000	0.04
6731160	Nausta, Nausta, N	1909–2000	4.06
6731280	Austena, Austena, N	1925–2000	3.00
6731300	Etna, Etna, N	1920–2000	0.80
6731455	Otta, Lalm, N	1914–2000	7.03

stations in Germany, 15 in Norway, 13 in the United Kingdom, 12 in Finland, 5 in Sweden, 2 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 9 decreases), while most (50) time series do not show any significant changes. Table 1 shows that even for rivers in the same country (such as Germany and Norway) both statistically significant decreases and increases have been observed.

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

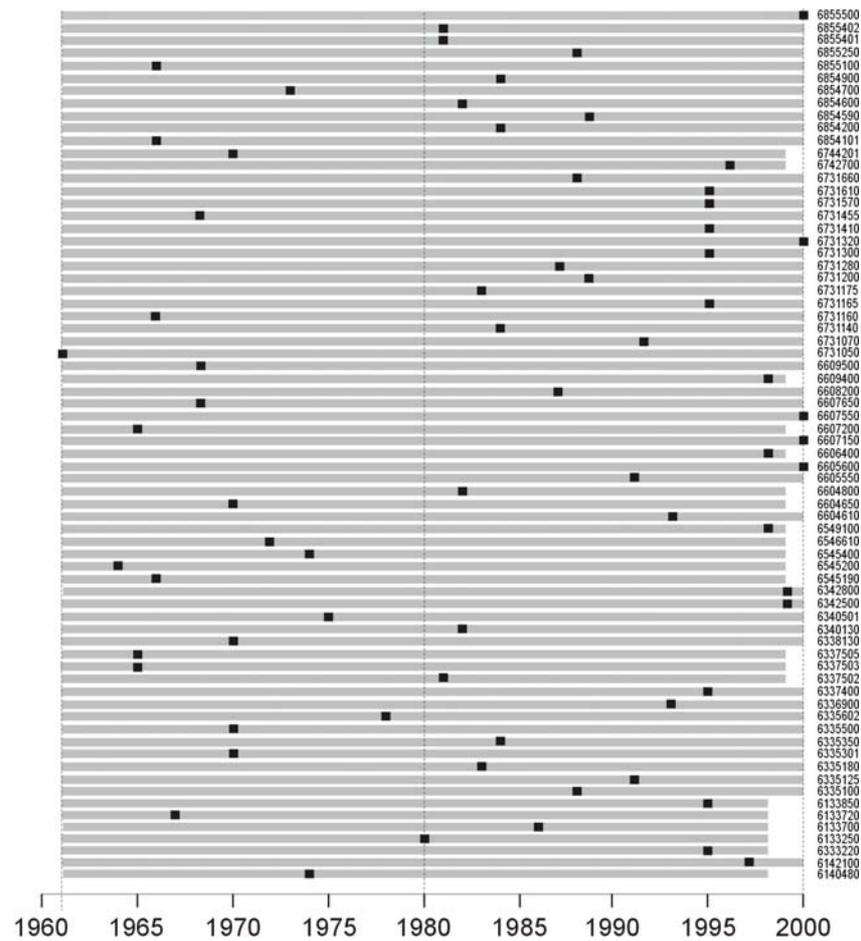


Fig. 1. Years of occurrence of annual maximum flows for different river gauge stations in Europe.

occurrences of highest maximum annual flow were noted (some records extend into the early 2000s, and in one case, up to 2002). Fewer occurrences of highest annual maximum flows have been noted in the earlier decades (11 in 1980–1989, 7 in 1970–1979, and only 4 in 1960–1969). In seven cases, the highest maximum annual flow occurred in the 1950s (there were 5 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.

The lengths of the data series are not the same, yet 69 datasets started before 1960 and one in 1960. Since all the series analysed by Kundzewicz *et al.* (2004; 2005b) commence no later than 1960, the year 1961 can be taken as the starting point for a forty-year common period for all data and then this common period can be divided into two twenty-year subperiods. It was found that the overall maxima (for the whole 1961–2000 period) occurred more frequently (45 times) in the later subperiod, 1981–2000, than in the earlier subperiod, 1961–1980 (25 times), cf. Fig. 1. 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. The occurrence of annual maximum flow values higher than two times average annual maximum flow has been more frequent in the last decade than earlier in the time horizon of interest (Table 2). All the time periods in Table 2 but the last one contain complete records for all 70 stations. In the time period 1996–2000, 21 records are incomplete, since six end in 1998 and 15 in 1999. Hence the number of occurrences of high annual maximum discharges in 1996–2000 may be underestimated.

