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Comparing impacts of climate change on streamflow in four large African river basins

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Abstract

This study aims to compare impacts of climate change on streamflow in four large representative African river basins: the Niger, the Upper Blue Nile, the Ubangi and the Limpopo. We set up the eco-hydrological model SWIM (Soil and Water Integrated Model) for all four basins individually. The validation of the models for four basins shows results from adequate to very good, depending on the quality and availability of input (observed climate, soils, land use, water management) and calibration (discharge) data.

For the climate impact assessment we drive the model with outputs of five bias-corrected Earth System Models of Coupled Model Intercomparison Project Phase 5 (CMIP5) for the Representative Concentration Pathways (RCPs) 2.6 and 8.5. This climate input is put into the context of climate trends of the whole African continent and compared to a CMIP5 ensemble of 19 models in order to test their representativeness. Subsequently, we compare the trends in mean discharges, seasonality and hydrological extremes in the 21st century. The uncertainty of results for all basins is high, mainly due to the climate input. Still, climate change impact is clearly visible for mean discharges but also for extremes in high and low flows. The uncertainty of the projections is the lowest in the Upper Blue Nile, where an increase in streamflow is most likely. In the Niger and the Limpopo Basins, the magnitude of trends in both directions is high and has a wide range of uncertainty. In the Ubangi, impacts are the least significant. Our results confirm partly the findings of previous continental impact analyses for Africa. However, contradictory to these studies we find a tendency for increased streamflows in three of the four basins (not for the Ubangi). Guided by these results, we argue for attention to the possible risks of increasing high flows in the face of the dominant water scarcity in Africa. In conclusion, the study shows that impact intercomparisons have added value to the adaptation discussion and may be used for setting up adaptation plans in the context of a holistic approach.

1 Introduction

Climate change impacts are commonly assessed on two different scales: the global or continental scale allows for a general view of the larger context and patterns, whereas regional studies focus on details, for example flood or drought hazards. By comparing climate change impacts between different regions, advantages of both approaches can be combined. This way of bridging these two scales is likely to give new insights into the characteristics of climate change in the actual regions, but also beyond.

Especially in the African context, this approach could be beneficial where climate change impacts are very likely to be most severe (Boko et al., 2007), and adaptation measures will increasingly stand in competition for finance and precedence (NWP, 2011). Here, regional intercomparison of climate impacts could be beneficial not only scientifically but also for developing regional adaptation strategies.

On the continental level, there have been several climate impact studies focusing on water resources in Africa. In a recent study, Faramarzi et al. (2013) modeled the whole African continent with the SWAT (Soil and Water Assessment Tool) model on a coarse spatial resolution (1496 subbasins), using five CMIP4 (Coupled Model Intercomparison Project Phase 4) Global Circulation Models (GCM: HadCM3, PCM, CGCM2, CSIRO2, ECHAM4). They compared their results to the available literature sources on future projections of streamflow in Africa, namely De Wit and Stankiewicz (2006) and Strzepek and McCluskey (2007), and several projections for smaller regions. They generally found similar trends in the studies, with decreases in the Sahel region and Southern Africa between 10 and 20 % and an increase in Central and Eastern Africa between 10 and 20 %, but with significant spatial variability. De Wit and Stankiewicz (2006) defined three different regimes according to a precipitation threshold for the African continent and calculated for these three regimes the perennial drainage density as a function of mean annual rainfall. By using six GCMs (not specified) to assess the projected changes in mean annual rainfall across Africa, they found that 25 % of the continent will be significantly affected by a decrease in streamflow by the end of this century.

Strzepek and McCluskey (2007) simulated changes in streamflow and soil moisture with a conceptual rainfall-runoff model called WatBal. It was applied on grids for five CMIP4 models (CSIRO2, HadCM3, CGCM2, ECHAM, PCM) and the scenarios A2 and B2 across the African continent, and results were provided by country. A study of Mahe et al. (2013) analyzed observed streamflow of the past decades in West and Central Africa and found a modification of seasonal regimes in the Equatorial area and a decrease in the groundwater table in the tropical humid area of West Africa.

However, no impact studies currently exist that investigate projected change in hydrological extremes on a regional resolution consistently across the African continent, that could for the first time enable an intercomparison of the future severity of change and consequently allow an assessment of the urgency of required adaptations. In this modeling study, we attempt to overcome this apparent lack by quantifying the impact of climate change on the mean river discharge as well as extremes for four major African basins that cover the main Sub-Saharan climate zones: the Niger, the Upper Blue Nile, the Ubangi (Upper Congo Basin) and the Limpopo. For these basins, we focus on water as the key resource for development and food security as well as economic development and livelihood. Moreover, we applied the most up-to-date knowledge (the model outputs from CMIP5 for the Representative Concentration Pathways, RCPs, Van Vuuren et al., 2011a) to investigate climate impacts in Africa. Therefore, the objectives of the study are (1) to investigate differences in the sensitivity of modeled annual discharge to climate parameters between the basins, (2) to study climate impacts on river discharge for four basins in terms of quantity and seasonality, (3) to explore changes in hydrological extremes (high flow, low flow) for the four basins, (4) to analyze the uncertainties of the projections, and finally (5) to identify and discuss the implications for adaptation.

To achieve these objectives, we analyze the output of 19 CMIP5 model with regard to temperature and precipitation trends. Then, data for five of these climate models which have been bias-corrected by the method of Hempel et al. (2013) are used to drive the eco-hydrological model SWIM (Soil and Water Integrated Model, Krysanova et al., 1998) for each basin. In the main part of this study, we compare projections of future discharge trends for mean discharges as well as for robust indicators of extremes considering 30 yr periods in the first and second halves of the 21st century under the RCPs 2.6 and 8.5. These quantitative results are interpreted and compared across the four case studies qualitatively. In a final discussion, we evaluate the potential of such an impact comparison to contribute to developing an agenda for climate change adaptation.

2 Study sites

2.1 Hydrology of the basins

The basins of the Niger, Upper Blue Nile, Ubangi and Limpopo were chosen because they cover most of the African climate zones. In addition, they are all highly dependent on the weather conditions, as their economy is mainly based on the primary sector. The hydrological regimes of all four rivers are classified as tropical; that is, they are characterized by the alternation of dry and wet seasons (Latrubesse et al., 2005). However, a wide spectrum of climates, geographical and ecological conditions shape unique hydrological regimes in each catchment and the discharge rates in the basins studied are extremely heterogeneous, ranging from about 13 $\mathrm{mm\,yr^{-1}}$ in the Limpopo catchment to 270 $\mathrm{mm\,yr^{-1}}$ in the Upper Blue Nile (Fig. 1 and Table 1).

The Niger River is the longest and largest river of West Africa. Its source is located in the Guinean highlands, from which the Niger flows in a northern arc through the dry Sahelian zone until it again enters the wetter tropical region north of the Gulf of Guinea. Topographically the basin also includes Algeria, but from this northernmost part in the Central Sahara, no water contributes to the streamflow. Geographically, the Niger Basin spreads over six different large agro-climatic and hydrographic regions. These range from the Central Sahara with less than 100 $\mathrm{mm\,yr^{-1}}$ average annual rainfall to tropical rain forests in the Guinean zone with more than 1400 $\mathrm{mm\,yr^{-1}}$. Besides this extreme heterogeneous setting, the regime of the Niger is substantially influenced by the Inner Niger Delta by delaying the peak runoff and smoothening the hydrograph. The fluvial regime at the analyzed Lokoja gauge is mainly shaped by the wetter climate of upstream parts of the basin and the Niger tributaries, particularly the Benue. However, the influence of the dynamics of the Inner Niger Delta and the Guinean headwaters is still noticeable (Andersen, 2005; Ogilvie et al., 2010).

The Ubangi River is the second largest tributary of the Congo River. The source of the longest tributary of the Ubangi is located in the mountains near Lake Albert. From the Bangui gauging station the Ubangi still flows 600 km further until it reaches the Congo River. Its regime follows the regional rainy season, with highest discharges from August to December and a total annual rainfall between 1300 mm yr^{-1} and 1700 mm yr^{-1}. The basin is dominated by a vast peneplain and only 5 % of its area is covered with mountains, mainly at the eastern and northeastern edges. The Ubangi Basin is the least investigated of all four African basins and data is – even for African conditions – very sparse (Shanin, 2002; Wesselink et al., 1996).

The Upper Blue Nile is the Ethiopian segment of the Blue Nile. After the White Nile, the Blue Nile is the second longest tributary to the Nile River. It contributes up to 80 % of the mean annual discharge to the Stem Nile. The source of the Blue Nile is Lake Tana and its tributaries. From Lake Tana, the Blue Nile flows across northwestern Ethiopia through numerous incised valleys and canyons and crosses the border to Sudan at El Diem. The major influences on the hydrological regime of the catchment are a distinct topography and a wide range of climatic conditions. The altitude within the basin ranges from 4050 m a.s.l. in the Ethiopian highlands to 500 m a.s.l. at the outlet at El Diem. Besides the influence of this landform, the effects of the summer monsoon determine the climate in the basin. Annual rainfall ranges from 1077 mm yr^{-1} to over 2000 mm yr^{-1} in the highlands (Conway, 2000).

