IMPROVED DROUGHT EARLY WARNING AND FORECASTING TO STRENGTHEN PREPAREDNESS AND ADAPTATION TO DROUGHTS IN AFRICA

DEWFORA

A 7th Framework Programme Collaborative Research Project

Hydrological climate scenarios for Africa and specific case study regions of the Nile and Niger river basins

WP3-Task3.2-D3.5

October 2013

Coordinator:	Deltares, The Netherlands
Project website:	www.dewfora.net
FP7 Call	ENV-2010-1.3.3.1
Contract no.	265454

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DOCUMENT INFORMATION

Title	Hydrological climate scenarios for Africa and specific case study regions of the Nile and Niger river basins
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Distribution	PP
Reference	WP3-Task3.2-D3.5

DOCUMENT HISTORY

Date	Revision	Prepared by	Organisation	Approved by	Notes
29/10/2013		Francois Engelbrecht	CSIR		

ACKNOWLEDGEMENT

The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement N°265454

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SUMMARY

The African river basins of the Niger, Blue Nile, Atbara, Ubangi and Limpopo cover a wide spectrum of climates, topographies and ecological conditions. The water management strategies applied over the various basins are also quite diverse. In order to examine and compare climate-change induced trends in river discharge over the different basins, the semi-distributed eco-hydrological model SWIM and the Nile Forecasting System (NFS) were set up over and adapted to the particular conditions and requirements of each basin. For each of the hydrological models, the set-up procedure involved specialized model calibration procedures as well as the adjustment of input data. The modelling systems also incorporated for each basin representations of water management infrastructure, such as reservoirs and irrigation schemes as well as wetlands and their inundation dynamics. In order to project changes in the hydrology of the basins under climate change, the models were driven by downscaled climate projections of five Earth System Models (ESMs).

Comprehensive validation revealed model efficiencies ranging from adequate to good, depending mainly on quality and availability of input and calibration data. The trends in mean discharges, seasonality and hydrological extremes were subsequently compared, across the different downscalings and hydrological models employed. The projections agree mostly regarding the direction of changes, however, the range of uncertainty of the simulations driven by different climate models is large as far as the magnitude of the projected changes is concerned. Despite the strong warming of the African climate system, a considerable probability for an increase in river discharge for means and extremes is projected across all five basins.

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1. INTRODUCTION

Hydrological modeling studies over Africa generally focus on specific regions, and are driven by questions focused on the local and regional impacts of hydrology and extreme hydrological events. Indeed, different river basins typically provide different environmental conditions, and different sensitivities within the context of climate impacts. Comparing the impacts of climate on the hydrology of different river basins is therefore not a trivial exercise. However, when trying to bridge the divide between the regional and continental scale in order to coordinate climate change adaptation, a comparison of impacts at the basin scale may reveal commonalities of climate change challenges more profoundly than global impact models can do. Within this context, eco-hydrological models were set up for three DEWFORA case studies, namely the river basins Niger, Blue Nile and Limpopo. Additionally, the Ubangi and Atbara basins were also modeled, and projected climate impacts across the five basins were compared. The analysis of common and particular sources of uncertainty in the modeling across the basins then facilitated a holistic interpretation of the results. On this basis general challenges for adaptation to climate change impacts on hydrology in Africa were identified. It may be noted that some of the results described in this section have been presented at Impacts World 2013, an international conference on climate change effects, by scientists of the Potsdam Institute for Climate Impact Research (PIK) (Aich et al.,2013).

2. HYDROLOGICAL MODELS APPLIED OVER THE DEWFORA CASE STUDY REGIONS

2.1 THE HYDROLOGICAL MODEL APPLIED AT PIK AND FORCING DATA FROM CLIMATE MODELS

At PIK, four African basins (The Niger, Blue Nile, Ubangi and Limpopo) were modeled using the eco-hydrological model SWIM (Krysanova et al. 1998). This semi-distributed model is based on the models SWAT (Arnold et al. 1993) and MATSALU (Krysanova et al. 1989) and is maintained mainly by PIK. SWIM is process-based and simulates the hydrological cycle, vegetation growth, erosion, and nutrient dynamics at the river-basin scale at a daily time step. The model is described in detail in Krysanova et al. (2000). Recent model developments that are relevant for this study include a reservoir module for integrating reservoir management (Koch et al., in press), a simple abstraction function for river-reaches for irrigation and a 2-dimensional inundation module for periodically inundated areas (Liersch et al. 2012). For each of the four basins, the model has been individually adapted and calibrated with regards to geographical and bio-physical setting.

For all four regions a digital elevation model constructed from the Shuttle Radar Topography Missions' 90 m resolution data set (SRTM n.d.) was used. Soil parameters were derived from the Digital Soil Map of the World (FAO n.d.). Land use data were reclassified from the Global Land Cover (GLCF n.d.).

For the calibration of the model a climate dataset produced within EU FP6 WATCH project (WATCH n.d.) was used. Observed river discharge data from the Global Runoff Data Centre were applied to calibrate and validate the model (GRD n.d.).

Climate scenarios were provided the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP). The scenarios were created by five Earth System Models (ESMs) (HadGEM2-ES, IPSL-5 CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2M, NorESM1-M), which have been downscaled using a trend-preserving bias-correction method with the WATCH reanalysis data, and have been resampled on a 0.5°x0.5° grid (Hempel et al. 2013). “Representative Concentration Pathways” (RCPs) cover different emissions and land-use change projections, and in this study the low emission rcp 2.6 and the high end scenario 8.5 were used to force the ESMs.