Table 2

The occurrence of annual maximum flow values higher than 200% of the average annual maximum flow

Time period	Number of occurrences
1961–1965	2
1966–1970	8
1971–1975	2
1976–1980	1
1981–1985	4
1986–1990	3
1991–1995	6
1996–2000	9

Svensson *et al.* (2004; 2005) studied changes in flood data for six European rivers, using a number of indices, such as: annual maximum daily mean river flow and peak-over-threshold (POT). The indices, POT1 and POT3, were set in such a way that, on average, one or three POTs were selected per year and used for both magnitude and frequency of floods. For each of the six European river stations, changes in five indices were evaluated, with the help of two methods for each (linear regression and the Mann–Kendall test with significance levels obtained by block bootstrapping). No uniform and general results were obtained. For two stations, none of the tests found a significant change for any of the indices. For another two stations, growing trends were detected in some indices by one or two methods, while at the remaining two stations, some indices show significant decreases.

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.

Quantification of flood statistics is subject to high uncertainty. In many places, flood risk is likely to grow, due to a combination of anthropogenic and climatic factors. It is difficult to disentangle the climatic component in the flood data subject to strong natural variability and influenced by man-made environmental changes. Vulnerability to floods can be regarded as a function of exposure and adaptive capacity (cf., IPCC, 2001b), and all three entities have been increasing in many areas, but typically exposure grows faster than the adaptive capacity. Box 1 illustrates possible reasons for change in flood risk and vulnerability.

Box 1

Possible reasons for changes in flood risk and vulnerability

- Changes in socio-economic systems (increasing exposure and damage potential – floodplain development, growing wealth in flood-prone areas, land-use change: urbanization, deforestation, elimination of natural inundation areas (wetlands, floodplains causing land-cover changes in terrestrial systems), changing risk perception).
- Changes in terrestrial systems (hydrological systems and ecosystems; land-cover change leading to change in characteristics of water storage in a catchment and runoff coefficient, changes of conditions of transformation of precipitation into runoff leading to a higher peak and shorter time-to-peak, river regulation – channel straightening, embankments).
- Changes in climate (holding capacity of the atmosphere, intense precipitation, seasonality, circulation patterns).

Highly skewed distributions render change detection in annual maxima of daily river flows difficult. Kundzewicz *et al.* (2004) 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 and 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 snow cover, 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 $3000 \text{ m}^3\text{s}^{-1}$ 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 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, 2001a), 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.

4. PROJECTIONS OF INTENSE PRECIPITATION

Regional precipitation scenarios developed under the ACACIA project (Parry, 2000; IPCC, 2001b) show a marked contrast between winter and summer precipitation change in Europe. Wetter winters are predicted throughout the continent, the two regions of highest increase being the Northeast of Europe and the Northwestern

Mediterranean coast, including Northern Italy. In summer, there is a strong difference in precipitation change between Northern Europe and Southern Europe, the former getting wetter by 2% per decade, while the latter becoming drier by 5% per decade. However, there are large quantitative differences between scenarios and models.

Based on global model simulations and for a wide range of scenarios, one can make future projections, understanding that prediction of extreme events for future climate is highly uncertain. 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 hazard (IPCC, 2001a).

Palmer and Räisänen (2002) analyzed the modelled differences between the control run with 20th century levels of carbon dioxide and an ensemble with transient increase in CO₂ and calculated around the time of CO₂ doubling (61-80 years from present). They found a considerable increase of the risk of a very wet winter in Europe and a very wet monsoon season in Asia. 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 and the island of Ireland and much of the Baltic Sea basin, and even over seven-fold increase for parts of Russia.

More intense precipitation events which are very likely to occur in the future (IPCC, 2001b) would lead to multiple adverse consequences, such as; increased flood, landslide, avalanche, and mudslide damage; increased soil erosion; increased pressure on government and private flood insurance systems and disaster relief. On the positive side, increased flood runoff could increase recharge of some floodplain aquifers.

