Floods and Streamflow Droughts in Europe under Climate Change

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Introduction

If there is one aspect of global climate change that is the most relevant to human society, it is probably a potential change in the frequency, intensity and duration of extreme events such as heatwaves, floods and droughts (Tebaldi et al., 2006). Generally speaking, climate extremes are responsible for most weather-related damages (Kunkel et al., 1999). In Europe, the yearly average economic impact of droughts has been estimated at € 5.3 billion, with the economic damage of the 2003 drought alone amounting to at least € 8.7 billion (European Communities, 2007). The annual average flood damage in Europe in the last few decades has been estimated at about € 4 billion per year (Barredo, 2007). Estimating potential future changes in the occurrence of these extreme events is therefore essential for local, regional and national adaptation and planning strategies (Tebaldi et al., 2006).

However, detecting trends in hydrometeorological extremes is more difficult, and the results are more uncertain, than for average conditions. This is because the natural variability is larger and climate models are less capable of reproducing the characteristics of extreme events that often manifest themselves at smaller spatial scales. For this reason most climate impacts studies in the field of hydrology have focused on changes in water resources and average flow conditions such as seasonal runoff (e.g., Milly et al., 2005; Alcamo et al., 2007; Kundzewicz et al., 2008), as long-term average values are generally considered more reliable outputs of climate and large-scale hydrological models. Relatively few studies have tried to make an assessment of potential future changes in extreme river flows, whether these are high flows (e.g., Charlton et al., 2006; Bell et al., 2007; Dankers et al., 2007; Leander et al., 2008; Veijalainen et al., 2010, Kay & Jones, 2011) or low flows (e.g., De Wit et al., 2007; Weiss et al., 2007). What is more, different climate scenarios, climate and hydrological models, as well as basin-specific characteristics make it difficult to compare the results of these studies and to draw an overall picture at European scale.

Few studies have tried to make a consistent, pan-European assessment of changes in river flow extremes. Lehner et al. (2006) made a first integrated assessment of changes in both high and low flows based on the global hydrology and water use model WaterGAP. However, in the climate signal only long-term trends and changes in seasonal climate were taken into account, while changes in climate variability were ignored. More recently, Dankers & Feyen (2008) and Feyen & Dankers (2009) looked at the potential impacts of climate change on extreme high and low river flows, respectively, based on a high resolution regional climate model simulation that was used to force a pan-European hydrological model. Both studies focused on projected changes by the end of the current century under the A2 greenhouse gas emission scenario of the Intergovernmental Panel on Climate Change (IPCC) (Nakicenovic & Swart, 2000).

Informing stakeholders about potential changes in flood and drought hazard also requires an assessment of uncertainties. In a follow-up study, Dankers & Feyen (2009) analysed changes in flood hazard in an ensemble of climate scenarios in an effort to explore the uncertainty related to climate modeling and the future levels of greenhouse gas emissions. The ensemble consisted of simulations from two regional climate models (RCMs), both run with boundary conditions from two global models, and for two scenarios of greenhouse gas emissions. At the scale of individual river basins, it was found that using a different combination of climate models or assuming a different emissions scenario sometimes results in a very different or even opposite climate change signal in flood hazard. Nevertheless, some changes were found to be robust, especially in northeastern Europe where a general decrease in extreme river discharge in the scenario period was observed suggesting a reduction in the hazard of extreme snowmelt floods. Some of the increases in flood hazard that were found in several other European river basins could at least partly be attributed to large, decadal-scale variability in the simulated climate, meaning that these changes can be expected to occur naturally when comparing two 30-year time periods, even without a change in greenhouse gas forcing (Dankers & Feyen, 2009).

