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Article

Climate change impacts on hydrology and water resources

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Abstract

Aim of our study is to quantify the impacts of climate change on hydrology in the large river basins in Germany (Rhine, Elbe, Danube, Weser and Ems) and thereby giving the range of impact uncertainty created by the most recent regional climate projections. The study shows mainly results for the A1B SRES (Special Report on Emission Scenario) scenario by comparing the reference period 1981–2010 and the scenario periods 2031–2060 and 2061–2090 and using climate projections of a combination of 4 Global Climate Models (GCMs) and 12 Regional Climate Models (RCMs) as climate driver. The outcome is compared against impacts driven by a more recent RCP (Representative Emission Pathways) scenario by using data of a statistical RCM. The results indicate that more robust conclusions can be drawn for some river basins, especially the Rhine and Danube basins, while diversity of results leads to higher uncertainty in the other river basins. The results also show that hydrology is very sensitive to changes in climate and effects of a general increase in precipitation can even be over-compensated by an increase in evapotranspiration. The decrease of runoff in late summer shown in most results can be an indicator for more pronounced droughts under scenario conditions.

Keywords: Climate change impacts, climate uncertainty, hydrology, water resources, water related sectors

1 Introduction

Over the past century global climate change has been observed which has had an impact on regional water resources through changes in precipitation, temperature and energy balance (IPCC, 2007a; IPCC, 2007b; IPCC, 2013). Possible warming in central Europe has, according to the fourth assessment report of the International Panel on Climate Change (IPCC), a bandwidth of approximately 1.5 to 6.0 degree Celsius by 2100. In different regions of Europe these trends may vary considerably on account of changes in large-scale atmospheric circulation or local orographic conditions (Eisenreich, 2005; Hattermann et al., 2007; Hattermann et al., 2008). The regional impact of climate change leads to the necessity of orienting adaptation measures to local climatic, geographic, economic and social conditions (Kabat et al., 2003; Krysanova et al., 2008; Varis et al., 2004; Hattermann and Kundzewicz, 2010).

In order to study regional climate change impacts, it is mandatory to regionalize global climate scenario data simulated by GCMs (global circulation models, (IPCC, 2000; Wilby et al., 1999). The regional climate models (RCMs) which are applied for this purpose can be broadly divided into two types: physical-deterministic and statistical RCMs (Varis et al., 2004). In reality, however, the results of physical-deterministic RCMs are also determined by factors such as the parameterization of the model and the numerical implementation. In the case of statistical RCMs the results are determined by the choice and number of large-scale boundary conditions, the availability and length of observed data, as well as the overall procedure. This means that, for the same global climate scenario, different regional manifestations of climate emerge when different RCMs are used (Wood et al., 2004). However, the sensitivity of the water balance to relatively small changes in the climate is substantial (Gädeke et al., 2014; Huang et al., 2010; Hattermann et al., 2008; Lehner et al., 2006).

Frequently, in the modeling of the effects of climate change on water budgets, only one regional climate model is employed, and the uncertainty arising from RCM uncertainty is ignored (Menzel and Bürger, 2002; Eckhardt and Ulbrich, 2003; Feyen and Dankers, 2009).

State-of-the-art is nowadays to apply ensembles of regional climate models (RCMs) driven by different global climate models (GCMs) and to feed their results into hydrological models in order to analyse the uncertainty propagation. So far this is done in Germany mostly for selected river basins or federal states and mostly only considering a subset of regional climate models. Kling et al. (2012), for example, use 21 regional climate projections of the ENSEMBE project and scenario A1B to quantify climate change impact uncertainty in the Danube basin. An impact assessment for the Rhine, Elbe and Danube basins has been done in the German project KLIWAS, applying ensembles of regional climate models for the A1B scenario (Nilson et al., 2011, Klein et al., 2012). A general result of these studies is that water availability in Germany decreases in summer and increases in winter, whereby uncertainty is yet high. This agrees with results pre-

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sented at the European scale, for example by Dankers and Feyen (2009) and Lehner et al. (2006), and also with trends in water availability already observed for the German river basins e.g. by Bormann (2010).

The novelty of this study is to provide a comprehensive overview about possible climate change impacts in Germany using the available climate projections for all large river basins in Germany and to discuss the sources of inherent uncertainties, using the same hydrological model and the same climate drivers for all river basins. In order to make as consistent and transparent the comparison as possible, only relative changes in hydrology are considered and no bias correction was carried out to the climate data (Hattermann et al., 2011). Huang et al. (2014a), for example, used bias corrected and uncorrected climate scenarios to drive a hydrological model for the largest German river basins and came to the result that the performance of bias correction depends on the method selected, length of calibration period and the used RCMs. In addition, bias correction can even lead to a change in trends especially for extremes. Bosshard et al. (2013) show that choosing different methods for bias correction can increase the uncertainty of modelled river runoff substantially. Following this discussion it can be concluded that in a study focussing on relative changes and not absolute values (of hydrological quantities), bias correction of climate input can increase the inherent uncertainty of the results while not adding much additional information. Whenever absolute values are the topic of the study (for example when the results are used in subsequent water management projections), bias correction of climate input becomes crucial.

2 Data and Methods

2.1 The regional climate models

The scenario data used in this study were simulated by two types of RCMs. In physical-deterministic RCMs the basic physical equations for the movement and transport of the atmosphere, with the land surface as one boundary condition, are resolved numerically (McGregor, 1997). For this purpose the area covered by the model must be divided into grid cells. The fluxes and magnitudes of the climate variables at the model's edges must be known for each time step of the simulation. For the past this information may be derived from observations. For climate change scenario runs the boundary conditions are normally taken from Global Circulation Model (GCM) runs (Varis et al., 2004). In principle, physical-deterministic climate models ought to be able to reproduce regional climate better than statistical climate models, especially under conditions of climate change. However, the physics of the atmosphere (e.g. clouds, precipitation) and its feedback effects, for example on surface processes, are highly complex, and physical-deterministic RCMs still lack the full inclusion of some of these processes. Furthermore, for reasons of stability, the solution of the basic physical equations must take place in very short time steps, with the result that the numerical simulation of regional climate is extremely time-consuming (Van der Linden and Mitchell, 2009).

