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Fluvial flood risk in Europe in present and future climates

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Abstract In this work we evaluate the implications of climate change for future fluvial flood risk in Europe, considering climate developments under the SRES A2 (high emission) and B2 (low emission) scenario. We define flood risk as the product of flood probability (or hazard), exposure of capital and population, and vulnerability to the effect of flooding. From the European flood hazard simulations of Dankers and Feyen (J Geophys Res 114: D16108. doi:10.1029/2008JD011523, 2009) discharges with return periods of 2, 5, 10, 20, 50, 100, 250 and 500 years were extracted and converted into flood inundation extents and depths using a planar approximation approach. Flood inundation extents and depths were transformed into direct monetary damage using country specific flood depth-damage functions and land use information. Population exposure was assessed by overlaying the flood inundation information with data on population density. By linearly interpolating damages and population exposed between the different return periods, we constructed damage and population exposure probability functions under present and future climate. From the latter expected annual damages (EAD) and expected annual population exposed (EAP) were calculated. To account for flood protection the damage and population exposure probability functions were truncated at design return periods based on the country GDP/capita. Results indicate that flood damages are projected to rise across much of Western Europe. Decreases in flood damage are consistently projected for north-eastern parts of Europe. For EU27 as a whole, current EAD of approximately €6.4 billion is projected to amount to €14–21.5 billion (in constant prices of 2006) by the end of this century, depending on the scenario. The number of people affected by flooding is projected to rise by approximately 250,000 to 400,000. Notwithstanding these numbers are subject to

The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

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uncertainty, they provide an indication of potential future developments in flood risk in a changing climate.

1 Introduction

Over the last decades, the costs of floods in Europe have exhibited a rapid increase (Barredo 2009). Most of the observed upward trend in flood damage can be attributed to socio-economic factors, such as the increase in population and wealth in flood-prone areas, as well as to changes in the terrestrial system, such as urbanisation and deforestation, that have lead to the loss of wetlands and natural floodplain storage (e.g., via dike construction, river straightening and floodplain sedimentation). Changes in climate may also have played a role. However, any conclusion on a positive contribution of climate change is premature (see e.g., Mudelsee et al. 2003; Kundzewicz et al. 2005), partly because of the inherent difficulties and uncertainties in detecting trends in extreme river flows amidst strong natural variability. We note that this work only considers fluvial floods. Coastal flooding is handled in a separate paper in this Special Issue (Bosello et al. 2010).

Recent advances in climate modelling, however, suggest that climate change will likely play a role in the future. For the coming decades, it is projected that global warming will intensify the hydrological cycle and increase the magnitude and frequency of intense precipitation events in most parts of Europe, especially in the central and northern parts (Christensen and Christensen 2003; Semmler and Jacob 2004; Frei et al. 2006). This will likely contribute to an increase in flood hazard triggered by intense rain, particularly the occurrence of flash floods. Flood hazard may also rise during wetter and warmer winters, with increasingly more frequent rain and less frequent snow. On the other hand, ice-jam and early spring snowmelt floods are likely to reduce because of warming (Kundzewicz et al. 2006).

In recent years, many climate change impact studies have appeared in the literature. The majority of impact studies in the field of hydrology have focused on water resources and average flow conditions such as changes in seasonal runoff (e.g., Milly et al. 2005; Alcamo et al. 2007; Kundzewicz et al. 2008), in part because long-term average values are generally considered the more reliable outputs of climate and large-scale hydrological models. Relatively fewer studies focused on the impacts of climate change on extreme flows. Amongst the studies focussing on regions in Europe, there is a geographical preference for catchments located in the UK (e.g., Charlton et al. 2006; Kay et al. 2006; Bell et al. 2007), Benelux (e.g., Booij 2005; Leander et al. 2008), Germany (e.g., Shabalova et al. 2003), Central Europe (e.g., Dankers et al. 2007) and Scandinavia (e.g., Graham et al. 2007; Thodsen 2007). Several studies report an increase in flood frequency and intensity, while others project a decreasing trend. However, the application of different climate scenarios, climate and hydrological models, as well as basin-specific characteristics render it difficult to compare the results of the different studies and to draw an overall picture of the possible effects of climate change on flood hazard at the European scale.

A first pan-European assessment of changes in flood hazard due to climate change was performed by Lehner et al. (2006). They used climate data from the ECHAM4 and HadCM3 General Circulation Models (GCMs), based on a scenario that is largely consistent with the no-policy IPCC-IS92a scenario, in combination with the global integrated water model WaterGAP to define large critical regions of increases in flood and drought hazard. The monthly averaged GCM output was disaggregated in space and time to the temporal scale (daily) and (coarse) spatial scale (0.5°) of WaterGAP. In the climate signal, only long-term trends and changes in seasonal climate were taken into account, while changes in short-range variability were neglected. These assumptions do not allow a proper evaluation of changes in climatic extremes, which may show a very different pattern compared to the average changes in climate, and constrain the reliability of the results with respect to changes in flood hazard.

More recently, Dankers and Feyen (2008, 2009) evaluated changes in flood hazard in Europe for the SRES A2 and B2 greenhouse gas emission scenarios using high-resolution regional climate simulations from the PRUDENCE (Prediction of Regional scenarios and Uncertainties for Defining European Climate change risks and Effects) project (Christensen et al. 2007). Their results show a consistent tendency toward a higher flood hazard in the majority of the model experiments in several major European rivers. In certain regions, notably in the northeast and parts of central and southern Europe, a considerable decrease in flood hazard was found. They furthermore found evidence for a considerable influence of especially the global model that is used to drive the RCMs. At the scale of individual river basins, using a different combination of climate models or assuming a different emissions scenario sometimes resulted in a very different or even opposite climate change signal in flood hazard.

The concept of risk has been developed and used across a wide range of disciplines. As a result, no unique definition of risk exists. Flood risk, typically used as a measure of economic losses from flooding, is defined here as the product of flood hazard, vulnerability and exposure. Flood hazard is the threatening natural event, including its probability of occurrence and magnitude. Exposure represents the capital, humans and ecological assets exposed to the hazard (typically expressed by statistics on population, socio-economic data on sectorial activities and infrastructure). Vulnerability describes the potential to be harmed or the susceptibility of the receptor to the flood hazard. It is therefore an indication of the measures taken to mitigate the effects of flood events. Thus, flood risk is a potential loss having an uncertain occurrence and size. It is a consequence of hazard, vulnerability and exposure. In practice, exposure and vulnerability are often captured in the assessment of the consequences.