In this paper we provide a first joint analysis of changes in both high and low river flow extremes at European scale, based on the same ensemble of simulations that was used by Dankers & Feyen (2009), who focused on flood hazard only. By using simulations of two RCMs, each driven by two different global models and run for two different emission scenarios, we can explore which patterns of change are robust to these sources of uncertainty. It should be noted here that we do not sample the full range of uncertainties: for example, in all experiments we use the same hydrological model setup to translate the simulated climatology into river discharge. Some authors have suggested hydrological modeling uncertainty is generally speaking less dominant than the climate modeling uncertainty (e.g., Arnell, 2011), although other studies have found that for some applications, particularly for drought conditions, the hydrological model uncertainty may also be significant (e.g., Bae et al., 2011). For practical reasons we also do not explore the uncertainty brought about by deriving information about hydrological extremes from a relatively short timeseries (30-year periods for both control and scenario period), which is achieved by fitting an extreme value distribution to the simulated river discharge, but we note here that this may be considerable as well (see e.g. Wehner, 2010).

Methodology

Our approach is similar to the one described in Dankers & Feyen (2009) (for high flows) and Feyen & Dankers (2009) (for low flows), but is summarized here. To simulate river discharges across Europe, we used the hydrological model LISFLOOD (De Roo et al., 2000; Van der Knijff et al., 2010). This model has been developed for operational flood forecasting at the European scale and is a combination of a grid-based water balance model and a one-dimensional hydrodynamic channel flow routing model. In the current simulations LISFLOOD was driven by climatological output from two different RCMs, HIRHAM (Christensen et al., 1996) and RCAO (Jones et al., 2004). 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 two different global models: the HadAM3H global atmosphere model (Pope et al., 2000) and the coupled ocean-atmosphere general circulation model (GCM) ECHAM4/OPYC3 (Roeckner et al., 1996, 1999). In turn, these models were run for two scenarios of future greenhouse gas emissions, the A2 and B2 scenarios of the IPCC (Nakicenovic and Swart, 2000). This brings the total number of climate experiments used in LISFLOOD to eight (see Table 1 or Christensen & Christensen (2007) for further details). Each of these experiments consisted of two 30-year time slices: a control run with a greenhouse gas forcing corresponding to 1961–1990, and a scenario run corresponding to 2071–2100. In each simulation the output from the two RCMs was re-gridded to the 5-km model grid of LISFLOOD without any further downscaling, bias correction or altitude correction. In this way, any differences between the different LISFLOOD model runs can directly be traced back to the climate simulations. In the end a time series of 30 years of daily discharges is produced at each river grid cell for both the control and scenario period of each experiment.

To estimate the probability of extreme river flows, a different approach was used for flood and for streamflow drought hazard. In order to be able to assess changes in peak discharge levels with a given return period (typically 50 or 100 years), a Gumbel distribution was fitted to the annual maximum values in every river cell using the maximum likelihood method. The Gumbel distribution is a special case of the Generalized Extreme Value (GEV) distribution (Coles, 2001; Katz et al., 2002) with the shape parameter explicitly set to 0. Using the same model setup, Dankers & Feyen (2008) fitted both the two-parameter Gumbel and the three-parameter GEV to the simulated annual maximum discharges and did a likelihood ratio test (Coles, 2001) to see if the GEV outperformed the Gumbel distribution. For the majority of the river cells (about 85%) in the European domain it turned out that this was not the case and that the use of the three-parameter GEV was not justified. By limiting the statistical fitting to the Gumbel distribution, we prevent large differences between the control and scenario period that are due to a change in the type of extreme value distribution (i.e., from two- to three parameter distribution or vice versa), although this, of course, is not necessarily a statistical artifact.

Table 1. Overview of the Regional Climate Model Experiments Used in the Present Study

Driving GCM:	**HadAM3H**			**ECHAM4/OPYC3**		
RCM	*Control*	*A2*	*B2*	*Control*	*A2*	*B2*
HIRHAM	HH-CL	HH-A2	HH-B2	HE-CL	HE-A2[a]	HE-B2
RCAO	RH-CL	RH-A2	RH-B2	RE-CL	RE-A2[a]	RE-B2

[a)] The ECHAM-driven simulations of HIRHAM and RCAO for the A2 scenario period used different realizations of the GCM experiment for their boundary conditions (see Christensen & Christensen, 2007).