This class of models includes the German RCMs REMO (Tomassini and Jacob, 2009) and CCLM (Böhm et al., 2006) and also the set of RCMs of the ENSEMBLES project (Van der Linden and Mitchell, 2009) which are considered in this study.

Statistical RCMs basically assume that certain relationships or correlations between observed climate variables and local weather do not undergo any considerable transformation, even under climate change conditions, but possibly occur with a different frequency or intensity (Gerstengarbe et al., 2015). The idea is thus to use these relationships in order to be able to produce regional climate scenarios under conditions of climate change. Chosen as independent or driving climate variables are those which can be reproduced with relative high accuracy by GCMs (e.g. temperature, circulation patterns). The variables which are reproduced with relative high inaccuracy by GCMs (e.g. radiation and especially precipitation) are then simulated using the observed correlations to the driving GCM variables. Since observation data are normally available in daily resolution, this is usually also the time step of the scenario simulation generated by statistical RCMs. In contrast to physical-deterministic RCMs, statistical RCMs are distinctly easier to use and also require much less computing. This means that a relatively large number of climate realizations can be generated using statistical RCMs, thus making it possible to quantify model scenario uncertainty to a certain degree.

This class of models include the German RCMs WettReg (Enke et al., 2005a; Enke et al., 2005b) and STARS (Gerstengarbe and Werner, 2005; Orlowsky et al., 2008) used in this study. Whereas WettReg mainly uses pressure (circulation pattern) and temperature as driving climate variables, STARS only uses temperature as driver. Recently, climate re-sampling techniques as the ones used in STARS have been criticized. Wechsung and Wechsung 2014 show that STARS-based climate projections turn short-term interannual variability between temperature and covariables into long-term climate trends, and as a result, the resampled German climate becomes dryer and associated with brighter skies and higher global radiation levels, owing to the dominance of summer over winter correlations at the sub-annual re-sampling levels.

The REMO and WettReg data comply with the 'official' scenarios for Germany commissioned by the Federal Environment Agency. The CCLM data are the so-called 'consortium runs' (Hollweg et al., 2008) for Europe, and the STARS scenarios were generated at the Potsdam Institute for Climate Impact Research as part of a study on Germany (Gerstengarbe et al., 2015).

In addition to the results of the before mentioned four German RCMs we also made use of results of a set

Table 1: Fourteen selected GCM/RCM simulations (SRES A1B) from the ENSEMBLES project (Van der Linden and Mitchell, 2009).

	Institute	**C4I**	**DMI**	**ETHZ**	**HC**			**ICTP**	**KNMI**	**MPI**	**SMHI**
	RCM	**RCA3**	**HIRHAM5**	**CLM3.21**	**HadRM3 Q0**	**HadRM3 Q3**	**HadRM3 Q16**	**REGCM3**	**RACMO2**	**M-REMO**	**RCA3**
GCM	*Resolution*	25 km	25 km	25 km	25 km	25 km	25 km	25 km	25 km	25 km	25 km
HC HadCM3 Q0				1951–2100	1951–2100					1951–2100	
HC HadCM3 Q3						1951–2100					1951–2100
HC HadCM3 Q16		1951–2100					1951–2100				
MPI-MET ECHAM5 r3			1951–2100					1951–2100	1950–2100		1950–2100
CNRM Arpege			1951–2100								
UIB BCM			1961–2099								1961–2100

of high-resolution climate model simulations performed by several state-of-the-art RCMs (driven by different GCMs) within the framework of the EU-FP6 ENSEMBLES project (Van der Linden and Mitchell, 2009) and considered 14 GCM/RCM combinations all for the SRES A1B emission scenario. The spatial resolution of the RCM data was approximately 25 km. These data sets were selected out of the ENSEMBLES matrix, under the criteria that they come with all required parameters for further hydrological analysis and were available from 1951 until 2100 (except BCM/RCA3 which was available for 1961–2100). For the HadCM3 GCM as well as the HadRM3 RCM, three realizations were included for 'normal' climate sensitivity (Q0), 'low' climate sensitivity (Q3) and 'high' climate sensitivity (Q16) to the external forcing (e.g. greenhouse gas concentrations, by perturbing HadRM3 internal parameters, see Collins et al. (2006)).

The chosen matrix (see Table 1) consists of four GCMs (HadCM3, ECHAM5, Arpege and BCM), including three different realizations of HadCM3 and eight different regional models (RCA3 (C4I), HIRHAM5, CLM3.21, HadRM3 (three realizations: Q0, Q3, Q16), REGCM3, RACHMO2, M-REMO and RCA3 (SMHI)).

2.2 The eco-hydrological model SWIM

To study the effects of climate change on water resources in Germany use was made of the eco-hydrological model SWIM (Soil and Water Integrated Model, Krysanova et al. (1998); Hattermann et al. (2005)). Integrated into this model are modules for computing the hydrology, plant growth (e.g. agriculture and forestry), nutrition cycle (nitrogen and phosphorus) and erosion.

The SWIM model system is a catchment model for the regional scale which operates continuously in time and is spatially structured. The disaggregation of the area under study occurs at three levels: i) the hydrotope level, which is homogeneous in its geographical characteristics; ii) the sub-catchment level consisting of hydrotopes; and iii) the all-integrating catchment areas. The lowest level, the hydrotope level, is created from a combination of different spatial information: digital elevation model, sub-catchment area, soil maps, land use, depth to groundwater, etc. It reflects exactly the heterogeneity of the actual area of the landscape (or the data). The computed vertical and lateral water flows and matter fluxes at the hydrotope level are aggregated at the sub-catchment level and routed through the flow system to the catchment outlet. The hydrological module in SWIM comprises four sub-systems: the soil surface, the root zone (where depending on the soil information up to 12 soil layers can be differentiated), the upper and lower aquifers, and the water transported in the rivers.

