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Evaluation of different sources of uncertainty in climate change impact research using a hydro-climatic model ensemble

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Abstract: The international research project QBic[3] (Quebec-Bavarian Collaboration on Climate Change) aims at investigating the potential impacts of climate change on the hydrology of regional scale catchments in Southern Quebec (Canada) and Bavaria (Germany). Yet, the actual change in river runoff characteristics during the next 70 years is highly uncertain due to a multitude of uncertainty sources. The so-called hydro-climatic ensemble that is constructed to describe the uncertainties of this complex model chain consists of four different global climate models, downscaled by three different regional climate models, an exchangeable bias correction algorithm, a separate method to scale RCM outputs to the hydrological model scale and several hydrological models of differing complexity to assess the impact of different hydro model concepts. This choice of models and scenarios allows for the inter-comparison of the uncertainty ranges of climate and hydrological models, of the natural variability of the climate system as well as of the impact of scaling and correction of climate data on mean, high and low flow conditions. A methodology to display the relative importance of each source of uncertainty is proposed and results for past runoff and potential future changes are presented.

Keywords: uncertainty, model ensemble, climate change, hydrology

1 INTRODUCTION

A major aim of the project QBic[3] (Quebec-Bavarian International Collaboration on Climate Change) is to quantify the potential impacts of climate change on the runoff regime of heavily managed, regional scale catchments in Southern Quebec, Canada and Southern Bavaria, Germany. In a second step, the impact of future changes in runoff on the management of dams, reservoirs and transfer systems is simulated to advise provincial and local water authorities on potential future risks and opportunities. Yet, the actual impact of climate change on river runoff and water management plans is highly uncertain due to a multitude of uncertainty sources, from greenhouse gas scenarios down to impact models used to project and adapt river management (Figure 1). The sources and reasons for these uncertainties cannot be discussed here, but the reader is referred to Foley [2010] for an overview regarding regional climate simulations and to Refsgaard et al. [2007] regarding the environmental modelling process.

The aim of this paper is to present a method to compare the relative importance of the uncertainties induced by different steps in the hydro-climatic model chain, from global climate models (GCMs) down to hydrological models (HyMs). This method is applied to results for two small natural flow tributaries (the Au Saumon and Loisach rivers) of two heavily managed river basins, namely the Haut-Saint-Francois (in Quebec) and Upper Isar (in Bavaria) catchments. Runoff in the Au Saumon is dominated by a distinct snow melt peak in spring followed by relative low flows in summer. The Loisach has high flows in spring and summer due to snow melt and a precipitation peak in summer, while low flows typically occur in late fall.

Model setups for hydrological research are usually “validated” against past runoff time series, yet scenarios are often assessed based on the relative change between known past conditions and potential future conditions. Therefore, both the uncertainties in the hydro-climatic model chain regarding the reproduction of past runoff (1971-2000) and regarding the potential future changes in runoff (for 2041-2070) are investigated. To characterize important runoff conditions for water management, runoff is investigated using important mean, high and low flow indicators.

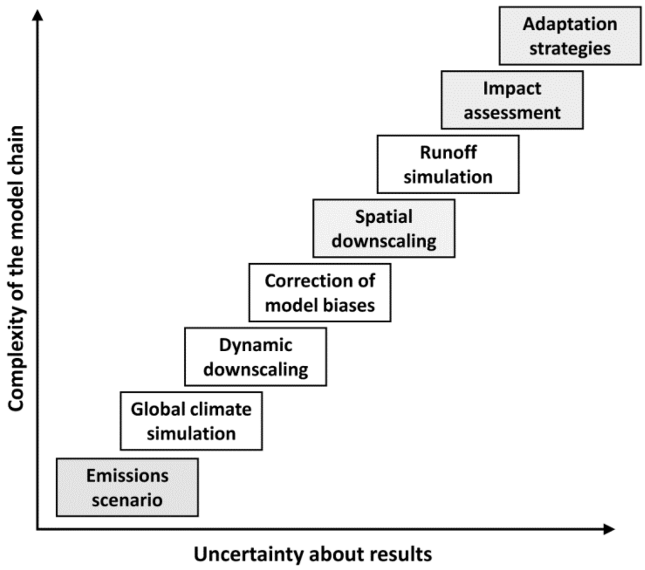

Figure 1: Complex model chain and increasing uncertainty in hydrological climate change research. Sources of uncertainty not considered in this paper are grey.

