Heavy Precipitation and Floods

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Abstract

The average annual economic flood damage worldwide has increased by order of magnitude in the last four decades, in inflation-adjusted monetary units. This has been due to socio-economic changes (increasing population and assets in flood-prone areas and land-use change); terrestrial (land-cover change and reduction of natural storage); and climatic factors. The anthropogenic increase in atmospheric concentration of greenhouse gases leads to enhancement of the greenhouse effect, resulting in the global warming and such impacts as glacier melt, and sea-level rise. Increase of temperature causes intensification of the hydrological cycle, by which floods and droughts get more frequent and/or more extreme. Indeed, several examples of occurrence of a drought and a flood in the same area in a short time interval have been observed recently (e.g. in Spain). The moisture-holding capacity of the atmosphere has been increasing with temperature, at a rate of about 7% per 1°C, with consequence to flood risk. Observational evidence indicates increasing probability (and number) of heavy precipitation events in the warming climate. However, due to strong natural variability in high river flows and multiple flood generating mechanisms, no ubiquitous, and statistically significant, change has been documented. Regional changes in timing of floods have been observed in many areas, with increasing late autumn and (rain-caused) winter floods. In contrast, the number and intensity of snowmelt and ice-jam-related floods has been decreasing in much of Europe. Climate-related changes in flood frequency are complex and depend on the flood-generating mechanism (e.g. heavy rainfall *vs* snowmelt).

Key words: extreme weather events, heavy precipitation, floods, climate change

1. Why have the flood damages grown?

Floods have been the most reported natural disaster events in many regions, affecting more than 100 million people in average year. In Bangladesh, during the 1998 flood, about 70% of the country's area was inundated. Destructive floods observed in the last decades all over the world have led to record high material damage. In several recent flood events the material losses exceeded US$ 10 billion, while in some events in less-developed countries the number of flood fatalities has exceeded a thousand. Most flood fatalities occur outside Europe, in particular in Asia (e.g. China, India, Bangladesh), but in the last decade floods have severely affected large parts of the European continent. For example, Poland suffered dramatic summer floods in 1997 (the event in the Odra basin also caused considerable damage in the Czech Republic and Germany), 1998, and 2001. The year 2002 was particularly marked by destructive floods in Europe. It is estimated that the material flood damage recorded in the European continent in 2002 was higher than in any single year before and exceeded €20 billion in August 2002 alone.

The costs of extreme weather events have exhibited a rapid upward trend and yearly economic losses from large events have increased by order of magnitude within four decades, in inflation-adjusted monetary units. However, the question remains as to whether or not the frequency and/or magnitude of flooding is also increasing and, if so, how to interpret this increase? Is it in response to climate change? Disaster losses, mostly weather and water-related have increased much more rapidly than population or economic growth and this suggests that a climate change factor is also present (Mills, 2005). However, in most areas, the dominant drivers of the upward trend of flood damage are socio-economic factors, such as increase in population and in wealth gathered in vulnerable areas, and land-use change.

2. Climate track – heavy precipitation and high river flows

2.1. Physics

At times, hydroclimatic variables take extremely high values. For instance, volumes of water in stores (e.g. in the atmosphere) and fluxes of water between stores (e.g., precipitation on land surface), may take extreme, unprecedented, values.

There has been an increasing body of evidence of the ongoing unequivocal warming at variety of scales, including the global scale (IPCC, 2007). The warming has manifested itself through increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global sea level. The best-estimate linear trend in global surface temperature over the last 100 years is a warming of 0.74°C, with a more rapid warming trend over the past 50 years.

Since the climate and freshwater systems are closely inter-connected, the warming and other accompanying climate changes induce changes in the freshwater systems. It is expected that in a climate that warms due to increasing greenhouse gases, a greater increase is expected in extreme precipitation, than in mean precipitation. This is because extreme precipitation is controlled by the availability of water vapour, while mean precipitation is controlled by the ability of the atmosphere to radiate long-wave energy (released as latent heat by condensation) to space, and the latter is restricted by increasing greenhouse gases (Bates *et al.*, 2008)

The Clausius-Clapeyron law states that there is more room for water vapour in the warmer atmosphere and hence potential for heavy precipitation grows. Therefore, instantaneous maximum value of the volume of water that can be stored in the atmosphere and the maximum water flux grow with temperature. Linearizing the Clausius-Clapeyron equation one finds that the moisture-holding capacity of the atmosphere increases at a rate of about

7% per °C warming, hence there is potential for heavier precipitation, with implications for flood risk.

2.2. Observations – Precipitation and heavy precipitation

There is no statistically significant linear trend in the time series of global mean precipitation during 1901-2005 (Trenberth *et al.*, 2007). Global changes are not uniform in time, showing significant decadal variability. There was an overall precipitation increase until the 1950s, with peaks in 1950s and then in 1970s, a decline from 1970s until the early 1990s and a recovery afterwards.