For streamflow droughts, not only the magnitude of a certain low discharge level is important, but also the development through time (i.e. the duration and severity) of a drought event (see also e.g., Smakhtin, 2001). For this reason we calculated two different low-flow indices. To evaluate changes in the magnitude of minimum flows we considered the 7-day minimum flows at several recurrence intervals n (7Qn). The 7-day period eliminates the day-to-day variations in river flow and was obtained by moving an averaging window with an interval of 7 days over the discharge time series. For each year the minimum was extracted from the smoothed discharge time series. As with the yearly maximum flows, a GEV distribution was fitted to the resulting sample of 30 yearly minima, in this case we did however not prescribe a shape parameter of 0.

To analyse the duration and severity of drought events we looked at flow deficits, here defined as the cumulative deficit of river flow for the duration of the period it is below a certain threshold level (Smakhtin, 2001). We defined this threshold level as an exceedance frequency of the flow duration curve, which describes the relationship between the magnitude and frequency of discharge levels. As such, series throughout Europe experience the same number of days with flow below the threshold level but deficit volumes may vary. Meaningful thresholds typically are in the range of discharges with 70–90% exceedance frequency for perennial streams. Here we present results using the 80% exceedance frequency of the flow duration curve (i.e., flow that is exceeded 80% of the time). Thresholds imposed to select drought events in the scenario period were derived from the flow duration curve of the control climate. A Generalised Pareto (GP) distribution was then fitted to the deficit volumes with the location parameter (or distribution origin) set to the lower bound (or threshold) of the partial duration series, in order to obtain drought deficits for different recurrence intervals. To reduce mutual dependency among individual drought events and to filter out minor droughts that may distort the extreme value analysis, a 7-day moving average procedure was applied to the discharge time series beforehand. Additionally, all events with a deficit volume smaller than 0.5% of the maximum deficit occurring in the time series were excluded from further analysis (cf. Zelenhasic & Salvai, 1987).

Climatologic and hydrologic conditions vary strongly across Europe. In highly seasonal climates streamflow droughts may be generated by different physical processes and two distinct low-flow seasons may result. In cold or mountainous regions, low winter flows are due to temporary storage of precipitation as snow, whereas summer low flows are caused by reduced precipitation and high evapotranspiration losses. As rivers in these regions typically have their lowest flows in winter, an annual analysis masks any changes that would occur in summer droughts. Combining drought events generated by different mechanisms also violates the basic requirement of frequency analysis, namely that the sample should come from an independent and identically (iid) distributed random variable. For this reason we perfomed our analysis for droughts separately for a frost and a non-frost season, whereby for both current and future climate the frost season at a given river grid cell is defined as the period when the monthly average temperature in its upstream area falls below 0 ºC. Using monthly average temperatures over the upstream area rather than at the grid cell itself avoids that at a given downstream location a period is labeled as frost-free while the majority of the upstream area may still be covered by snow. In this paper we present results only for the non-frost season, which in most regions would be indicative of summer droughts. For more details on the exact procedures that were followed, the reader is referred to Feyen & Dankers (2009) for droughts and Dankers & Feyen (2009) for floods.

Results: floods

The changes in extreme high discharge level in the scenario period, exemplified by changes in the 100-year return level (Q_{100}), are shown in Figure 1 for both the HIRHAM and RCAO experiments. Note that the increases and decreases in the magnitude of the 100-year discharge that are shown in these plots translate as an increase or decrease in the probability (and therefore frequency) of the current 100-year flood level. Even a modest increase in magnitude can have a substantial impact on the expected return time of such an event (Allen & Ingram, 2002). Like Dankers & Feyen (2008), we find a considerable decrease in the Q_{100} in northeastern Europe that is very robust among the different models and scenarios. This decrease is noticeable in each of the experiments although the exact extent and location of the area with decreasing flood hazard differs, and is related 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 the same region. The ECHAM-driven scenarios result in an increase in Q_{100} particularly in western Europe, including the British Isles. The HadAM3H runs, on the other hand, show more increases in eastern Europe, especially in the B2 scenarios. Also the RE-B2 scenario shows considerably higher flood levels over the Balkans (Figure 1h). There are furthermore differences between the two RCMs, as can be seen over the Iberian Peninsula in the two ECHAM scenarios. Here, the HIRHAM simulations result in small and only localized responses in Q_{100}, but the RCAO runs give a strong increase in flood hazard in the southwest, even though this area is getting much drier on average. Nevertheless, several major European rivers such as the Loire, Garonne and Rhone in France, the Po in Italy and the Danube in central and eastern Europe show a consistent tendency toward a higher flood hazard in at least the majority of the model experiments. Also worth noting is that the changes in the B2 scenarios are generally speaking comparable in magnitude to the A2 scenarios, although the temperature rise is higher in the latter (see Dankers & Feyen, 2009).