2 METHODOLOGY

2.1 The hydro-climatic ensemble

The quantification of the different sources of uncertainty regarding the reproduction of past flows and the projection of future changes in runoff is accomplished by combining ensembles of regional climate model (RCM) simulations and hydrological models. In the context of QBic[3], two different RCM ensembles for Quebec and Bavaria are available. Over Quebec, an ensemble of CRCM4 simulations driven by five different members of CGCM3 represents the uncertainty caused by the simulated natural variability of climate [de Elía and Côté 2010]. However, the five regional climate simulations that are used over Bavaria represent climate model diversity. It includes one regional simulation of CRCM4 with CGCM3 (CRC-CGC), one RACMO2 simulation driven by ECHAM5 (RAC-ECM) and three RCA3 simulations driven by the global models BCM, ECHAM5 and HadCM3 (accordingly abbreviated RCA-BCM, RCA-EC2 and RCA-HCM) as produced for the European ENSEMBLES project [Hewitt and Griggs 2004].

Bias correction is applied to the RCM fields to improve the reproduction of past runoff characteristics. Precipitation is corrected by the LOCI method of Schmidli et al. [2006] using monthly parameters, air temperature simply by monthly additive factors, both resolved at the RCM's spatial scales. It has to be noted that the CGCM3-CRCM4 members are corrected with one set of parameters based on member average precipitation and temperature to preserve the inter-member variability. Bias corrected (BC1) as well as direct (BC0) RCM outputs are scaled to the HyM resolution with the scaling tool SCALMET [Marke 2008], which preserves energy and mass at the scale of the RCM grid, therefore preserving changes in climate at the RCM scale as well.

The ensemble of HyMs used to simulate actual daily runoff for the investigated catchments consists of four models with different structural complexity: The lumped model HSAMI (HSA) [Fortin 2000], the semi-distributed model Hydrotel (HYD) [Fortin et al. 2001] and the distributed models WaSim-ETH (WAS) [Jasper and Schulla 1999] and PROMET (PRO) [Mauser and Bach 2009]. The HyMs are calibrated or optimized on observed daily runoff of a 10-year period which is included in the reference period.

In the end, for both catchments 40 different runoff time series are produced by the combination of these four HyMs with five climate simulations either bias corrected or not. The indicators presented are the overall mean flow during an investigated period, as well as the maximum high flow with a twenty years return period and the minimum 7-day low flow magnitude with a two years return period. More details on the hydrological models ensemble and the chosen runoff indicators are given in Velasquez et al. [2012].

2.2 The quantification of uncertainties in complex model chains

Using the hydro-climatic ensembles, several estimations of a given indicator are simulated for the reference (1971-2000) and the future period (2041-2070). Depending on the indicator, the disparity amongst the reference period simulations or the uncertainty associated with the potential future change of an indicator principally arise from a different component of the model chain. The distinction between disparity (in the reference period) and uncertainty (in the climate change signal) is introduced to emphasize that in the context of the reference period, bias correction is not a source of uncertainty, but rather a method to bring results closer to observations. In the following, a graphical method that allows evaluating the contribution of each model chain component to the overall disparity of reference flows or the overall uncertainty of change signals is proposed. (In the description below, 'uncertainty' is used, but the same applies for 'disparity'.)

1) One component of the total uncertainty (e.g. the choice of hydrological model) is picked and allowed to vary, while all other uncertainty components must remain fixed. For example, one member of the CGCM3-CRCM4 ensemble that has been bias corrected is picked, while hydrological models vary. That way, one case to quantify the impact of hydrological model choice on e.g. mean flow is constructed.

2) By choosing all combinations of the other components, each possible way to isolate one uncertainty component is extracted from the data. This is repeated for each component and displayed as a series of boxes (colour coded for each component) on a graph. The relative size of each collection of boxes then visually exposes the contribution of one component to the overall uncertainty. The example on the left side of Figure 2 shows the components of the overall disparity of mean flow during the reference period at Au Saumon.

