Reg Environ Change (2015) 15:461–473
DOI 10.1007/s10113-014-0606-z

ORIGINAL ARTICLE

Projections of climate change impacts on floods and droughts in Germany using an ensemble of climate change scenarios

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Received: 19 December 2012 / Accepted: 28 February 2014 / Published online: 20 March 2014

Abstract Under a warming climate, changes in hydrological extremes may be more significant than changes in hydrological mean conditions. Due to the high risk of damage and the increasing trends of floods and droughts in Germany, the potential changes in hydrological extreme events are of high importance. However, projections of extreme events particularly for floods are associated with large uncertainties and depend on climate scenarios. If only a few scenarios are applied, there is a danger that the impact assessment is biased. This study aims to evaluate the performance of a set of climate scenarios from the ENSEMBLES project for flood and drought projections and to detect the robust changes using the eco-hydrological model SWIM in five large river basins covering 90 % of the German territory. The study shows that there is a moderate certainty that most German rivers will experience more extreme 50-year floods and more frequent occurrences of 50-year droughts. Projected changes with a high certainty include an increasing trend of floods in the Elbe basin and more frequent extreme droughts in the Rhine basin in 2061–2100. Wetter conditions, i.e., more extreme floods and less frequent droughts, are projected for the alpine rivers in 2021–2060. Using only those RCMs for impact assessments that perform best in the reference period does not guarantee more consistent and certain future projections. Hence, the use of the whole ensemble of available scenarios is necessary to quantify the "full" range of uncertainties corresponding to the current state of knowledge and assuring the robustness of projected change patterns.

Keywords SWIM · Climate impact assessment · ENSEMBLES project · Flood · Drought · Germany

Introduction

A changing climate intimately links to changes in the hydrological cycle, and changes in hydrological extremes may be more significant than changes in mean conditions (Katz and Brown 1992; IPCC 1996). Summer precipitation is expected to decrease, and the 99-percentile precipitation is likely to increase over a substantial part of Europe in 2071–2100 compared to that in 1961–1990 (Christensen and Christensen 2004). This implies that more intensive rainfalls, which can lead to extreme floods, may occur in the areas suffering long dry spells. In short, both extreme flood and drought events may occur more frequently in Europe in the future.

Compared with changes in mean conditions, the extreme events pose a greater risk to the human society. Thus, growing attention is directed to understanding changes in the frequency and magnitude of extreme events and their resultant risks with regard to global change. One important example is the special report related to extreme events by the intergovernmental panel on climate change (IPCC 2012). This recent report highlights the significance of impact studies related to extreme events for developing suitable adaptation strategies under a warming climate.

Located in central Europe, Germany is experiencing increasing trends in flood and drought conditions (Petrow and Merz 2009; Stahl et al. 2010). Some of the recent

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Electronic supplementary material The online version of this article (doi:10.1007/s10113-014-0606-z) contains supplementary material, which is available to authorized users.

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destructive events caused substantial financial losses. For example, more than 11.6 billion Euro losses were caused by the Elbe and Danube floods in 2002 (Thieken et al. 2005), and around 1.3 billion Euro losses were reported for the agricultural sector only due to the 2003 drought (Munich Re 2009). In order to plan adaptation strategies for future hydrological extreme events, more information on the potential changes in floods and droughts is necessary.

However, extreme event projections particularly for floods are associated with large uncertainties (Kay et al. 2009, Huang et al. 2012a). Huang et al. (2012a) investigated the changes in 50-year floods for the five large river basins in Germany under ten scenario conditions generated by three regional climate models (RCMs) under three emission scenarios, whereas the boundary conditions originated from one general circulation model (GCM). That study has shown that contradictory change directions are projected under different driving climate scenarios. As a result, the uncertainty of projections was high, and no robust change pattern could be detected for most of the regions. The reason is partly due to differences in RCM structures, emission scenarios and GCM realizations, and partly due to the natural variability of rare events. That study, however, did not account for the differences in GCM structures, which were found to induce the largest uncertainty for flood projections (Kay et al. 2009).

In order to better account for the uncertainty in the extreme event projections, the use of ensembles of climate scenarios was suggested (Cameron 2006; Graham et al. 2007; Faramarzi et al. 2013). Due to the high computational demand of the physically based dynamical models, such an ensemble-based assessment in climate impact studies is still not common (Teutschbein and Seibert 2010). Fortunately, as a benefit from the European ENSEMBLES project (2009), a large number of RCM simulations driven by different GCM outputs are now available for Europe. These multiple scenarios make it possible to re-investigate the potential changes in flood and drought events in Germany under climate change based on our previous studies (Huang et al. 2012a, b). In addition, such a study can include the uncertainties from different GCM structures.

However, it is still questionable whether all the RCM simulations should bear equal weight in the impact studies. A common assumption is that those RCMs that perform well in reproducing past climates are also more likely to yield robuster results for future. This assumption serves as a basis of many studies, which weighted the results from different climate models based on selected performance metrics in the past (e.g., Tebaldi and Knutti 2007; Raisanen et al. 2010). Some flood impact studies only selected the climate models, which perform well for the past to drive the hydrological models based on this assumption (e.g., Rojas et al. 2011). In contrast, Giorgi and Coppola (2010) found that the regional bias does not appear to be a dominant factor in determining the simulated regional climate change in the majority of cases. Hence, it would also be interesting to know whether the hydrological projections in the future driven by the best performing RCMs in the past are more robust (i.e., provide notably lower uncertainty ranges) than the ones driven by the whole ensemble of RCMs.

The objectives of this paper are (a) to evaluate the performance of the ensemble climate scenarios for flood and drought impact assessment in Germany, (b) to analyze the uncertainty of the future projections using a few best performing in the reference period RCM outputs and the whole RCM ensemble, and (c) to project the changes in flood and drought conditions in the five large river basins in Germany under climate change including estimation of uncertainties. Here, floods and droughts are strictly defined in terms of river discharge. Daily river discharge was simulated by the eco-hydrological model SWIM (soil and water integrated model, Krysanova et al. 1998). The 50-year floods and droughts were estimated by fitting the peak discharges above threshold and the deficit volume.

Study area

The study area includes five large river basins in Germany: the upper Danube, Elbe, Ems, Rhine and Weser (Fig. 1), covering about 90 % of the territory of Germany and parts of the neighboring countries. Figure 1 also shows the location of 30 selected gauge stations that were used for assessing the flood and drought conditions at the main rivers and their large tributaries.