Socio-economic drivers and climate affect the components of flood risk in a variety of ways and are often interlinked. This renders it difficult to detangle the effects on flood risk of an individual driver such as climate change. As the focus of this paper is on the evaluation of the impact of climate change on flood risk, exposure is therefore assumed to be static.

Monetary assessments of the impacts of climate change on floods in Europe have been poorly covered to date. Hall et al. (2005) presented a national-scale assessment of current and future coastal and river flood risk in England and Wales. Their analysis uses information on flood defences (including probability of failure), land use, impact (depth-damage and population data) together with datasets on floodplain extent and topography. Results indicated an up to 20-fold increase in real terms economic risk by the 2080s for the scenario with the highest economic growth. No studies have yet appeared in the literature with a European coverage.

The aim of this paper is to evaluate the implications of climate change on future flood risk in Europe. For the SRES A2 and B2 greenhouse gas emission scenarios (Nakicenovic and Swart 2000) we estimate, with respect to the end of the previous century, changes by the end of this century in the expected annual flood damage and the number of people affected by floods. The flood risk analysis described in this paper builds upon the flood hazard assessment of Dankers and Feyen (2009). Based on the results of their analysis, flood inundation extents and depths are derived employing high-detail topographic information. Flood damages and the number of people affected by floods are subsequently obtained by combining the calculated flood depths with land use, country-specific depth-damage functions and population data. In the following sections, the different steps of the methodology, including some of the limitations, are detailed, followed by a discussion of the results and conclusions.

2 Methodology

2.1 Flood hazard assessment

In recent years, the horizontal resolution of RCM simulations has increased considerably and now approaches a level of detail that allows capturing fine-scale climatic structures induced by complex topography or land use patterns, which is essential for flood hazard assessment. The ensemble flood hazard simulations of Dankers and Feyen (2009) that form the basis of the current damage assessment used regional climate simulations conducted within the framework of the PRUDENCE project (Christensen et al. 2007). The two RCMs that were selected are the HIRHAM model of the Danish Meteorological Institute (Christensen et al. 1996) and the Rossby Centre Atmosphere Ocean Model (RCAO) of the Swedish Meteorological and Hydrological Institute, which is a combination of the atmospheric model RCA2 (Jones et al. 2004) coupled to an ocean model, RCO (Meier et al. 2003). Both RCMs were run over the European domain with a horizontal grid spacing of ~0.5° latitude by longitude (approximately 50 km) with boundary conditions coming from the HadAM3H global atmosphere model of the Hadley Centre in the UK (Pope et al. 2000) for HIRHAM and the coupled ocean–atmosphere GCM ECHAM4/OPYC3 of the Max Planck Institute for Meteorology and the German Climate Computing Centre in Hamburg, Germany (Roeckner et al. 1999) for RCAO. These models were run for two scenarios of GHG emissions, the SRES A2 and B2 scenarios of the Intergovernmental Panel on Climate Change (IPCC) (Nakicenovic and Swart 2000). Each of these experiments consisted of two 30-year time slices: a control run with a GHG forcing corresponding to 1961–1990, and a scenario run corresponding to 2071–2100. The different climate experiments are further herein denoted as follows (with the average European temperature increase for the scenario given between brackets): B2 Had-HIR (+2.5°C), A2 Had-HIR (+3.9°C), B2 Ech-RCAO (+4.1°C), A2 Ech-RCAO (+5.4°C). More details on the climate data used in this study can be found in Christensen et al. (2010).

The RCM simulations of temperature, precipitation, solar and thermal radiation, humidity and wind speed data were used to drive the hydrological model LISFLOOD (van der Knijff et al. 2008). This model has been developed for operational flood forecasting at European scale and is a combination of a grid-based water balance model and a 1-dimensional hydrodynamic channel flow routing model. Since it is spatially distributed, the model allows incorporating the spatial variation in land use, soil properties and meteorological forcing data. The current, European-wide set-up uses a 5 km grid and input parameters on soil and land use were derived from European databases. The model parameters that control infiltration, snowmelt, overland and river flow, as well as residence times in the soil and subsurface reservoirs, were estimated by calibrating against historical records of river discharge in 231 catchments and subcatchments. For catchments where discharge measurements were not available simple regionalization techniques (regionally averaged parameters) were applied to obtain the model parameters. A more detailed description of the different model processes and governing equations, as well as of the European-wide model setup and calibration exercise can be found in van der Knijff et al. (2008) and Feyen et al. (2007, 2008).

In the current simulations the RCM data were re-gridded to the 5 km grid scale of LISFLOOD without any further downscaling or altitude correction. This means that any bias in (especially) the precipitation fields will directly influence the LISFLOOD simulations. However, at European scale there is presently no high-quality precipitation dataset available with sufficient observation length and spatial detail that would allow a proper downscaling of the RCM climate data.

To estimate the probability of extreme discharge levels, a Gumbel distribution was fitted to the annual maximum values in every river grid cell, whereby the location and scale parameter were estimated using Maximum Likelihood Estimation (MLE), following Gilleland and Katz (2005). From the fitted Gumbel distributions of extreme discharges, return levels were derived for every river pixel for return periods of 2, 5, 10, 20, 50, 100, 250 and 500 years. For validation, the simulated extreme discharges from the LISFLOOD model run driven by the control climate were compared with observations at 209 gauging stations across Europe for which long enough daily data (30 years covering 1961–90 or 1971–2000) were available. The LISFLOOD model, when being driven by the RCM data, was able to reproduce both mean and high discharge levels across Europe reasonably well (for more details see Dankers and Feyen 2008; 2009).

2.2 Derivation of flood inundation extents and water depths

When a flood wave exceeds bank full height, water will extend rapidly over the low lying floodplains. Accurate estimation of the out-of-bank flow, flood inundation extent, water depth and surface flow velocity is a difficult task due to the complexity of the dynamics of a flood pulse and its translation onto the 2-dimensional floodplain. There exists a plethora of numerical hydraulic models for floodplain flow modelling, ranging from 1-dimensional solutions of the St. Venant equations to complex 3-dimensional solutions of the Reynolds-averaged Navier–Stokes equations. These models often suffer from a lack of distributed data to parameterize and validate the codes, as well as from a lack of adequate theory to scale parameter values derived for point-based equations to effective parameter values at the grid scale or to relate point validation measurements to the time- and space-averaged quantities actually predicted by the models (Bates 2004). As a result, their use is typically limited to small scale applications (e.g., Pappenberger et al. 2008).