Patterns of precipitation change are spatially and temporally variable, but some regional regularities could be detected (Fig. 1). As summarized in Trenberth *et al.* (2007), over the period from 1901 to 2005, long-term precipitation trends have been found in many large regions, though data are often insufficient to produce reliable trends. Precipitation has generally increased over land in most areas of higher latitudes of Northern Hemisphere, where distinct, and statistically significant upward trends were found in many regions. Annual precipitation for the region north of 50°N has increased during the past 50 years by approximately 4% but this increase has not been homogeneous in time and space (Groisman *et al.*, 2005).

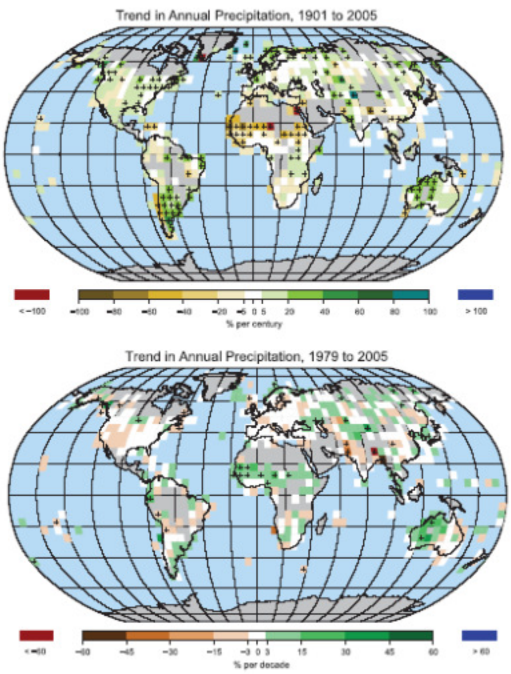

Figure 1. *Trend of annual land precipitation amounts for 1901 to 2005 (top, % per century) and 1979 to 2005 (bottom, % per decade). The percentage is based on the means for the 1961 to 1990 period. Areas in grey have insufficient data to produce reliable trends. Note the different colour bars and units in each plot. Trends significant at the 5% level are indicated by black + marks. (Source: Trenberth et al., 2007).*

In Europe, trends in observed annual and seasonal precipitation differ between northern and southern parts of the continent. Over the 20th century, the mean annual precipitation has increased in northern Europe and has decreased in southern Europe. Pronounced increase in autumn and winter precipitation in the latter part of the 20th century has been observed over northern Europe and western Russia.

Over large areas of high latitudes in Northern Hemisphere, where mean temperatures were close to or higher than 0°C, the total winter precipitation is composed of less snow and more rain. The liquid precipitation season has become longer by up to three weeks in some regions of the boreal high latitudes over the last 50 years (Trenberth *et al.*, 2007).

The observational and modelling studies lead to an overall conclusion that, in the period of instrumental observations, there has been an increasing probability of heavy precipitation events for most extratropical regions (cf. Groisman *et al.,* 2005). It is likely that there have been widespread increases in the in the contribution to total annual precipitation from very wet days (Fig. 2) within many land regions, even in those areas where a reduction in total precipitation amount has been observed. This is consistent with a warming climate and observed significant increasing amounts of water vapour in the atmosphere. However, only a few regions have sufficient data to assess trends in rare precipitation events. The rainfall statistics are strongly influenced by interannual and inter-decadal variability.

2.3. Observations - High river flows

The effects of climate change on streamflow, which vary regionally, largely follow changes in the prime driver, precipitation. However, changes in river flow are the integrated result of natural factors (such as volume and timing of precipitation, catchment storage, evapotranspiration and snowmelt, and whether precipitation falls as snow or rain), as well as watershed management practices and river engineering works (such as dams and reservoirs) that alter the water conveyance system over time. It is very difficult to separate the climatic effects from the effects of human interventions in the catchment, such as land-use change and reservoir construction.

The river discharge, which is the most important variable for freshwater management, has not shown general and coherent changes, globally. It integrates influences of many climatic and non-climatic factors. Changes in streamflow volume, both increases and decreases, have been recorded in many regions, but often these trends cannot be definitively attributed to changes in climate, due to existence of several other factors. There is substantial uncertainty in trends of hydrological variables because of large regional differences, and because of limitations in the spatial and temporal coverage of monitoring networks.

There have been many studies related to trends in river flows during the 20th century at scales ranging from catchment to global. Significant trends in some regional indicators of river flow have been found in some, but not all, studies, but no globally homogeneous trend has been reported. Actually, many studies have found no trends, or have been unable to separate the effects of variations in temperature and precipitation from the effects of human interventions in the catchment, such as land-use change and reservoir construction. In some regions, interannual variability of river flows is also very strongly influenced by large-scale