2.2 THE HYDROLOGICAL MODEL APPLIED AT NFC AND FORCING DATA FROM CLIMATE MODELS

In order to obtain forcings for the hydrological model applied at the Nile Forecasting Centre (NFC), ESM simulations were selected following a two-step process. Firstly, a set of climatic processes considered important for the hydrology of the Nile basin were identified. The most important of these is considered to be the seasonal cycle of precipitation, over West Africa (West African monsoon) and over the Great Horn of Africa. The ESM ensemble members were then ranked according to their ability to reproduce observations of these processes. The model uncertainty in representing present-day climate was subsequently sampled as evenly as possible, in order to provide a representative envelope of uncertainty. This process resulted in five ensemble members being selected to supply boundary conditions to a regional climate model applied in the research.

The regional model REGCM3 was used to downscale the ESM simulations to high resolution over the Blue Nile region, in order to obtain spatially more detailed output for the forcing of the hydrological model. The regional model domain was chosen to extend well beyond the natural border of the Nile basin, and consisted of 180 x 150 grid points at 50 km resolution. This choice of domain ensures that the area of Blue Nile sources, which account for most of the river runoff, were central to the domain.

Regional and global climate change models often have systematic biases between the observed present-day climate and that simulated by the climate model. The delta change method is often used to correct such biases. The first step of this methodology involves that the climate is simulated for a control period (typically a 30-year period, e.g. 1961-1990, but extended in this study to a 50-year period). The climate model is then integrated for the future, under one or more emission and development scenarios. The differences between the control scenario and the future development scenario are subsequently calculated (often in terms of differences of present-day and monthly means).

In this study the Delta-change factors were based on the following periods:

- Control period: 1961-1990
- Future period: 2021-2050

Monthly Delta-change factors were estimated for each of the grid points in the domain, for the following combinations:

- 6 ESM ensembles members (referred to as Q1, Q3, Q4, Q7, Q11 and Q15)
- 3 variables (Temperature, precipitation and potential evapotranspiration)
- 12 months

Thus, a total of 216 combinations of delta-change factors were produced. For precipitation and temperature, the delta-change factors could be estimated directly from the output from the RCM simulations. Potential evapotranspiration (PET) is not a direct output from the RCM simulations and a different approach therefore had to be used. First, mean monthly PET maps for the baseline and future periods are calculated using the FAO Penman-Montheith method using the mean monthly RCM outputs of temperature, humidity, surface wind speed, and shortwave radiation for each ensemble member. Then, DCFs for PET were calculated as ratios of future to baseline PET. These are then used to modify the PET climatology of the Nile Forecast System (NFS) to adjust for climate change.

Based on the estimated delta-change factors calculated on a monthly basis for each of the six ensembles, six new sets of input data on rainfall and potential evapotranspiration (PET) were generated. For each month, and for each ensemble member, the multiplicative change factors for rainfall were used to modify present-day daily time series for the period 1989-2007 and consequently generate perturbed time series representative of future conditions. The same was done for PET, but as NFS uses monthly climatologically (long-term average) fields for PET these were perturbed accordingly. The results from the six runs of the NFS model based on the six new future sets of input data – one for each of the ensemble members – were subsequently analysed in detail in order to assess the possible impact of the flow in the Eastern Nile.

3. STUDY AREAS AND MODEL SET-UP

3.1 HYDROLOGY OF THE BASINS

Each of the river basins considered here is characterized by a unique hydrological regime, caused by a wide spectrum of climates, geographical and ecological conditions, and the role of these effects in the lives of the riverine populations (Fig.1 & Table1).

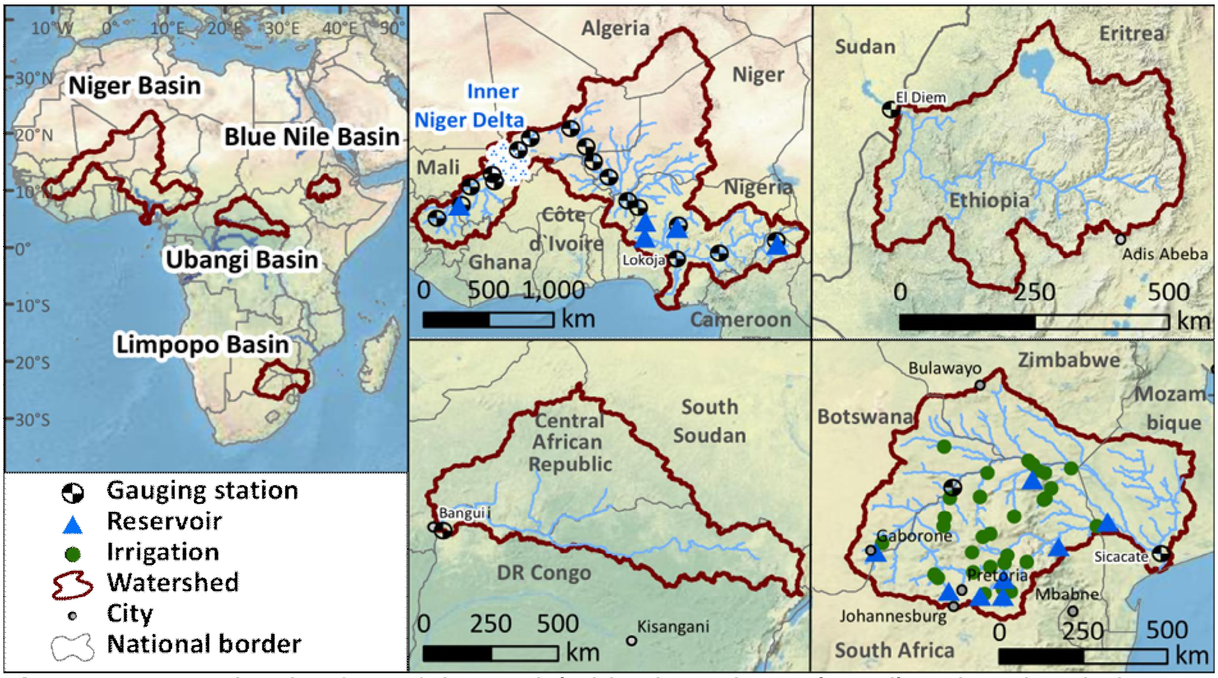

Figure 1. Maps showing four of the modeled basins: Niger, Blue Nile, Ubangi and Limpopo (top left to bottom right).