An important factor in the modeling of the hydrological conditions under climate change is a dynamic representation of vegetation development since, exposed to higher temperatures, plant phenology undergoes change and plants begin to grow earlier in the year and lose their leaves later in the year. By way of plant transpiration this has great feedback effects on the regional water balance (Hattermann et al., 2008).

Plant growth is calculated on the basis of a simplified EPIC approach (Williams et al., 1983). Here, a dataset specially parameterized for the region is used, by means of which various crops (wheat, barley, maize, potatoes, rape, etc.) as well as natural vegetation types (forest, grassland) can be modeled dynamically on a daily basis. A detailed description of the processes reproduced by SWIM can be found in Krysanova et al. (1998).

2.3 The data used

All spatial data for the study (information on land use and soils, borders of sub-catchment areas and the digital elevation model) was transferred to a uniform grid with a cell size of 250 m. The soil parameters are based on the German Soil Survey Map (BÜK 1000), and the land-use data is based on the CORINE 2000 (Bossard et al., 2000) classification. Altogether 109 different main soil types and 15 land-use types were differentiated. The borders of sub-catchment areas in Germany were taken from data of the Federal Environment Agency in Berlin and for areas outside Germany they were calculated from elevation models. In total, the model set-up consists of 5,473 subbasins and 124,671 hydrotopes (thereof 3,766 subbasins and 63,926 hydrotopes in Germany). Meteorological data from 270 meteorological and 2,072 precipitation stations of the German Weather Service was made available for the modeling and reprocessed at PIK. In addition, for the sub-catchment areas of the Rhine, Elbe and Danube which lie outside Germany the data of further weather stations and re-analysis data

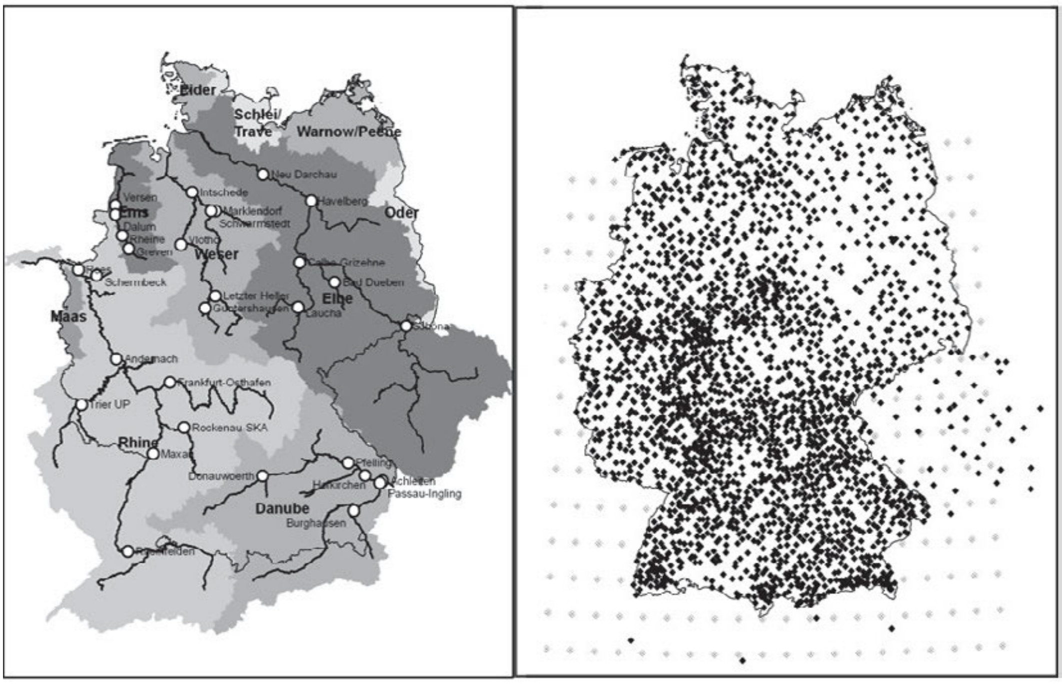

Figure 1: Catchments of the main German rivers and location of the runoff gauge stations for the validation (left) and location of the climate and precipitation stations (right). In light grey locations where climate re-analysis data where used.

was processed (Fig. 1). Four different procedures for interpolating the climate data were compared (Thiessen polygons, inverse distance, ordinary kriging and external drift kriging). By means of cross validation the most suitable procedure was determined for each of the climate variables. It turned out that, in view of the density of the available data, the inverse distance procedure displayed a quality that was comparable with geostatic procedures but required much less computation and hence was 'faster', which is important for stochastic applications (multiple realizations per climate scenario).

The regional scenarios of the German RCMs REMO, CCLM, STARS and WettReg, all driven by the A1B scenario of the German GCM ECHAM5 (Röckner et al., 1999; Röckner et al., 2003), as well as 14 additional scenarios realizations delivered by the ENSEMBLES project, served as climate boundary condition for projections up to the year 2090. The first set of climate scenarios – IS92 – were published in 1992, the second – SRES – in the year 2000. These results were additionally compared against a RCP8.5 regional scenario of the RCM STARS (Gerstengarbe et al., 2015). The 'Representative Concentration Pathways' (RCP) are the third and newest generation of IPCC climate scenarios.