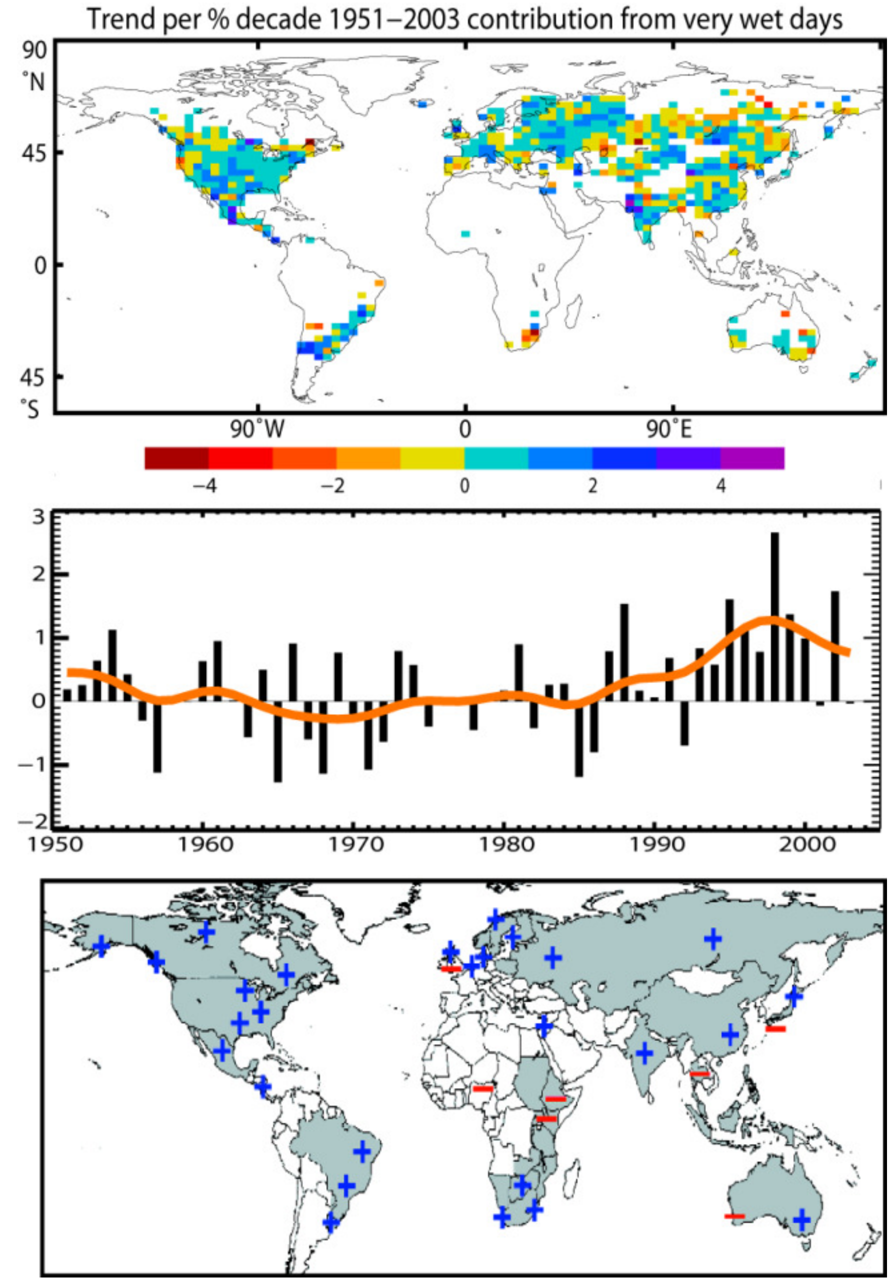

Figure 2. *(Top) Observed trends in the contribution to total annual precipitation from very wet days (95th percentile). Trends were only calculated for grid boxes where both the total and the 95th percentile had at least 40 years of data during this period and the data extended until at least 1999. (Middle) Anomalies (%) of the global annual time series (with respect to 1961 to 1990) defined as the percentage change of contributions of very wet days from the base period average (22.5%). The smooth red curve shows decadal variations. (Bottom) Regions where disproportionate changes in heavy and very heavy precipitation during the past decades were documented as either an increase (+) or decrease (–) compared to the change in the annual and/or seasonal precipitation (updated by Trenberth et al., 2007, from Groisman et al., 2005). Changes in heavy precipitation frequencies are always greater than changes in precipitation totals and in some regions, an increase in heavy and/or very heavy precipitation occurred while no change or even a decrease in precipitation totals was observed. Source: Trenberth et al. (2007).*

atmospheric circulation patterns associated with ENSO, NAO and other variability systems that operate at within-decadal and multi-decadal time-scales.

At a large scale (Milly *et al.*, 2005), there is evidence of a broadly coherent pattern of change in annual river runoff. Many regions at higher latitudes of the Northern Hemisphere, such as southeastern through central North America, parts of western North America and northern Eurasia experience runoff increase. Increase in river runoff has been also observed in the La Plata Basin of South America, the southeast quadrant of Africa and northern Australia. Decrease of river runoff in parts of West Africa, sub-Saharan Africa, southern Europe and southernmost South America was observed.

There is abundant evidence for significant altering of the timing of river flows in many regions where winter precipitation falls as snow. Higher temperatures mean that a greater proportion of the winter precipitation falls as rain rather than snow, and the snowmelt season begins earlier. This leads to an earlier occurrence (by 1-2 weeks during the last 65 years in North America and northern Eurasia) of spring peak river flows and an increase in winter base flow in basins with important seasonal snow cover in North America and northern Eurasia, in agreement with local and regional climate warming in these areas. The early spring shift in runoff leads to a shift in peak river runoff away from summer and autumn, which are normally the seasons with the highest water demand (Rosenzweig *et al.*, 2007).