The Limpopo River originates in Witwatersrand, South Africa, from which it flows in a northern arc and then enters the Indian Ocean. The hydrology of the Limpopo is characterized by its location in the transition zone between the intertropical convergence zone and the tropical dry zone, with additional maritime influence in the east. Its topography is dominated by plains of higher altitude in the inland and lower coastal plains, both separated by the Great Escarpment, which runs through the center of the basin from north to south. This geographical setting results not only in a typical subtropical intra-annual, but also a very distinct inter-annual variability of flow (UN-HABITAT, 2007; Frenken and Faurès, 1997; FAO, 2004).

2.2 Water management in the basins

The intensity of human influence on the hydrological processes differs remarkably in the four basins. The Limpopo River Basin is located in an arid to semi-arid region where water is the critical limiting factor on all development. Water resources including groundwater are heavily utilized due to the densely populated area and many irrigation schemes (UN-HABITAT, 2007). In order to satisfy the intensive use of water resources, the Limpopo River is quite developed in terms of storage reservoirs and dams. In the South African part of the Limpopo Basin alone, there are 160 dams classified as large dams in accordance with the criteria of the International Committee on Large Dams. Among these 160 dams, 15 of them have storage capacities above 100 $\mathrm{M\,m^{-3}}$, and 34 are between 10 and 100 $\mathrm{M\,m^{-3}}$ (LBPTC, 2010). In addition, there has been a lot of mining activity in the Limpopo River Basin with about 1900 mines over the years (Ashton et al., 2001b), and part of them are considered to have extensive impacts on water resources (Ashton et al., 2001a).

However, water management does not play a major role and currently there are only five major reservoirs in the catchment with volumes of over 1000 $\mathrm{M\,m^{-3}}$, mainly built for irrigation and hydropower: Selingué (Mali), Kainji, Jebba, Shiroro (all three Nigeria) and Lagdo (Cameroon). According to Frenken and Fauré (1997), there is a large potential for more irrigated agriculture in the Niger Basin, with an additional 2.8 Mha of natural savannah that could be transformed into cultivated areas. In recent years, plans for new irrigation schemes as well as for additional reservoirs have been developed and some are under construction. The Niger is navigable from Koulikoro in central Mali to

Lokoja in Nigeria, mainly in the season of highest discharge from October to January (Andersen, 2005).

In the Upper Blue Nile Basin, water management still plays a moderate role. At the end of the 1990s, the irrigation potential was estimated by the FAO to be more than 2.2 Mha (Frenken and Faurès, 1997). Since then, efforts to exploit this potential have been moderate. However, over the last decade many efforts have been made for intensification of irrigated agriculture and other management measures, of which the Grand Ethiopian Renaissance Dam is the most prominent. After planned completion in 2017, the dam should store a water volume of 63 000 Mm^{-3} and will serve power generation of 5000 MW (Salman, 2013). The Upper Blue Nile is not navigable for larger boats (Awulachew et al., 2007).

In the Ubangi Basin, information and data on water management is very sparse. There are three reservoirs in the headwater part that generate hydropower. The river serves as a major traffic route for the Central African Republic, though there are reports of insufficient streamflow for navigation over an increasing period throughout the year (UN, 2009). Consumption and small-scale irrigation along the river play a minor role and the influence on the discharge and hydrological regime is small (Vanden Bossche and Bernacsek, 1990).

3 Methodology

3.1 Model

All four African basins were modeled using the eco-hydrological model SWIM (Krysanova et al., 1998). The model was chosen because it is able to reproduce discharge on the desired scales on a daily basis with high efficiency and has been used extensively in many catchments of various sizes all over the world, including in Africa (Liersch et al., 2012; Koch et al., 2013). This semi-distributed model is based on the models SWAT (Arnold et al., 1993) and MATSALU (Krysanova et al., 1989).

SWIM is process-based and simulates the dominant eco-hydrological processes at the mesoscale such as evapotranspiration, vegetation growth, runoff generation and river discharge, and also considers feedback among these processes. It allows the simulation of all interrelated processes within a single model framework using regionally available data (climate, topographical map, land use and soil).

SWIM disaggregates a river basin to subbasins and hydrotopes. These hydrotopes have the same hydrological setting and daily weather input is added to each of these hydrological response units (HRU). Climate data includes mean, minimum and maximum temperature, as well as precipitation, relative humidity and global radiation. The hydrological module of the model is based on the water balance equation, taking into account precipitation, evapotranspiration, percolation, surface runoff, and subsurface runoff for the soil column subdivided into several layers. Its hydrological system includes the soil surface, the root zone of the soil, the shallow aquifer, and the deep aquifer. The water balance for the shallow aquifer includes ground water recharge, capillary rise to the soil profile, lateral flow, and percolation to the deep aquifer. The percolation from the soil profile is assumed to recharge the shallow aquifer. The water balance of the soil includes precipitation, evapotranspiration, percolation, surface runoff, and subsurface runoff. Return flow from the shallow aquifer contributes to the streamflow. The model is described in detail in Krysanova et al. (2000). Recent model developments and extensions that are used in the different basin models for this study are described in the model set-up.

For each African basin, the model has been individually adapted and calibrated with regard to its geographical and bio-physical settings (see Sect. 3.3).

3.2 Data

For all four regions, a digital elevation model derived from the Shuttle Radar Topography Missions with 90 m resolution (SRTM, 2008) was used. Soil parameters were derived from the Digital Soil Map of the World (FAO et al., 2012). Relevant soil data for SWIM includes its depth, clay, silt and sand content, bulk density, porosity, available water capacity, field capacity, and saturated conductivity for each of the soil layers. Land use data were reclassified from the Global Land Cover (GLC2000, 2003). Land use classes of SWIM include water, settlement, industry, road, cropland, meadow, pasture, mixed forest, evergreen forest, deciduous forest, wetland, savannah (heather) and bare soil.

Climatic observations are generally sparse in Africa and very inhomogeneously distributed over the continent. Therefore, and for better comparability of the results, we calibrated the model for four basins using a reanalysis climate data set produced within the EU FP6 WATCH project (WFD, 2011; Weedon et al., 2011). This data contains all variables required for SWIM on a daily basis on a $0.5^{\circ} \times 0.5^{\circ}$ grid. Observed river discharge data from the Global Runoff Data Centre was applied to calibrate and validate the model (GRDC, 2013).

For analyzing climate trends we used the output of an ensemble of 19 CMIP5 ESMs. Of this ensemble, five ESMs (HadGEM2-ES, IPSL-5 CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2M, NorESM1-M) outputs were used for driving the hydrological model (Table 2). The outputs of these five models were chosen because they practically cover the ranges of the whole ensemble and were available in a bias-corrected version (Hempel et al., 2013). Uncorrected CMIP5 ESMs show strong systematic deviations in their seasonal behavior, and therefore cannot be directly used to drive the eco-hydrological model.

The climate scenarios have been downscaled using a trend-preserving bias-correction method with the WFD reanalysis data, and have been resampled on a $0.5^{\circ} \times 0.5^{\circ}$ grid for the time period 1950–2099 (Hempel et al., 2013). “Representative Concentration Pathways” (RCP) cover different emission concentrations, and in this study the RCP 2.6 and 8.5 scenarios were used to cover the low and high ends of possible future climatic projections. The RCP 2.6 corresponds likely to a warming of less than 2 °C increase of global temperature above the pre-industrial level until the end of the century (Van Vuuren et al., 2011b), and the RCP 8.5 to a likely increase of 3.8–5.7 °C (Rogelj et al., 2012).

3.3 Model set-up and calibration

Table 3 summarizes the basic model set-up and calibration information as well as the results of the validation. The Niger Basin is geographically the most heterogeneous of the four basins and covers the largest area (Table 1). Therefore, the availability of a sufficient number of discharge gauging stations to cover the heterogeneity of the basins was crucial for the set-up of the model. The 1923 subbasins were integrated to form 18 subcatchments, each associated with a gauge at its outlet. These subcatchments were calibrated individually in order to adapt the model as closely as possible to the regional conditions. In addition to this heterogeneity, the flood plains of the Inner Niger Delta influence the discharge regime of the Niger substantially and had to be integrated into the model to adequately represent the discharge downstream. Therefore, a 2-dimensional inundation module for periodically inundated areas was developed and integrated into the model (Liersch et al., 2012). The five largest reservoirs were included in the model set-up (see Sect. 2.2). A reservoir module developed by Koch et al. (2013) was used for this purpose.

The calibration of the model for the Upper Blue Nile Basin was limited to one gauging station, namely El Diem at the Sudanese–Ethiopian border. For this basin, the quality of radiation data within the WFD dataset was insufficient when compared with the World Radiation Data Center (WRDC, 2000) data. Radiation was underestimated, especially during the rainy season. Therefore, global radiation was estimated for this basin by means of the latitude as well as minimal and maximal daily temperatures, using the method of Hargreaves and Samani (1982). Further, the vegetation module was adapted to spatially varying temperature conditions in the topographically very heterogeneous catchment to provide more realistic regional vegetation growth. Water management was not implemented in the model of this basin because the influence of streamflow management is still negligible.