These five river basins have significant differences in climatic and hydrological regimes. From the northwest (Ems basin) to the east and southeast (Elbe and Danube basins), the maritime climate gradually changes into a more continental climate. It is warmer in the northwestern basins Ems and Weser (annual mean temperature ca. 9.3 and 8.6 °C, respectively), while the upper Danube and Upper Rhine basins are the two coldest regions (annual mean temperature ca. 6.6 and 7.2 °C, respectively). These two colder basins have the highest precipitation, particularly in the south alpine regions (more than 2,000 mm a^{-1}), and the northern three basins receive less precipitation ranging from 700 to 840 mm a^{-1}. Most German rivers correspond to the pluvial type (with local nival influences) (HAD 2000), i.e., they experience high water levels in winter and low flows in summer. The tributary Inn to the Danube and the upper Rhine show a nival runoff regime, i.e., they have the main flood season in late spring or early summer due to a large amount of melt water from snow and glaciers. In the German part of the Danube and the Upper/

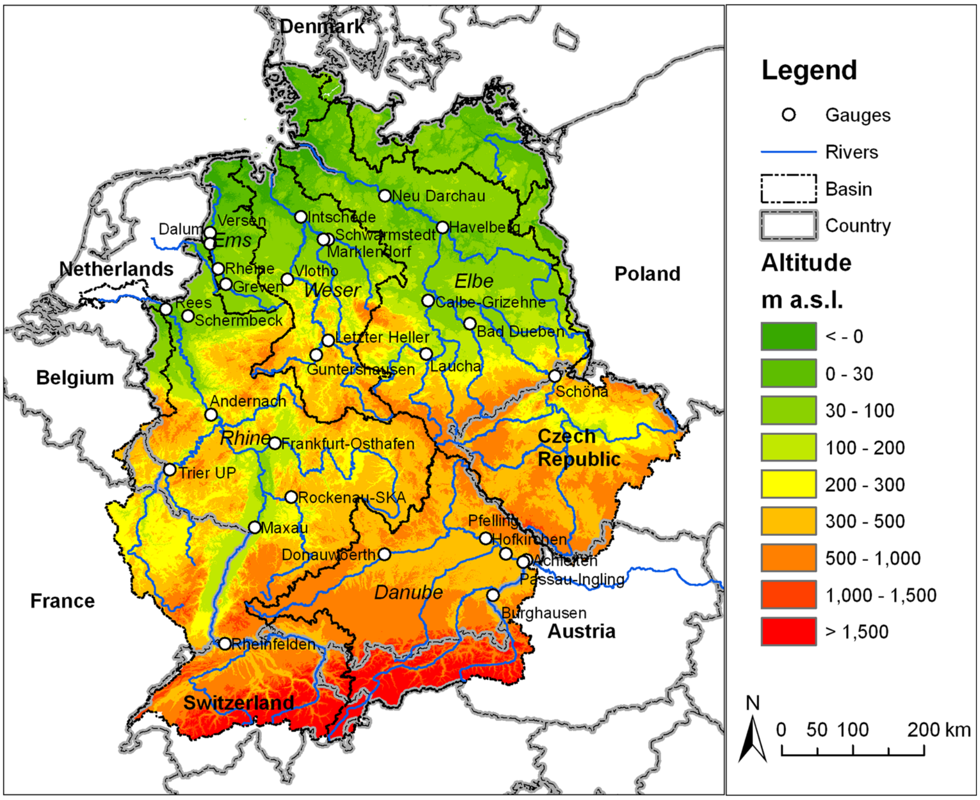


Fig. 1 Five large river basins of this study and the location of 30 selected discharge gauges

Middle Rhine, there are also combinations of nival and pluvial regimes characterized by two flood seasons in winter and summer.

Data

There are four spatial maps required to setup the SWIM model: a digital elevation model (DEM), a soil map, a land use map and a sub-basin map. All these maps are stored in a grid format with a 250 m resolution.

The DEM map was re-sampled from the data provided by the NASA Shuttle Radar Topographic Mission.

The soil map was merged from the general German soil map "BÜK 1000" [Federal Institute for Geosciences and Natural Resources (BGR)], the soil map of the Czech Republic (Kosková et al. 2007) and the soil map from the European soil database (Joint Research Centre, Ispra).

The standard sub-basin maps from the Federal Environment Agency (Umweltbundesamt, Germany) and the T.G.M. Water Research Institute (the Czech Republic) were used. The sub-basins in the Danube and Rhine basins outside of Germany were discretized on the basis of the DEM and stream network. There are 5,473 sub-basins in total for the SWIM application in this study.

The land use map was obtained from the CORINE 2000 land cover dataset of the European Environment Agency and the Swiss land cover data 1992 from the Swiss Federal Statistical Office GEOSTAT database. Land use patterns were assumed to be static in the reference and scenario periods, and water management was not included so that only the "pure" climate change impacts were analyzed in the study.

Observed climate data (daily temperature, precipitation, global radiation and relative humidity) were used to calibrate and validate the SWIM model for streamflow and extremes in the historical period 1961–2000. The observed climate data were obtained by interpolating data of 2,546 climate and precipitation stations located in Germany, the Czech Republic, Austria and Switzerland to the 5,473 sub-basins. The daily temperature and precipitation data in France were interpolated from the "Daily high-resolution gridded climate data set for Europe" (www.ensembles-eu.org).

A long-term observed discharge data are also needed for model calibration and validation. The observed discharge data at the 30 selected gauges (Fig. 1) were obtained from the Global Runoff Data Centre, Koblenz, Germany and from the database of the Potsdam Institute for Climate Impact Research.

There are in total 16 RCM climate simulations used in this study, including 13 ones from the ENSEMBLES project (ENSEMBLES 2009) and three ones from the CCLM (Rockel et al. 2008) and REMO (Jacob 2001) models

Table 1 Regional climate model data used in this study

Acronym	Institute	GCM	RCM	Data period	Emission scenarios	Nr. of realization	Resolution (km)
C4IRCA3	C4I	HadCM3Q16	RCA3	1951–2099	A1B	1	25
DMI-Arpege	DMI	Arpege	HIRHAM	1951–2099	A1B	1	25
DMI-ECHAM5	DMI	ECHAM5-r3	HIRHAM	1951–2099	A1B	1	25
ETHZ	ETHZ	HadCM3Q0	CLM	1951–2099	A1B	1	25
ICTP	ICTP	ECHAM5-r3	RegCM	1951–2100	A1B	1	25
KNMI	KNMI	ECHAM5-r3	RACMO	1951–2100	A1B	1	25
METO	HC	HadCM3Q0	HadRM3Q0	1951–2099	A1B	1	25
METO-Q3	HC	HadCM3Q3	HadRM3Q3	1951–2100	A1B	1	25
METO-Q16	HC	HadCM3Q16	HadCM3Q16	1951–2099	A1B	1	25
MPI	MPI	ECHAM5-r3	REMO	1951–2100	A1B	1	25
SMHIRCA-BCM	SMHI	BCM	RCA3	1961–2099	A1B	1	25
SMHIRCA-ECH	SMHI	ECHAM5-r3	RCA3	1951–2100	A1B	1	25
SMHIRCA-HAD	SMHI	HadCM3Q3	RCA3	1951–2099	A1B	1	25
REMO	MPI	ECHAM5-r2	REMO	1951–2100	A1B	1	10
CCLM	CLM-community	ECHAM5-r2	CCLM	1960–2100	A1B	2	22

