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Hydrology and Earth System Sciences
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Discussions

Interactive comment on "Simulated Hydrologic Response to Projected Changes in Precipitation and Temperature in the Congo River Basin" *by* N. Aloysius and J. Saiers

Anonymous Referee #1

Received and published: 4 May 2016

This manuscript aims to elucidate the spatiotemporal variability of runoff under the cli- mate changes the climate changes in the Congo River Basin, where long-term data are currently unavailable. Output of 25 global climate models (GCMs) for two rep- resentative concentration pathways (RCPs), combined with downscaling method, are used as input of Soil Water Assessment Tool (SWAT) model. This paper is a valuable contribution to existing literature and also suitable for the HESS scope. However, the resolutions of the topography, precipitation, temperature, land use and soil data used for the modelling with SWAT are not clear in current manuscript. A detailed description of the basin in its current stage (land use, climatic conditions, soli, topography etc.) is needed. The bias-corrected precipitation is slightly over-estimated by the statisticalmethod proposed by Li et al. (2010), what about the bias- temperature? Why have these two RCP scenarios (RCP 8.5 and RCP 4.5) been selected? Why not including the other two RCP scenarios as well (RCP 2.6 and RCP 6.0)? The language could be polished in various places in order to facilitate understanding.

The main and supplemental text are revised to include information about the river basin's physiographic information.

We used the outputs from the Coupled Model Inter-comparison Project phase 5 (CMIP5). The CMIP5 experimental design guidelines [*Taylor et al.*, 2012] recommend the use of RCP4.5 and RCP8.5 simulations as they provide high-interest information about future climate change. We followed these guidelines and decided to present only these two future scenarios.

Overall temperature bias is 0.15 ^{o}C. An assessment of how climate models simulate precipitation and temperature in the Central African region is presented in a separate paper [*Aloysius et al.*, 2016]. Figure 5 e-h in that manuscript (see below) compares the overall biases in temperature. I have also attached the full manuscript for easy reference.

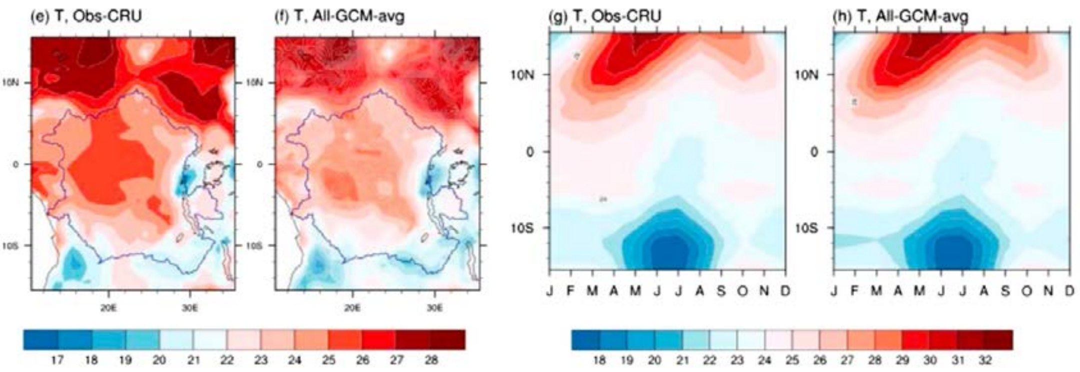

Figure 1 Comparison of observed and bias-corrected annual (e,f) and monthly (g-h) climatology of temperature in the historical period. The units are °C.

Specific comments

Page2 Line 25: “with the projected decrease” should be “with the projected decrease in accessible runoff”??

Revised as suggested

Page3 Line41: “due the region’s heavy. . .” should be “due to the region’s heavy. . .”

Revised as suggested

Page6 Line92: “∼41,000km3/s” should be “∼41,000m3/s” - corrected

Page6 Line96: “a strong dry and wat seasons” or “a strong dry and wet season”? Please check it. - corrected

Page8 Line 135: “The Curve Number and . . . to predict the first two”. This is not clear.

Revised the text and clarified

Page8 Line136-137: “A power law relationship is employed to simulate to the lake area-volume-discharge”. Reference?