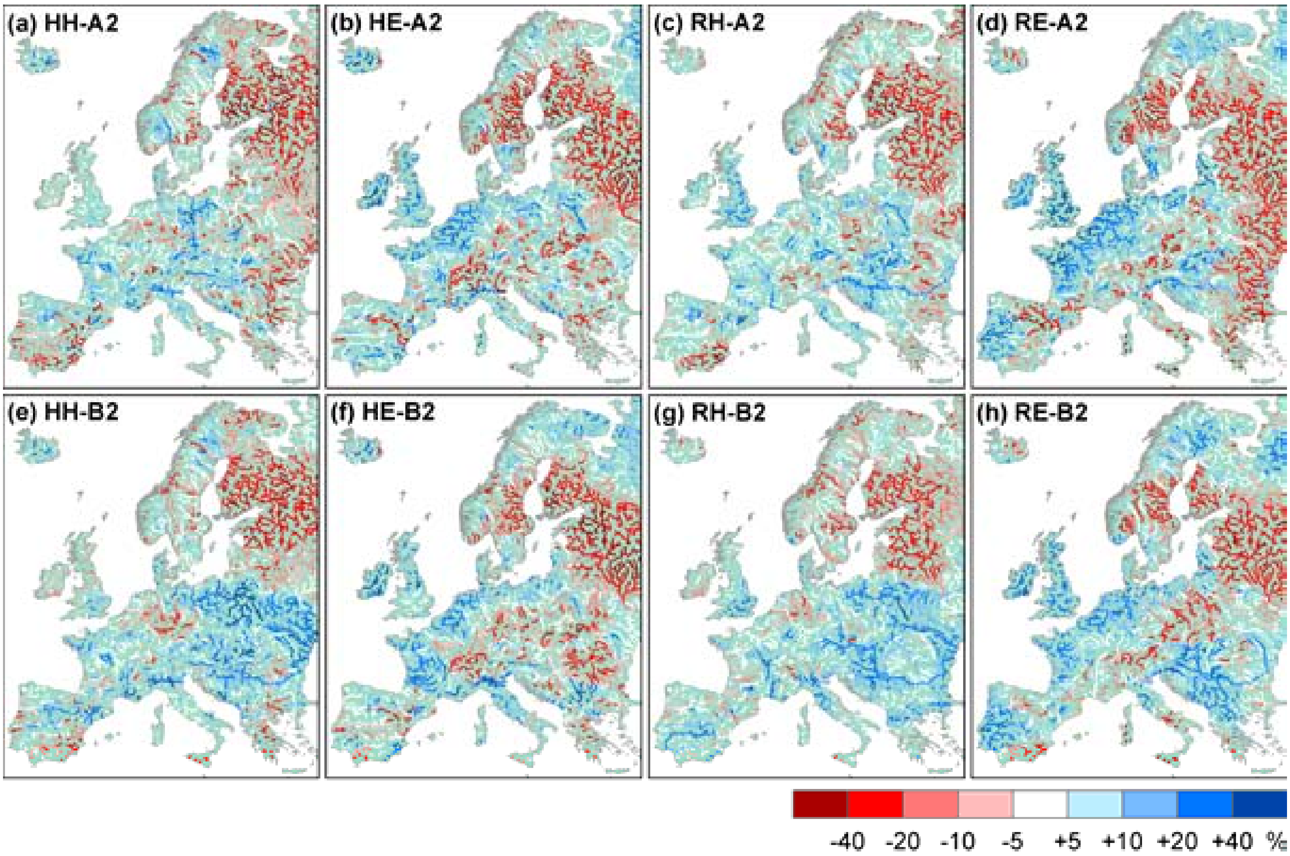

Figure 1: Change in the 100-year return level of river discharge (Q100) in the scenario period in each of the LISFLOOD model experiments of the present study: (a,e) HIRHAM driven by HadAM3H; (b,f) HIRHAM driven by ECHAM4/OPYC; (c,g) RCAO driven by HadAM3H; (d,h) RCAO driven by ECHAM4/OPYC. The top row (figures (a) to (d) show results for the emission scenario A2, the bottom row for scenario B2.

Results: streamflow droughts

In Figure 2 we show the changes in 7-day minimum flows with a recurrence interval of 20 years in all experiments. In these plots, a decrease in minimum flows (indicated in red) means that low flows are getting lower, while an increase (indicated in blue) implies that streamflow droughts are becoming less severe. Generally speaking minimum flows are projected to decrease in most parts of Europe, except in the most northern and in northeastern regions. This pattern is robust amongst all experiments, although the magnitude of change differs. In many regions, for example the Iberian Peninsula, southern France and the Alpine region, reductions of 20 up to 40% are projected in almost all experiments. In western, central and eastern Europe on the other hand, the runs driven by HadAM3H show relatively little change in minimum flow, while the ECHAM-driven runs show a strong decrease. As with floods, the differences between the two emission scenarios appear relatively small, although the changes are somewhat smaller in magnitude on average in the B2 scenario (cf. Figure 2e and 2j). Locally there can be a larger difference between the two scenarios, however, for example in the Balkan region in the HadAM3H runs (cf. Figure 2a and 2f, and Figure 2c and 2h). The decrease in minimum flows that is projected for many regions is caused by reduced precipitation and higher evaporative demands due the rise in temperature. The latter, however, does not necessarily result in higher absolute actual evapotranspiration rates, which may be limited by the reduced availability of water in the soil. In the northernmost parts of Europe, a strong increase in precipitation over summer outweighs the effects of a rise in temperature, which is also less strong here than in southern Europe.