developed in Germany (Table 1). The ensemble simulations are generated by eight different RCMs using seven GCMs as driving forces. The 13 simulations were selected out of a set of 23 simulations available, as they provide all climate parameters required by SWIM and long-term scenario runs until the end of this century. All 13 simulations have spatial resolution of 25 km and represent the A1B emission scenario only. Three simulations from the CCLM and REMO models, which were used in our previous studies (Huang et al. 2012a, b), were also included in this study because they also represent the A1B emission scenario, but in a finer spatial resolution. The two CCLM simulations were generated based on two realizations of the control experiment from ECHAM5. All the climate outputs before and after 2000 are considered as references and scenarios, assuming 1961–2000 as the reference and 2021–2060, 2061–2100 as two scenario periods.

Methods

SWIM (soil and water integrated model) is a process-based, semi-distributed eco-hydrological model based on two previously developed models: SWAT (soil and water assessment tool: Arnold et al. 1998) and MATSALU (Krysanova et al. 1989). It is model of intermediate complexity developed specifically to investigate climate and land use change impacts at the regional scale. SWIM simulates all processes (see short description in Appendix 1 of ESM) at a daily time step by disaggregating a basin to sub-basins and hydrotopes, whereas the hydrotopes are defined as sets of elementary units in a sub-basin with homogeneous soil and land use types. A full description of the basic version of SWIM can be found in Krysanova et al. (1998, 2000).

In this study, SWIM simulated daily discharges at 30 selected gauges using observed climate data and 16 RCM outputs. The climate data (both the observed point data and the RCM gridded data) were interpolated to the centroids of the sub-basins using the inverse-distance method with terrain-correction. The uncertainty introduced by this interpolation procedure is minor.

No bias correction was applied to the interpolated RCMs outputs because there are still large doubts about the bias correction procedures. Ehret et al. (2012) recently argued that the correction of GCM/RCM model outputs for climate change impact studies is not a valid procedure. Kay et al. (2006) and Lenderink et al. (2007) also claimed that the direct use of the RCM data might be preferred for impact studies on hydrological extremes. Moreover, Giori and Coppola (2010) found that the precipitation biases are not the dominant factor in determining the simulated regional change in most of their study areas worldwide. In this study, since we only focused on the extreme events, we decided to compare the results driven by the interpolated RCM outputs directly for both reference and scenario periods assuming that the RCM biases in the future are approximately the same as the ones in the reference period.

The 50-year floods and droughts were estimated by fitting the peak discharges above threshold and the deficit volume using the Generalized Pareto Distribution (GPD) (Coles 2001). A more detailed description of the used statistical methods follows in Appendix 2 (ESM).

Results

Calibration and validation of the hydrological model

SWIM was intensively calibrated and validated in terms of river discharge and water balance components (Huang et al. 2010) for our five case study rivers in Germany. Table A3 in Appendix 3 (ESM) shows the performance of SWIM in simulating river discharge driven by climate observations using usual criteria of fit: the Nash and Sutcliffe efficiency (NSE) (Nash and Sutcliffe 1970) and the relative deviation in water balance (DB) describing the long-term difference of the observed values against the simulated ones in percent. In both the calibration (1981–1990) and validation (1961–1980) periods, more than 90 % of the gauges show a NSE above 0.7 and deviations within ±5 %, although about one-third of gauges were not calibrated. These results show that SWIM can reproduce daily discharges well using observed climate data for most rivers across Germany with different runoff regimes.

The modeling performance of SWIM for floods and low flows using observed climate data has been intensively tested for the same rivers considering 95 and 99 percentiles of discharge, 10- and 50-year flood discharge, flood frequency curves and low flow frequency curves, and the validation results are presented in Huang et al. 2012a, b and in Figure A3 in Appendix 3 (ESM). The deviations of the observed and simulated 10- and 50-year floods are within ±10 % for more than 80 % of studied gauges (see Table 5 and Figure 4 in Huang et al. 2012a). The performance of SWIM for low flow was validated by the indicator AM7 (annual minimum 7-day mean flow, unit: m^3/s). The trends of the simulated AM7 were well comparable with the observed ones during the period 1952–2003, especially in southern Germany, where the trend toward less severe low flows was observed (see Figures 4 and 5 in Huang et al. 2012b). It was shown that SWIM can also reproduce the low flow frequency curves reasonably well for large river basins in Germany (Figure 6 in Huang et al. 2012b).

Evaluation of RCM data

The annual and summer (May–October) mean temperature and precipitation for the entire study area simulated by 16 RCMs were calculated for three time slices: the reference period and two scenario periods. Summer period was considered in addition to annual scale because summer conditions are most important for droughts. The differences between the RCM outputs and the observed climate parameters in 1961–2000 are plotted in Fig. 2 to illustrate biases between RCM data and observations for the reference period, as well as changes in three time periods by comparing the box plots.

In the reference period, the annual and summer mean temperatures are slightly overestimated (<1 °C) by the median output of the RCM ensemble. About 75 and 50 % of the RCMs show biases <1 °C for the annual and summer temperatures, respectively. However, some of the RCMs show considerable biases, so that the ranges of the differences are from −1.5 to 2.4 °C and from −1.5 to 3.2 °C. Compared to temperature, the overestimation of precipitation is more notable. The annual and summer mean precipitation is overestimated by 87 and 62 % of the RCMs. The median bias is about 9 and 11 % with a total range of (−10, +34 %) and (−33, +25 %) for the annual and summer precipitation, respectively. In general, the RCMs have a slightly better agreement for the annual mean precipitation than for the summer one.