Several climatic and non-climatic processes influence flood generation mechanisms, for different flood types (river floods, flash floods, urban floods, sewer floods, glacial lake outburst floods and coastal floods). The flood-producing processes include intense and/or long-lasting precipitation, snowmelt, dam break, reduced conveyance due to ice jams or landslides, or by storm. Floods depend on precipitation intensity, volume, timing, phase (rain or snow), antecedent conditions of rivers and their drainage basins (e.g., presence of snow and ice, soil character and status (frozen or not, saturated or unsaturated), wetness, rate and timing of snow/ice melt, urbanisation, existence of dykes, dams and reservoirs). Human encroachment into flood plains and lack of flood response plans increased the damage potential.

Documented trends in high water flows show no evidence for a significant, and ubiquitous, change. Milly *et al.* (2002) identified an apparent increase in the frequency of 'large' floods (exceeding 100-year levels) in 16 large drainage basins across much of the globe during the 20th century. They examined long series of monthly river flow data and concluded that seven out of eight 100-year observed discharge (monthly) occurred in the second (more recent) half of the records. However, subsequent studies have provided less widespread evidence.

Kundzewicz *et al.* (2004, 2005) carried out a global change detection study of annual maximum river flows. Their results do not support the hypothesis of an ubiquitous increase of annual maximum river flows. They found significant increases and decreases (in 27 and 31 cases, respectively) and no significant trend in the remaining 137 cases of the 195 catchments examined worldwide. Out of 70 time series for Europe, only 20 show statistically significant changes (11 increases and 9 decreases), while most (50) time series do not show any significant changes. Examples of changes in Europe are shown in Fig. 3.

However, it was found that the overall maxima (for the whole 1961–2000 period) occurred more frequently (46 times) in the later sub-period, 1981–2000, than in the earlier sub-period, 1961–1980 (24 times), cf. Fig. 4. A regional change in timing of floods has been observed in many areas of Europe, therein less snowmelt and ice-jam-related floods.

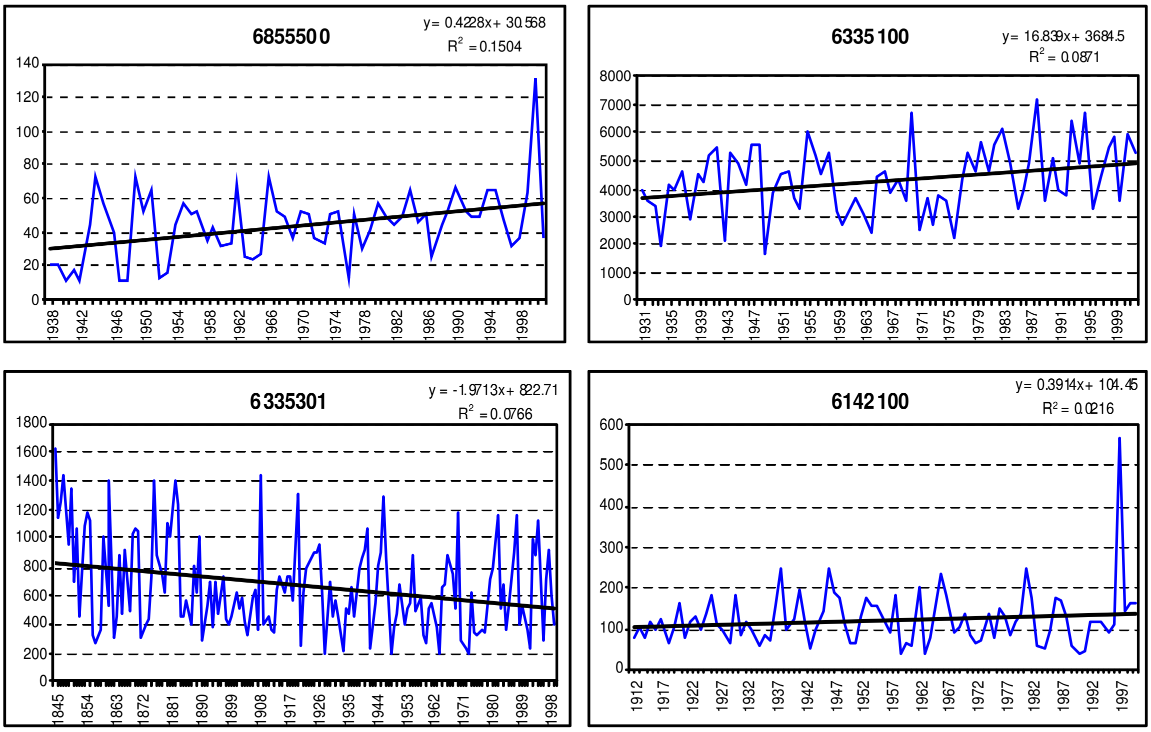

Figure 3. *Changes in maximum annual river flow. (a) Karjaanjoki, Lohjanjarvi-Peltokoski, Finland; (b) Rhine, Kaub, Germany; (c) Main, Schweinfurt, Germany; (d) Morava, Moravicany, Czech Republic. Source: Kundzewicz et al. (2004).*

The formation of lakes occurs as glaciers retreat from prominent Little Ice Age (LIA) moraines in several steep mountain ranges (including the Himalayas, the Andes and the Alps). These lakes thus have a high potential for glacial lake outburst floods (GLOFs), many tens of which exist in the Himalayas, the Andes, and other mountain ranges.