The Ubangi Basin consists mainly of a peneplain and is more homogeneous than the other basins. Therefore, this large basin could be calibrated with only one gauging station at Bangui. Precipitation data for the Ubangi Basin in the WFD are based on very sparse climate observation data from the Global Precipitation Climatology Centre's precipitation data (GPCC). The interpolation and correction method for precipitation of WFD thus produced unrealistically high precipitation values for the Ubangi. Therefore, WFD precipitation was replaced by original uncorrected GPCC data for the calibration (Schneider et al., 2013). Another particularity of the Ubangi Basin is the almost complete cover by tropical evergreen forest. As the SWIM vegetation module has not yet been adapted to this type of vegetation, it was not been simulated in the Ubangi catchment. Instead, Leaf Area Index and rooting depth were used as additional calibration parameters. Due to the sparse data, the reservoirs of the Ubangi Basin could not be included in the model.

The SWIM model was calibrated for the Limpopo Basin using discharge data from the Sicacate gauging station in South Africa and the Botswanian station Oxenham Ranch. However, the main challenge for the modelling of this basin was a strong effect of human intervention on the river discharge. Therefore, the largest eight reservoirs were included in the model with the input data on reservoir capacity and withdrawal amount from the reservoirs. In addition, 31 intensive irrigation sites with an annual abstraction rate over $6.3\,\mathrm{M\,m^{-3}}$ were identified and included in the model. Taking into account the annual abstraction rate, the monthly share of irrigation and the estimated return flow after irrigation, the daily irrigation demand was calculated for each irrigation site. The irrigation module of SWIM abstracts the irrigation demand from the specific river reaches as long as the amount of irrigation water is available in the river.

4 Results

4.1 Validation of the model

The SWIM model was validated for the gauging stations at the outlets of the four basins; the results are presented in Fig. 2. To quantify the efficiency of the model we applied the method of Nash and Sutcliff (1970) (NSE), and percent bias (PBIAS) was used for evaluation of model error. The validation period was chosen independently from the calibration period and lasted at least eight years (Table 3). The focus of the calibration and model set-up for all four basins was to achieve adequate efficiency for streamflow simulations for daily time steps, for mean as well as high and low flows.

The SWIM model was basically able to reproduce the hydrological characteristics of each basin reasonably well, with NSE ranging between 0.63 and 0.9. However, the validation showed heterogeneous results in terms of the NSE, ranging from adequate in the Ubangi Basin to very good in the Niger Basin. The model was able to reproduce high and low flows for the Niger well, and in terms of seasonality the results are very good. The Upper Blue Nile shows good results with adequate representation of high and low flows and good simulation of seasonality. For the Limpopo, the validation shows a slight underestimation of high flow and overestimation of low flow, but the total efficiency is good. The model for the Ubangi catchment has distinct deficiencies in high and low flows, but regarding seasonality discharge the model gives adequate results during the validation period. In terms of PBIAS, results are very good for the Niger and the Limpopo Basin, whereas for the Ubangi and the Upper Blue Nile they show distinct deviations.

4.2 Climate trends

Precipitation and temperature are the key drivers for the hydrological regime of rivers, and climate change has its main impact through changes in these two variables. In Fig. 3, we show the mean trends for these two parameters from 2006 until 2100 projected by 19 CMIP5 models for the whole African continent. Shown are the results for RCP 8.5 in order to illustrate the most pronounced trends under extreme scenario conditions.

All models agree on a distinct temperature rise over the whole African continent, while in the tropics much of the additional energy input is converted to latent heat. The highest increase of 6 to 7 °C, in some parts even up to 8 °C, is projected over the already driest and hottest areas in the Sahara and Southern African savannahs and deserts. The catchments of the Niger and Limpopo are partly located in these zones of the most extreme temperature increases. The Upper Blue Nile and Ubangi basins are located in regions with a lower but still very distinct warming trend. Here, temperatures rise between 4 and 6 °C, whereas the coastal zones generally show a lower rise in temperature.

For precipitation, the model agreement is considerably lower. The Niger Basin can be divided into an area with a negative precipitation trend in the headwaters of the river in the west, and a positive trend in the eastern part. The longitudinal trend intensifies eastwards, and in the headwaters of the Benue tributary in Cameroon most models agree on a distinct precipitation increase. The Upper Blue Nile and the Ubangi are located in the inner tropical belt, where at least 80 % of the models agree on the positive precipitation trends. The precipitation trend for the Limpopo Basin is negative, with a high agreement in the western part of the basin, where most of the rain falls. Here major changes seem most probable.

In Fig. 4, we compare the seasonal changes of the corrected model runs (HadGEM2-ES, IPSL-5 CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2M, NorESM1-M) with their original runs and with the results of the other 14 CMIP5 models.

The differences between mean monthly temperatures show a distinctly homogeneous pattern. In all four basins, the temperature rises between ∼ 3 and ∼ 6 °C. In the basins of the Niger, Ubangi and Upper Blue Nile, all 5 models chosen project a homogeneous increase throughout the year; Hadley and IPSL outputs are the most extreme with increases between 5 and 6 °C, GFDL and Nor project a moderate increase of less than 4 °C, and MIROC results are in the middle with the highest variance. In the Limpopo Basin, all models agree on the range of warming between 2.5 and 6.5 °C, and on the same pattern of warming, most pronounced from August to December. Hadley and GFDL again show the highest mean annual warming, and GFDL reaches the same level of warming during the first half of the rainy season from August to December. The bias correction did not practically influence temperature. The five selected model outputs cover the temperature range of the CMIP5 ensemble in all four basins well.

In Fig. 5, we compare monthly precipitation in the same periods for the RCP 8.5. For the Niger, the range of uncertainty for the five models chosen is very high. It ranges from ~ 150 mm mon^{-1} increase during the rainy season (MIROC model) to 25 mm mon^{-1} decrease (GFDL model), which means a range between ~ 120 % and minus ~ −20 %. Compared with the uncorrected model runs, the MIROC model unexpectedly shows a distinct increase in trend, caused by the correction (see discussion in Sect. 5.4). For the other models, the correction slightly decreases the means of the monthly trend. During the dry season from November to March, there is no visible trend in precipitation. The selection of five models represents the precipitation range of the CMIP5 ensemble well for the Niger Basin though there are deficits between March and June.

The five bias-corrected models for the Upper Blue Nile Basin all agree on an increasing trend in precipitation. The increase in the IPSL model of almost 400 mm mon^{-1} (~ 100 %) at the end of the rainy season is striking. All other bias-corrected models show a slight increase in precipitation of less than 40 mm mon^{-1} during the rainy season, which corresponds to less than 20 %. The difference from the uncorrected model runs is minor in this basin, except for the IPSL run which again unexpectedly shows a distinct increase in trend as a result of the correction (see discussion in Sect. 5.2). During the dry season from December to May, there is no trend in precipitation (except IPSL). In this basin, selection of the five corrected climate runs diminishes the range of the whole CMIP5 ensemble particularly from June to September, which should be taken into account when interpreting the results.

In the Ubangi catchment, the trends of the five CMIP5 models chosen are rather minor. All models agree on an increasing precipitation trend from ~ 20 to ~ 50 mm mon^{-1}, which is less than 20 % with no obvious pattern. The effects of the bias corrections are minor for all five models. As the dry season is not significant in this region and lasts not longer than two months, the precipitation trends are distinct throughout the entire year. The selection of the five corrected climate runs results in a substantially reduced range of the whole CMIP5 ensemble, which also reduces the informative value for the discussion.

Precipitation trends for the five models chosen in the Limpopo Basin all agree on a decrease at the beginning of the rainy season in October. During the main rainy season from December to March, Hadley and GFDL show an increase of over 50 mm mon^{-1}, which corresponds to an increase of over 50 %. The other three models show minor decreases or no trend at all. The correction of the models with the ISI-MIP method results in less distinct trends for increases as well as for decreases (see discussion in Sect. 5.2). In the Limpopo Basin, the dry season lasts from May to November and during this period there are no trends in precipitation. The selection of five models of the CMIP5 ensemble covers the whole range of precipitation trends in the Limpopo Basin with deficits from August to November.

4.3 Climate sensitivity

Figure 6 illustrates the sensitivity of river discharge to climate variability and change in the four basins. Shown is the change in percentage for the total precipitation over 12 months beginning with the driest month, against the total discharge during the related hydrological year. As base values for all five selected climate models runs of RCP 8.5 serve the means of the base period (1970–1999). The anomalies are then plotted for each year from 2006 until 2099. Additionally, we show the anomalies for the runs with the reanalysis WFD climate input from 1960–2001. Changes in precipitation are shown in the range from −50 to 100 %, and for discharge from −100 to 200 %. Values outside this range are not shown but are included in the calculation of the fitted local regression, plotted as a black line.