A pan-European flood risk assessment requires a macro-scale approach that prohibits simulating flood inundation with a high level of complexity. Therefore, in this work a planar approximation approach was employed in which the flood wave is considered as a plane that is intersected with a high resolution digital elevation model to estimate flood inundation extent and water depth. Bates and De Roo (2000) showed that for a 35-km reach along the River Meuse (the Netherlands) the planar approximation approach performed nearly as well as two-dimensional storage cell and full two-dimensional hydraulic models, especially for reaches that are short compared to the wavelength of the flood. The planar approximation approach was implemented here as follows. First, river discharges were translated into river water depths based on approximated river channel geometries. The river water depths were resampled from the 5 km river network to 100 m resolution based on the river network obtained from the pan-European River and Catchment Database CCM2 (Vogt et al. 2007). Finally, river water levels were extrapolated onto the high-resolution (100 m) digital elevation model of the CCM2 database to delineate flooded areas and inundation depths. In this step, flood protection measures were not taken into account.

2.3 Flood risk assessment

Flood risk assessment requires the integration of the physical impact results (flood inundation extent and depth) with information on exposure and vulnerability or impact. For the damage assessment, exposure was assessed based on the land use classification of CORINE Land Cover 2000 (EEA 2000). We note that in the calculation of future flood risk land use changes or projected growth in exposed values is not accounted for, hence all damages are based on current exposed values. Also, no discounting or inflation is applied to future damages as they are calculated using today's prices. Vulnerability, defined as the susceptibility of the exposed assets at contact with water, was appraised using country specific flood depth-damage functions (Huizinga 2007). The depth-damage functions represent, for each country and for each land use class (e.g., residential, industrial, etc.), the absolute amount of damage as a function of flood inundation depth. This method is considered as the standard approach for regional scale damage assessments (Messner et al. 2007). The country specific depth-damage functions were further rescaled by the GDP/capita of administrative level NUTS2 to account for the large regional differences in exposed assets for a given land use class that exist in some countries.

Direct damage estimates were obtained by overlaying the flood water depth map with the land use map linked with the corresponding depth-damage functions. This resulted in a damage map at a resolution of 100 m for each of the return periods considered (2, 5, 10, 20, 50, 100, 250 and 500 years), which allows evaluating the change in flood damage between current and future climate for the respective return periods. By linearly interpolating damages between the different return periods, damage probability functions were constructed for each grid cell under present and future climate. Such functions represent flood damage as a function of the probability of occurrence (or return period) of a flood. The integral of this function represents the expected annual damage (EAD) at the particular location due to flooding.

In reality, most countries have flood defence measures up to a certain design flood to prevent areas from flooding. To account for flood protection the damage-probability functions need therefore to be truncated at the corresponding design return period. In this way, damages from floods with lower return periods are discarded. The integral of the remaining part of the function corresponds to the expected yearly loss due to flooding taking into account flood protection measures. However, data about flood protection levels, including their probability of failure, are hardly available at the national or European level. We therefore estimated, for illustrative purposes, the standard of flood protection for EU countries indirectly using GDP/capita as a measure of protective capacity (see Table 1). For countries with a GDP/capita larger than 110% of the average EU27 GDP/capita we assumed protection up to 100-year flood events (shaded dark gray in Table 1). For countries with a GDP/capita between 55 and 110% of the average EU27 GDP/capita (shaded medium gray in Table 1) a 75-year return level protection was imposed. For countries with a GDP/capita lower than 55% of the average EU27 GDP/capita (shaded light gray in Table 1) the damage probability functions were cut-off at the 50-year return level.

To evaluate population exposure to river floods the resampled flood inundation maps were overlain by a dataset of gridded population density of Europe at 100 m resolution (Gallego and Peedell 2001). Similarly to flood damages, population exposure probability functions were derived for each grid cell, which were truncated at the corresponding protection levels to obtain expected annual population exposure (EAP) estimates.

2.4 General limitations

The different steps in the chain "emissions→climate→extreme flow→flood inundation→ damage" are subject to uncertainty. When applying the framework outlined above for

Table 1 Country-averaged expected annual damage (EAD) in billion €/year for control and scenario period for the different scenarios. Different levels of flood protection are imposed based on country GDP (dark gray: 100 year return level protection; medium gray: 75 year return level protection; light gray: 50 year return level protection). Note that Cyprus and Malta are not part of the model domain

Country	ctrl Had-HIR	B2 Had-HIR (+2.5°C)	A2 Had-HIR (+3.9°C)	ctrl Ech-RCAO	B2 Ech-RCAO (+4.1°C)	A2 Ech-RCAO (+5.4°C)
AT	0.218	0.668	0.409	0.202	0.171	0.085
BE	0.156	0.103	0.269	0.188	0.890	1.221
DE	0.581	0.647	1.418	0.483	1.183	1.575
DK	0.013	0.070	0.093	0.016	0.068	0.157
FI	0.330	0.033	0.046	0.313	0.248	0.131
FR	1.042	2.294	3.985	1.141	2.940	5.491
IE	0.024	0.010	0.054	0.031	0.251	0.194
LU	0.011	0.016	0.039	0.013	0.069	0.067
NL	0.412	0.321	0.990	0.489	2.224	3.717
SE	0.134	0.116	0.248	0.138	0.120	0.133
UK	0.780	1.548	3.605	0.777	3.336	5.580
CZ	0.256	0.321	0.941	0.196	0.074	0.086
ES	0.265	0.465	0.576	0.309	0.261	0.226
GR	0.045	0.035	0.230	0.031	0.054	0.003
HU	0.340	1.527	0.768	0.282	1.175	0.964
IT	0.870	2.927	2.486	0.782	1.000	0.769
PT	0.023	0.012	0.010	0.022	0.077	0.064
SI	0.046	0.074	0.040	0.038	0.184	0.113
SK	0.135	0.279	0.247	0.144	0.228	0.277
BG	0.057	0.091	0.126	0.042	0.084	0.028
EE	0.017	0.001	0.006	0.014	0.001	0.003
LV	0.053	0.020	0.061	0.063	0.011	0.028
LT	0.030	0.026	0.127	0.036	0.032	0.035
PL	0.418	1.940	1.145	0.384	0.252	0.356
RO	0.231	0.594	0.157	0.206	0.312	0.120
EU27	6.49	14.14	18.08	6.34	15.24	21.42

macro-scale flood damage assessment it was necessary to adopt the following assumptions, which should be kept in mind when interpreting the results:

- The climate scenarios used only capture a part of the uncertainty range attributable to emissions of greenhouse gases (with the A2 and B2 scenarios only two out of six SRES storylines are considered) and to inter-GCM and inter-RCM variability. Dankers and Feyen (2009) find evidence for a considerable influence on flood return level estimates of especially the GCM that is used to drive the RCMs and suggest that a multi-model approach provides the best way to address climate input uncertainty.
- No downscaling or bias correction was applied to the climate data because at present no high-quality, high-resolution meteorological dataset exists at European scale that would allow a proper downscaling of the RCM climate data. This may locally lead to underestimation of flood frequencies due to the inability of the RCM to explicitly

represent fine-scale climatic structures such as small-scale convective storms (Trapp et al. 2010) that trigger flash and pluvial floods.