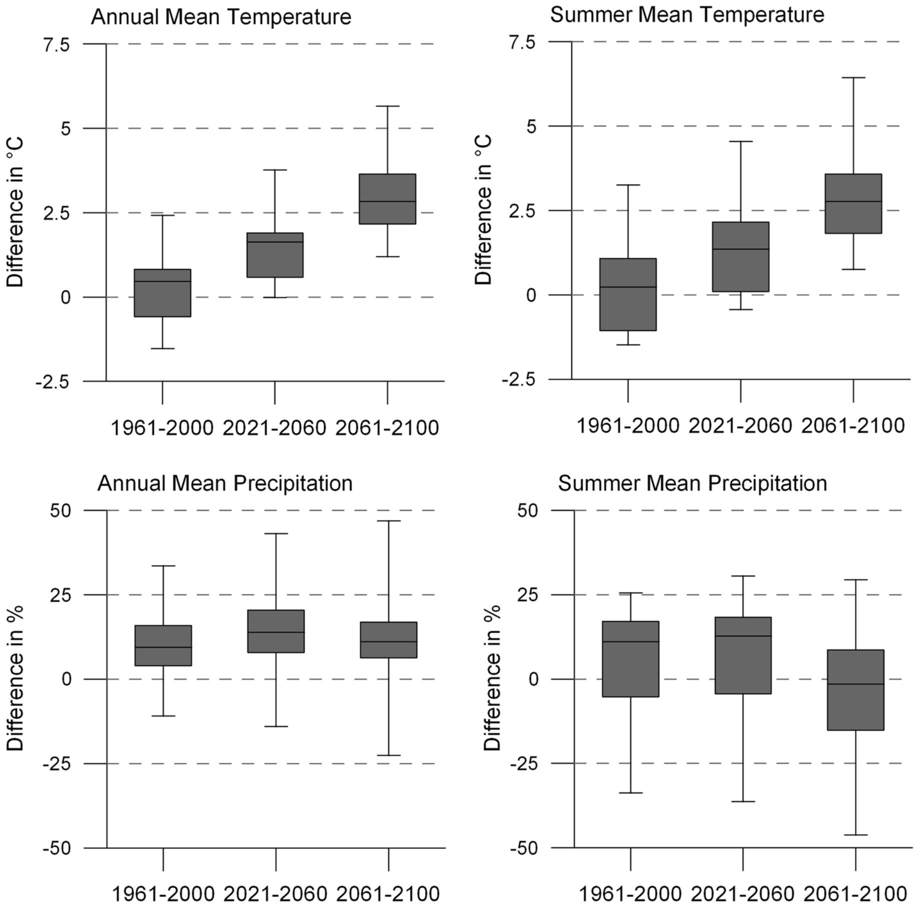
Despite the different performance of the RCMs in the reference period, all the RCMs project a steady increase in both annual and summer temperatures. Comparing the box plots in Fig. 2, the increases in both annual and summer temperatures are ranging from 0.5 to 2.4 °C with a median increase of 1.3 °C in the near future (2021–2060). In the second scenario period (2061–2100), the increases in both temperatures are more significant, with a median increase of 2.8 °C and the range of 1.4–5.3 °C. The median annual and summer precipitation shows a slight increase of 4 % and practically no change (+0.4 %) in the first scenario period, and practically no change (+0.3 %) and a decrease of 11 % in the second period, respectively. The total range of the changes in precipitation is getting wider over the scenario time.

RCM forced hydrological simulation for the reference period

Due to the considerable bias usually existing in the RCM outputs, the simulated annual mean discharges, 50-year deficit volumes and floods driven by RCM simulations in 1961–2000 at the downstream gauges of the five river basins were compared with observations for the same period (Fig. 3). This served for evaluating the influence of the RCM biases and finding the "best" five models with the smallest biases for the flood and drought simulations.

Driven by the RCM data for the reference period, the simulated annual mean discharge is higher than the observed one in 62–81 % of the simulations for all rivers, mainly due to the precipitation bias. The overestimation of the mean discharge is in some cases even as high as 100 % of the observed discharge in three of five basins. The whole range of the differences between the simulated and observed mean discharges is ranging from −30 to +120 %,

Fig. 2 Differences between observed and simulated mean temperature and precipitation under the ensemble of RCM simulations in both reference and scenario periods for the entire study area



indicating a substantial discrepancy among the ensemble of climate data for the reference period.

Figure 3b shows a significant deviation of simulated 50-year deficit volumes (droughts indicator) driven by RCM simulations for the reference period compared to observations. The median deviation is ranging from −22 to 73 % for the five gauges, whereas the gauge Intschede (Weser) has the lowest deviation of −14 %. The deviation of 50-year drought has much larger spread than that for the mean discharge, ranging from −62 to +340 %. It indicates a larger uncertainty using RCMs to project extreme drought events compared to seasonal average conditions.

Compared to the extreme drought events, the simulated 50-year floods show a better agreement with the observations (Fig. 3c), especially for the rivers Rhine and Elbe. The median deviation is from −22 to 1 %, and the total range of deviations is within ±40 % for all the rivers.

Based on outputs presented in Fig. 3, the best five RCM simulations for the past, under which the smallest deviations in 50-year droughts and floods were generated, are listed in Table 2. It is evident that the best RCM simulations for the past vary for different rivers and extreme events. All the RCM outputs can be considered as the best RCMs for simulating the flood or drought events in certain rivers. But there is not a single RCM output providing the best results for all the rivers or for a certain extreme event. This result highlights the importance of using an ensemble of RCM data because a single RCM output is insufficient to provide a reliable climate data for such a large study area and for both hydrological extremes.

Projections in the scenario period

The changes in the 50-year flood discharge and deficit volume under all RCM scenarios are summarized in Fig. 4 for the five main gauges. In addition, the changes using the "best" five models, which are shown in Table 2, are compared with the changes simulated using all RCM data.

According to the median simulated results, the drought events are likely to become more severe in the Rhine, Danube and the Elbe in 2021–2060, with increasing severity for the Rhine in the second scenario period 2061–2100. Looking at the median floods of all simulations, it is apparent that all the rivers tend to have more extreme floods in both periods.

However, the full projected range of the changes is considerably larger for droughts (from −100 to 800 %) than for floods (from −20 to 90 %). High agreement (more than 75 % of the ensemble-driven results showing the same change direction) can only be found for the 50-year drought in the Rhine and the 50-year flood for the Elbe in the second scenario period. Hence, we can conclude that the uncertainty of the extreme event projections using the ensemble of RCMs is too large to identify the robust change signals for most German rivers.