Four RCPs exist: RCP8.5, RCP6, RCP4.5, and RCP2.6. The numbers refer to radiative forcings (global energy imbalances), measured in watts per square metre, by the year 2100. In this study we applied the high end scenario RCP8.5. Jacob et al. (2014) compared regionalized RCP scenarios for Europe with the ENSEMBLES results and concluded that, with some regional differences, the general climate trends are confirmed.

Fig. 2 illustrates the range of monthly changes in precipitation given by the ENSEMBLES output under SRES A1B scenario forcing (left) and the range simulated by STARS with RCP8.5 scenario forcing (right, 100 realizations) for two periods (1981–2010 to 2031–2060 and to 2061–2090). Both scenarios give mostly an increase in winter and a decrease in summer precipitation, whereby the trend is more pronounced in the second scenario period. The change is more uncertain when looking at the ENSEMBLES A1B, results with possibly increases in winter and decreases in summer precipitation, while the range of change is narrower when looking at the STARS RCP8.5 results. The larger uncertainty in precipitation change given by the SRES A1B scenario reflects the fact that a combination of different driving GCMs and RCMs were taken into account (thus showing the specific climate model uncertainty), while the range in the RCP8.5 scenario reflects only the internal uncertainty of one RCM (STARS).

3 Results

3.1 Validation of the simulated river runoffs

The simulated runoff of the SWIM model was compared with observed runoff at altogether 29 water gauge stations in Germany by (Huang et al., 2010) to investigate the general ability of the model to reproduce the hydrological dynamics. Climate input are the daily observations of the 270 meteorological and 2,072 precipitation stations of the German Weather Service corrected by measurement errors after Richter (1995). The results

Table 2: Results for daily river runoff (calibration only for runoff of 19 main gauges 1981–90, additional validation for 11 more gauges and the period 1961–80) (from Huang et al. (2014b), changed NSE: Nash-Sutcliffe Efficiency, DB: bias in runoff).

River basin	Rivers	Gauges	Area (km2)	Calibration period 1981–1990		Validation period 1961–1980	
				NSE	DB	NSE	DB
Ems	Ems	Versen	8,369	0.88	0 %	0.86	−7 %
	Ems	Dalum[1]	4,981	0.86	5 %	0.81	−4 %
	Ems	Rheine[1]	3,740	0.81	4 %	0.76	−1 %
	Ems	Greven[1]	2,842	0.88	6 %	0.83	0 %
Weser	Weser	Intschede	37,720	0.90	1 %	0.89	−5 %
	Weser	Vlotho[1]	17,618	0.87	0 %	0.84	−2 %
	Aller	Marklendorf	7,209	0.82	−1 %	0.75	−15 %
	Leine	Schwarmstedt	6,443	0.82	−1 %	0.86	−7 %
	Fulda	Guntershausen	6,366	0.52	6 %	0.57	1 %
	Werra	Letzter Heller	5,487	0.85	1 %	0.83	−4 %
Danube	Danube	Achleiten[1]	76,653	0.87	−1 %	0.86	−4 %
	Danube	Hofkirchen	47,496	0.87	0 %	0.82	−5 %
	Danube	Pfelling[1]	37,687	0.84	−1 %	0.79	−6 %
	Danube	Donauwoerth	15,037	0.82	−1 %	0.79	−2 %
	Inn	Passau Ingling	26,084	0.83	−2 %	0.84	−1 %
	Salzach, Inn	Burghausen[1]	6,649	0.72	−10 %	0.72	−9 %
Rhine	Rhine	Rees	159,300	0.89	3 %	0.89	−1 %
	Rhine	Andernach[1]	139,549	0.88	0 %	0.87	1 %
	Rhine	Maxau[1]	50,196	0.76	1 %	0.80	−1 %
	Rhine	Rheinfelden	34,550	0.83	0 %	0.81	1 %
	Main	Frankfurt-Osthafen	24,764	0.83	−1 %	0.77	3 %
	Moselle	Trier UP	23,857	0.83	1 %	0.83	3 %
	Neckar	Rockenau SKA	12,710	0.80	−1 %	0.75	4 %
	Lippe	Schermbeck[1]	4,783	0.77	16 %	0.78	2 %
Elbe	Elbe	Neu-Darchau	131,950	0.83	0 %	0.85	−1 %
	Elbe	Schoena	51,391	0.77	5 %	0.79	6 %
	Havel	Havelberg	24,037	0.62	−7 %	–	–
	Saale	Calbe-Grizehne	23,719	0.80	1 %	0.81	−2 %
	Mulde	Bad Dueben	6,171	0.80	−1 %	0.79	1 %
	Unstrut	Laucha[1]	6,218	0.59	0 %	0.67	−5 %

[1]Gauges not calibrated

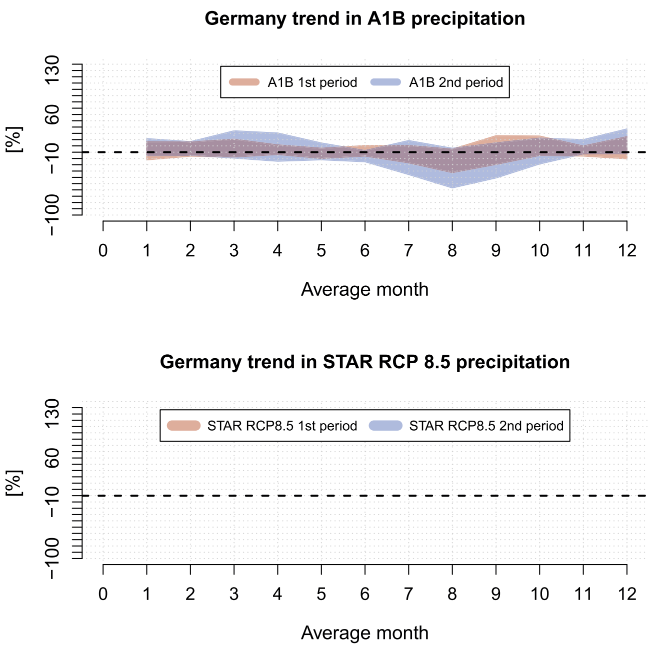

Figure 2: Changes in precipitation 1981–2010 (reference) to 2031–2060 (1st scenario period) and 2061–2090 (2nd scenario period). Top: SRES scenario A1B (results of 14 different RCMs), Bottom: RCP8.5 (one RCM with 100 realizations).