- Hydrological uncertainty is not accounted for. Several studies (e.g., Wilby 2005) showed, however, that this layer of uncertainty is generally much lower than the uncertainty of the climate input to the hydrological model.
- Flood return levels are estimated using extreme value analysis based on simulated time series of 30 years, which may result in large extrapolation errors for high return periods.
- In the calculation of river water levels, river cross sections had to be approximated due to the absence of national or European datasets on riverbed geometries.
- Inaccuracies in the SRTM DEM may induce bias in the estimation of flood inundation levels.
- Changes in land use and land cover are not incorporated in the climate runs or in the economic impact evaluation due to the absence of reasonable macro-scale land use change scenarios for the SRES storylines. This may result in an underestimation of future flood risk.
- The approach used is based on direct estimated potential flood damage caused by water depths on land use typologies. Other factors that might contribute to the increase of losses, such as flood velocity, building characteristics, content of sediment in water, as well as indirect economic losses, are not included in this study.

The above list of assumptions implies that monetary estimates of flood damage are inherently uncertain. It should be noted, however, that the goal of this study was to evaluate changes in flood damage due to climate change, rather than to estimate absolute values of flood damage. Given that most of the assumptions apply to both the control and scenario period it can be expected that estimates of changes in flood damage are relatively less affected by the assumptions compared to the absolute flood damage estimates. Also, validation of the flood damage estimates for the control period (as discussed in the next section) compare relatively well with estimates of flood damage from other studies.

3 Results and discussion

3.1 Changes in flood hazard in Europe due to climate change

Figure 1 shows the change in extreme discharge level, exemplified by changes in the 100-year return level (Q_{100}), between the scenario and control run for the 4 climate futures. Note that an increase or decrease in the 100-year return discharge translates as an increase or decrease in the probability of occurrence—or frequency—of a current 100-year flood level. We observe a considerable decrease in the Q_{100} in northeastern Europe. This decrease is noticeable in each of the experiments, although the exact extent and location of the area with decreasing flood hazard differs, and relates to a reduction in snow accumulation. In this region the snowmelt runoff peak in spring is the most prominent feature of the natural flow regime, and because of the rising temperatures the snow season is reduced considerably. Whether or not a shorter snow season leads to less snow accumulation depends on the changes in winter precipitation, which in northern Europe is generally predicted to be higher. This explains why in some northern rivers the Q_{100} is not changing significantly or sometimes even increases, as the higher winter precipitation compensates for the shorter snow season.

The rest of the continent shows a more mixed pattern of increases and decreases in extreme river discharge, but considerable increases do occur in any of the scenarios, albeit not always in

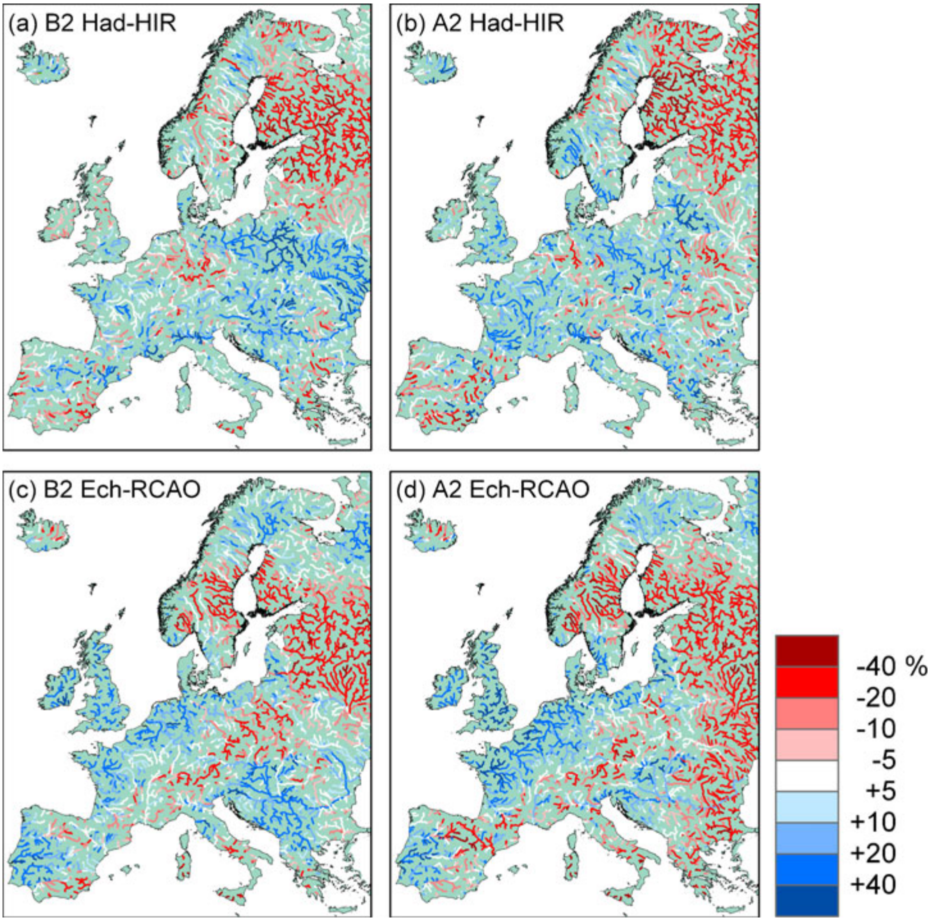

Fig. 1 Relative change in 100-year return level of river discharge between scenario (2071–2100) and control period (1961–1990) for climate scenarios B2 Had-HIR (**a**), A2 Had- HIR (**b**), B2 Ech-RCAO (**c**) and A2 Ech-RCAO (**d**). Shown here are only rivers with an upstream area of 1,000 km^2 or more (from Dankers and Feyen 2009)