Reference included

Page9 Line164: “W m-2”; “m3/s” should be used by negative exponents. Units should be displayed using exponential formatting.

All units have been revised as suggested

Page11 Line190: “1,450 mm/year” should be “1,450 mm”

Revised as suggested

Page11 Line194: The linear-regression slope (1.16) should be illustrated in Figure 2.

Regression details added to Figure 2.

Page11 Line195: “show that” should be “shows that” – revised as suggested

Page11 Line197: “and within the four regions identified in Figure 1 (SI Table S3)”. I could not draw the conclusion from SI Table S3.

SI Figure S2 shows the seasonal precipitation. SI Table S3 provides the mean values within the regions identified in Figure S1. The text has been modified.

Page11 Line204-205: “Seventeen of the 30 gages show NSE greater than or equal to 0.5” This sentence is not clear.

Literature suggests that model simulations can be considered satisfactory if Nash-Sutcliff values are ≥ 0.5. This is clarified in the text and a reference is added to support [*Moriasi et al.*, 2007].

Page12 Line212: “indicating the hydrology model’s skill in simulating runoff satisfactorily over a wide range in watershed areas”. ?? This sentence is not clear.

Catchment areas of all gages considered vary between 5,000 to 900,000 km^2 and encompass a range climatic regions on both sides of the equator. In this context, our hydrology model performance is satisfactory. The text has been modified to clarify.

Page13 Line239: “vary” should be “varies” – text revised

Page13 Line243: delete “, with indications of spatial patterns” – sentence revised

Page14 Line249-250: “Most GCMs (>15) predict . . . in the SE”. I could not draw the conclusion from all figures in the manuscript and the supplemental material. A figure showing the percentage agreement in the increase runoff at each unit would be helpful. The percentage of ensemble members that agree on the sign of change for projected change in runoff could be calculated.

A figure is added to reflect the author’s comments.

Page14 Line267: “Although northern and equatorial CRB” should be “Although the northern and equatorial CRB” – sentence revised

Page15 Line274: “The variability is larger NC and SE . . . during the rainy seasons.” This sentence is not clear.

The sentence is revised to clarify.

Page15 Line278: “in SE” should be “in the SE” – sentence revised

Page15 Line282: “most part of EQ” should be “most part of the EQ” – sentence revised

Page15 Line287: “produce compatible . . . and provide their . . .” should be “produces compatible . . . and provides their . . .” – revisions are incorporated in the revised version

Page17 Line316-317: “Figure 8 also shows moderate increase in the SW to decrease or no-change in the SE during the rainy season (DJF).” should be “Figure 8 also shows moderate increase in the SW and decrease or no-change in the SE during the rainy season (DJF).” - revised

Page18 Line349: “reveal” should be “reveals” Page21 Line393: “;” should be “,” - revised

Page21 Line394-395: “. . . of Historical and Future Simulations of Precipitation and Temperature in Central Africa from CMIP5 Climate Models”. The initial letters should be lowercase. - revised

Page21 Line400: “GLC2000: a” should be “GLC2000: A” - revised

Page21 Line405: “World agriculture: towards 2015/2030: an FAO perspective” should be “World agriculture: Towards 2015/2030: An FAO perspective” - revised

Page22 Line430: “Giorgetta, M. A., et al.” Please add all authors. – This reference has 39 co-authors, therefore, we decided to include only the first author.

Page22 Line441: “cycle: mechanisms . . .” should be “cycle: Mechanisms . . .” - revised

Page22 Line452: “Nature Clim. Change” Please do not use the abbreviation of the journal. - revised

Page23 Line461-464: The initial letters of the paper title should be lowercase. And please do not use the abbreviation of the journal.

revised

Page23 Line469; Page24 Line501; Page25 Line549 and Line 558: Please do not use the abbreviation of the journal. –

revised

Page23 Line477-478: “Climate Change Projections in CESM1(CAM5) Compared to CCSM4” should be “Climate change projections in CESM1(CAM5) compared to CCSM4” - revised

Page23 Line479: “life: a” should be “life: A” - revised

Page23 Line482; Page24 Line503 and Line508; Page25 Line550 and Line558: “et al.” Please add all authors. – These references have more than 10 co-authors