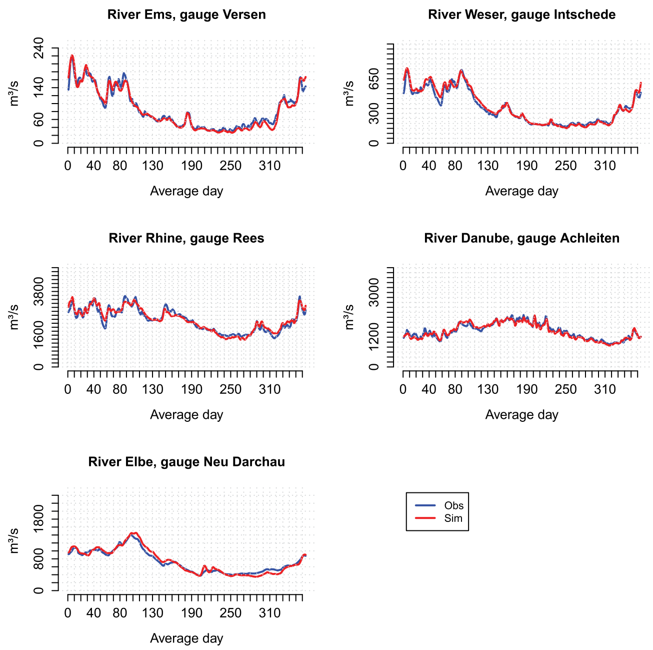

Figure 3: Simulated and observed long-term daily average of river runoff for the period 1981–90 at the gauges Versen (Ems), Intschede (Weser), Rees (Rhine), Neu Darchau (Elbe) and Hofkirchen (Donau).

relating to the large German rivers are presented in Fig. 3 and Table 2 (see Hattermann et al. (2011), Huang et al. (2010); Huang et al. (2014b)). As can be seen, the SWIM model is able to reproduce well the observed daily runoff in the different river catchments. However, significant problems occur in places where - on account of either human intervention, for example through extensive mining activities (in the case of the Havel river), or poor data, such as in the French sub-catchment area of the Rhine (in the case of the Moselle basin at gauge Trier and the Elbe basin at gauge Schöna) – there is uncertainty concerning the boundary conditions.

In order to be able to compare location-related results of the SWIM model set-up, for example local runoff formation, the results for the reference period were also compared by Huang et al. (2010) with the values given in the German Hydrological Atlas (HAD). The result is that with regard to long-term mean runoff per unit area the values agree in their spatial distribution.

3.2 Scenario results

In this section the impacts of the climate model projections on the water balance in Germany are presented and discussed, exemplified by the runoff for large river catchments. Fig. 4 shows the change in mean simulated scenario runoffs for the period 2031–60 as a relative difference compared with the mean simulated scenario runoffs for the period 1981–2010 (see Equation 3.1). In order to make as consistent and transparent the comparison as possible, only relative changes in long-term mean daily runoff $\bar{Q}_d$ (%) are considered and no bias correction was carried out in the climate data (see also Hattermann et al. (2011)):

$$\bar{Q}_d = \frac{\sum_{n=2031}^{2060} Q_d(i,j)}{2060\text{–}2030} \Big/ \frac{\sum_{n=1981}^{2010} Q_d(i,j)}{2010\text{–}1980} \cdot 100 \qquad (3.1)$$
$$j = (1.\text{ Jan}, 2.\text{ Jan}, \ldots, 31.\text{ Dec})$$

with Q_d denoting the daily runoff in $m^3 s^{-1}$, i is the year in the reference and scenario period and j the simulation day.

Thus, positive deviations mean that, overall, the runoff – and hence also water availability - increases under the specific scenario conditions; by contrast, negative deviations are a sign of decreased water availability and large deviations an indication for possibly long periods of drought, especially in the summer months. This comparison is possible because the climate scenarios start already in the reference period (year 1960), making a consistent comparison of scenario and reference periods possible with the same climate model input as driver. Because of the fact that there are 20 WettReg climate realizations per scenario and 100 STARS realizations per scenario, leading to problems of representativeness, a limited selection of 5 WettReg and STARS results (mirroring the respective distribution) was applied for further computation covering the range of simulation results.

The first scenario period 2031–60 has been chosen for the comparison because it is a time horizon relevant for water management, for example for planning of new reservoirs. The second scenario period gives the long-term projections, but in this case only for the A1B scenario and for the climate projections of the dynamical RCMs and the statistical RCM WettReg, as the statistical RCM STARS relies on the assumption that observed climate pattern in a region is a function of temperature only and it therefore may leave the corridor of its applicability if climate boundary conditions change too much (cf. Wechsung and Wechsung 2014, Gerstengarbe et al., 2015).

A number of patterns and trends are observable in the results.

Ems For the river Ems, the range of uncertainty in the ensemble results driven by scenario A1B is relatively high (mostly between +50 % and −40 %) without showing a clear trend to more or less water availability and higher range of uncertainty in the summer months. The results driven by scenario RCP8.5, with STARS climate as input, show in contrast a clear decrease in summer runoff until 2060.

Weser The results under A1B climate also give a large range of uncertainty, but in total have a stronger bias to negative changes, especially in the summer months. The STARS RCP8.5 scenario leads to even less water availability until 2060 with possible increases only in the winter months December to February.