the same region. At the scale of individual river basins, using a different combination of climate models or assuming a different emission scenario sometimes results in a very different or even opposite climate change signal in flood hazard. In some areas, for example parts of central and eastern Europe, the B2 scenario shows a strong increase in extreme river flows whereas the A2 scenario results in little change or even a decrease. This implies that with respect to changes in discharge extremes, the lower-emissions B2 scenario should not necessarily be regarded as less extreme (as is the case for temperature). This counterintuitive result highlights two aspects: first of all, flood risk, like extreme precipitation, does not scale linearly with rising temperatures. Secondly, decadal-scale internal variability in the simulated climate likely plays an important role in determining the changes in extreme discharge levels, as found by Dankers and Feyen (2009). This means that part of the differences in extreme flood levels between two separate model runs can be attributed to internal variability obscuring the "signal" of a difference in greenhouse gas concentrations. Nevertheless, when analysing an ensemble of three different integrations of the same climate model each with different internally generated climate variability, Dankers and Feyen (2009) found that some of the increases in the 100-year return level were statistically significant, particularly in rivers in northwestern Europe, as well as in northern Italy and the Upper Danube. For assessing changes in hydrological extremes, such multiple realizations of climate simulations are indispensable in order to reduce the influence of decadal-scale variability that is inherent to climate and to obtain more accurate results and identify longer-term trends. Unfortunately, because of the computational demands ensemble climate simulations are not yet standard practice. In our case, no further simulations were available for the B2 scenario that would have allowed us to test the robustness of this finding.

Comparison of the patterns of change also shows the considerable influence of the driving global climate model. The ECHAM-driven scenarios (plates c and d of Fig. 1) result in an increase in Q_{100} particularly in western Europe, including the British Isles. The HadAM3H runs (plates a and b of Fig. 1), on the other hand, show more increases in eastern Europe, especially in the B2 scenario.

Although not shown here, for all scenarios the patterns of change between the control and scenario period that can be seen in Fig. 1 are comparable to the changes for other return intervals (Dankers and Feyen 2009). We note again, however, that the estimation of discharge levels with high return periods from a 30-year long time series is subject to large uncertainties due to extrapolation.

3.2 Changes in flood damage in Europe due to climate change

Expected annual damages (EAD) were calculated from the damage-probability functions for both control and scenario periods. For the future period, no adaptation to projected changes in flood levels was taken into account. Therefore, the same levels of protection in terms of design discharge were applied for the control and scenario period. To this end, design discharge levels imposed in the control period (reflecting current levels of protection) were converted into the corresponding return periods in the future climate. These are not necessarily the same as for the control period: a 100-year flood in the control period may have a return period of, say, 70 years in the scenario run. Hence, defence measures that are currently sufficient to defend against a 100-year flood event may only represent adequate defence against a 70-year event by the 2080s. The future return periods of the design discharge were then used to appropriately truncate the damage-probability functions derived for the future climate.

Country-averaged EAD values for the control climate of the A2 and B2 climate runs are tabulated in columns 2 and 5 of Table 1, respectively. The differences in damage between the two control periods result solely from the discrepancies in reference climate as simulated by the coupled climate models (Had-HIR vs. Ech-RCAO) for 1961–1990. For most countries the differences between the control periods are relatively small. The largest difference is observed for Greece, where the EAD for the Had-HIR control run is approximately 30% higher than for the Ech-RCAO control run. Aggregated over EU27 the difference in EAD between the two reference climates is less than 3%.

Very few macro-scale studies exist to verify the estimated damages for the control period. According to the Association of British Insurers, present-day average losses from flooding in Europe total \$8–10 billion (€5.5–7 billion) annually (ABI 2005), which is in agreement with the estimated EAD of approximately €6.4 billion (see bottom rows of column 2 and 5 in Table 1). In 2001 the UK Department for Environment, Food and Rural Affairs (DEFRA) performed a national appraisal for England and Wales of assets at risk from flooding. Under the levels of protection at that time the EAD from river flooding amounted to £521.3 million (€643 million), compared to £262.8 million for sea/tidal flooding (DEFRA 2001). Hall et al. (2006), on the other hand, report that the AED due to coastal flooding in England and Wales, which was estimated to be £0.5 billion in 2002, represented roughly half of the flood risk due to fluvial and coastal flooding combined. The Flood and Coastal defence project reported an EAD of £1090 million for river and coastal flooding in the UK (Evans et al. 2004). Hall et al. (2005) performed a national-scale assessment of current and future flood risk in England and Wales and EAD of river and coastal flooding under current climate conditions was estimated to be approximately £1 billion, with an uncertainty range between £0.6 and £2.1 billion. If we assume that for the latter two studies the same ratios apply between damages from river and coastal flooding as in the DEFRA (2001) and Hall et al. (2006) study, the EAD from river flooding corresponds to approximately £550–£725 million (€672–€894 million) in the Evans et al. (2004) and £500–£665 million (€617–€820 million) in the Hall et al. (2005) study, respectively. The current estimate of EAD for the UK in the control period (~€780 million, see Table 1) compares reasonably well with the numbers reported in these studies.

Figure 2 shows the relative change in EAD damage (aggregated over administrative level NUTS 2) between the control climate and the climate at the end of the century under