The basin of the Niger spreads over six different agro-climatic and hydrographic regions, of which each has individual drainage characteristics. Besides this heterogeneous setting the regime of the Niger is substantially influenced by the Inner Niger Delta (IND) (Ogilvie et al. 2010).

The Ubangi is located in Central Africa and flows into the Congo River. Its flow regime follows the regional rainy season, with highest discharges from August to December (Vanden Bossche & Bernacsek 1990).

For the Upper Blue Nile catchment the most important influences on the hydrological regime are the distinct topography of the Ethiopian highlands, as well as the effects of the summer monsoon during the rainy seas. The Blue Nile contributes about 60% of the main Nile flow and is thus is very important for the water resources of downstream countries.

The Atbara is the north-most tributary of the Nile Basin and is characterized by semi-arid to arid conditions. These conditions result from the occurrence of rainfall within a very short period (June-September). It is characterized by very high PET values during the dry season. Streamflow peaks in August, with the river running nearly dry in the months of December until June.

The hydrology of the Limpopo river is characterized not only by a typical subtropical intra-annual, but also a very distinct inter-annual variability of flow (UN-HABITAT 2007).

Table 1 Basin characteristics

	Niger	Blue Nile	Ubangi	Limpopo
area in km²	2.156.000	167.000	489.000	185.000
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 April/ 17 in Dec.	26 in March/ 24 in Dec.	25 in Feb./ 15 in July
mean prec. in mm/ a	682	1382	1507	530
dominant land uses	cropland: 20% grassland: 18% savannah 14%	cropland: 57% savannah: 30%	forest: 50% cropland: 32%	forest: 34% cropland: 32%, savannah: 20%

3.2 WATER MANAGEMENT IN THE BASINS

The intensity of human influences on hydrological processes differs remarkably across the five basins. The Limpopo catchment has the strongest anthropogenic factor, with over 160 dams built mainly for irrigation and/or hydropower. Water resources including groundwater are heavily utilized, due to the area being densely populated, and through the presence of numerous irrigation schemes (UN-HABITAT 2007). This holds only partly for the other four basins, where water management plays a more moderate role. However, the Niger and the Blue Nile still have large potential for water management and new irrigation schemes, as well as for additional reservoirs that are under construction or planned (Andersen 2005). In the Ubangi basin consumption and small-scale irrigation along the river play a minor role and the influence on the discharge and the hydrological regime is slight (Vanden Bossche & Bernacsek 1990).

3.3 MODEL ADJUSTMENT AND SET-UP IN THE BASINS

The individual set up of SWIM for each basin includes adjustment of input data and adapting the model to be consistent with key regional forcings. For the Niger the inundation module was integrated for modeling the IND, and five large reservoirs were simulated with the reservoir module. For the Blue Nile and the Ubangi catchments, the WATCH data set underestimates the global radiation significantly and therefore this parameter was derived using the method of Hargreaves (1982). As the SWIM vegetation module has not been extended yet to cater for tropical evergreen vegetation, the vegetation dynamics have not been simulated in the Ubangi catchment. Instead, the effects of vegetation on the basin's hydrology were included directly by using the relevant statistical characteristics. In the Limpopo basin, 8 reservoirs and 27 irrigation schemes have been included. The model was calibrated for four basins using different numbers of gauges, depending on their availability. For the validation, the gauging station at the outlet of each catchment was used (Niger: Lokoja; Blue Nile: El Diem; Ubangi: Bangui, and Limpopo: Sicacate) (see Fig.1).

The NFS models the Blue Nile basin using pixel scale water balance models, without explicitly modelling Lake Tana or the small dams currently existing in the upper basin. However, NFS takes full account of the Roseries and Sennar dams in Sudan as well as the Sudanese abstractions for irrigation and municipal purposes.

Similarly, the NFS models the Atbara sub-basin using pixel scale models without explicitly accounting for the small Khashm El-Girba dam. Irrigation abstractions from the dam are, however, considered.

4. PROJECTED CHANGES IN HYDROLOGY

4.1 CALIBRATION AND VALIDATION

For all basins the modeling strategies focused mainly on the hydrology. Discharge rates in the catchments are extremely heterogeneous, ranging from about 13 mm per year in the Limpopo catchment to 270 mm per year in the Blue Nile. The SWIM model was able to reproduce the basic hydrological characteristics of each basin. However, the validation using a different time period than the calibration period shows heterogeneous results in terms of the Nash and Sutcliffe efficiency, ranging from adequate in the Ubangi basin to very good in the Niger basin (Fig. 2). The model for the Ubangi catchment is inadequate in representing certain aspects of high and low flows, but seasonality and mean discharge show adequate results during the validation period. The Blue Nile shows better results with adequate representation of high and low flows, and good simulation of seasonality and mean discharge. For the Limpopo the validation shows a slight underestimation of high and low flows, but the total efficiency of the model is good. The model was able to reproduce high and low flows for the Niger well, and in terms of both seasonality and means the results are very good.