Rhine The majority of results for the river Rhine driven by A1B projections have a slight decrease in runoff, especially in summer, and are in total attached by less uncertainty than the results for the rivers Ems, Weser and also Elbe. The trend in summer to less water availability until 2060 is more pronounced under STARS RCP8.5 scenario conditions. Obviously, possible increases in winter term precipitation and subsequent runoff generation cannot counterbalance the decrease in summer.

Elbe The results for the Elbe show in total the highest uncertainty especially in summer (+80 % to −80 % for the A1B scenario results), while no specific trend in runoff is visible until 2060. The A1B results give also no clear seasonal trend, in contrast to the RCP8.5 results, where almost all realizations have less runoff than in the reference period and increases in runoff are only visible in mid-winter.

Danube The A1B results for the Danube show, after the Rhine, the second lowest range of uncertainty with mostly a decrease in runoff up to ∼ −40 % in summer and possible increases only in winter. The results of the RCP8.5 scenario are at the lower range of the A1B impact corridor.

Summarizing the results for the first scenario period, some robust patterns are visible for the rivers Rhine and Danube with mostly decreases in runoff, especially in summer. Here, the decreases in summer cannot fully be compensated by increases in winter induced for example by the winter increase in precipitation and earlier

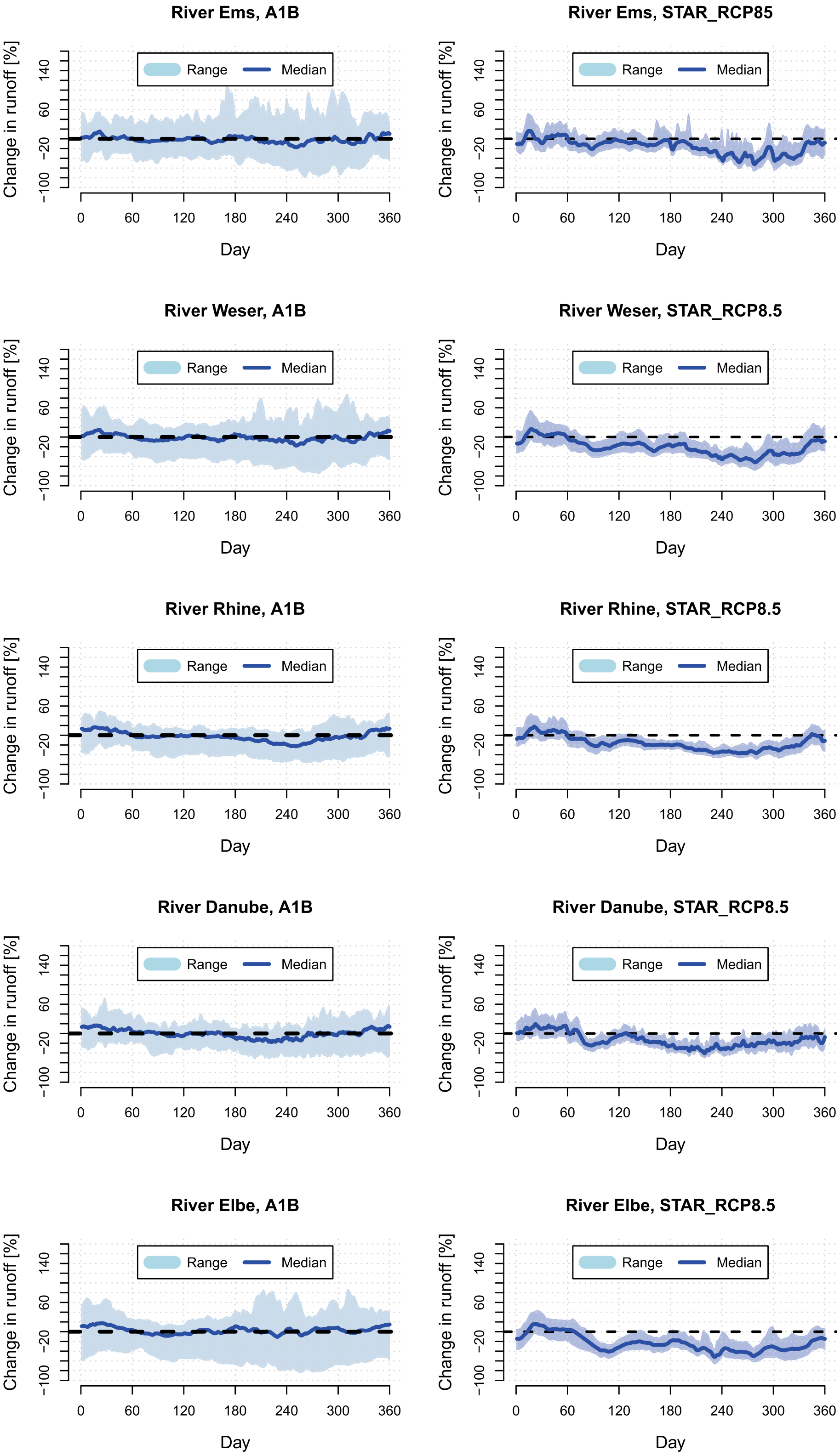

Figure 4: Relative changes in daily runoff comparing the long-term daily mean 1981–2010 and 2031–60 for the rivers Ems, Weser, Rhine, Danube and Elbe. Left – results for the ensemble of A1B realizations, right – results for the STARS RCP8.5 scenario.

snow melt. This is important, because the Rhine is one of the most important waterways for river navigation and transport in Europe, and the Danube is the second most important one for navigation in Germany. This decrease in summer runoff can serve as an indicator for the water availability in the entire basin, and under such conditions also impacts on water related sectors are likely, e.g. on electricity generation (Koch et al., 2015). The A1B results are more uncertain for the rivers Ems, Weser and Elbe, with no clear trend in total or seasonal runoff.