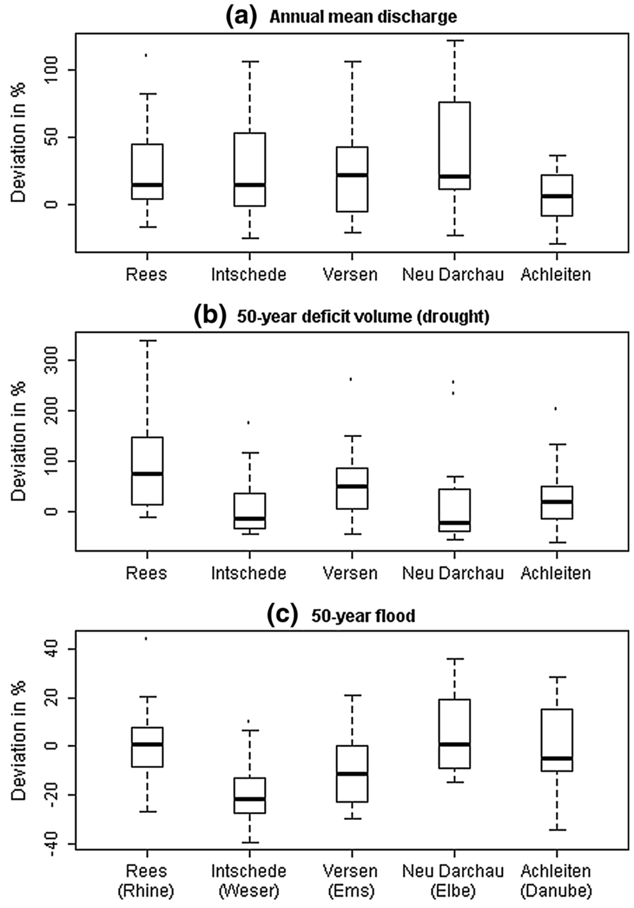


Fig. 3 Differences between the observed and simulated annual mean discharge, 50-year drought and flood driven by RCM data for the reference period

The "best" five scenarios, which are assumed to generate more reliable projections due to their better performance in the reference period, cannot effectively help reducing the large uncertainty from the ensemble-driven results. In about half of the cases, the changes under the five "best" scenarios still cover more than 75 % of the total range of changes using all ensemble data.

Finally, the changes in the 50-year flood discharge and the return period of the current 50-year droughts in the future were calculated for each RCM scenario at 30 selected gauges. Due to the large uncertainty from different RCM outputs used to drive SWIM, we present the final results in Figs. 5 and 6 in terms of the median result of all simulations and emphasize the gauges at which more than or equal to 80 and 60 % of all results agree in change direction. All results for 30 gauges indicating the uncertainty bounds can be found in Figure A4 in Appendix 4 (ESM).

Figure 5 shows the median of changes in 50-year floods with moderate certainty (agreed by ≥60 % projections) and high certainty (agreed by ≥80 % projections) for two scenario periods. With 60 % certainty, about two-thirds of the selected gauges in all the five basins show an increase in 50-year flood discharge for both scenario periods. A decreasing trend is found in the upper Weser basin and in the Moselle and Neckar tributaries of the Rhine. If only the results with the high certainty are considered, then, in accordance with the modeling results, only the Elbe and the Inn River (flowing from the southern alpine region) will have increasing trends of extreme flood discharge in 2061–2100.

Table 2 The five best fitting RCMs using which the simulated 50-year floods and droughts have the best agreement with the observations for five rivers

	Rees (Rhine)	Intschede (Weser)	Versen (Ems)	Neu Darchau (Elbe)	Achleiten (Danube)
Flood	SMHIRCA-ECH	DMI-ECHAM5	SMHIRCA-BCM	SMHIRCA-BCM	REMO
	SMHIRCA-HAD	CCLM1	ETHZ	SMHIRCA-HAD	METO-Q16
	METO	ICTP	REMO	METO-Q16	SMHIRCA-ECH
	MPI	CCLM2	MPI	SMHIRCA-ECH	METO-Q3
	ICTP	METO	METO	METO	DMI-ECHAM5
Drought	DMI-Arpege	SMHIRCA-ECH	C4IRCA3	CCLM1	KNMI
	METO-Q3	KNMI	METO	SMHIRCA-ECH	SMHIRCA-ECH
	C4IRCA3	CCLM1	METO-Q3	METO-Q3	REMO
	CCLM2[a]	METO-Q16	METO-Q16	KNMI	ETHZ
	MPI	C4IRCA3	ETHZ	C4IRCA3	SMHIRCA-HAD

[a] CCLM realization 2

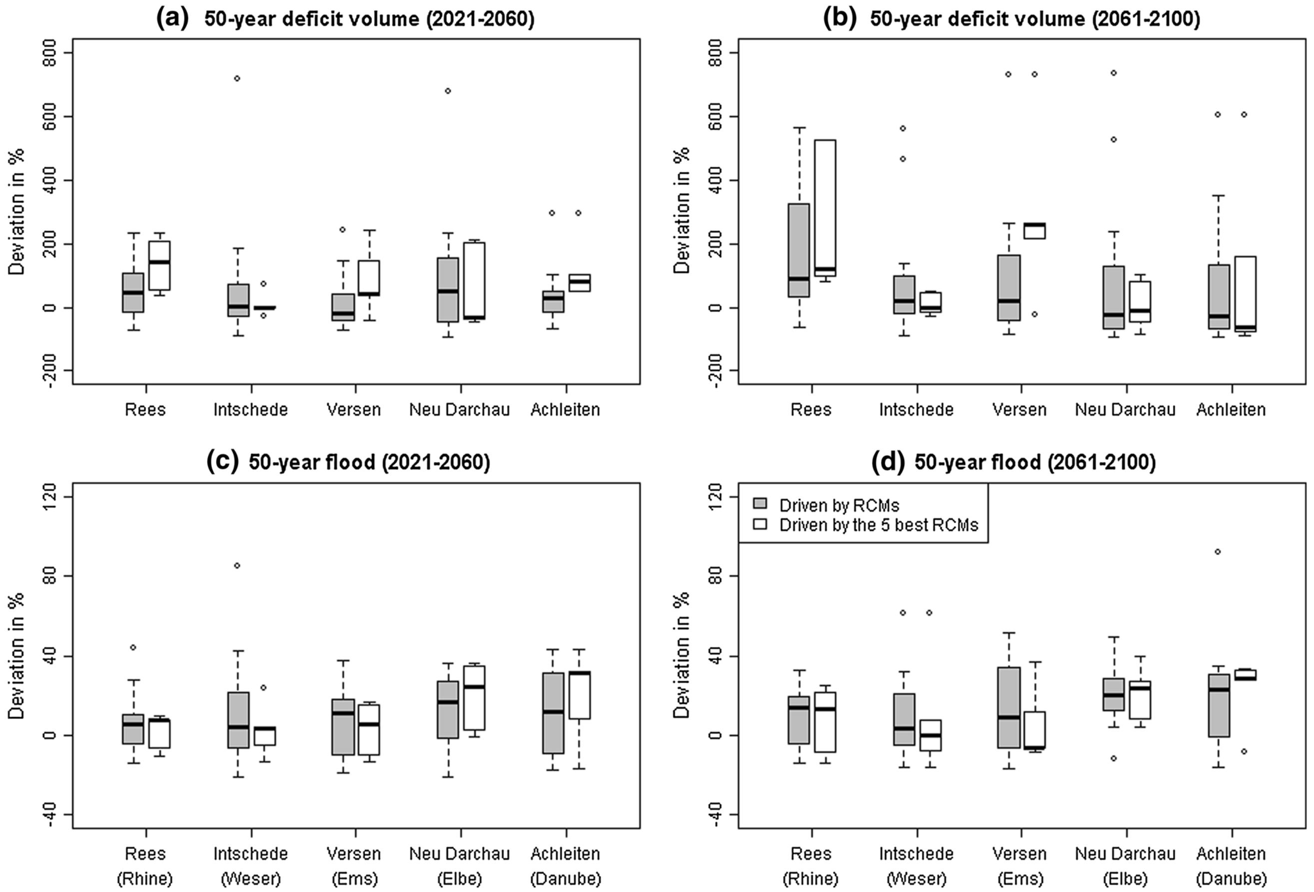


Fig. 4 The changes in the 50-year deficit volumes and floods at the five gauges of each basin under the ensemble RCM and the best five scenarios, respectively (percent change from the reference scenario), over the two scenario periods