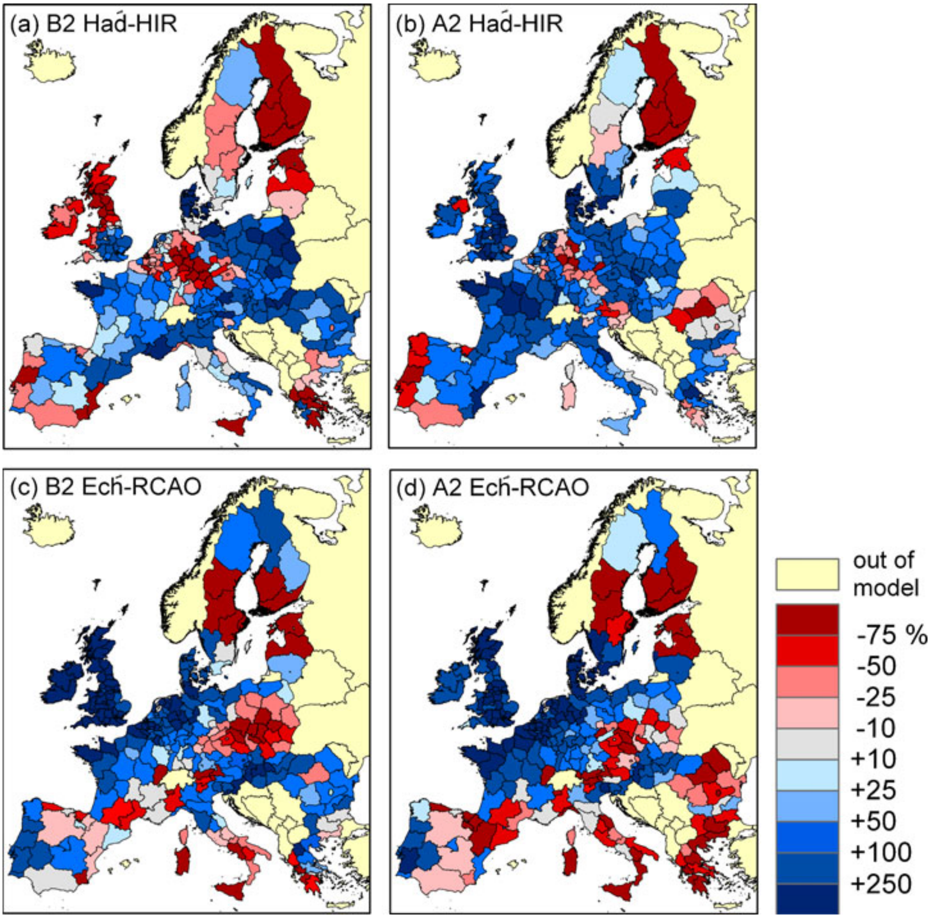

Fig. 2 Relative change in EAD (averaged over administrative level NUTS2) between scenario (2071–2100) and control period (1961–1990) for climate scenarios B2 Had-HIR (**a**), A2 Had- HIR (**b**), B2 Ech-RCAO (**c**) and A2 Ech-RCAO (**d**)

the different scenarios. The patterns in flood damage changes in Europe reflect largely those observed in the changes in flood hazard (Fig. 1), but locally differences can be noted especially in the magnitude of change. The ECHAM-driven regional climate simulations (plates c and d of Fig. 1) show a strong increase in flood damage particularly in western Europe, including Portugal and the British Isles. The HadAM3H runs (plates a and b of Fig. 1) show more increases in eastern Europe, especially in the B2 scenario, as well as in Italy and large parts of Spain. Areas showing a consistent decrease in flood damage in the different climate futures are southern parts of Finland, Estonia and the middle regions of Sweden.

The changes in future EAD observed in Fig. 2 are reflected in the country-averaged EAD values that are tabulated in Table 1. Of the EU27 countries (minus Cyprus and Malta which are out of the hydrological model domain), 7 show a consistent increase in flood damage under the different climate futures, namely Denmark, France, Germany, Hungary, Luxembourg, Slovakia and the United Kingdom. The Netherlands, Belgium and Ireland show increases in all scenarios but the B2 Had-HIR (+2.5°C) scenario. The projected rise in damage varies strongly, depending on the country and the climate future considered, with increases ranging between 10% up to more than 600% (e.g., Denmark, the Netherlands and UK for the Ech-RCAO (+5.4°C) scenario). Consistent decreases in future flood damage across the scenarios are projected for Finland and Estonia, but also Sweden, Latvia and Lithuania show a decrease in flood risk for 3 of the 4 scenarios (only not under the A2 Had-HIR (+3.9°C) scenario).

For EU27 as a whole, current EAD of approximately €6.4 billion is projected to reach (in constant prices of 2006) respectively €14 billion (B2 Had-HIR, +2.5°C), €18 billion (A2 Had-HIR, +3.9°C), €15 billion (B2 Ech-RCAO, +4.1°C) and €21.5 billion (A2 Ech-RCAO, +5.4°C) by the end of this century. Hence, notwithstanding the regional differences between the different climate futures, the higher emission scenario does result in overall higher flood losses. It should be noted that the estimates of future flood losses are based on current exposed values; hence no growth in exposed values is taken into account.

For the UK, flood damage is projected to rise across all scenarios, with the increase ranging between 100% and 600%. Under the B2 Had-HIR (+2.5°C) scenario, the reduction in flood damage projected for Scotland and the northern and western parts of England (plate a in Fig. 2) is offset by the strong rise in flood damage in south-eastern England. This results in an overall increase in flood damage by nearly 100% for the UK under this scenario. Reported projections about future flood risk in the UK by the 2080's vary substantially, depending on the assumed or estimated increase in flood level and the socio-economic scenario used. The DEFRA study (DEFRA 2001) reports an increase in EAD of 43% and 92%, respectively, for a 10% and 20% rise in flood flow. Hall et al. (2005) used the UK Climate Impacts Programme scenarios (UKCIP02) that integrate both climate change and socio-economic projections. For the UKCIP02 Medium-high emissions scenario (based on SRES A2 scenario) future flood damage would rise up to 15 fold. Under the UKCIP02 Medium-low emissions scenario (based on SRES B2 scenario) the increase would be limited to 50%. Projections based on the Foresight Futures socio-economic scenarios show comparable increases (Evans et al. 2004). Under the Foresight National Enterprise scenario (based on SRES A2 scenario) flood damage by the end of century would increase to nearly 20 fold, whereas under the Foresight Local Stewardship (based on SRES B2 scenario) the increase would be approximately 100%. The strong rise in damage under the A2-like scenarios is attributable to a large extent to a strong increase in economic vulnerability in flood prone areas. It should also be noted that the above studies all assumed that defence structures remain physically unchanged in the future scenarios.

3.3 Changes in people exposed by floods in Europe due to climate change

Estimates of the expected annual population exposed (EAP) were obtained using the same assumptions on protection levels as for the damage calculations. Country-averaged EAP estimates are presented in Table 2. Relative changes in population exposure between control and scenario periods for the different climate futures are similar to the changes of EAD since the underlying changes in hazard are identical and exposure is typically strongly linked with population density. Assuming static population, for EU27 current EAP of approximately 195,000 people is projected to rise to respectively 468,700 (B2 Had-HIR, +2.5°C), 513,300 (A2 Had-HIR, +3.9°C), 445,100 (B2 Ech-RCAO, +4.1°C) and 589,900 (A2 Ech-RCAO, +5.4°C) by the end of this century.