Changes in 7-day deficits with a recurrence interval of 20 years were derived at each river pixel from the GP distributions fitted to the partial duration series of deficit volumes from both control and scenario climate and are shown in Figure 3. Note that in this figures an increase in flow deficits (indicated in red) implies a tendency toward drier conditions. Consistent with the changes in minimum flow, a strong increase in flow deficits is projected for most parts of Europe, except in northeastern regions where flow deficits will in general become less severe. Compared to the changes in minimum flows (cf. Figure 2), however, the changes in flow deficit are generally more severe, more widespread and more robust among the different experiments. Even in regions where minimum flows were projected to remain relatively stable, deficit volumes are projected to increase. This suggests that (1) droughts tend to become more persistent, i.e., develop longer in time; (2) droughts may occur more frequently in the scenario period; and (3) extreme low flows are less affected than more frequently occurring low-flow conditions, meaning that flows in the range of 70-90% exceedance frequency are more affected than the very extreme low flows. As a result, the simulated discharge in the scenario climate may fall more frequently under the 80% exceedance threshold of the control period, even when extreme minimum flows show little change in magnitude (see also Feyen & Dankers, 2009).

For most parts of the continent the signal of more persistent and more severe flow deficits in the future is remarkably robust among the model experiments and even between the two emission scenarios. In some areas in northernmost Europe, however, a more mixed pattern is observed resulting from the combined effects of a general increase in precipitation and evapotranspiration, as well as reduced snowmelt caused by less accumulation of snow in winter. Depending on the magnitude of these processes, flow deficits may either increase or decline.