3) By scaling the size of each box to the total uncertainty range, the relative range of each case compared to the total range of results is computed.

4) Averaging all cases of one uncertainty component quantifies the relative contribution of one component to the total uncertainty. Yet, as the contribution of one source of uncertainty may be dependent on other components of the model chain, the sizes of the boxes belonging to one component may differ significantly. Hence, to quantify this variability the standard deviation (StdDev) between all cases of one component is computed, disregarding the type of distribution of the data as the available sample usually cannot be assumed representative for all cases that could be produced using all possible models.

5) By constructing radar charts, as for example at the right side in Figure 2, one may visualize the average relative contributions to total uncertainty (or disparity) as well as the agreement between cases based on the standard deviation. Yet, as the cases are intertwined, the relative contributions do not necessarily sum up to one.

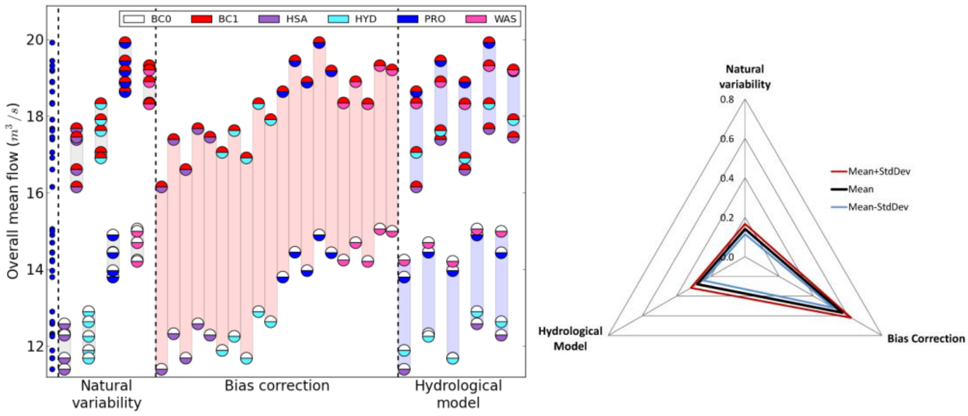

Figure 2: Disparity by model chain component (left) and relative contributions to this disparity (right) of past mean flow for the Au Saumon river.

3 RESULTS AND DISCUSSION

In the following, additional graphs as proposed in section 2.2 are presented and the sources of uncertainty relevant to different hydrology indicators based on different climate drivers for either past flows or future changes are discussed. It is noted that a major aim is to discuss the ability of the method to summarize sources of uncertainty rather than to present a complete set of results for each catchment.

3.1 Discussion of reference period flow variability

In the case of Au Saumon, bias correction has the largest impact on simulated mean flows (see Figure 2). The spread of results (the size of the bars) are very similar within each of the three sources of uncertainty and mostly unaffected by bias correction. This is explained by the fact that the method used preserves the natural variability of the CGCM3 members. Hence the StdDev of all three components in the radar chart is very small.

In case of past mean flows for the Loisach (Figure 3), the spread of HyM results again is quite small and largely unaffected by bias correction or choice of climate models (small StdDev). The impact of bias correction on the results is again larger, yet, as bias correction was applied on different RCMs separately, the spread of the bars now differs more strongly. Furthermore, the spread of the bars (the variability of results) due to climate model type now differs significantly between direct and corrected RCMs. Hence, the climate model choice has the largest impact on the disparity of simulated past mean flow, but mainly because of the large differences between the direct RCM drivers.