To better reveal the changed patterns of increasing floods in the Elbe basin, we additionally analyzed the seasonal characteristics of floods at the gauge Neu Darchau (Elbe) in the reference period and the second scenario period. In general, there is no substantial change in the monthly flood distribution. The most distinct change is a shift to earlier floods: More floods tend to occur in January instead of April in the future. This is mainly due to the higher temperature in winter, causing less precipitation to be stored as snow in December–January. The monthly mean discharges in the scenario period are generally higher in almost all months. This can be attributed to an increase in extreme precipitation in the basin.

Similar to Fig. 5 for floods, Fig. 6 shows the median return period for current 50-year droughts in the future accounting for moderate (60 %) and high (80 %) certainties. With a moderate certainty, the today's 50-year droughts may occur more frequently in the Rhine and some sub-regions in other basins, with increasing severity by the end of this century. A trend to less frequent droughts was found for the Inn river and some northern regions in Germany in both periods.

The projections with a high certainty are as follows: The current 50-year droughts may occur (a) more often with a frequency of <25 years along the Rhine River and its tributary Moselle over the last 40 years of this century and (b) less frequently in the Inn River flowing from the Austrian alpine region in the period 2021–2060.

An additional analysis was done for these robust projections at two gauges: Rees in the Rhine basin and Burghausen in the Inn, Danube (Fig. 7). The drought events simulated for the Rees were further analyzed in terms of the drought duration and intensity. The median drought duration is about 36 and 54 days in the reference and the second scenario periods, respectively. Correspondingly, the median deficit volume in 2061–2100 is 1.8 times larger than that in the reference time. In short, both the drought duration and intensity are likely to increase at the end of twenty-first century. From July to November, more than 75 % of the ensemble-driven outputs suggest a decrease in low flow for the gauge Rees. The median low flow for this dry period in 2061–2100 is about 75 % of discharge in the reference period. In addition, all the scenario results show much drier periods in August and

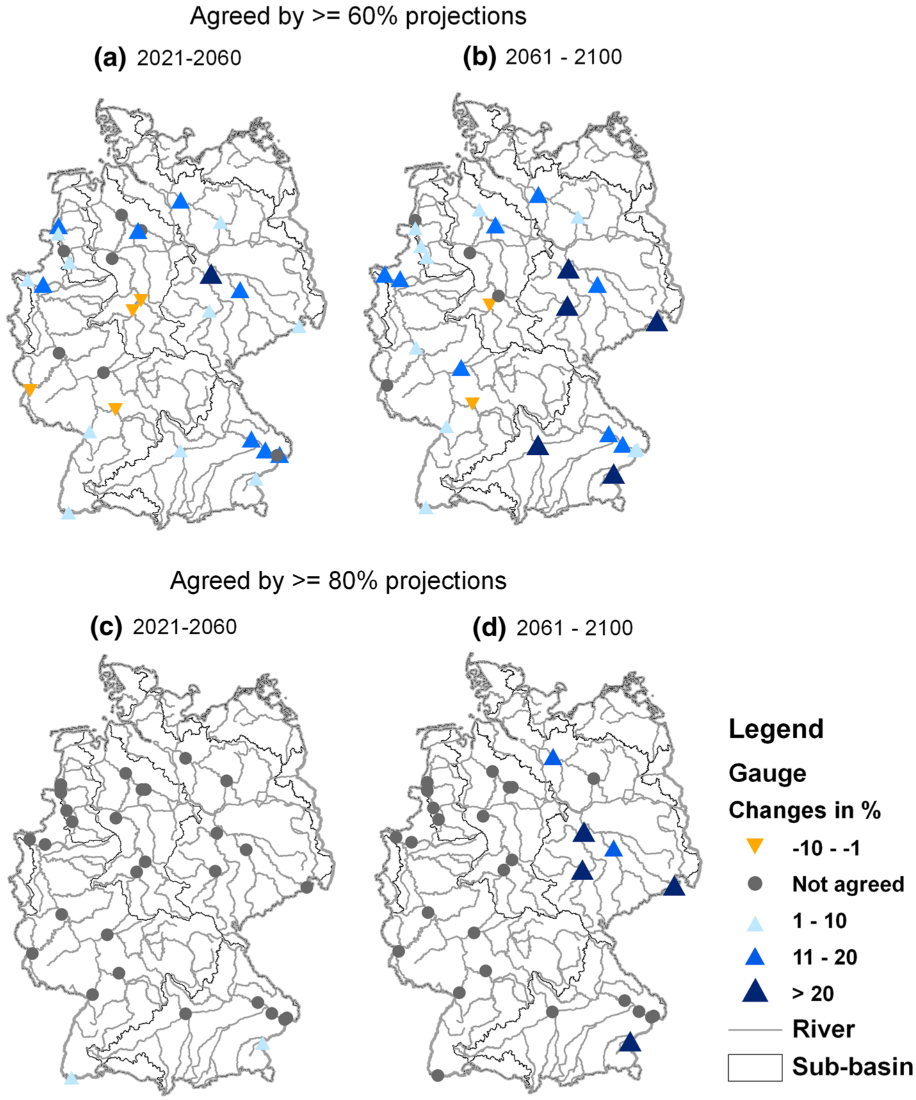


Fig. 5 Changes in 50-year floods (median values under all scenarios, unit: %) with the change directions agreed by ≥60 % projections (**a**, **b**), and ≥80 % projections (**c**, **d**) for two scenario periods

September under a warmer climate. The major trigger of the significantly drier conditions in the Rhine is the significant decrease in summer precipitation (about 13 % for the Rhine compared to <8 % for the other basins).