The sensitivity varies distinctly from basin to basin. In the Niger Basin, an increase in annual precipitation by 25 % results in an increase in modeled discharge by ∼ 90 %, and 25 % less precipitation causes a decrease in annual discharge of almost 50 %. In the Upper Blue Nile, a 25 % increase in precipitation leads to ∼ 50 % higher modeled discharge, whereas a 25 % reduction in annual rainfall leads to ∼ 25 % reduction in discharge. In the Ubangi, climate sensitivity is least pronounced. Namely, a 25 % increase in precipitation results in less than 30 % increase in annual discharge, and a 25 % decrease reduces discharge by ∼ 40 %. In the Limpopo Basin sensitivity is highest, and already small changes in the precipitation regime may cause huge effects on the discharge regime. So, a 25 % increase in annual precipitation results in ∼ 125 % higher discharge, and a 25 % reduction in precipitation leads to a decrease in discharge of ∼ 40 %. In addition, the spread of impacts in the Limpopo Basin is the largest of all four basins.

The response of discharge to rainfall anomalies for the model runs with the observed WFD agrees with the scenario runs in the Niger and the Upper Blue Nile basins. In the Limpopo Basin, the form of the curve corresponds to the scenario values, whereas the position shifts. This can be explained by the distribution of rainfall that changes in the scenarios, and rainfall during the dry period becomes more likely (Fig. 4). In the Ubangi Basin, the runs with WFD data agree with the scenario runs, though there are some years with an outlying relation of annual precipitation to discharge. This can be explained by a temporal concentration of rainfalls and hence an increased runoff coefficient.

4.4 Impact of climate change on discharge and seasonality

For the base period (1970–1999), the agreement between the simulated discharge driven by WFD and the five chosen climate models is good for the Niger and Ubangi (Fig. 7, topmost row), yet there are some differences for the Ubangi. However, for the Limpopo and Upper Blue Nile basins the results differ more distinctly. Especially in the Limpopo catchment, only the simulation driven by climate input from one model, HadGEM2-ES, gives results comparable to that driven by the WFD input. However, with regard to the small absolute numbers of discharge in the Limpopo Basin, these results are still acceptable.

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Interactive Discussion

Regarding the changes in river discharge from the base period to the near (2021–2050) and far (2070–2099) scenario periods, we focus mainly on the rainy season of each basin (Fig. 7, grey shaded area). The spread between the simulations driven by different climate models is high for all basins, ranging from strong increase to little or moderate decrease, depending on basin and climate model (Fig. 7, four lower rows).

For the Niger Basin the directions of change differ, which corresponds to the location of the basin in the transition zone of increasing and decreasing precipitation projections of the whole CMIP5 ensemble (Fig. 3). The SWIM model projects changes of monthly discharge when driven by the climate simulation results of Hadley, Nor, IPSL and GFDL for both periods and both RCPs, ranging from an increase of up to 50 % to a decrease of up to 50 %. The change in discharge produced with the MIROC climate projections is remarkably higher than that simulated by other climate models. The discharge for the near and far scenario periods increases by the end of the rainy season by 200 % and for the RCP 8.5 in the far period even by 500 %.

In the Upper Blue Nile Basin, the projections of the SWIM model driven by the five corrected climate models agree almost completely on positive trends which correspond to the precipitation trends shown in Fig. 3. In the near scenario period, there is a slight increase of fluctuations around 0 % at the beginning of the rainy season from June to August for both RCPs. Furthermore, the climate scenarios show an increase at the end of the rainy season. This holds also for the far scenario period, with a slightly stronger increase for the RCP 8.5 at the end of the rainy season. The discharge projections driven by IPSL show the most extreme results, with increases between 50 and 100 % and even 300 % in October of the far period. According to the results obtained, all models including IPSL agree on a shift in peak discharge for both RCPs of around one month.

According to Fig. 6, the Ubangi River is least sensitive to climate variability. This is in line with projections, which show the smallest trends out of all four basins, with the highest increase of discharge up to 60 % in the second period for the RCP 8.5. The projections of the SWIM model driven by the five corrected climate models for both RCPs range from decreases of 15 % to increases up to 20 %. However, as the selected climate models in this case do not represent the whole CMIP5 spectrum very well, the validity of this information is limited (Fig. 5).

In the Limpopo Basin with its extremely low runoff coefficient and very high sensitivity to climate variability (Fig. 6), the projected trends are the most extreme of all of the four basins. However, analyzing the results in percentage, the small amount of discharge in absolute numbers has to be taken into account, which implies that the annual runoff is still limited. The GFDL-driven model runs show an increase in discharge during the peak of the rainy season of ∼ 200 % in the near period for both RCPs and in the far period for RCP 2.6. The discharge for RCP 8.5 in the far period increases by 350 %. The discharge projected with IPSL output also increases by ∼ 50 % in the near period and in the far period by 100 % for RCP 2.6, and by 200 % for RCP 8.5. The model output with Nor climate input produces no visible trends for both periods and RCPs. The MIROC model driven runs result in a slightly reduced discharge by ∼ 25 % in the near period and RCP 2.6 in the far period. The projected discharge driven by RCP 8.5 for the far period decreases even up to 50 % in the rainy season. The Hadley-driven simulation produces a striking increase in discharge of ∼ 300 % during the peak of the rainy season in February in the near period for RCP 2.5, and of ∼ 250 % for RCP 8.5. For the far period, the increase is even more extreme in February at ∼ 550 and ∼ 700 % for both RCPs.

4.5 Changes in extremes

The Q10 value is a robust indicator for high flow and designates a value of river discharge which is only exceeded 10 % of the time. A negative trend in Q10 means a reduction in flood risk, and a positive trend represents an increase. The results for changes in Q10 under scenario conditions are presented in Fig. 8 for two periods and two RCPs.

In the Niger catchment, Q10 produced with input from all climate models reflects the direction of changes in mean discharge. The MIROC-driven outputs show a rise in Q10 to over 100 % in all four cases. The RCP 8.5 scenario for the far period shows the most extreme increase of over 300 %. The outputs driven by all other models show rather moderate changes in Q10, which correspond roughly to the percentage of change in the mean discharge during peak flow in the rainy season.

In the Upper Blue Nile Basin, the discharge projections for almost all climate models and both RCPs show an increase from ~ 10 to ~ 50 %. Only for the RCP 8.5 in the far period, IPSL-driven output projects an increase in Q10 of 150 %.

The scenarios for the Ubangi produce the lowest Q10 trends out of all four basins. An increase in Q10 is not projected. The GFDL and MIROC-driven results show a decrease in Q10 of ~ 15 %, and the other outputs fluctuate around 0 % for both scenario periods and both RCPs.

In the Limpopo Basin, the patterns of changes identified for the mean discharge also hold for Q10. The Hadley climate-driven output yields the strongest positive Q10 trend of almost 250 % for RCP 2.6 in the far period. For RCP 8.5 the increase is about 200 %. In contrast, the increase in the near scenario period is higher for RCP 8.5 at almost 150 % than for RCP 2.6 at ~ 100 %. The projections with GFDL input in the near future are almost the same for both RCPs at ~ 75 %. For the far period, the trend reduces to 50 % in the RCP 2.6 case, and for RCP 8.5 it strengthens to 120 %. The IPSL-driven projection shows slight increases in both periods for RCP 2.6 and a decrease of almost 50 % in the near period for RCP 8.5. This decrease tends to zero in the far period. The MIROC-driven output shows negative Q10 trends for both RCPs in both periods.

A Q90 value is used for identifying low flows, indicating that 90 % of the time the value is exceeded (Fig. 9). If the value shows a negative trend, it implicates that low flow is further decreasing and river droughts are likely to occur more often.

In the Niger Basin, the Q90 trend is mostly positive for both RCPs and both scenario periods. Only GFDL and IPSL-driven outputs show slight negative trends in the far period, between 10 and 20 %.

In the Upper Blue Nile Basin all trends are positive, showing strong increases. The IPSL-driven simulations again produce extreme results, with increases up to 450 %

in the far period for RCP 8.5. The Nor-driven scenarios result in a Q90 increase of ~ 100 % in the far period for both RCPs and ~ 50 % in the near period for both RCPs. Simulations driven by all other climate models lead to increased Q90 trends in a range of 40 to 60 %.

In the Ubangi Basin, only model runs driven by GFDL and MIROC climate inputs produce a decrease in Q90. For GFDL, Q90 is reduced by ~ 25 % for both periods and both RCPs. The MIROC-driven results show a ~ 20 % decrease in Q90 for both RCPs in the near period, a ~ 25 % decrease for RCP 2.6 in the far period, and almost no trend for RCP 8.5 in the far period. All other simulations produce trends that fluctuate around 0 %.

For the Limpopo catchment, MIROC and IPSL climate inputs lead to negative Q90 trends. In the near period of RCP 2.6 scenario, only the MIROC climate input leads to a slightly negative trend, whereas for RCP 8.5 the IPSL-driven runs project a decrease of ~ 15 % and MIROC ~ 30 %. In the far future period, the IPSL and MIROC-driven outputs show a decrease of ~ 40 to ~ 50 %. Simulations driven by the other 3 climate models project a positive Q90 trend.

Summarizing the results for changes in extremes, it can be said that the direction of changes identified for the mean discharge holds mostly also for the high and low flow extremes.