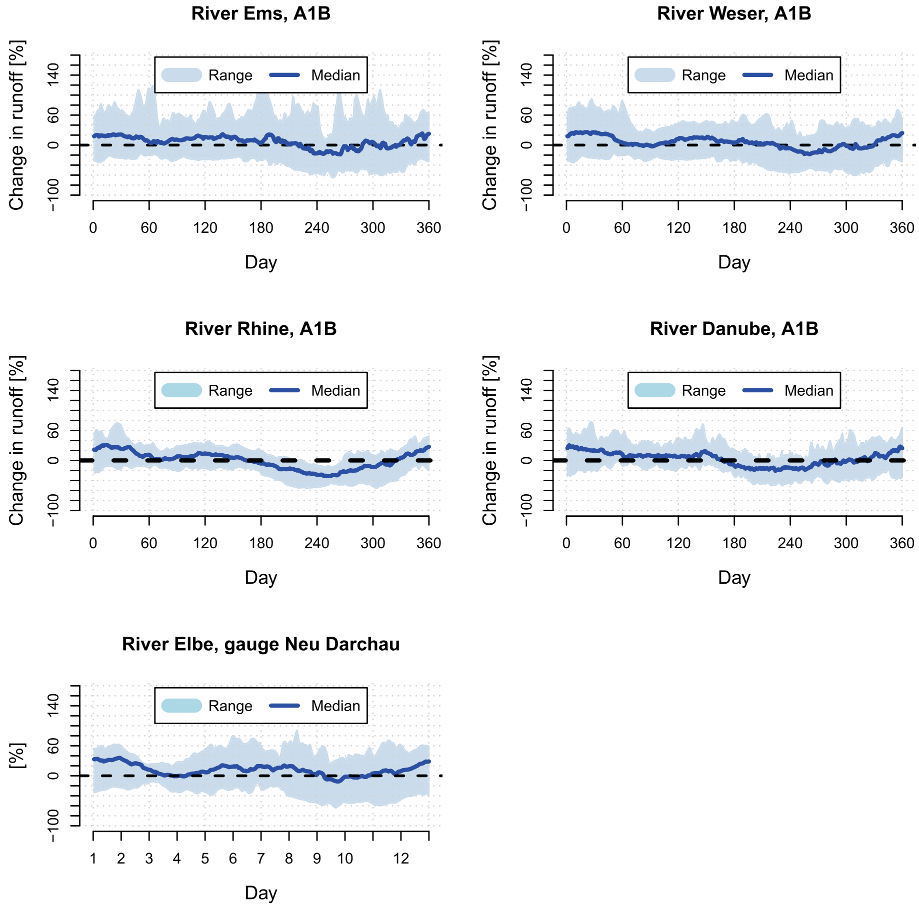

Figure 5: Relative changes in daily runoff comparing the long-term daily mean 1981–2010 and 2061–90 for the rivers Ems, Weser, Rhine, Elbe and Danube (scenario A1B only).

The range of uncertainty is lower when looking at the RCP8.5 scenario with climate data simulated by STARS as input, and will certainly increase when also output of other RCMs will be available for the hydrological modelling. For all rivers, most realizations give a decrease in runoff in summer, with the weakest trend in the Ems and Elbe basins.

Fig. 5 illustrates the impacts for the second scenario period (2061–2090) under A1B climate. The outcome for the rivers Rhine and Danube is that the trends in runoff manifest in both cases with even stronger decreases in summer runoff than for the first scenario period, while the results remain highly uncertain for the other basins. As a result the certainty for a decrease in summer runoff and increase in winter runoff rises in total, especially for the summer runoff in the Rhine basin.

The question remains whether the seasonal changes in precipitation shown in Fig. 2 are the only driver for the changes in runoff and how far also changes in evapotranspiration or soil and groundwater storage play a role. Figs 6 and 7 give the changes in precipitation and potential and actual evapotranspiration for the annual and monthly sums, respectively, for the German parts of the Rhine basin as a result of the REMO A1B scenario. When looking at the annual sums one can see that precipitation increases in the first and decreases in the second scenario period, while potential evapotranspiration increases slightly in the first and more pronounced in the second scenario period. As a result, the increase in precipitation in the first scenario period is mostly compensated by an increase in actual evapotranspiration, while the decrease in precipitation in the second scenario period leads subsequently to a decrease in actual evapotranspiration despite the steep increase in potential evapotranspiration, simply because the additional evapotranspiration demand cannot be satisfied by the available water in the second scenario period.

The monthly changes in Fig. 7 illustrate that the already observed trend to lower precipitation in summer and higher precipitation in winter continues in the REMO A1B climate scenario and leads to a decrease in actual evapotranspiration in summer indicating that plants cannot satisfy their additional transpiration demand (stimulated by the increase in potential evapotranspiration) during the main vegetation period.

Fig. 7 gives also the changes in monthly flow components until end of the century. The simulations show that the increase in winter precipitation leads to an increase in both flow components during winter (direct runoff as the sum of surface runoff and interflow and groundwater runoff being the slow runoff component). Important for summer runoff is the increase in groundwater recharge