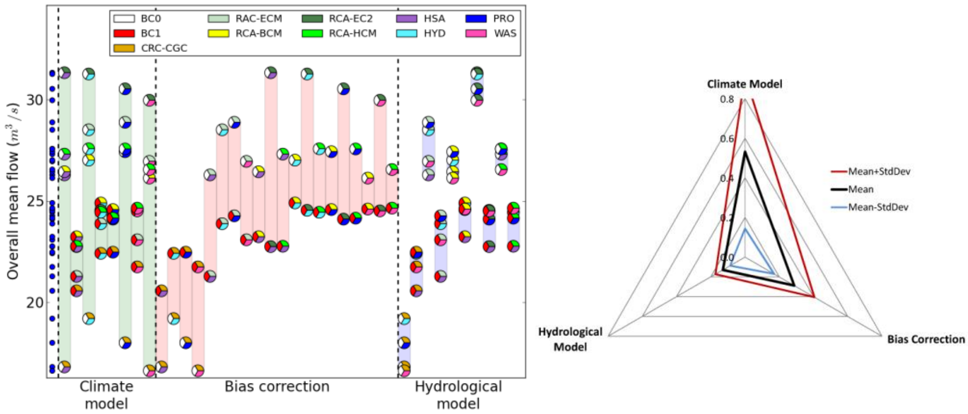

Figure 3: Disparity by model chain component (left) and relative contributions to this disparity (right) of past mean flow for the Loisach river.

Although the LOCI method applied to correct precipitation biases does correct the frequency and the intensity of events, the high and especially the low flow magnitudes (see Figure 4) are only partly affected. The differences between climate model members are again comparatively small, too. Actually, the reproduction of past low flow magnitudes is largely determined by the choice of hydrological model structure. This is obvious from both the bar graph and the radar chart. Yet, the main issue is that some HyMs are strongly affected by bias correction, while others are not. This is obvious especially for WaSim-ETH (WAS) and HSAMI (HSA) in the case of low flows. The question if these sensitivities are plausible or not cannot be answered within this manuscript, yet the importance of HyM structure is obvious in the proposed graphs.

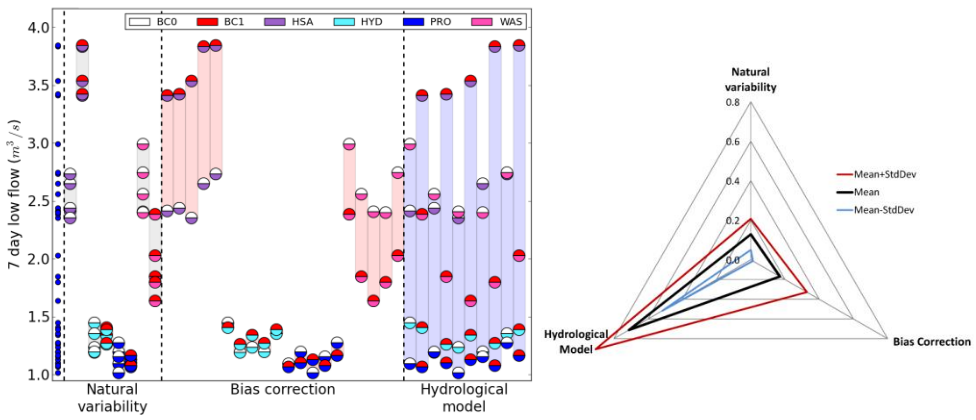

Figure 4: Disparity by model chain component (left) and relative contributions to this disparity (right) of 7-day low flow magnitudes for the Au Saumon river.

3.2 Analysis of climate change signal uncertainties

In the previous section, the disparities in our model ensembles regarding the reproduction of past runoff characteristics have been analysed. Yet, in most climate change impact studies conclusions regarding the relative change of certain indicators between a reference (here: 1971-2000) and a future time period (here:

2041-2070) are provided. Hence, the uncertainties regarding this relative change are now analyzed and discussed.

For overall mean flow, Figures 5 clearly demonstrates for both catchments that the bias correction methods chosen for this investigation induce the least uncertainty in the change signal. Yet, they had been most or second most important in the reference period analysis. Then again, compared to the total range of results (-10 % to +25 % for Au Saumon and -20 % to +10 % for Loisach) the uncertainty in the projected future change of mean flow is most importantly affected by the choice of GCM members at Au Saumon and the GCM-RCM setup at Loisach. For Au Saumon, where only natural variability is investigated, this is again a stark contrast to the results for the reference period (Figure 2).

Furthermore, the choice of HyM had been of little importance in the reproduction of past mean flows, just because HyMs are optimized to reproduce past runoff. Yet, the projected future change of mean flow is significantly affected by the choice of HyM (e.g. the evapotranspiration formulation), although the high StdDev in the case of Loisach shows that the spread of the HyM uncertainty is affected by certain climate model and bias correction cases.