5 Discussion

The following discussion is structured according to the research objectives presented in the introduction.

5.1 Differences in climate change sensitivity among the basins

First aim was to investigate differences in the sensitivity of modeled annual discharge to climate parameters between the basins. The response to changes in precipitation is not a linear process but rather depends on the basin's characteristics. Figure 6 shows that the response to changes in annual precipitation is augmented with regard to percent change in streamflow in all basins.

The relationship between changes in precipitation to changes in discharge is most extreme in the Limpopo Basin, where we also found the highest probability of major changes to the precipitation regime. This high sensitivity can be explained by the very low runoff coefficient of the Limpopo Basin, which makes the catchment very sensitive to changes in precipitation (Table 1). Also for the Upper Blue Nile and Niger Basins, the changes in precipitation are likely to intensify the impacts of climate change on discharge in both directions for both drier and wetter years.

These findings are independent of the projected climate scenarios and their uncertainties. Hence, climate change will most likely have significant impacts on river discharge in the Limpopo, even if climate change is more moderate than in other basins studied.

5.2 Seasonality of discharge under climate change in the future

Our results related to objective 2. on the seasonality of discharge for the four basins in the future mainly confirm the results of former studies on streamflow projections in Africa. Possible decreases in streamflow for the Limpopo, Niger and Ubangi are in the same range (up to –20 % per year, Fig. 7) as in the studies discussed in the introduction. For the Niger Basin, the results on increasing streamflow at the downstream part of the river where the Lokoja gauge is located (Table 4) agrees with the findings of other studies (Mahe et al., 2013; Faramarzi et al., 2013). The results for the Ubangi Basin are also in line with previous studies, which project varying results with a tendency for decreasing flow as a mean over all projections (De Wit and Stankiewicz, 2006; Strzepek and McCluskey, 2007).

However, the increasing discharge produced for the Upper Blue Nile Basin by all climate models and for the Limpopo Basin by the majority of the climate projections are partly contradictory to previous studies' results (De Wit and Stankiewicz, 2006;

Strzepek and McCluskey, 2007) and also to the African chapter of the Fourth Assessment Report of the IPCC (AR4) (Boko et al., 2007). Especially for the Upper Blue Nile Basin, simulations driven by all climate input runs chosen resulted in higher annual discharge, on average even up to 40 % for the first half of the 21st century. However, also for the Limpopo Basin where other studies projected decreases in streamflow (Zhu and Ringler, 2012; De Wit and Stankiewicz, 2006), the multi-model mean of the climate models resulted in an increase of mean annual streamflow for both scenario periods with a high agreement for the first half of the century at RCP 2.6. As both previous studies focused on the continental scale on a defined grid, it is difficult to compare the outputs directly.

Regarding the differences between RCP 2.6 and 8.5, our findings agree with the observations of the AR4, which states that the differences between the emission scenarios mainly take effect in the second half of the 21st century (Solomon et al., 2007). This holds for all four basins.

5.3 Changes in hydrological extremes

Results with regard to research question 3. on changes in hydrological extremes affirm the occurrence of trends found previously. Concerning flood risk in Africa at the continental scale or for large regions in Africa, most previous assessments focused on changing vulnerability (Di Baldassarre et al., 2010; Mngutyo, 2012; Tschakert et al., 2010; Hastenrath et al., 2010) and less on climate change. However, a recent study by Jury (2013) found a return to wet conditions throughout Africa in the period 1995–2010 by means of trends in monthly river flow records, meteorological reanalysis data, and satellite observations. This tendency of increasing high flows in the observations matches our findings in all basins studied except the Ubangi (Fig. 8, Table 4). This holds especially for the Upper Blue Nile Basin, where simulations driven by all climate models resulted in a distinct increase in high flows for both RCPs and both scenario periods.

Our study also shows that climate change might play a major role in the increasing risk of hazardous floods in Africa. For a few model runs, these trends are extreme, especially for the Limpopo and the Niger. For the Ubangi Basin, the model results agree on a relatively low change in high floods and show discrepancies in the direction of the trend. As flood risk is caused not only by a higher frequency or amplitude of the hazard itself, but is also linked to a rising vulnerability in Sub-Saharan Africa, flood hazards should be taken into account when assessing climate change impacts and adaptation in Africa.

When it comes to low flows, the existing literature agrees mostly on an increase of frequency and magnitude of river droughts throughout the African continent (e.g. Boko et al., 2007; Faramarzi et al., 2013). These findings are not always connected to climate change, but to the increase in water use. As we focus on climate change and neglect changes in land use, it is difficult to compare the results. However, the mean changes in Q90 are positive for the Niger, Upper Blue Nile and Limpopo (Table 4). In the Limpopo Basin, where previous studies mainly agreed on an increase of hydrological droughts (Zhu and Ringler, 2012), our results driven by three of the five climate model outputs show a positive tendency for the low flow level, which means a reduced likelihood of riverine droughts (Fig. 9). In the Niger Basin, where droughts are also an issue (Oguntunde and Abiodun, 2013), the Q90 trend is mostly positive, and only results driven by two climate models show slightly negative trends. Only for the Ubangi Basin do the results indicate an increased likelihood of low flows, but with a very high degree of uncertainty (based on results driven by only two climate models). Hence, taking climate change into account, our study with the five chosen climate projections does not support the widespread view of a distinctly higher probability of decreasing low flows for these regions in Africa.

5.4 Sources of uncertainties

Our research objective 4 focuses on the sources of uncertainty in this climate impact study. As with the first finding, we see a broad range of projected changes in precipitation in the five chosen ESMs in each basin, and the associated uncertainties are striking for the near future but even greater for the far future (Fig. 3). In contrast, the analysis shows that the direction of the temperature trend on the African continent is confirmed by all CMIP5 models; the temperature change in the four basins ranges from 3 to 6 °C until the end of the century under RCP 8.5 (Fig. 4). Hence, the uncertainty in terms of streamflow, which is largely influenced by these two parameters, derives mainly from uncertainties in precipitation. This uncertainty could not be reduced with the bias correction method used. As we have found, even some additional uncertainty in the climate scenario projections exists due to the bias correction.

For the Niger, Ubangi and Limpopo there is one climate model for each that produces outlying results that should be interpreted with particular caution when discussing the impacts. The MIROC model for the Niger and the IPSL model for the Upper Blue Nile show outlying increases in discharge, distinctly different from the other results. These extreme increases can be explained by the extreme increase in precipitation, produced by the bias correction of the climate output using the method of Hempel et al. (2013) (see Fig. 5). The correction is meant to preserve the relative trend of the model, which in exceptional cases can lead to extreme precipitation corrections. An example of this can be seen in the case of the IPSL model in the Upper Blue Nile Basin, where the almost rainless October was corrected by a high factor during the base period. In the future scenarios, this factor resulted in a very strong increase in precipitation during October, which exceeds the usual peak of the rainy season in August (see Supplement, Fig. 2). In the Limpopo Basin, the extreme discharge resulting from the simulation driven by the Hadley model can be explained by extremely high rainfall. The high sensitivity to weather extremes in the Limpopo Basin most likely resulted in the very high discharge peaks (Table 1; Fig. 8).

The uncertainties derived from the climate model runs are propagated in the cascade of uncertainty to the hydrological model, resulting in the broad range of changes in discharge for each basin. Here, the intercomparison of model set-ups and validation results among the four basins confirmed the dependency of model performance on availability and quality of the input data. With increasing basin size, the data requirements grow, but even more influential are the basins' characteristics in terms of heterogeneity and complexity, including water management, wetlands, etc. Nevertheless, as the performance of the SWIM model is adequate for all basins, the hydrological model probably plays a minor role in this uncertainty. This assumption is supported by the small differences between river discharge amounts simulated with the WFD climate input and the climate models' input during the reference period. Especially in areas with very low runoff coefficient and high sensitivity as in the Limpopo Basin, the model is very sensitive to climate input and the requirements for consistent and reliable climate scenarios are very high.

5.5 Implications for adaptation

The final research question takes a broader view and looks at the general suitability of a regional intercomparison in order to assess adaptation. Compared to literature reviews in which the comparison of results is usually hampered by the differences between the applied models, scenario assumptions and periods applied, a regional impact comparison study as shown here gives more coherent and comparable results. This holds for the mean changes as well as for the ranges of uncertainty with which they are affected.

As far as adaptation is concerned, we are able to distinguish two types of uncertainty in our results: in one case, the simulations driven by the climate models agree on the direction of the trend. This is mostly the case for the Upper Blue Nile Basin, where the trend agreement for the mean, Q10 and Q90 was far higher than in the other catchments (Table 4). In other cases, they do not even agree on the trend's direction. For the purposes of adaptation, the latter case seems to be the most difficult to react to. Regarding an agenda for adaptation, this might be a factor for decision making where impact comparisons may be involved. In addition, the magnitude of change for high flows is the highest in the Upper Blue Nile Basin, and additional studies could focus on this particular issue.