Page24 Line496: “The Seasonal Evolution of the Atmospheric Circulation over West Africa and Equatorial Africa” should be “The seasonal evolution of the atmospheric circulation over west Africa and equatorial Africa” - revised

Page24 Line508: “The Global Land Data Assimilation System” should be “The global land data assimilation system” - revised

Page24 Line519: “scheme: linking” should be “scheme: Linking” - revised

Page24 Line521: “Hydrological Cycles over the Congo and Upper Blue Nile Basins: Evaluation of General Circulation Model Simulations and Reanalysis Products” should be “Hydrological cycles over the Congo and Upper Blue Nile Basins: Evaluation of general circulation model simulations and reanalysis products” - revised

Page25 Line550: “model: description” should be “model: Description” - revised

Page25 Line556: “climatology: can” should be “climatology: Can” - revised

Page25 Line 559-560: The initial letters of the paper title should be lowercase except the first word. - Revised

Page30 Line582: “water yield” is the same as “runoff”?? –revised the figure caption

Page30 Line585: “show” should be “shows” - revised

Page37 Line606 and Page40 Line624: “Figure 1A” don’t exist. Please check it. Page38: What the unit of Figure 8 is??

Revised

Some specific comments in the supplemental material Page1 Line11: “H Lehner et al.” should be “Lehner”

Revised

Page1 Line17; Page9 Line77; Page10 Line84; Page14 Line100; Page15 Line104; Page17 Line109; Page19 Line119 and 121: “Figure 1A” don’t exist. Please check it.

Revised

Page9 Line76; Page10 Line83; Page11 Line89: “projected” should be “Projected”

Revised

Page13: What the unit of Figure S1 is??

The units are in mm month^{-1}. The figure caption is revised.

Page16 Line104: “(D) Sep-Oct-Nov).” should be “(D) Sep-Oct-Nov.” Page18: The legend in each sub-figure could be deleted.

Revised. The square dots show projections of a subset of models outputs.

Page19 Line119: “accessible” should be “Accessible” - Revised

Page21 Line128: “GLC2000: a new” should be “GLC2000: A new” – revised

Page21 Line 141: The initial letters of the paper title should be lowercase except the first word. – revised a suggested

Page21 Line149: “et al.” Please add all authors.

This reference has 15 co-authors

Page21 Line153-154: The initial letters of the paper title should be lowercase. And please do not use the abbreviation of the journal.

All references have been revised as suggested

References

Aloysius, N., J. Sheffield, J. E. Saiers, H. Li, and E. F. Wood (2016), Evaluation of historical and future simulations of precipitation and temperature in Central Africa from CMIP5 climate models, *Journal of Geophysical Research - Atmospheres, 121*(1), 130-152, doi: 10.1002/2015JD023656.

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Hydrology and Earth System Sciences
Discussions

Interactive comment on "Simulated Hydrologic Response to Projected Changes in Precipitation and Temperature in the Congo River Basin" *by* N. Aloysius and J. Saiers

Anonymous Referee #2

Received and published: 22 May 2016

General comments

The authors address future change in water availability in the Congo Basin. This topic is welcomed given the relative lack of research for this important region. The authors have embarked on a thorough analysis using projections from 50 climate model experiments which are bias corrected and downscaled and run through a hydrologic model. As with any impacts study of this nature, there are a host of uncertainties and methodological choices which can influence the outcomes, and it is challenging to distill information about future impacts in this context. There are also different views amongst scientists as to the best way to approach these uncertainties. However, personally I feel that the balance of emphasis on uncertainties is not quite right in this study, and would like to see more discussion/emphasis on the climate model uncertainty (and less emphasis on the multi-model mean), as well as more analysis of observational uncertainty. Therefore I suggest major revisions. Please note that my background is in climate science so I will mainly comment on this component of the study, and do not have the relevant expertise to comment on the hydrological modelling.