2.4. Projections – Heavy precipitation

On the global scale, the water vapour content of the atmosphere is projected to increase in response to warming, providing a positive feedback, since water vapour is a powerful greenhouse gas. However, the associated change in the vertical profile of atmospheric temperature ('lapse rate') partly offsets the positive feedback.

Climate projections using multi-model ensembles show increases in globally averaged mean water vapour and precipitation over the 21st century. The global distribution of the 2080–2099 change in annual mean precipitation (for the SRES A1B scenario) shows that increases in annual precipitation exceeding 20% occur in most high latitudes, as well as in eastern Africa, the northern part of central Asia and the equatorial Pacific Ocean. Increases in precipitation at high latitudes in both the winter and summer seasons are highly consistent across models. Precipitation increases in some of the monsoon regimes, e.g., the south Asian monsoon in summer (June to August) and the Australian monsoon in summer (December to February), are projected and considerable agreement is found at the broader scale in the tropics. There are widespread decreases in mid-latitude summer precipitation (e.g., tropical Central American—Caribbean and the Mediterranean), except for increases in eastern Asia, cf. Meehl *et al.* (2007).

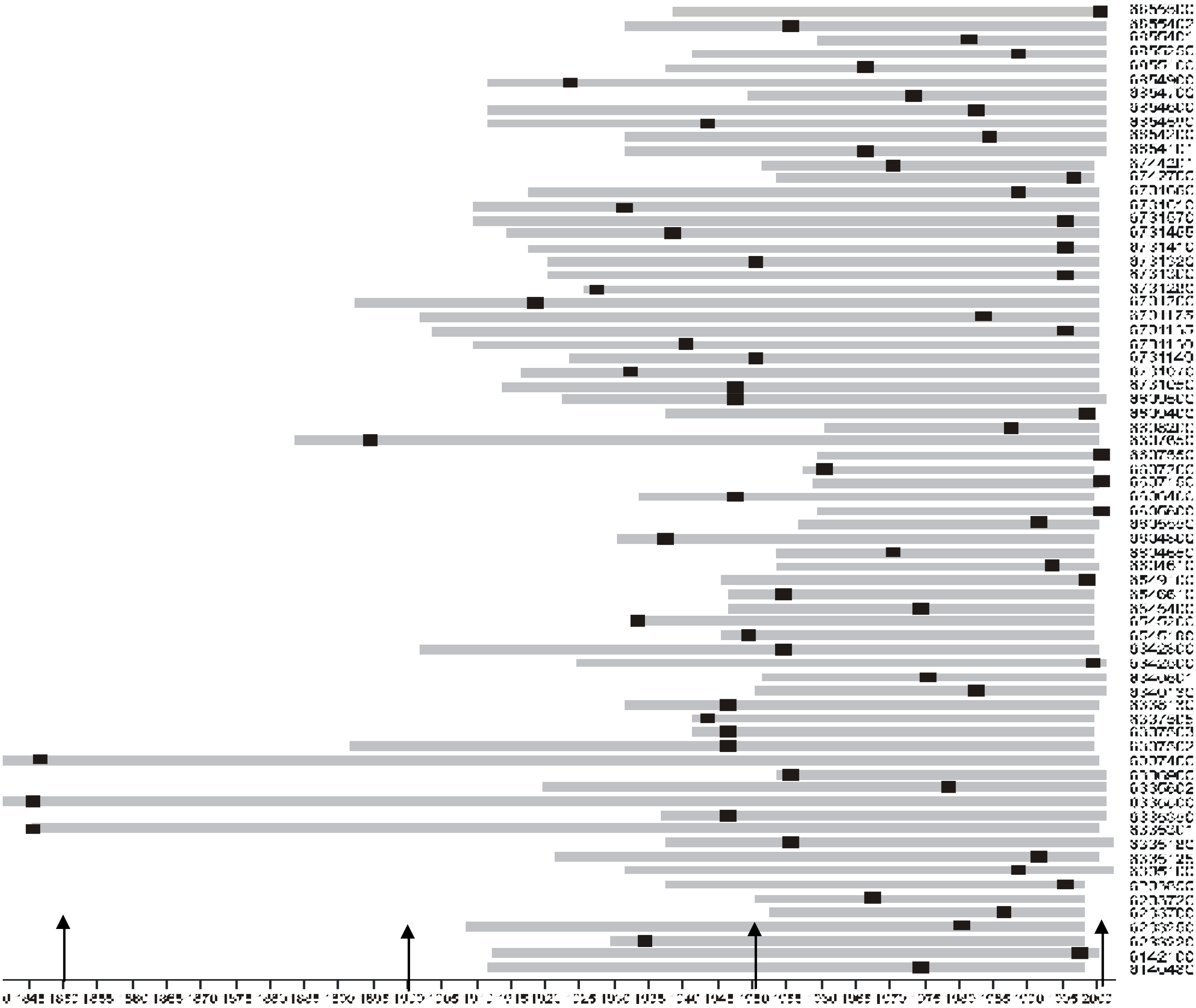

Figure 4. *Year of occurrence of maximum flow in European rivers from 1840 to 2000 (arrows indicate 1850, 1900, 1950, 2000). Source: Kundzewicz et al. (2005).*

Regional precipitation scenarios show a marked contrast between future winter and summer precipitation change in Europe. Wetter winters are predicted throughout the continent. In summer, a strong difference in precipitation change between northern Europe (getting wetter) and southern Europe (getting drier) is projected. This holds for some models for annual totals (Fig. 5).