In terms of adaptation planning in Africa, there is additional information that can be derived from the comparison. For all four basins, basin-wide action plans for water management (and in many of the riparian states, the additional national plans as well) exist or are in development (Niger: Niger Basin Authority, 2007; Upper Blue Nile: Block et al., 2008; Ubangi: Commission Internationale du Bassin Congo–Oubangui–Sangha, 2007; Limpopo: UN Habitat and UNEP, 2007). These plans all include adaptation to climate change in the water sector. However, due to the overwhelming threat of droughts and water scarcity in many regions of Africa, all of these plans account mainly or solely for decreasing streamflow and river droughts. In our study, we show that in the Niger, Upper Blue Nile and Limpopo the risk of high flows will increase. Of course, these results have to be interpreted carefully, as our projections are driven by five bias-corrected climate models that do not cover the entire range of the whole CMIP5 ensemble (Fig. 4), and uncertainty in the projections is still unavoidable even if the whole ensemble were to be used. Still, disastrous floods in the past decades in many parts of Africa have shown that these catastrophes represent one of the main challenges and an increasing threat under global change in many regions in Africa (e.g. Jury, 2013; Di Baldassarre and Uhlenbrook, 2012; Di Baldassarre et al., 2010). Our findings support this perception and underpin the need for broad adaptation strategies, taking projections for future flooding into account.

However, in the face of these high uncertainties deriving mainly from the climate projections, adaptation is very challenging. Recent studies argue for a “bottom-up” approach to reduce vulnerability instead of adapting “top-down” on the basis of uncertain projections (Richardson et al., 2011; FEW et al., 2007). Also, with state-of-the-art climate projections and modeling approaches, these conclusions cannot be disproved and uncertainties reduced. Still, a comparison of climate change impacts on river discharge and their uncertainties, even using a very general and basic approach, may support decision makers in answering the challenges of climate change.

6 Summary and conclusions

The differences between the sensitivities of streamflow regimes to climate variability among the four basins studied are remarkably large; the Limpopo Basin with the lowest runoff coefficient being the most sensitive. With regard to future changes in quantity and seasonality of streamflow, we show that the most extreme changes in discharge are likely to happen in the Upper Blue Nile catchment. Here, all climate model projections result in increased streamflow and an extension of the streamflow peaks at the beginning and end of the rainy season. In the Niger and Limpopo Basins, the direction of the trend is unclear, whereas the magnitude of change is large for simulations driven by single climate models. In contrast, impacts on the Ubangi River are not so significant compared to others, but still do not all lead in the same direction. In general, this also holds for the extremes. In the Upper Blue Nile Basin, there is a clear picture of increasingly high flows for all model runs and a reduction of risk for low flows. For the Limpopo and Niger the trends are diverse, but the majority of runs project increasingly high flows and higher low flows (reduction of risk for low flows). In the Ubangi, the trend for the extremes is unclear and the magnitude of changes is less significant.

In terms of uncertainty, our results confirm that the most uncertainty in regional impact studies derives from climate models, even if the input is bias corrected. In our case, an improvement in the regional hydrological model's performance seems unlikely to diminish uncertainties in streamflow projections substantially, due to the huge range of uncertainty deriving from the climate models' projections. In order to identify and quantify the whole cascade of uncertainty, communication between regional impact modelers and regional climate modelers should be intensified. Particularly the efforts toward improvement of bias correction methods of the climate model outputs should be strengthened.

These broad uncertainty ranges, in which the probabilities of trend directions are in some cases even equally distributed, are of little use for planning actual adaptation measures. Moreover, it should be noted that only five bias-corrected ESMs were applied in our study, and a larger number of climate projections would most likely have resulted in an even broader range of uncertainty (Fig. 4). However, some robust trends still can be detected:

- The direction of trends for the Upper Blue Nile Basin is almost uniform, and our results clearly suggest an increase in discharge and high flows. This strongly indicates that water management in this region should adapt to a longer and more intense rainy season and more intense and frequent flooding in the future.
- The agreement of the projections on increasingly high flows in three of the four regions (except the Ubangi) is remarkable. It agrees with many studies on increased flood frequency and amplitude in past decades in many rivers (e.g. Jury, 2013; Di Baldassarre and Uhlenbrook, 2012; Di Baldassarre et al., 2010). Adaptation efforts in Africa should consider this threat, even if water scarcity is still the main challenge in most of the African regions.

For the Niger and the Limpopo, the diversity of projected trends in average runoff suggests a need for implementation of a wider range of possible adaptation measures. In both cases, our results imply that the focus of adaptation strategies should be broad and include a general reduction of vulnerability of the riverine population. In the Ubangi Basin, the trends are unclear and more moderate, which would imply a lower priority level for climate change adaptation for this catchment.

Still, the results should be interpreted carefully, not only because the uncertainties are remarkably high. For very large basins such as the Niger, future studies should also consider the main sub-regions in order to be able to compare impacts for different climate zones. In addition, detailed future studies for planning adaptation strategies have to consider the need for development of flood protection measures.

Supplementary material related to this article is available online at http://www.hydrol-earth-syst-sci-discuss.net/10/13005/2013/hessd-10-13005-2013-supplement.pdf.

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Table 1. Basin and river characteristics.

	Niger	Upper Blue Nile	Ubangi	Limpopo
Area in km^2	2 156 000	167 000	489 000	413 000
Alt. range in m a.s.l.	0–2961	526–4187	341–2046	0–2326
Mean temp. in °C	28	19	25	21
Mean temp. warmest/ coldest month in °C	32 in May/ 24 in Jan	21 in Apr/ 17 in Dec	26 in Mar/ 24 in Dec	25 in Feb/ 15 in Jul
Mean prec. in $mm\,a^{-1}$	682	1382	1507	530
Dominant land uses in %	cropland: 20 grassland: 18 savannah 14	cropland: 57 savannah: 30	forest: 50 cropland: 32	forest: 34 cropland: 32 savannah: 20
Length of river in km[a]	~ 3650	~ 800	~ 1670	~ 1750
Mean annual discharge in $mm\,a^{-1}$	~ 170	~ 370	~ 224	~ 13
Runoff coefficient[b]	~ 18 %	~ 17 %	~ 21 %	~ 2 %

[a] Until the relevant gauging stations. Niger: Lokoja, Upper Blue Nile: El Diem, Ubangi: Bangui, Limpopo: Sicacate.

[b] Amount of precipitation that reaches the outlet.

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Table 2. Earth system models driving the SWIM model.

Model name	Institution
HadGEM2-ES	Met Office Hadley Centre Earth System Modeling group, England
IPSL-5 CM5A-LR	Institut Pierre-Simon Laplace, France
MIROC-ESM-CHEM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute, Japan
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory of the National Oceanic and Atmospheric Administration, USA
NorESM1-M	Norwegian Climate Centre, Norway

Table 3. Characteristics of basin models and validation results.

	Niger	Upper Blue Nile	Ubangi	Limpopo
Number of subbasins	1923	558	377	2020
Number of HRUs[a]	13 883	1700	1734	13 085
Number of included reservoirs	5	0	0	8
Number of included irrigation schemes	0	0	0	31
Number of gauging stations used for calibration	18	1	1	2
Gauging station used for validation	Lokoja	El Diem	Bangui	Sicacate
Validation period	1983–1992	1971–1980	1971–1980	1980–1987
NSE/PBIAS[b]	0.9/2.1	0.73/39	0.63/15.7	0.8/3.4

[a] Hydrological response units, see Sect. 3.1.

[b] Nash–Sutcliffe Efficiency/percent bias.

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Table 4. Summary of modeling results.

	Change between 2020–2049 and 1970–1999 (RCP 2.6/8.5)[a]					
	Direction of trend in %[b]			Mean amount of change in %		
	Mean	Q10	Q90	Mean	Q10	Q90
Niger	60/60	80/60	< 50/60	28/27	32/30	28/26
U. Blue Nile	100/100	100/100	100/80	38/40	56/57	18/21
Ubangi	< 50/ < 50	< 50/ < 50	< 50/ < 50	0/−2	2/0	−3/−5
Limpopo	80/60	80/< 50	80/60	34/23	14/10	32/31
	Change between 2070–2099 and 1970–1999					
	Direction of trend in %			Mean change in %		
	Mean	Q10	Q90	Mean	Q10	Q90
Niger	60/60	60/60	60/60	30/56	38/44	28/65
U. Blue Nile	100/100	100/100	80/80	44/81	68/132	16/41
Ubangi	< 50/80	> 50/60	< 50/ < 50	−5/7	−4/12	−9/−2
Limpopo	60/60	60/60	60/60	48/53	16/−4	51/52

[a] Changes in annual mean discharge above 5 % or under −5 % have been counted as positive/negative. Less than 5 % trend was counted as no trend.

[b] Percent values have been calculated by comparing the five corresponding model runs driven by the chosen climate projections.