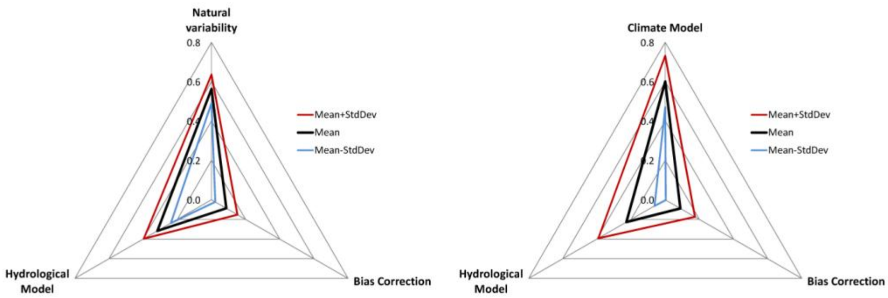

Figure 5 Relative contributions to the uncertainty for the projected change of overall mean flow in the Au Saumon (left) and Loisach (right) rivers.

As for the reproduction of the past magnitude of 7-day low flows, the main reason for the uncertainty about the future change of low flow magnitude (about +5 % to -50 %) is the choice of HyMs (Figure 6). Similar to the projected change of OMF, bias correction has the least importance regarding projection uncertainty. Although GCM members affect the projected change in low flow magnitude for Au Saumon more than bias correction, the StdDev of the GCM member bars is large. Especially WaSim-ETH reacts strongly to different GCM members, while other HyMs result in slight differences in low flow magnitude change only, when forced by different GCM members (not shown). In summary, the described contributions to overall uncertainty are again obvious in the radar chart.

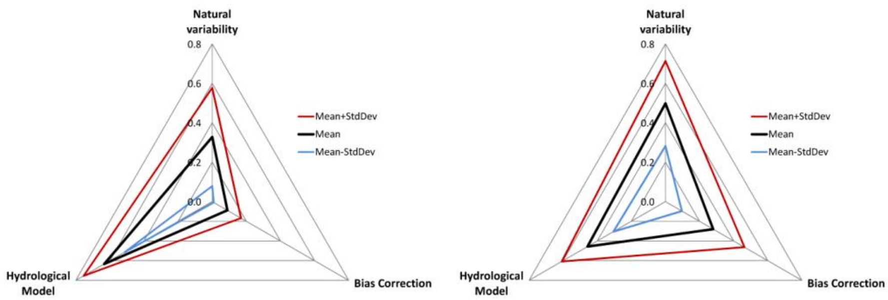

Figure 6: Relative contributions to the uncertainty of 7-day low flow (left) and high flow (right) change in magnitude for the Au Saumon river.

Finally, the projected change in high flow magnitude has a very large total uncertainty, ranging from -30 % to +50 %. Furthermore, the contributions from all three sources of uncertainty, presented for Au Saumon, are of similar importance. This suggests that the reproduction of the complex processes leading to peak flows in rivers is very sensitive to both, HyM structure and calibration as well as simulated temporal sequence of weather conditions. A detailed analysis of hydrological indicator sensitivity to the choice of hydrological model structure is given in Velazquez et al. [2012].

4 CONCLUSION

To this day, the assessment of current and future hydrological conditions on the climatological timescale requires the use of a complex modelling chain, which introduces several sources of uncertainty that simply cannot be ignored without careful justification. The quantification of these sources of uncertainty and the behaviour of specific components of the modelling chain with respect to various uncertainty components is nontrivial. Here, compact graphical tools for such an analysis are presented. Using such tools, it is clearly and succinctly shown that different hydrological indicators have drastically different relationship to each of the uncertainty components. To name a few, while all hydrological models were in fairly good agreement when it came to reproducing current overall mean flow, they represented the largest source of uncertainty when looking at high and low flow indicators. Also, the simulation of current flows can be strongly influenced by the use of bias correction, but when looking at climate change signals, this component of uncertainty often became the least important. A natural extension of this analysis would seek to add different emission scenarios and complete the ensemble such that natural variability over Bavaria and the choice of climate model over Quebec are assessed, yielding five uncertainty dimensions in the full analysis.

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