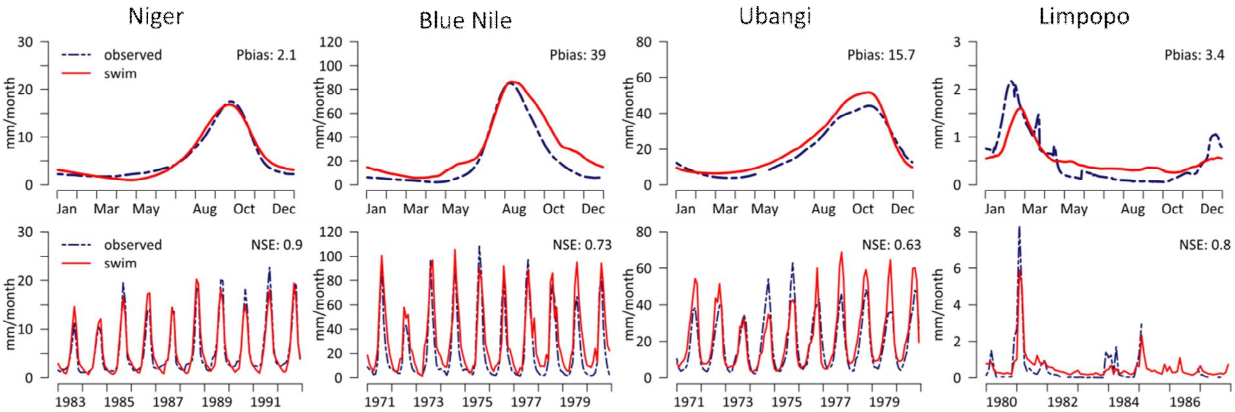

Figure 2. Validation of SWIM at the outlets of four basins. In the top row the seasonality of monthly runoff rate over the validation period is shown (the bias is expressed as a percentage over/under estimation) and in the bottom row the monthly runoff rate over the validation period, with the Nash-Sutcliffe efficiency, is displayed.

The NFS performance for the Blue Nile at both Diem (**Error! Reference source not found.** 3e) representing the upper basin and Khartoum (**Error! Reference source not found.**e) representing the whole basin is very good in terms of overall agreement of hydrograph shape, time series, and volume bias (-0.3% for Diem and 1.8% for Khartoum).

The baseline simulation underestimates the peak flow at Atbara, and consequently the mean annual volume by about 12.6% (Fig. 5e).

4.2 IMPACT ON MEAN DISCHARGE AND SEASONALITY

For the base period, the agreement between the discharge of the models driven by the inputs from WATCH and five climate models is mostly good (Fig. 6). For the Niger, the model outputs driven by the climate projections agree very well with the model output generated with WATCH input data during the base period (1971-2000). This also holds largely for the Ubangi. However, for the Limpopo and Blue Nile basins the results differ distinctly, and especially in the Limpopo catchment only the simulation driven by climate input of one model, HadGEM2-ES, revealed results comparable to that driven by the WATCH input.

Regarding the changes in river discharge in the scenario period (2021-2050) compared to the base period (Fig. 6), the spread between the simulations driven by different climate models is high for all basins, ranging from strong increases to small or moderate decreases, depending on basin and climate model. Among all four basins the majority of SWIM simulations forced using the different models show an increase in discharge, for some cases even up to 100% and higher. For the Niger, Blue Nile and Ubangi one of the climate models produces an output that differs significantly from the other outputs. For the Niger, MIROC-driven results show an increase in discharge of about 100%, for the Blue Nile the Hadley model driven output has an increase of over 50% during the rainy season, and for the Limpopo the Hadley model driven simulation (which performs best during the base period), shows an increase of over 150%. In the Ubangi basin changes are rather small, all not exceeding 10%: two models show an increase during the rainy season, two models a decrease and one model almost no change. Differences between the emission pathways (RCPs) are small compared to these variations.

The NFS simulations indicate that for both the upper basin at Diem (Fig. 3) and the whole basin at Khartoum (**Error! Reference source not found.**), changes in rainfall are rather modest (2.5% to 8% for the upper basin, and 5-10% for the whole basin in terms of annual totals). The projected changes for dry months are large when expressed as a percentage change for the dry months, but are not significant in terms of annual rainfall amounts. The mean rainfall change during the wet season is generally positive, with only a couple of ensemble members projecting reductions during September. Changes in PET are also small, in the order of 5% in annual totals for both sub-basins, but tend to be positive except for a minority of ensemble members that simulate reductions in PET during the wet season. The physical mechanism responsible for these simulated reductions in PET is increased cloudiness (associated with increased rainfall in these simulations). The general tendencies of a rainfall increase and PET increase are translated as a general tendency to produce increases in flow. Once again there is uncertainty in the projections, however, since a minority of ensemble members project reductions in streamflow (up to 6% for both stations at the annual level) – even though the majority of models project increases up to 29% and 39%, for Diem and Khartoum respectively (at the annual level). The Blue Nile basin is generally sensitive to climatic variations as revealed by previous studies (e.g. Elshamy et al., 2009b) and thus small changes in rainfall and PET are amplified in changes in flow. In terms of the monthly distribution, most members simulate a broader peak than the baseline for Diem. There is considerable uncertainty for the wet months, as Fig. 3f and 4f reveal, as the uncertainty bandwidth is large during the summer months compared to the remainder of the year.

For the Atbara sub-basin, there is a general consensus across all 6 ensemble members of rainfall increase ranging between 3.5% and 21% (in terms of annual totals). This is seen as increases mainly during the wet season. The relative uncertainty (**Error! Reference source not found.**5) is rather high for rainfall, especially in the dry months, but this is of little significance. However, the range of uncertainty of the projections is not as small for the wet season as it is for other sub-basins, including the adjacent Blue Nile. In terms of PET, there is consensus of increases during the dry season, and reductions during the wet season, reinforcing the effect of the projected rainfall increases. The projected increase in intensity of the dry season has minor effects on the flow, as the PET is not realised. Summarized over the whole year, the projected changes in annual rainfall changes are small, ranging from -1.7% to +3.3%. The relatively large increases in rainfall combined with a tendency of PET reduction during the wet season are translated into relatively large increases in flows (**Error! Reference source not found.**e, f) ranging from 2 to 83% in annual totals. This range should be treated with caution, as the baseline simulation shows an underestimation of flow. The hydrographs are scaled up for the different ensemble members, with no changes in peak times. This basin is highly sensitive to climate change, as previous studies revealed (Elshamy et al., 2009a). The uncertainty range of the projected changes in flow is large, even for the wet months (**Error! Reference source not found.**f), indicating different behaviors for the individual ensemble members.