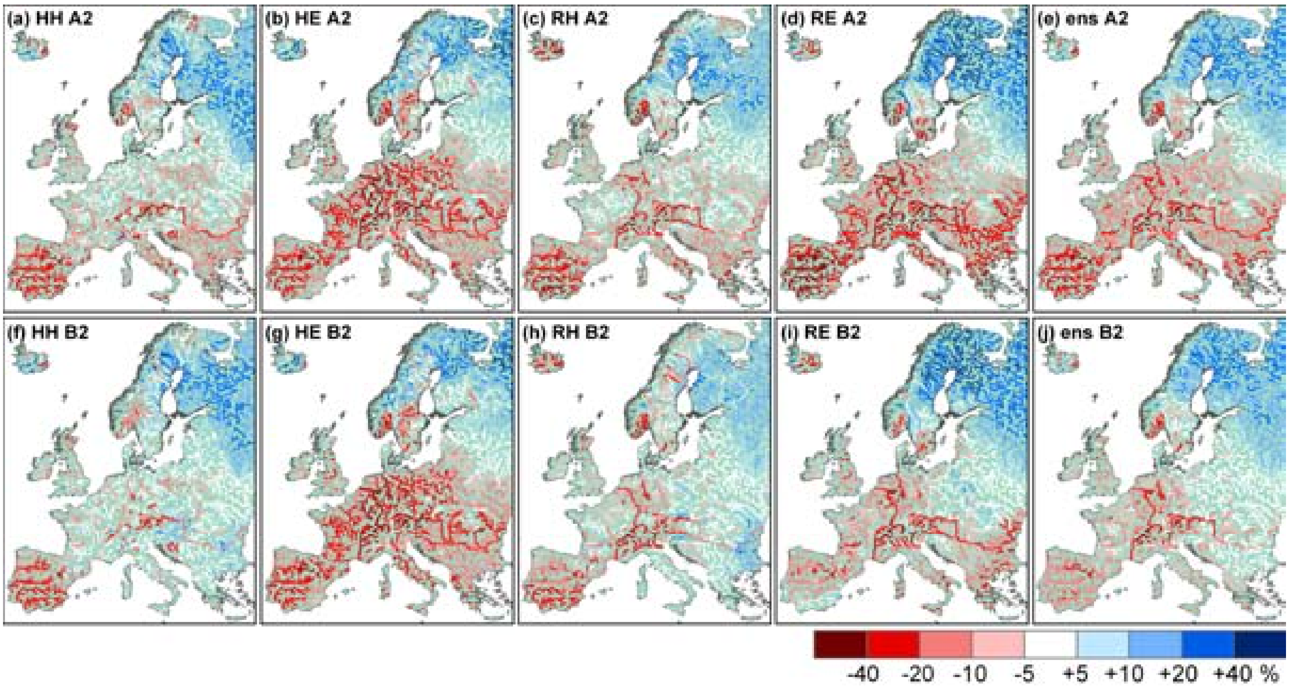

Figure2: As Figure 1 but for changes in 7-day minimum flow with a recurrence interval of 20 year. Figures (e) and (j) show the average change across the ensemble for the A2 and B2 emission scenarios, respectively.

Discussion and conclusions

In this paper we used a combination of future climate projections, hydrological modeling and extreme value analysis to estimate the likely impact of climate change on extreme river flows in Europe. Results suggest that in many European rivers extreme high discharge levels may increase in magnitude and frequency, except in northeastern Europe where a reduction in snowmelt floods dominates the signal. Changes in flood hazard are, however, subject to considerable uncertainty due to effects of climate model formulation on the simulation of extreme precipitation. Projections of changes in streamflow drought are much more robust and show an increase in severity and persistency of droughts in most parts of Europe, except in the most northern and northeastern regions. Interestingly the differences between the two emission scenarios that were considered appear to be of relatively minor importance. In many European rivers, except for those in the north, an increase in the persistency and severity of drought conditions seems therefore highly likely under future climate conditions, while an increase in flood hazard may not be ruled out.