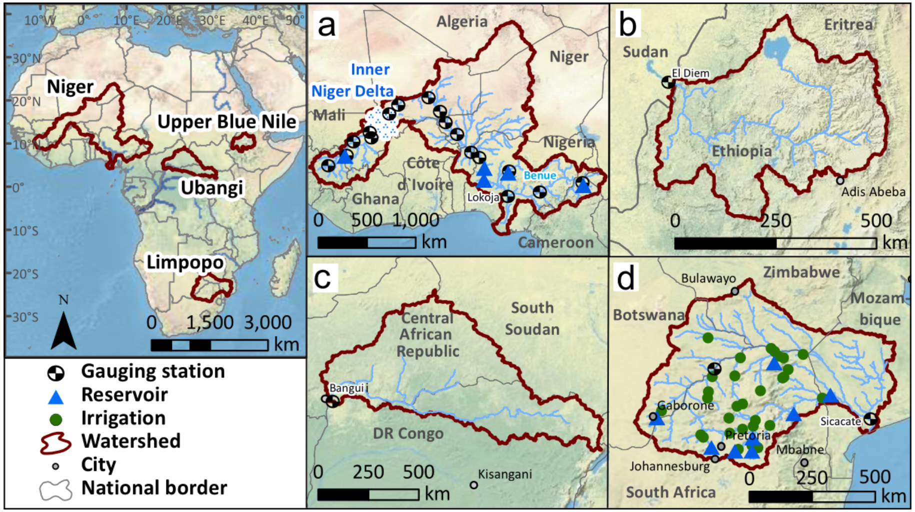

Fig. 1. Map of the four modeled basins: Niger **(a)**, Upper Blue Nile **(b)**, Ubangi **(c)**, Limpopo **(d)**.

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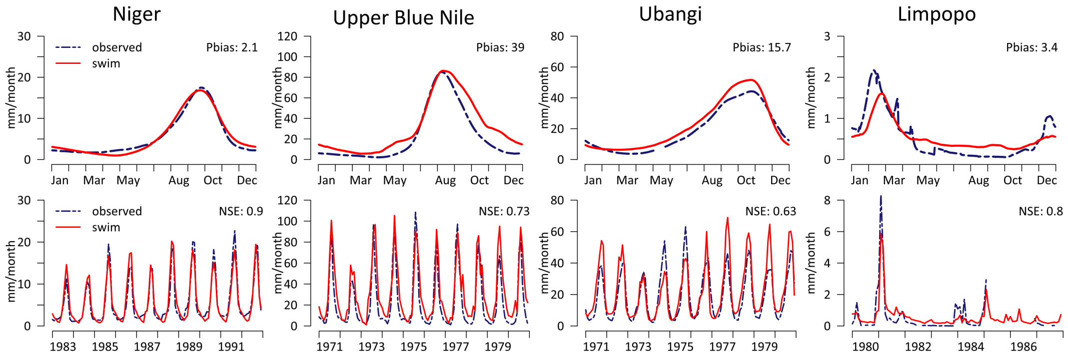

Fig. 2. Validation of SWIM at the outlets of the four basins. In the top row the seasonality of monthly runoff rate in validation period and bias in %, in the bottom row the monthly runoff rate in the validation period with Nash–Sutcliffe efficiency.

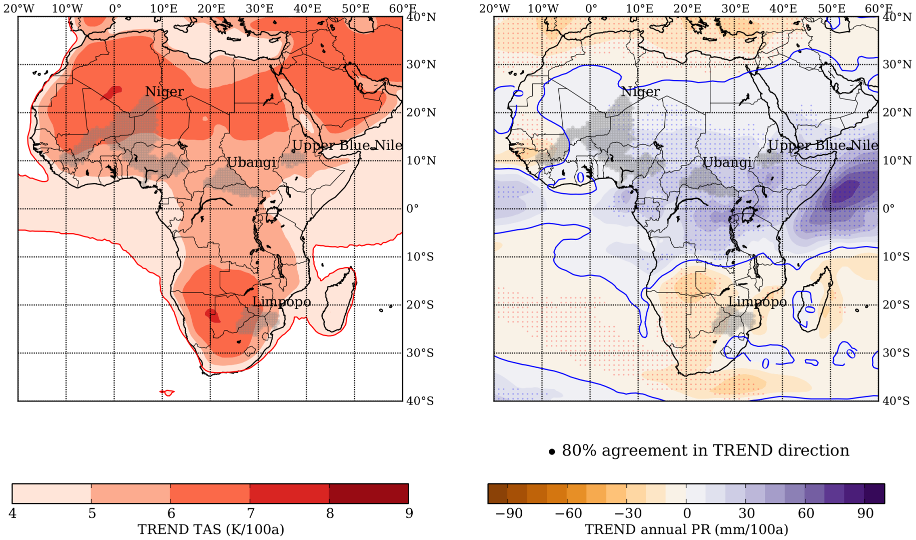

Fig. 3. Mean temperature (left panel) and precipitation (right panel) trends over the African continent for 19 CMIP5 models from 2006–2100 for RCP 8.5. For precipitation, an agreement in trend direction of 80 % or more of the models is marked with a dot.

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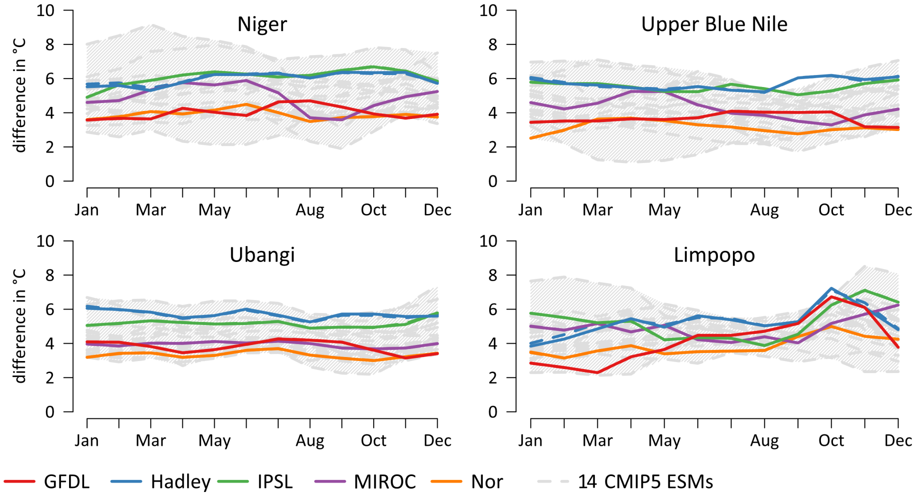

Fig. 4. Difference in monthly mean temperature in the far projection period (2070–2099) relative to the base period (1970–1999) for RCP 8.5 for five bias-corrected model projections (colored lines), the uncorrected ESMs (colored dashed lines) and 14 ENSEMBLE ESMs (grey dashed lines).

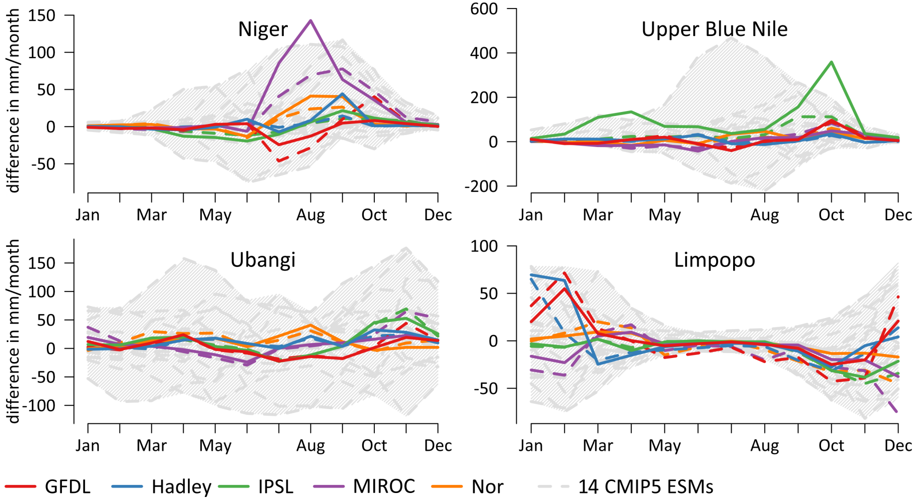

Fig. 5. Difference in monthly precipitation in the far projection period (2070–2099) relative to the base period (1970–1999) for RCP 8.5 for five bias-corrected model projections (colored lines), the uncorrected ESMs (colored dashed lines) and 14 ENSEMBLE ESMs (grey dashed lines).