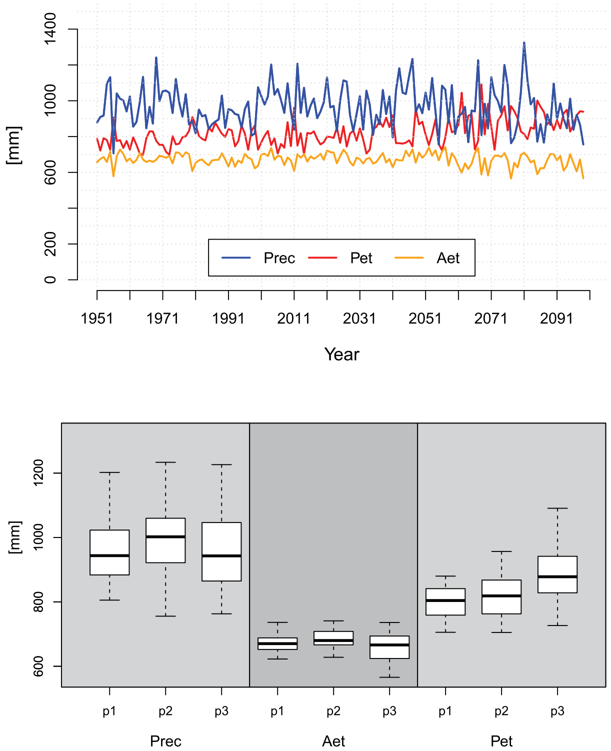

Figure 6: Change in precipitation (Prec), potential evapotranspiration (Pet) and actual evapotranspiration (Aet) in the German part of the Rhine basin (with REMO scenario A1B as climate driver). Top: annual sums, Bottom: boxplot of annual sums for the periods 1981–2010 (p1), 2031–2060 (p2) and 2061–2090 (p3).

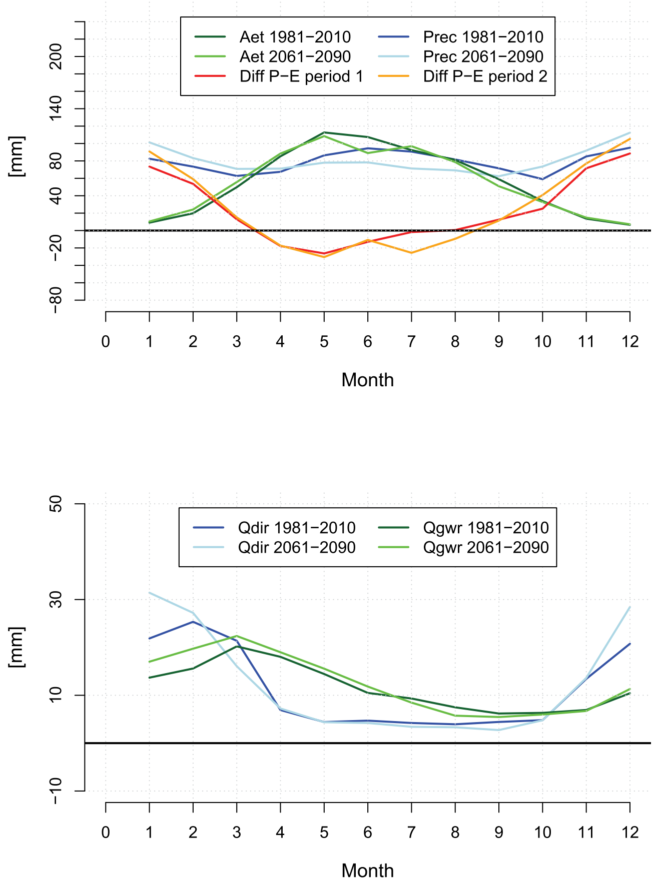

Figure 7: Top: Change in monthly precipitation (Prec), potential evapotranspiration (Pet) and actual evapotranspiration (Aet) in the German part of the Rhine basin (with REMO scenario A1B as climate driver). Bottom: Change in monthly flow components (Qdir: direct runoff, Qgwr: groundwater runoff).

and storage during the winter term. The water is released with some delay and this additional groundwater runoff in spring and summer can partly compensate the decrease in direct flow components, while both, direct and groundwater runoff decrease in the end of the summer and early autumn.

4 Summary and conclusions

The results presented show that in regional hydrological research there is relatively large uncertainty with regard to midterm regional climate change impacts on river runoff and water availability. The relatively small difference in climate input (change in precipitation under scenario conditions) leads to relatively high differences in river runoff when comparing the A1B and RCP8.5 scenarios.

However, some robust trends can be detected: a) a decrease of runoff in summer in the Rhine and Danube, more pronounced by end of this century, and b) earlier snow melt in spring and often increased runoff in winter in almost all river basins. This is in line with the observed trends in runoff and in water availability discussed by Bormann (2010), and also with the scenario trends in runoff described in Kling et al. (2012) and Klein et al. (2012) for the Danube basin and by Nilson et al. (2011) for the Rhine.

The decrease of runoff in late summer in large parts of Germany is additionally an indication for more pronounced droughts under scenario conditions. This decrease can be partly compensated by more runoff in winter when considering water storage in soils, groundwater and reservoirs. Impacts on water-related sectors, finally, are dependent on the specific type of water use in terms of total annual demand (with the possibility of water storage) and seasonal or daily demand (without the buffering capacity of water storage).

The results shown in this study using the same hydrological model and the same climate drivers for the five largest river basins in Germany agree generally with the outcome of other studies for particular river basins.

There is a great need for further research. Uncertainty in climate change projections is still high and it is questionable to which extend further development of RCMs will help reducing uncertainty. Krahe et al. (2009), for example, applied the ENSEMBLES A1B climate scenario realizations to run a hydrological model of the Rhine and came to the conclusion that the uncertainty induced by the different GCMs is larger than the one induced by the subsequent downscaling using RCMs. Another topic on the research agenda is the uncertainty in impacts on hydrology induced by the hydrological models, and different studies indicate that this can be notably (Ott et al. (2013), Hattermann et al. (2013), Vetter et al. (2014), Bosshard et al. (2013), Gädeke et al. (2014)).

Finally one has to mention that our scenario analysis focuses solely on changes in climate, while changes in land use and land cover are not considered. As mentioned before, plant composition and vegetation cover have a strong impact on evapotranspiration, and changes in land management (e.g. crop rotations) which are discussed as possible adaptation measures will certainly have an impact on the scenario results.

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