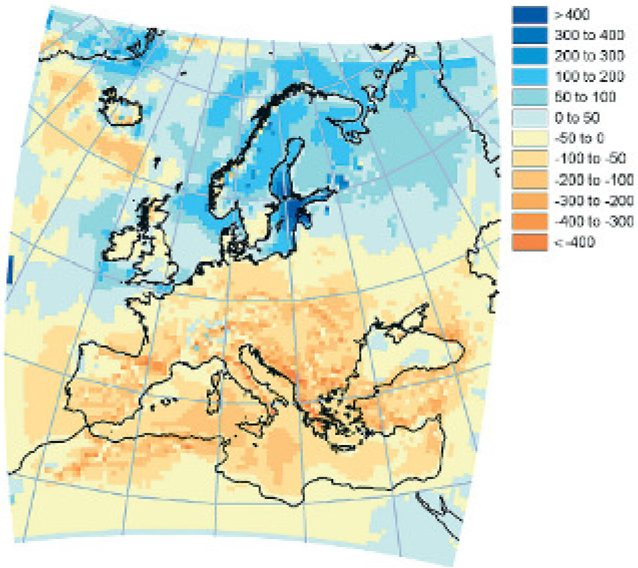

Figure 5. *Difference in mean precipitation (annual values, mm) over Europe between the control period (1961–1990) and future projection (2070–2099) (HadRM3-P, SRES A2 scenario). Source: Kundzewicz et al. (2006).*

Generally, the extremes in precipitation are likely to be impacted more than the means. Changes in precipitation extremes are projected by climate model simulations in many areas of the globe. According to some climate model results (cf., HadRM3-P), the behaviour of precipitation extremes is notably different from the mean precipitation over much of Europe (Fig. 6). The highest quartiles of daily precipitation (Fig. 7) amounts and annual maximum daily precipitation are anticipated to increase over many areas, also where the mean precipitation is projected to decrease (Kundzewicz *et al.*, 2006).

Projected increase in the risk of intense precipitation and flooding does not contradict the projected increase in the risk of drying. Though somewhat counter-intuitive, this is because precipitation is projected to be concentrated in more intense events, with longer periods of lower precipitation in between. Therefore, intense and heavy episodic rainfall events with high runoff amounts are interspersed with longer relatively dry periods with increased evapotranspiration, particularly in the sub-tropics. An increase in the frequency of dry days does not necessarily mean a decrease in the frequency of extreme high-rainfall events (cf. Bates *et al.*, 2008).

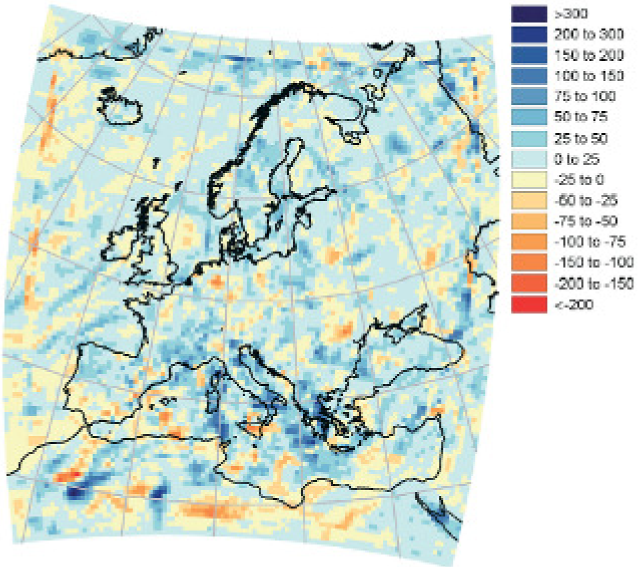

Figure 6. *Difference in annual maximum daily precipitation (mm) over Europe between the control period (1961–1990) and future projection (2070–2099) (HadRM3-P, SRES A2 scenario). Source: Kundzewicz et al. (2006).*