We note once more that, by using a multi-model and multi-scenario ensemble of climate simulations, we are able to evaluate some of the uncertainty associated with future climate projections, but we do not address the full range of uncertainties. In particular, we have not explored uncertainties related to the hydrological model setup that was used, or the uncertainties associated with the fitting an extreme value distribution to a relatively short (30 years) timeseries. What is more, in our modeling approach only changes in climatology are considered and not changes in land use or the effects of a higher CO2 concentration on the water use efficiency of the vegetation. Such changes may affect evapotranspiration as well as soil moisture redistribution and groundwater recharge, and consequently the development of droughts. And although our results provide a European-wide overview, local effects may be different from the large-scale patterns of change found in this study (see e.g. Veijalainen et al., 2010). Further research remains therefore necessary but we believe that that a multimodel, multiple-realization and multiscenario approach, as adopted in the present paper provides the best way to address the various uncertainties in impact studies of hydrometeorological extremes. To obtain more accurate results and to better identify a climatic signal amidst large decadal variability, probabilistic scenarios that consist of multiple (or longer) realizations of the current and future climate state are indispensable.

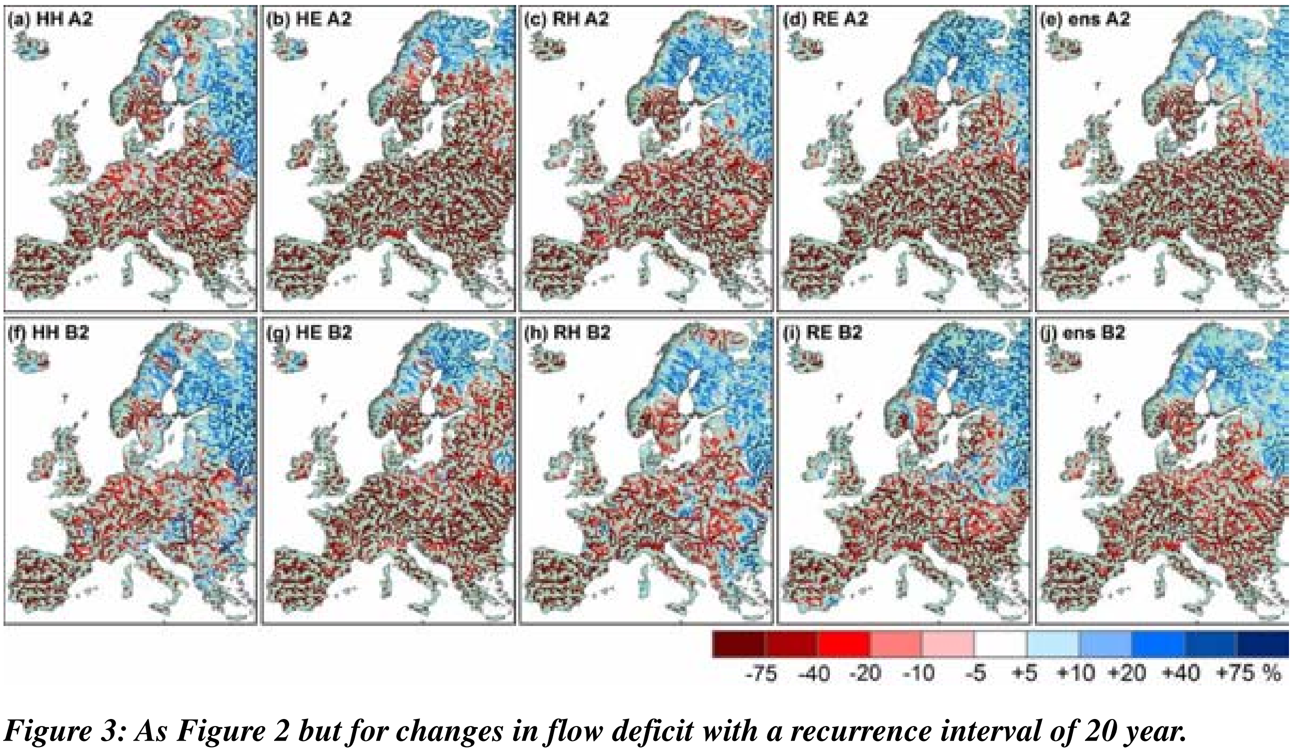

Figure 3: As Figure 2 but for changes in flow deficit with a recurrence interval of 20 year.

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