Table 2 Country-averaged expected annual people affected (EAP) in 1,000 s/year for control and scenario period for the different scenarios. Different levels of flood protection are imposed based on country GDP (dark gray: 100 year return level protection; medium gray: 75 year return level protection; light gray: 50 year return level protection). Note that Cyprus and Malta are not part of the model domain

Country	ctrl Had-HIR	B2 Had-HIR (+2.5°C)	A2 Had-HIR (+3.9°C)	ctrl Ech-RCAO	B2 Ech-RCAO (+4.1°C)	A2 Ech-RCAO (+5.4°C)
AT	3.37	10.52	5.98	3.23	2.50	1.28
BE	4.03	3.06	7.78	5.49	26.62	36.27
DE	32.18	43.30	69.67	26.13	85.78	109.39
DK	0.14	0.77	1.05	0.17	0.70	1.38
FI	2.33	0.16	0.26	2.41	1.51	0.61
FR	21.87	49.63	89.31	25.03	70.77	132.28
IE	0.46	0.22	1.27	0.56	4.90	3.85
LU	0.07	0.11	0.29	0.07	0.41	0.42
NL	9.63	10.22	31.15	11.66	56.42	96.85
SE	1.29	1.07	2.38	1.40	1.19	1.38
UK	12.22	24.04	59.23	12.29	51.24	87.71
CZ	7.56	11.53	27.53	6.46	2.49	2.63
ES	11.05	16.19	22.86	12.42	9.70	9.08
GR	1.61	1.44	6.53	1.18	1.77	0.12
HU	11.54	56.38	24.31	9.94	41.23	33.96
IT	19.50	58.08	51.39	19.32	25.34	18.63
PT	1.07	0.49	0.42	1.05	3.81	3.17
SI	1.55	2.71	1.19	1.42	6.89	4.86
SK	4.85	9.96	7.82	5.16	6.41	8.88
BG	3.25	5.15	6.41	2.50	4.67	1.83
EE	0.50	0.02	0.18	0.38	0.05	0.12
LV	2.72	1.08	3.32	3.38	0.73	1.70
LT	1.06	0.89	4.36	1.10	0.99	1.06
PL	28.30	122.32	78.13	27.38	20.61	25.81
RO	14.00	39.38	10.47	13.85	18.33	6.64
EU27	196.2	468.7	513.3	194.0	445.1	589.9

4 Conclusions

Global warming is expected to considerably affect future flood risk in Europe. We presented an assessment of the implications of climate change for future flood damage and people exposed by floods in Europe. The projections in this study assume no growth in exposed values and population or adjustments of current flood protection standards, hence only reflect the impact on flood risk of changes in climate. Results indicate that several countries in Europe will see an increase in EAD and EAP in the coming century due to climate change, depending on the climate scenario. Most notable increases in flood losses across the different climate futures are projected for countries in Western Europe (Belgium, Denmark, France, Germany, Ireland, Luxembourg, the Netherlands and the United Kingdom), as well as for Hungary and Slovakia. A consistent decrease across the scenarios is projected for northern countries (Estonia, Finland, Latvia, Lithuania and Sweden). For EU27 as a whole, current EAD of approximately €6.4 billion is projected to at least double or triple by the end of this century, depending on the scenario. In several countries, however, flood risk is projected to decrease or increase depending on the scenario. Consequently, the impacts at the regional level vary substantially amongst regions and deviate strongly from the EU average. Changes in EAP reflect well the changes in EAD, and for EU27 an additional 250,000 to nearly 400,000 people are expected to be affected by flooding yearly, depending on the scenario.

It is important to note that in this work only two greenhouse gas emission scenarios were used (IPCC SRES A2 and B2) and that climate simulations from only two regional climate models driven by two general circulation models have been considered. Simulations based on other greenhouse gas emission scenarios or with other driving GCMs may deviate from those described herein. An ensemble approach based on multiple driving models and considering different emission scenarios should provide a more robust estimate of future flood risk. Also, estimates of the expected annual damages and population affected are uncertain as a result of some of the assumptions underlying the macro-scale approach used, as well as by uncertainties in both the estimation of the flood frequency relationship from limited time series and the relationships between flood magnitude and damage. Nonetheless, pan-European assessments of possible changes in flood risk do potentially provide decision-makers with a basis for exploring responses to flood risk that are robust across plausible futures.

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References

ABI (2005) Financial risks of climate change. Association of British Insurers (http://www.abi.org.uk/climatechange)

Alcamo J, Flörke M, Märker M (2007) Future long-term changes in global water resources driven by socio-economic and climatic changes. Hydrol Sci J 52(2):247–275

Barredo JI (2009) Normalised flood losses in Europe: 1970–2006. Nat Hazard Earth Syst Sci 9(1):97–104

Bates PD (2004) Remote sensing and flood inundation modelling. Hydrolog Process 18:2593–2597

Bates PD, De Roo APJ (2000) A simple raster-based model for flood inundation simulation. J Hydrol 236:54–77

Bell VA, Kay AL, Jones RG, Moore RJ (2007) Use of a grid-based hydrological model and regional climate model outputs to assess changing flood risk. Int J Climatol 27(12):1657–1671

Booij MJ (2005) Impact of climate change on river flooding assessed with different spatial model resolutions. J Hydrol 303:176–198

Bosello F, Nicholls R, Richards J, Roson R, Tol RSJ (2010) Economic impacts of climate change in Europe: sea-level rise. Clim Chang (this issue)

Charlton R, Fealy R, Moore S, Sweeney J, Murphy C (2006) Assessing the impact of climate change on water supply and flood hazard in Ireland using statistical downscaling and hydrological modelling techniques. Clim Chang 74:475–491

Christensen OB, Christensen JH (2003) Severe summertime flooding in Europe. Nature 421:805–806

Christensen JH, Christensen OB, Lopez P, Van Meijgaard E, Botzet M (1996) The HIRHAM4 regional atmospheric climate model. DMI scientific report 96–4. Danish Meteorological Institute, Copenhagen

Christensen JH, Carter TR, Rummukainen M, Amanatidis G (2007) Evaluating the performance and utility of regional climate models: the PRUDENCE project. Clim Chang 81:1–6

Christensen OB, Goodess CM, Ciscar JC (2010) Methodological framework of the PESETA project on the impacts of climate change in Europe. Clim Chang (this issue)

Dankers R, Feyen L (2008) Climate change impact on flood hazard in Europe: an assessment based on high resolution climate simulations. J Geophys Res 113:D19105. doi:10.1029/2007JD009719

Dankers R, Feyen L (2009) Flood hazard in Europe in an ensemble of regional climate scenarios. J Geophys Res 114:D16108. doi:10.1029/2008JD011523

Dankers R, Christensen OB, Feyen L, Kalas M, De Roo A (2007) Evaluation of very high-resolution climate model data for simulating flood hazards in the Upper Danube Basin. J Hydrol 347:319–331