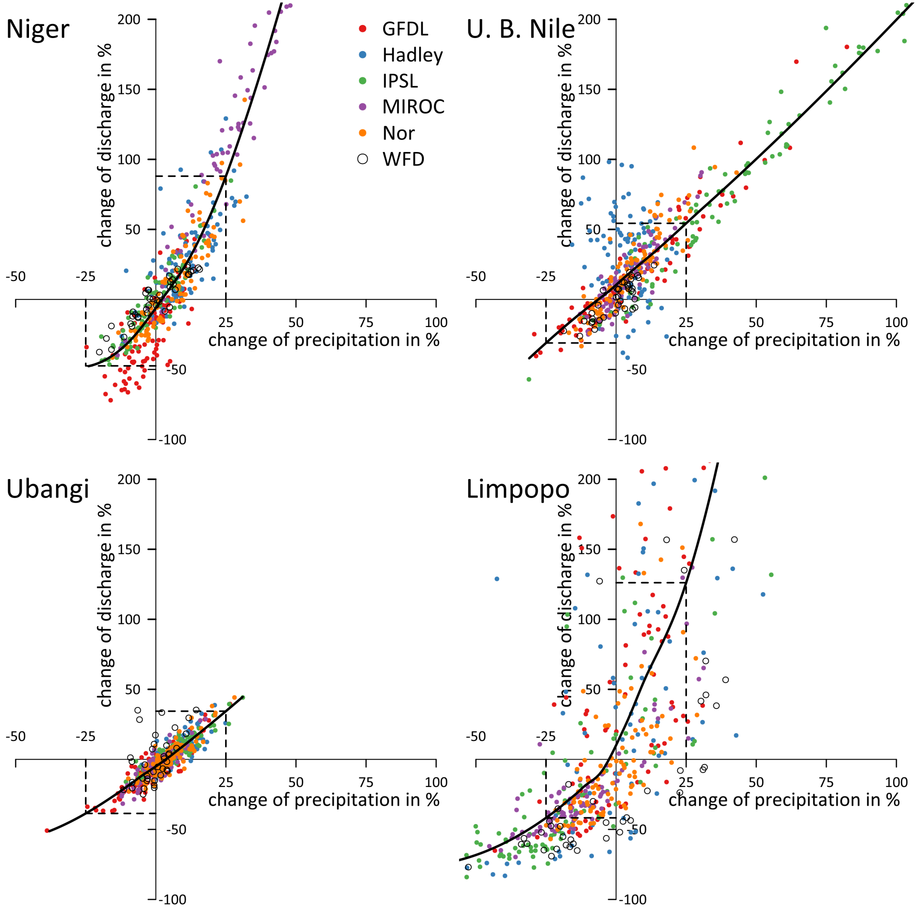

Fig. 6. Climate sensitivity in the four basins. Change in modeled annual discharge [%] per change of precipitation [%] for 2006–2099 compared to the mean of base period 1970–1999 for five climate models in RCP 8.5 and WFD. Curve shows fitted local regression over all values.

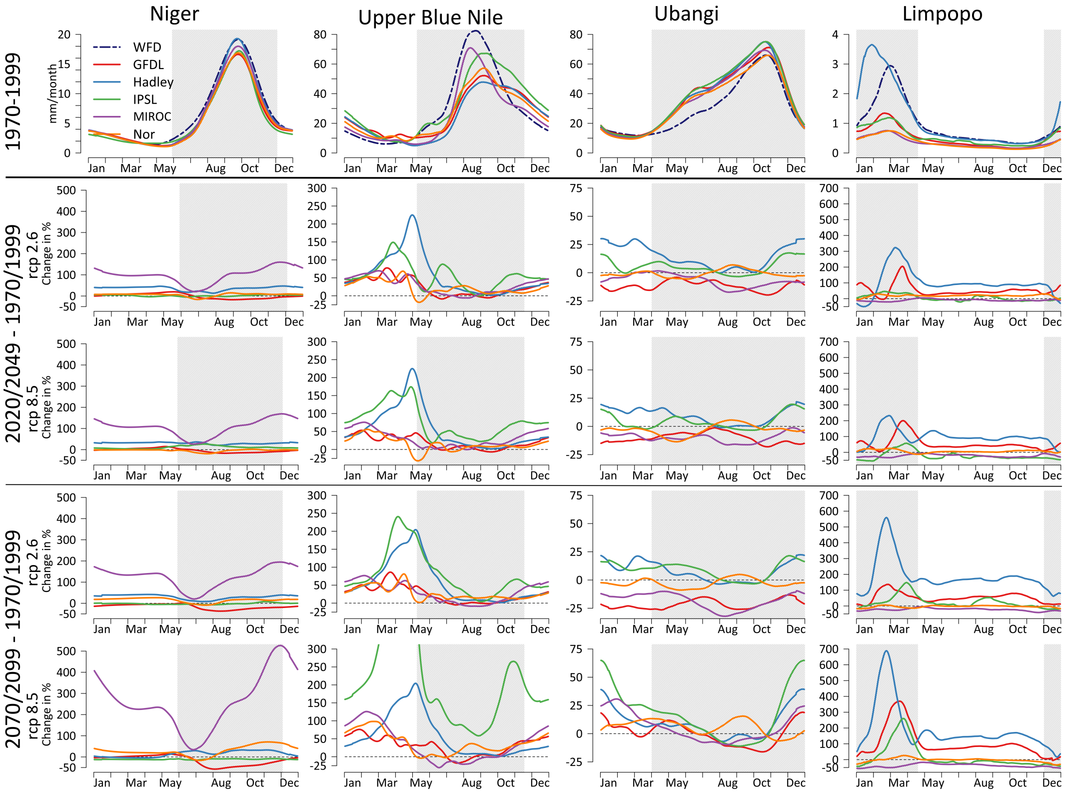

Fig. 7. First row: seasonality of monthly discharge for the reference period; second and third rows: changes in % of discharge between a near scenario period and reference periods for RCP2.6 and RCP 8.5; fourth and fifth rows: changes in % of discharge between a far scenario period and reference periods for RCP 2.6 and RCP 8.5. Recent rainy season as grey shaded area.

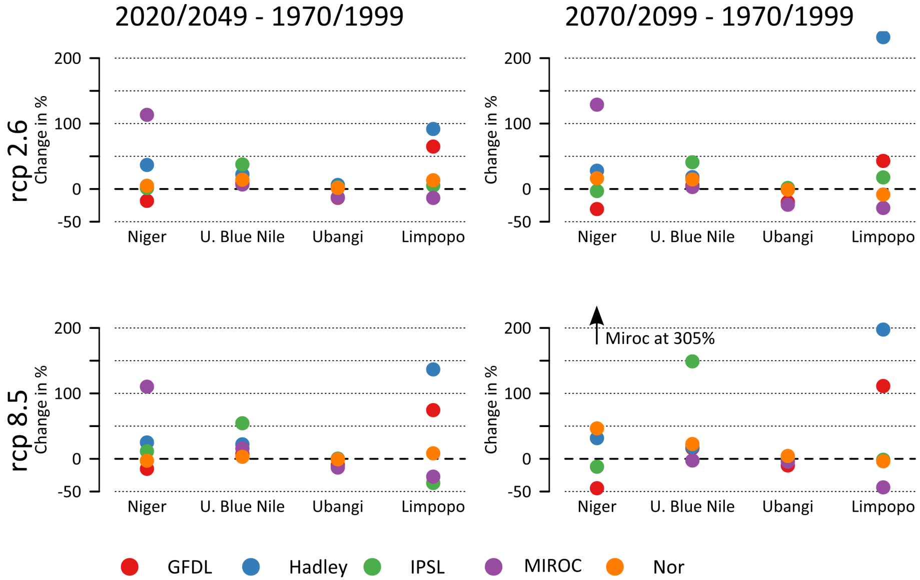

Fig. 8. Change in Q10 (high flows) of five bias-corrected model projections in near (2020–2049, left column) and far (2070–2099, right column) scenario periods compared to the reference period (1970–1999) for RCP 2.6 (upper row) and RCP 8.5 (lower row) in %.

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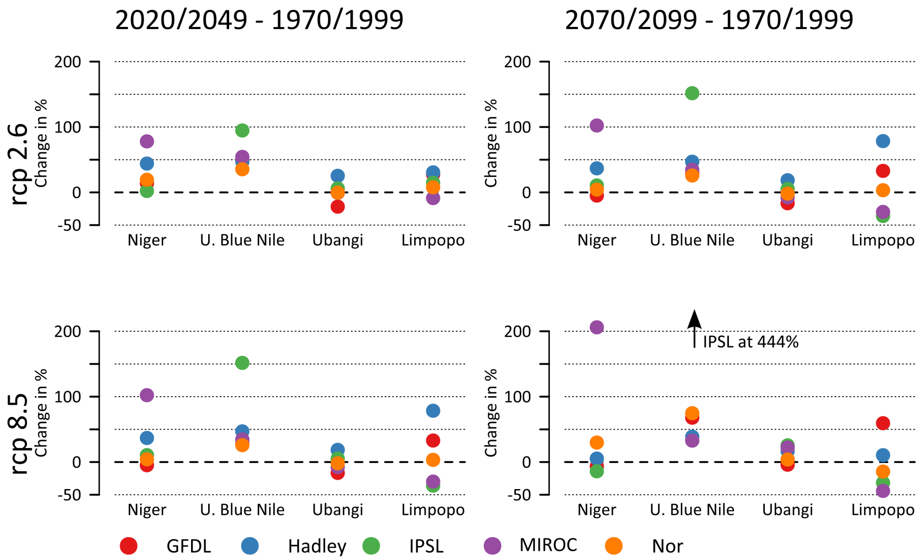

Fig. 9. Change in Q90 (low flows) of five bias-corrected model projections in near (2020–2049, left column) and far (2070–2099, right column) scenario periods compared to the reference period (1970–1999) for RCP 2.6 (upper row) and RCP 8.5 (lower row) in %.