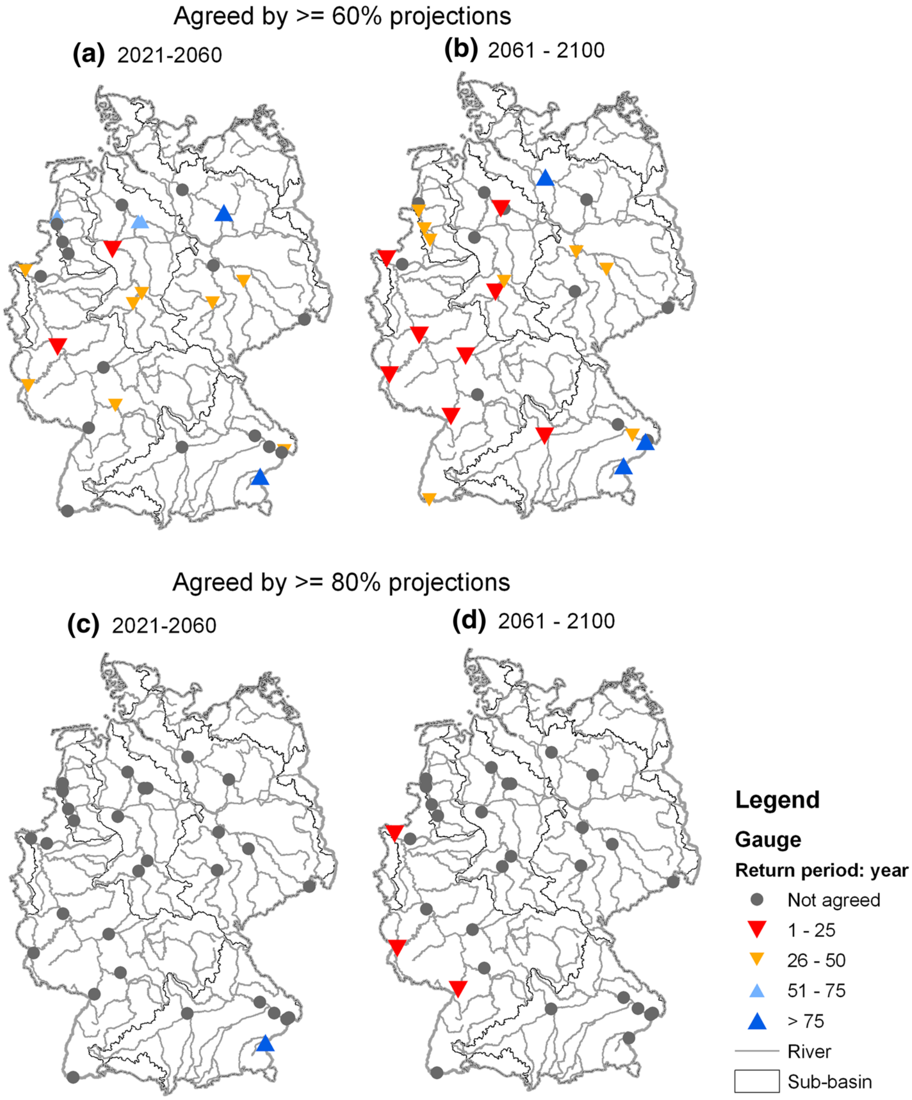
The same as Rhine, the Inn River flowing from the Alps is likely to face lower discharges in the summer period. Nevertheless, less frequent drought events are projected for the Inn, particularly in the near future. This is due to the difference in the runoff regimes of these two rivers. Getting substantial water supply from snow and glacier melt in summer time, the Inn River usually has high flows in summer and low flows in winter. A warmer climate results in more rainfall instead of snow in winter, more snow and glacier melt and higher evapotranspiration over the year. Meanwhile, a strong decrease in summer precipitation is expected in this region. Consequently, the difference in river discharge between summer and winter is not as distinct as it is now. As a result of all factors, less frequent drought events are projected for the Inn, particularly for the first scenario period.

Discussion

Climate model performance for the past and future

As shown above (Fig. 3), a bias exists in all hydrological modeling results driven by the RCM simulations for the past compared to the observations. No one single RCM can provide climate outputs for the reference period with an acceptable bias (e.g., <10 % for floods and <40 % for droughts) for all river basins studied. We also showed that even when applying the best performing RCM outputs, which are assumed to provide more robust results for the future, the differences in the extreme event projections are substantial in many cases (Fig. 4).

Fig. 6 Return period for today's 50-year droughts (median values under all scenarios, unit: year) with the change directions agreed by ≥60 % projections (**a**, **b**), and ≥80 % projections (**c**, **d**) for two scenario periods



This shows that there is no direct link between the model performance in the past and the robustness of trends in the future. It further indicates that the large uncertainty in the projection of extreme events is attributable not only to the bias of the RCM outputs, but also to the RCM concepts and their parameterizations, as well as GCM boundary conditions driving RCMs. It emphasizes again the necessity of using the ensemble of RCMs in impact studies, rather than a small number of scenarios even if they better represent climate conditions in the past.

This is in line with the findings by Kling et al. (2012), who compared the projections of mean runoff conditions driven by the ensemble of RCM outputs after bias correction, and could not find a systematic relationship between historical performance and projected future changes. As a result, they also suggest using ensemble of scenarios rather than the selected "best" ones.

Comparison of robust projections with other studies

Figures 5 and 6 show that most changing signals have only a moderate certainty due to the large differences in projections driven by the ensemble scenarios. However, some robust changes can still be identified by ≥80 % of the projections. They include an increasing trend of floods in the Elbe basin, more frequent droughts in the Rhine basin in the period 2061–2100, and more extreme floods and less frequent drought events in the Inn basin.

In our previous studies (Huang et al. 2012a, b), only the outputs from two dynamical RCMs, CCLM and REMO, and one statistical model Wettreg were applied to drive SWIM for the flood and drought analysis. For floods, due to the large uncertainty originating from the model structures (caused especially by differences between physical and statistical models), no robust changes in 50-year floods could be found for rivers in Germany. If only the scenarios