4.3 CHANGES IN EXTREMES

The directions of changes identified for the mean discharge are generally also valid for extremes. The Q10 value is a robust indicator for floods, and designates a value which is only exceeded in 10% of the time. In the catchments of Niger, Limpopo and the Blue Nile, the Q10 value increases for the majority of the simulations driven by the climate models (Fig. 4). In

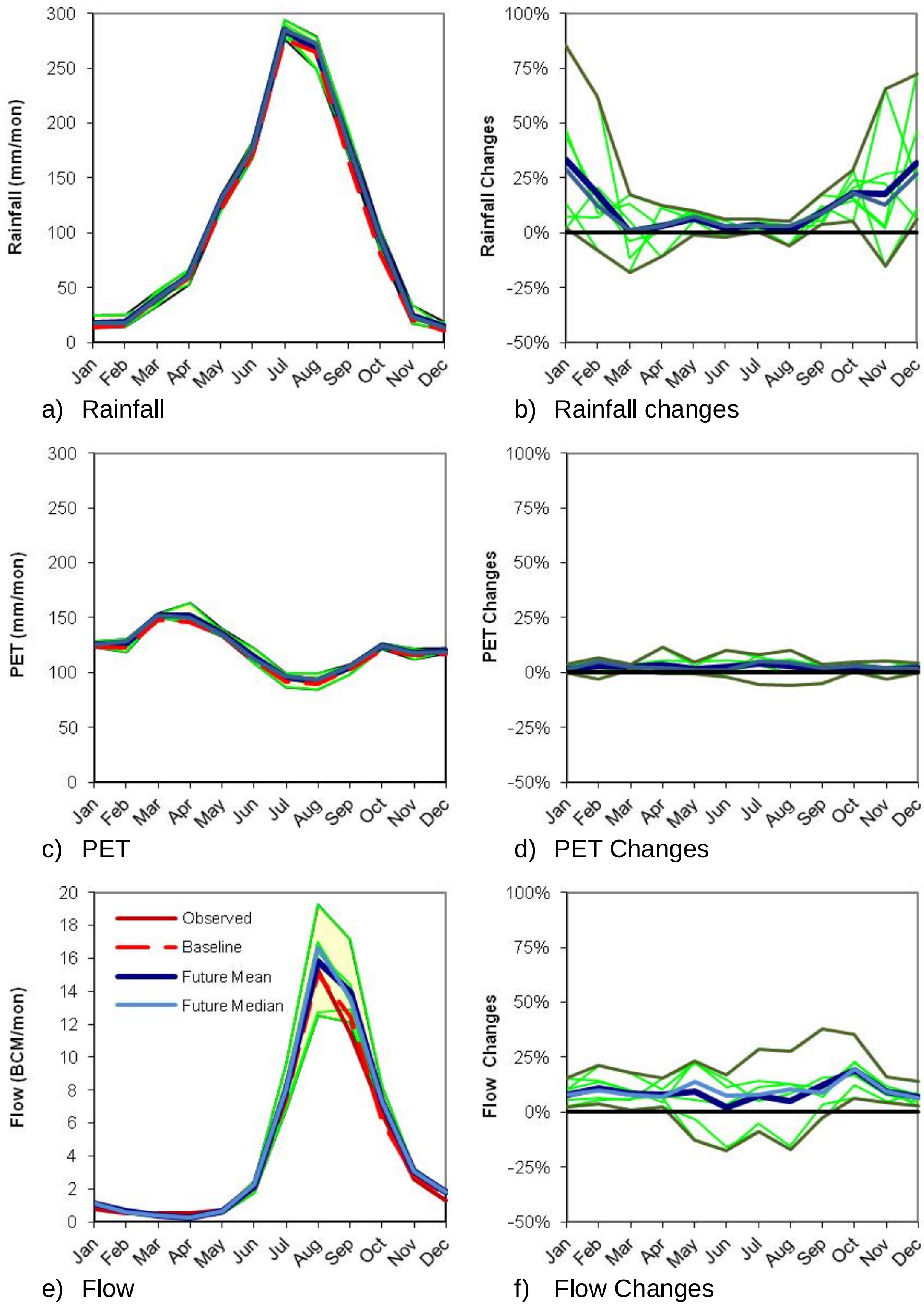

Figure 3. NFS simulated changes in the sub-catchment rainfall and PET and flow of the upper Blue Nile Basin at Diem from 6 RCM ensemble members. The thin green lines show the different RCM ensemble members while the thick green lines show the range.