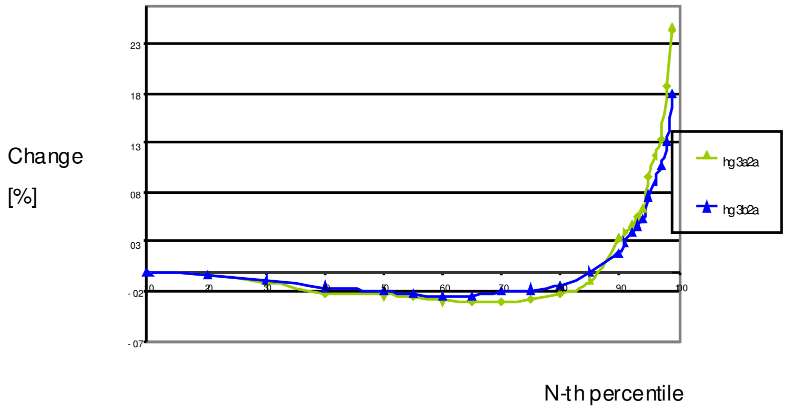

Figure 7. *Projected changes in percentiles of precipitation for the grid cell of the regional climate model HadRM3, containing the town of Poznań. Changes refer to difference in N-th percentile of precipitation between the time horizon of future projection, 2070-2099 and the control period, 1961-1990. Two curves represent two model runs.*

Multi-model climate projections for the 21st century show increases in precipitation intensity (Figure 8), which increases almost everywhere, but particularly at mid- and high latitudes where mean precipitation also increases.

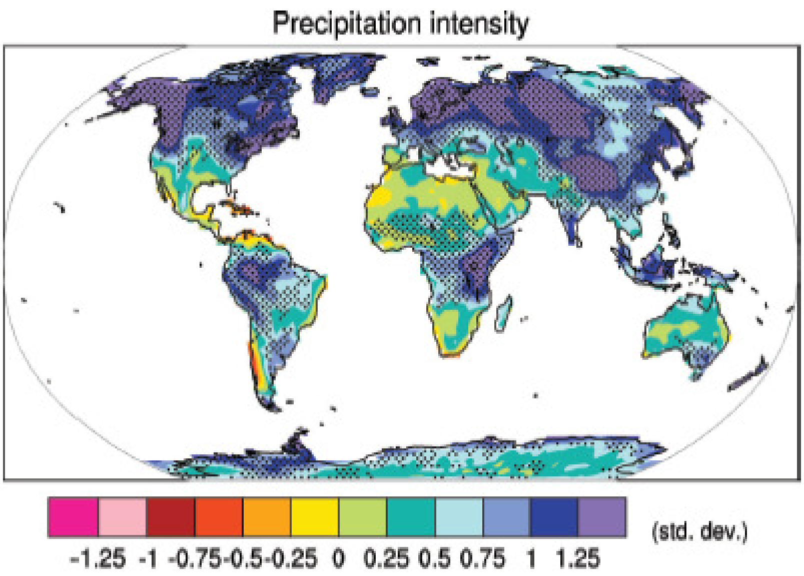

Figure 8. *Changes in spatial patterns of precipitation intensity (defined as the annual total precipitation divided by the number of wet days) over land, based on multi-model simulations from nine global coupled climate models in 2080–2099 relative to 1980–1999 for the A1B scenario. Stippling denotes areas where at least five of the nine models concur in determining that the change is statistically significant. The changes are given in units of standard deviations. Source: Meehl et al. (2007).*

2.5. Projections – High river flows

Changes in river flows due to climate change depend primarily on changes in the volume and timing of precipitation and, crucially, whether precipitation falls as snow or rain. Changes in evaporation also affect river flows. Milly *et al.* (2005) studied the mean runoff change until 2050 for the SRES A1B emissions scenario from an ensemble of multi-model runs. Almost all model runs agree at least with respect to the direction of runoff change in the high latitudes of North America and Eurasia, with increases of 10-40%. This is in agreement with results by Nohara *et al.* (2006), who showed that outside of this region, the standard deviation of the runoff changes until the end of the 21st century is larger than the mean change everywhere except in Northern high latitudes. With higher uncertainty, runoff can be expected to increase in the wet tropics. Prominent regions with a rather strong agreement between models on decreasing runoff (by 10-30%) include the Mediterranean region, Southern Africa and Western U.S/Northern Mexico. The global maps of annual runoff changes (e.g., Milly *et al.*, 2005) illustrate large-scale changes and are not intended to be interpreted at small temporal (e.g., seasonal) and spatial scales. In areas where rainfall and runoff are very low (e.g., desert areas), small changes in runoff can lead to large percentage changes. In some regions, the sign of projected changes in runoff differs from recently observed trends. In some areas with projected increases in runoff, different seasonal effects are expected, such as increased wet-season runoff, with implications to flood risk, and decreased dry-season runoff (Kundzewicz *et al.*, 2007, 2008).

Over large areas, even for large river basins, climate change scenarios of different climate models may result in very different projections of future runoff change. Even the direction of change is uncertain (*e.g.* in Australia, South America, and Southern Africa). The effects of CO_2 enrichment may lead to reduced evaporation, and hence either greater increases or smaller decreases in the volume of runoff.

A robust finding is that warming would lead to changes in the seasonality of river flows where much winter precipitation currently falls as snow, with spring flows decreasing because of the reduced or earlier snowmelt, and winter flows increasing. The effect is greatest at lower elevations, where snowfall is more marginal, and in many cases peak flows by the middle of the 21st century would occur at least a month earlier. In regions with little or no snowfall, changes in runoff are much more dependent on changes in rainfall than on changes in temperature. Most studies in such regions project an increase in the seasonality of flows, often with higher flows in the peak flow season.