DEFRA (2001) National appraisal of assets at risk from flooding and coastal erosion, including the potential impact of climate change. UK Department of Environment, Food and Rural Affairs (http://www.defra.gov.uk/environ/fcd/default.htm)

European Environment Agency (2000) The European topic centre on terrestrial environment: corine land cover raster database 2000–100 m

Evans EP, Ashley R, Hall JW, Penning-Rowsell EC, Saul A, Sayers PB, Thorne CR, Watkinson A (2004) Foresight flood and coastal defence project, scientific summary: volume I, future risks and their drivers. Office of Science and Technology, London, p 366

Feyen L, Vrugt JA, Nualláin BÓ, van der Knijff J, De Roo A (2007) Parameter optimisation and uncertainty assessment for large-scale streamflow simulation with the LISFLOOD model. J Hydrol 332(1):276–289

Feyen L, Kalas M, Vrugt JA (2008) The value of semi-distributed parameters for large-scale streamflow simulation using global optimization. Hydrol Sci J 53(2):293–308

Frei C, Schöll R, Fukutome S, Schmidli J, Vidale PL (2006) Future change of precipitation extremes in Europe: intercomparison of scenarios from regional climate models. J Geophys Res 111:D06105. doi:10.1029/2005JD005965

Gallego J, Peedell S (2001) Using corine land cover to map population density. Towards Agri-environmental indicators, Topic Report 6/2001. European Environment Agency, Copenhagen, pp 92–103

Gilleland E, Katz RW (2005) Extremes toolkit (extRemes): weather and climate applications of extreme value statistics, tutorial. Univ. Corp. for Atm. Res, Boulder

Graham LP, Andréasson J, Carlsson B (2007) Assessing climate change impacts on hydrology from an ensemble of RCMs, model scales and linking methods—a case study on the Lule river basin. Clim Chang 81:293–307. doi:10.1007/s10584-006-9215-2

Hall JW, Sayers PB, Dawson RJ (2005) National-scale assessment of current and future flood risk in England and Wales. Nat Hazard 36:147–164

Hall JW, Sayers PB, Walkden MJA, Panzeri M (2006) Impacts of climate change on coastal flood risk in England and Wales: 2030–2100. Phil Trans Royal Society A 364:1027–1049

Huizinga HJ (2007) Flood damage functions for EU member states. Technical report, HKV Consultants. Implemented in the framework of the contract # 382441-F1SC awarded by the European Commission—Joint Research Centre

Jones CG, Willén U, Ullerstig A, Hansson U (2004) The Rossby Centre regional atmospheric climate model Part I: model climatology and performance for the present climate over Europe. Ambio 33:199–210

Kay AL, Jones RG, Reynard NS (2006) RCM rainfall for UK flood frequency estimation. II. Climate change results. J Hydrol 318:163–172

Kundzewicz ZW, Graczyk D, Maurer T, Pińskwar I, Radziejewski M, Svensson C, Szwed M (2005) Trend detection in river flow series: 1. Annual maximum flow. Hydrolog Sci J 50(5):797–810

Kundzewicz ZW, Radziejewski M, Pińskwar I (2006) Precipitation extremes in the changing climate of Europe. Clim Res 31:51–58

Kundzewicz ZW, Mata LJ, Arnell NW, Döll P, Jimenez B, Miller K, Oki T, Sen Z, Shiklomanov I (2008) The implications of projected climate change for freshwater resources and their management. Hydrol Sci J 53 (1):3–10

Leander R, Buishand TA, van den Hurk BJJM, de Wit MJM (2008) Estimated changes in flood quantiles of the river Meuse from resampling of regional climate model output. J Hydrol 351:331–343

Lehner B, Döll P, Alcamo J, Henrichs T, Kaspar F (2006) Estimating the impact of global change on flood and drought risks in Europe: a continental integrated analysis. Clim Chang 75:273–299

Meier HEM, Döscher R, Faxén T (2003) A multiprocessor coupled ice-ocean model for the Baltic Sea: application to salt inflow. J Geophys Res 108(C8):3273. doi:10.1029/2000JC000521

Messner F, Penning-Rowsell E, Green C, Meyer V, Tunstall S, van der Veen A (2007) Evaluating flood damages: guidance and recommendations on principles and methods. T9-06-01, FLOODsite Project—Integrated flood risk analysis and management methodologies

Milly PCD, Dunne KA, Vecchia AV (2005) Global pattern of trends in streamflow and water availability in a changing climate. Nature 438:347–350

Mudelsee M, Börngen M, Tetzlaff G, Grünewald U (2003) No upward trends in the occurrence of extreme floods in central Europe. Nature 425:166–169

Nakicenovic N, Swart R (eds) (2000) IPCC special report on emission scenarios. Cambridge University Press, Cambridge

Pappenberger F, Beven KJ, Ratto M, Matgen P (2008) Multi-method global sensitivity analysis of flood inundation models. Adv Water Resour 31:1–14

Pope VD, Gallani ML, Rowntree PR, Stratton RA (2000) The impact of new physical parametrizations in the Hadley Centre climate model—HadAM3. Clim Dyn 16:123–146

Roeckner E, Bengtsson L, Feichter J, Lelieveld J, Rodhe H (1999) Transient climate change simulations with a coupled atmosphere-ocean GCM including the tropospheric sulfur cycle. J Clim 12:3004–3032

Semmler T, Jacob D (2004) Modeling extreme precipitation events—a climate change simulation for Europe. Glob Planet Chang 44:119–127

Shabalova M, van Deursen W, Buishand T (2003) Assessing future discharge of the river Rhine using RCM integrations and a hydrological model. Clim Res 23:233–246

Thodsen H (2007) The influence of climate change on stream flow in Danish rivers. J Hydrol 333:226–238

Trapp RJ, Robinson ED, Baldwin ME, Diffenbaugh NS, Schwedler BRJ (2010) Regional climate of hazardous convective weather through high-resolution dynamical downscaling. Clim Dyn, doi:10.1007/s00382-010-0826-y

van der Knijff J, Younis J, De Roo A (2008) LISFLOOD: a GIS-based distributed model for river-basin scale water balance and flood simulation. Int J Geogr Inform Sci, doi:10.1080/13658810802549154

Vogt JV, Soille P, de Jager A, Rimavičiūtė E, Mehl W, Foisneau S, Bódis K, Dusart J, Paracchini ML, Haastrup P, Bamps C (2007) A pan-European river and catchment database. EUR 22920 EN. Office for Official Publications of the European Communities, Luxembourg

Wilby RL (2005) Uncertainty in water resource model parameters used for climate change impact assessment. Hydrolog Process 19:3201–3219