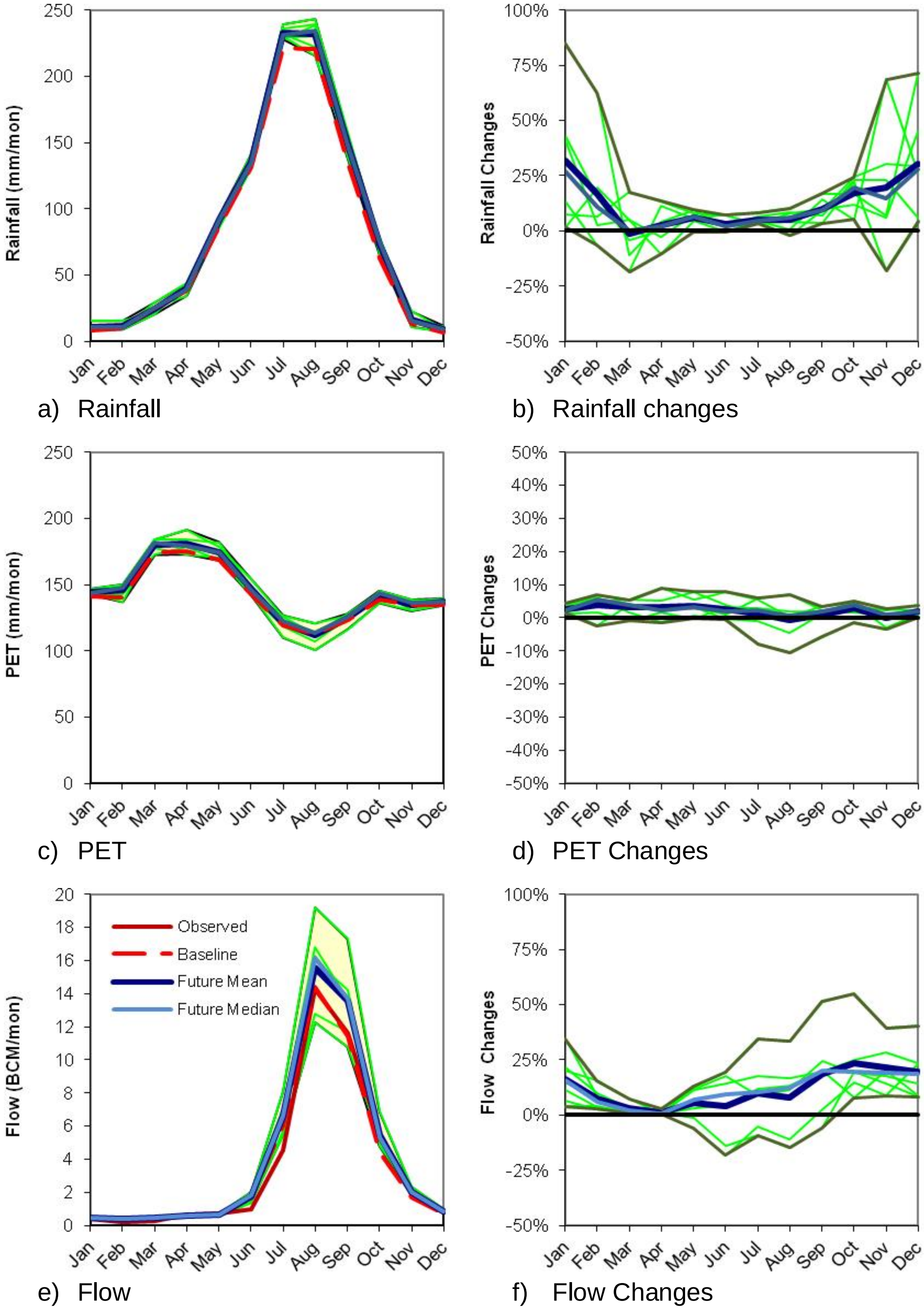

Figure 4. Changes in the sub-catchment rainfall and PET and flow of the Blue Nile Basin at Khartoum from 6 RCM ensemble members. The thin green lines show the different RCM ensemble members while the thick green lines show the range.