The Modelling the Impact of Climate Extremes (MICE) project within the 5th Framework Programme of the European Union examined 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 (cf. Kundzewicz *et al.*, 2005a). This is in agreement with the findings of Christensen and Christensen (2003), who, using another regional climate model (HIRHAM4) concluded that the amount of summer precipitation exceeding the 95th percentile is very likely to grow in many areas of Europe, even if the mean summer precipitation may decrease over a substantial part of the European continent.

5. PROJECTIONS OF RIVER FLOW

Changes in future flood frequency are complex, depending on the generating mechanism, e.g., increasing flood magnitudes where floods result of heavy rainfall and

decreasing magnitudes where floods are generated by spring snowmelt (Arnell and Liu Chunzhen, 2001). However, climate change is likely to cause an increase of the risk of riverine flooding across much of Europe. In some areas, where snowmelt is the principal flood-generating mechanism, the time of greatest flood risk would shift from spring to winter. Winter flood hazard is likely to rise for many catchments under many scenarios. However, global warming may not necessarily reduce snowmelt flooding everywhere. Since an increase in winter precipitation is expected, snow cover may increase in areas where the temperature is still below 0°C.

Milly *et al.* (2002) demonstrated adverse changes in the risk of great floods (exceeding 100-year levels). For all (but one) large basins (over 200 000 km²) analyzed, the control 100-year flood is exceeded more frequently as a result of CO₂ quadrupling. In some areas (beyond Europe), what is given as a 100-year flood in the control run, is projected to become much more frequent, even occurring as often as every 2 to 5 years. Milly *et al.* (2002) found that the likelihood that these changes are due to natural climate variability is small.

The existence of a so-called *Vb*-track situation has accompanied recent occurrences of extreme precipitation events in summer over Central Europe. Occurrence of such situations and comparison of the role of these cyclone tracks for extreme rainfall under present-day and future climate conditions have been investigated. In order to detect changes of weather regimes connected with the occurrence of *Vb*-tracks, a specific analysis of *Vb*-tracks under climate change conditions, as well as an objective classification method of synoptic weather situations (*Grosswetterlagen*) were applied by Ulbrich and co-authors (cf. Kundzewicz *et al.*, 2005b). The climate change signal of *Vb*-tracks reveals an overall reduction of the track density of the order of 20 to 30%. Thus, under changed climate, a tendency to a reduced number of *Vb*-track situations in summer is identified.

As a result of the decrease in the number of tracks, less flood-prone situations are found, while the amount of rainfall related to extreme precipitation events increases. Thus, for days with intense rainfall events, *Vb*-track related circulation pattern is likely to become more important under enhanced greenhouse gas concentrations than for the present-day climate. While there are less *Vb* situations under enhanced GHG forcing, these situations are likely to lead to extreme rainfall more frequently than under present conditions.

6. CONCLUDING REMARKS

No uniform increasing trend in flood flows has been detected in Europe. Changes in future flood frequency depend on the generating mechanism, but climate change is likely to change the risk of riverine flooding across much of Europe.

Floods have been identified by the IPCC TAR (2001a) among regional reasons of concern. Yet, it is difficult to disentangle the climatic component in the flood data from strong natural variability and influence of the human impacts: urbanization, deforestation, human occupation of hazardous areas, reduction in storage capacity and increase in runoff coefficient. According to IPCC (2001a), “the 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”. Change detection in flood data remains an exciting scientific challenge.

The general conclusion drawn from the science of the climate change is as follows: the hydrological cycle is likely to accelerate in the warmer climate. Yet, there is a great deal of uncertainty in findings about future climate change impacts on water resources, and this refers particularly to extreme events. Part of the problems is due to a spatial and temporal scale mismatch between coarse-resolution climate models and hydrological (catchment) spatial scale and between monthly/daily data and daily/hourly dynamics of flood routing. Only in some, but not all, areas, the projected direction of change of hydrological processes is consistent across different scenarios (emissions of greenhouse gases, which drive climate models) and across different models.

The climatic impact on flood preparedness depends, in general, not only on changes in the characteristics of streamflow, but also on such system properties, as: pressure (stress) on the system, its management (also organizational and institutional aspects), and adaptive capacity. Climate change may challenge existing practices by contributing additional uncertainty, but in a particular place, non-climatic changes may have posed a greater impact.

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