The general conclusion drawn from the science of the climate change is that hydrological cycles are likely to accelerate in the warmer climate. However, climate models are not good at reproducing local climate extremes yet, due to, *inter alia*, inadequate (coarse) resolution. Only in some 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. Hence, future projections of extreme events for future climate are highly uncertain. However, it is projected that frequency and intensity of precipitation and floods will grow in the warming climate.

For a wide range of models and scenarios, global average atmospheric concentration of water vapour and precipitation are expected to increase further during the 21^{st} century. This has multiple adverse consequences, such as: increased floods, landslides and mudslides (possibly leading to flow obstructions), 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.

Changes in future flood frequency are projected to be 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. However, global warming may not necessarily reduce snowmelt flooding everywhere, as an increase in winter precipitation is expected, and snow cover may increase in areas where the temperature is still below 0^0C. 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 (rain-caused) flood hazard is likely to rise for many catchments under many scenarios.

Palmer and Räisänen (2002) projected a considerable increase in the risk of a very wet winter in Europe and a very wet monsoon season in Asian monsoon region. For example, for CO_2 doubling (61-80 years from present), an over five-fold increase of the risk of a very wet winter is projected over Scotland, Ireland and much of the Baltic Sea basin, and even over seven-fold increase for parts of Russia.

Milly *et al.* (2002) demonstrated changes in the flood risk over several large basins, worldwide. The control 100-year flood was found to be exceeded more frequently as a result of CO_2 quadrupling. In some areas, a 100-year flood in the control run, is projected to become much more frequent, even occurring every 2 to 5 years.

Floods have been identified (IPCC, 2007a) among the prime reasons of concern in nearly all regions. In the Himalaya, glacier melt will lead to increasing numbers and severity of melt-related floods (including glacial lake outburst floods), ice and rock avalanches from destabilized slopes (IPCC, 2007). Flooded area in Bangladesh is projected to increase at least by 23-29% with a global temperature rise of 2°C (Mirza *et al.*, 2003), i.e. warming that will likely occur in a few decades. In North America, projected warming in the western mountains is very likely to cause increased peak winter flows and flooding by the mid 21st century. Up to 20% of the world population live in river basins that are likely to be affected by increased flood hazard by 2080s in the course of global warming (Kleinen and Petschel-Held, 2006).

It is not a contradiction that climate projections for the 21st century show increases in both precipitation intensity and number of consecutive dry days, in many regions. Though somewhat counter-intuitive, this is because precipitation is projected to be concentrated in more intense events, with longer periods of lower precipitation in between. Therefore, intense and heavy episodic rainfall events with high runoff amounts are interspersed with longer relatively dry periods with increased evapotranspiration. Another aspect of these changes has been related to changes in mean precipitation, with wet extremes becoming more severe in many areas where mean precipitation increases, and dry extremes becoming more severe where mean precipitation decreases. However, there are regions of increased runs of dry days between precipitation events in the subtropics and lower mid-latitudes, but decreased runs of dry days at higher mid-latitudes and high latitudes where mean precipitation increases.

3. Final remarks

Observations to date provide no conclusive and general proof as to how climate change affects flood behaviour. Documented trends in heavy rains (Trenberth *et al.*, 2007) show that hydrological cycle has become more intense in some regions (cf. Huntington, 2006) but ubiquitous increase in flood maxima is not evident (e.g. Kundzewicz *et al.*, 2005).

Climate-related changes in flood frequency are complex and dependent on the flood-generating mechanism (e.g. heavy rainfall *vs* spring snowmelt). The inherent uncertainty in analysis of any set of extreme flood flows stems also from the fact that accuracy of measurements is problematic (rating curves not available for the high flow range, gauges destroyed by the flood wave, observers evacuated), even if indirect determination of the highest stage is often possible.

Flood risk and vulnerability tend to increase over many areas, due to a range of climatic and non-climatic impacts whose relative importance is site-specific. Apart from changes in the climatic system, changes affecting flood hazard have also occurred in economic and social systems, and in terrestrial systems (hydrological systems and ecosystems). Land-use changes, which induce land-cover changes, control the rainfall-runoff relations. Deforestation, urbanization, and reduction of wetlands diminish the available water storage capacity and increase the runoff coefficient, leading to growth in the flow amplitude and reduction of the time-to-peak of a flood triggered by 'typical' intense precipitation. However, a 'typical' intense precipitation event has also been increasing in the warming climate. Furthermore, human encroachment into unsafe areas has increased the potential for damage. Societies become more exposed, developing flood-prone areas (maladaptation).

Detection of changes in long time series of hydrological data is an important scientific issue, fundamental for planning of future water resources and disaster protection. If changes are occurring within hydrological systems then existing procedures for designing dikes, spillways, dams and reservoirs, by-pass channels, etc., based on the stationarity assumption will have to be revised. Without this (Milly *et al.*, 2008), systems will be over- or under-designed and will either not serve their purpose adequately, or will be overly costly.

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