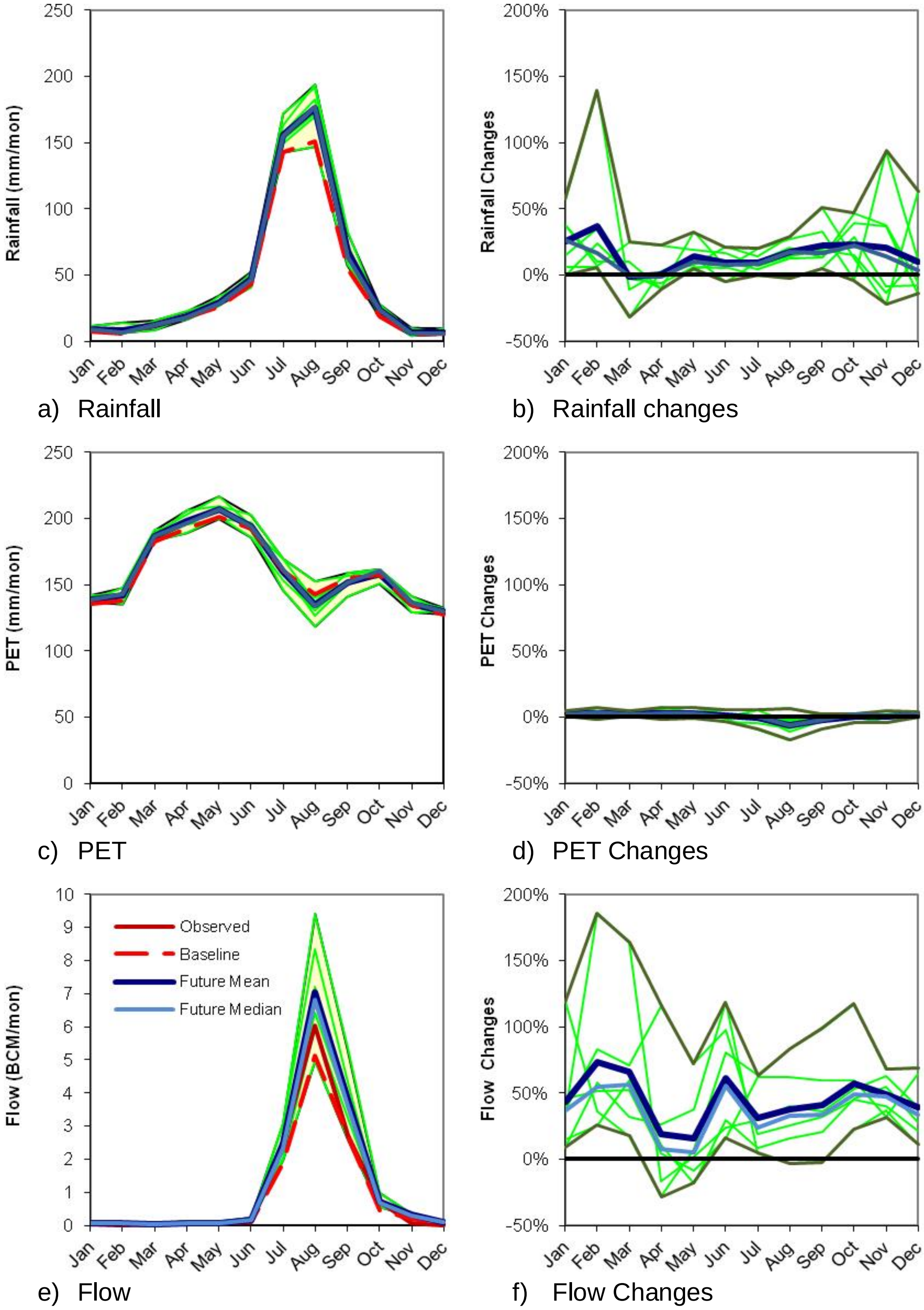

Figure 5. NFS simulated changes in the sub-catchment rainfall and PET and the flow of the Atbara Basin at its mouth from 6 RCM ensemble members. The thin green lines show the different RCM ensemble members while the thick green lines show the range.

MIROC-driven results show the strongest increase of over 100%, whilst other simulations indicate smaller increases (but still of over 20%). In the Limpopo basin, the GFDL and Hadley-driven simulations show a strong increase in discharge, but those driven by IPSL and MIROC indicate decreases. For the Blue Nile, all the simulations indicate a higher Q10 value, but with the simulated increases less than 50%. In the Ubangi basin, highflows are projected to stay at the same or slightly reduced levels under climate change.

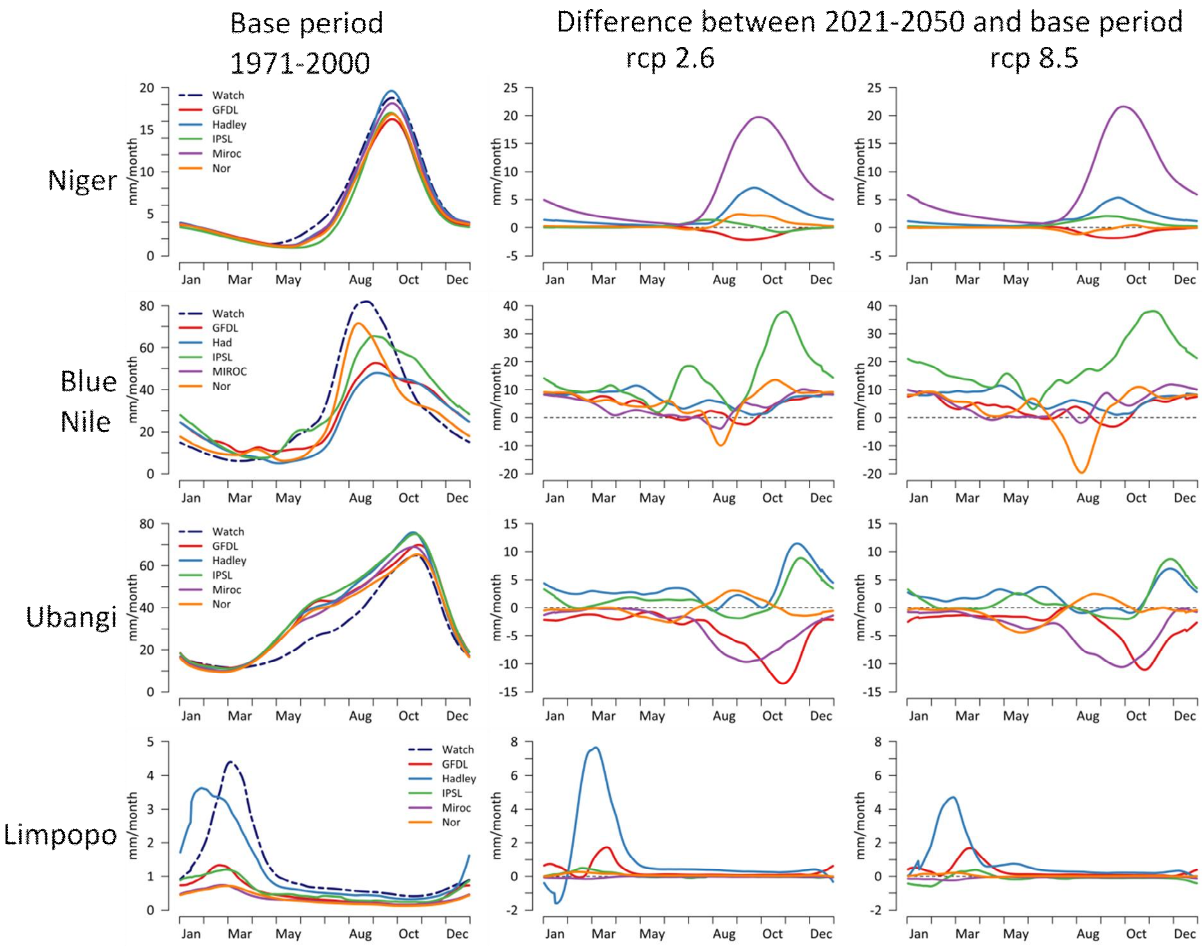

Figure 6. Left column: seasonality of monthly discharge for the reference period, middle and left column: differences in discharge between the scenario and reference periods, for RCP 2.6 and RCP 8.5.