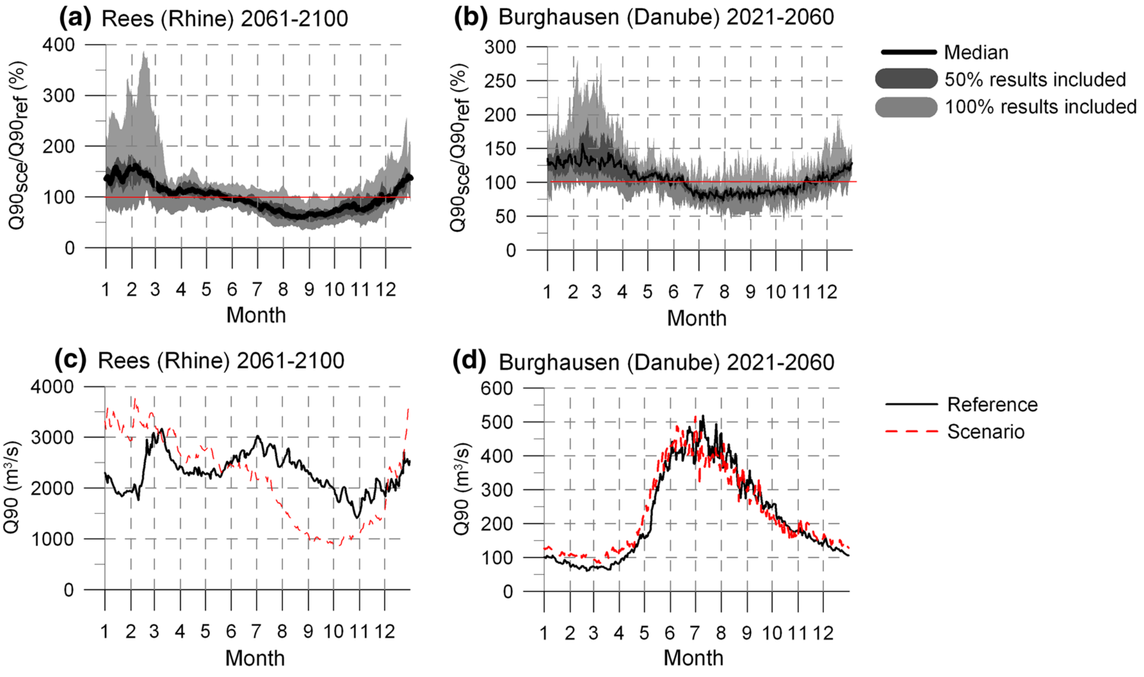


Fig. 7 Changes in the average Q90 between the scenario and reference periods for the gauges Rees, Rhine (**a**) and Burghausen, Inn (**b**) and their simulated Q90 under the CCLM realization 1 (**c**, **d**)

from CCLM and REMO were considered, an increase in flood discharge for the rivers Weser, Elbe and Rhine, and a decrease for the Neckar were suggested by more than 75 % of the results. In our current study, all the ensemble scenarios were generated by the dynamical RCMs. The projected changes in floods comply with the previous results only partly, with larger uncertainty for the Weser and the Rhine basins.

There are also several other studies which investigated potential impacts of climate change on floods for some river basins in Germany but driven by a limited number of scenarios. So, more extreme floods were projected for the Rhine with higher 100-year flood levels or more frequent occurrence of 100-year floods (Lenderink et al. 2007; Hurkmans et al. 2010). An increase in flood hazard was also suggested in large parts of the Upper Danube basin at the end of twenty-first century (Dankers et al. 2007). These results comply with our results agreed with 60–70 % of the whole ensemble simulations. It is still difficult to determine whether these previous studies showed robust changes as they only used a single or a limited number of climate scenarios.

On the European scale, Dankers and Feyen (2009) simulated flood hazards driven by an ensemble of two RCMs, two GCMs and two emission scenarios. According to their results, robust trends (agreed by ≥6 out of 8 simulations) could only be found for northern Europe with a decreasing trend while some large rivers in France, the Po and the Danube showed a tendency toward a higher flood risk. They also found that using a different combination of climate models or a different emissions scenario sometimes results in a very different or even opposite climate change signal and trend in flood hazards. A similar outcome could be found in our study, where the robust changes with high certainty are not prevailing.

Regarding droughts, our previous results with three driving climate models indicated drier condition in southern, western and central Germany at the end of twenty-first century agreed by more than 80 % of model outputs (Huang et al. 2012b). In general, there are no contradictions compared to the current ensemble scenarios driven results, but the more severe drought conditions in the Danube and upper Weser can only be confirmed by 60–70 % of all ensemble-driven results, meaning less robust outcomes in these areas than before.

A strong signal of more severe low flow conditions in the future was found in other studies for Germany applying a limited number of scenarios. For example, Hennegriff et al. (2008) found that the monthly average low flow from July to September may decrease by 10–20 % in the Neckar and Danube in the period 2021–2050 compared to 1971–2000. The projections for the Danube basin (Mauser et al. 2008) showed that the AM7 could be reduced to half of the reference value by 2030s and to one-third by 2060s. According to the results by Lehner et al. (2006) for Europe driven by two GCMs, the current 100-year droughts may occur more frequently at the end of this century in parts of the Rhine, Danube and Elbe basins. Hence, we can only conclude that the previous results comply with our current results to some extent.

The discussion above shows that using an ensemble of climate scenarios for impact study certainly leads to an increase in the overall uncertainty of results compared to studies driven by one or two RCMs. However, the robust signals agreed by the majority of the ensemble-driven simulations may be better corresponding to the current level of knowledge and more reliable for detecting the hotspots under a changing climate.

Besides, it is worth mentioning that for some regions facing strong natural variability, it is articulated (Hawkins and Sutton 2012) that a climate change signal would not emerge until the end of the twenty-first century. The question on how much natural climate variability may obscure anthropogenic climate change on timescales of a few decades is still open and should be investigated in the future.

Finally, it should be noted that in this study, all the RCM outputs represent the A1B emission scenario only. A more comprehensive uncertainty assessment could be performed including more emission scenarios and involving different hydrological impact models. In this study, we could only project the climate impacts on extremes in Germany using the best available source of climate scenarios. The real “full” uncertainty of the projected climate impacts still remains unknown, and hopefully, the improvement in resolution and parameterization of climate and impact models could also reduce the uncertainty bounds in the future.

Conclusions

This study projected the flood and drought conditions in the five large river basins in Germany using an ensemble of 16 RCM scenarios. The results show that many German rivers may experience higher 50-year floods and more frequent occurrences of current 50-year droughts with a moderate agreement by 60–70 % of projections. Robust changing signals agreed by ≥80 % of projections include an increasing trend of floods in the Elbe basin and more frequent extreme droughts in the Rhine basin in 2061–2100. Besides, wetter conditions with higher risk of floods and less frequent droughts are projected for the rivers flowing from the Alps (particularly the Inn River) in the near future.

The use of the best performing RCM outputs for the reference period does not guarantee a reduced uncertainty of the future projections. The use of all ensemble scenarios is necessary to provide the associated uncertainty of the climate input data corresponding to present knowledge. The uncertainty sources in this study include the differences between GCMs, RCMs and between the realizations generated from one GCM. More uncertainty sources could be included in the following studies, such as emission scenarios and different hydrological impact models. The inter-comparison across the projections using various GCMs, RCMs, emission scenarios and hydrological models can help detecting the robust signals of change and investigating the contribution of various uncertainty sources in the overall uncertainty of climate impacts.

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