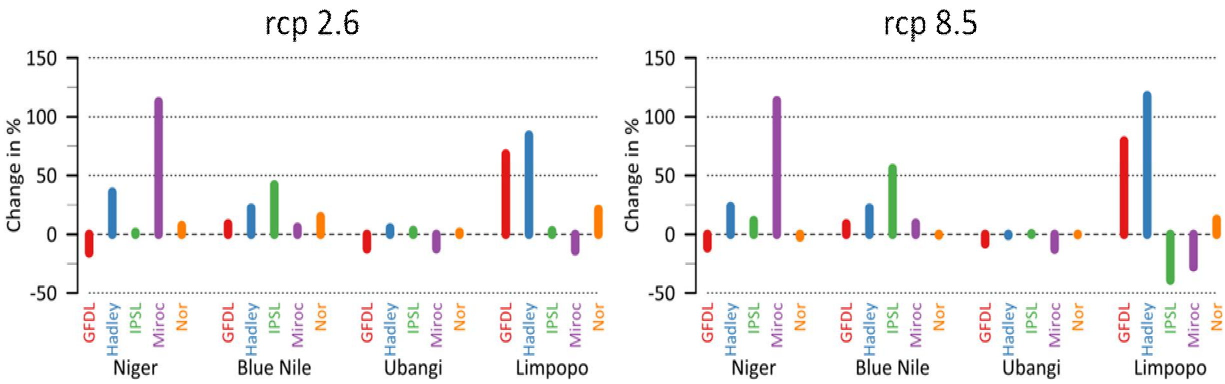

Figure 7. Change of Q10 between 2021-2050 and 1971-2000 for rcp 2.6 (left) and rcp 8.5 (right).

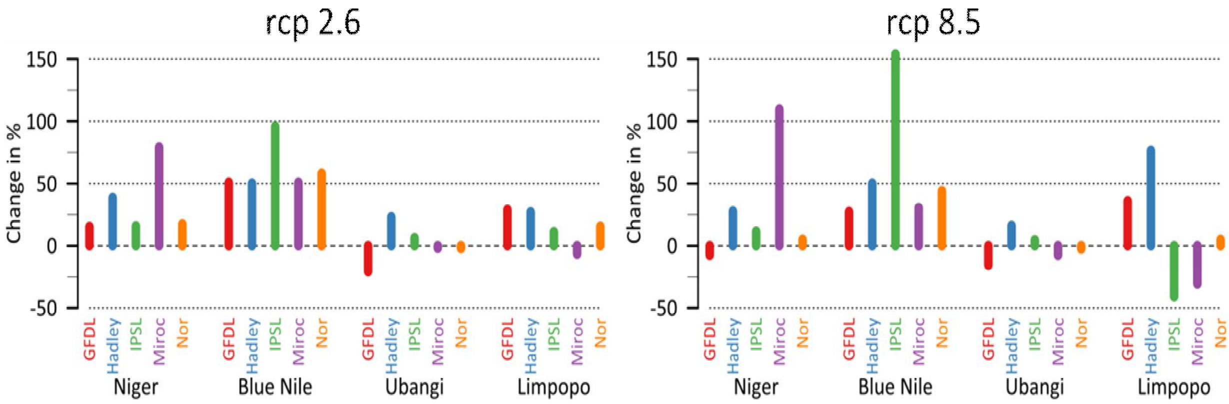

Figure 8. Change of Q90 between 2021-2050 and 1971-2000, for RCP 2.6 (left) and RCP 8.5 (right).

For identifying projected changes in low flows, the Q90 value was used, indicating that 90% of the time that value is exceeded. In all four basins and for almost all simulations the direction of the Q10 trends hold also for Q90 (Fig. 5). For the Niger, MIROC-driven output shows the level of low flows increased to over 100%, a result that also holds for the Blue Nile for the IPSL-driven results. For the Blue Nile, the simulations driven by other climate models show also an increase of over 50%. For the Ubangi basin, low flows are projected to stay almost at the baseline levels. The differences between the RCPs are minor, and there is no agreement whether more emissions would lead to a rise or decline of the extremes in all regions. Still, most trends are stronger in the RCP 8.5 simulations, when compared to the RCP 2.6 simulations.

5. DISCUSSION

The broad range of projected changes in discharge for each basin according to simulations driven by five climate models, and the associated uncertainties, are striking. This holds for means as well as for extremes, and makes the interpretation of results difficult. Notable is the fact that the most extreme projected changes are produced by simulations driven by different climate models for different basins. For the Niger it is the MIROC model, for the Limpopo basin it is the Hadley Centre model, and for the Blue Nile the IPSL-driven results that exceed others very distinctly. Only in the Ubangi basin all projections are in agreement of rather moderate changes in discharge.

As the performance of the SWIM and NFS models for all basins is adequate compared to the observed discharge, the contribution of the hydrological models to these uncertainties is probably minor. This assumption is supported by the small differences between river discharge simulated with WATCH input and with the inputs produced by climate models during the reference period. Especially in areas with very low discharge rates such as in the Limpopo basin, the model is very sensitive to climate input and the requirements for reliable climate input are very high.

6. CONCLUSIONS

The study confirmed that realistic reproduction of the observed discharge depends strongly on availability and quality of data. Data requirements increase with the size of a basin, and also with increases in heterogeneity and complexity (in terms of hydrology and water management). However, an improvement of the regional hydrological model performance will not diminish uncertainties in discharge changes under climate scenarios, as a major share of this uncertainty comes from the climate model projections. These high uncertainties are problematic to communicate to decision makers. Additionally, research into the bias correction of climate projections should receive more detailed attention, as is the case in the ISIMIP. For communicating the differences between RCPs, and therewith the human influence, several runs of bias-corrected climate projections should be provided. Considering a larger set of regional climate model outputs may help to better quantify the inherent uncertainty and to detect some robust trends.

The increasing discharges for all four basins and almost all climate projections have to be interpreted carefully, because uncertainties are remarkably high. Additionally, the needs and efforts on basin development and in intensification of water management in Africa are already high and growing fast. This increased water demand will have an impact on water availability and quality. However, the agreement of many models in the basins of the Niger, Limpopo and Blue Nile on increasing high flows agrees with observations of the past decade of an increase in flood frequency and amplitude (Di Baldassarre et al. 2010). Adaptation efforts on climate change in Africa should not neglect this potential threat, even if water scarcity is still the main challenge in most of the African regions.

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