1. Model uncertainty: Given the uncertainties associated with future climate, I think that the comments on the implications of the findings, particularly in the abstract and conclusions, are too strong. The "challenges" described for planners in the abstract occur only if the projections are valid (which we won't know for 50 years). The authors also make several comments about the importance of providing "details" for planners. I disagree. I think it is more important that planners are aware of uncertainties in future climate, and would benefit more from information about the range of future projections than the multi-model mean. (This is in line with a body of researchers and literature discussing such issues e.g. Weaver et al. 2011; Dessai et al. 2009; Knutti et al. 2008).

The authors have quite a large ensemble of projections from their modelling which could be made much more useful in this regard. I think it would be more useful if they commented on the size of the uncertainty and what this means for planning – are there any regions for which there is not a great deal of model uncertainty, where planners can prepare for wetter or drier conditions? Or is there also uncertainty in the direction of change which might mean that adaptive/robust planning strategies are more appropriate? How does the uncertainty from climate models compare to other uncertainties e.g. if a different hydrological model were used?

In general I think they should put more emphasis on understanding the range (e.g. Figure 7 which is useful) and less on the multi model mean (e.g. Figure 6, which should include a measure of uncertainty).

We have revised the text and abstract to highlight the projection ranges and the uncertainties planners will encounter. Figure 6 has been modified to show model projection agreement in runoff change. This figure also highlights the spatial variability in the direction of change (i.e. increase or decrease in runoff).

The historical simulation period is from 1950-2008. The model was calibrated during the early part of the simulation period in order to take advantage of available observed river flow data at 30 gage locations within the basin. The model simulations were validated outside the calibration period at 30 gage locations (Figure 1 and 2). The region had sufficiently detailed data during early part of the simulation period [*Alsdorf et al.*, 2016; *L'vovich*, 1979]. Satellite measurements, sparse ground-based measurements and reanalysis products provide the most reliable climate data for the reminder of the simulation period [*Alsdorf et al.*, 2016; *Munzimi et al.*, 2014].

We only used one hydrological model. However, recent research suggest that projection uncertainties dominate compared to other sources of uncertainties (e.g. model structure and parameters) in hydrologic projections [*Maurer and Pierce*, 2014]. Suggested references have also been used to improve the discussion section.

2. Observational uncertainty. The first sentence of the paper states that efforts to understand the impacts of climate change in the Congo Basin are hindered by data availability. However, the authors do not make clear in the paper how they have overcome this, or the extent to which their findings are valid given observational uncertainty. They use an observational dataset from Sheffield et al. and (I think) use this for (a) bias correction (b) temporal downscaling to daily data and (c) sub-selecting climate models based on their ability to represent the region. Therefore, the observations might have a very important influence on their findings.

It is generally accepted (e.g. Washington et al. 2013) that availability of observed climate data in this region is a huge problem which might prevent subselection of models or bias correction. How can we say which model is more valid when there are basic questions remaining about the quantity of precipitation or where the precipitation maximum occurs? What dataset should we use assess and correct biases when there are large differences between the observational datasets used? The Sheffield et al. dataset does sound like an impressive undertaking and an important initiative but in the absence of rain gauge records it is difficult to validate it for this region, so it it still just one estimate of the observed state. I think the authors should, as a minimum, comment on the extent to which this dataset is reliable for the region and the extent to which their results might be influenced by observational uncertainties. They could also repeat their correction analyses with an alternative observational estimate and see whether this influences their results.

I am particularly concerned about the temporal downscaling to daily data, and think the authors should comment on the extent to which this is reliable, give that our understanding of day-to-day variability in precipitation/organisation of convection/meso-scale convective systems in this region is just beginning.

As mentioned in the earlier response, the region had sufficiently detailed ground-based observational data (e.g. precipitation and river flows) during early part of the simulation period. Satellite-based and limited ground-based observations are used to develop historical precipitation data used in our study. The dataset is developed and evaluated using multiple observation-based and reanalysis products (TRMM, GPCP, CRU, NCEP-NCAR and the second Global Soil Wetness Project) [*Sheffield et al.*, 2006]. During the development of the this dataset, the NCEP-NCAR precipitation product was examined and corrected for total monthly precipitation and monthly rain day statistics using CRU, GPCP and a 15-year gage-based dataset. The downscaling process also took into consideration the spatial consistency.

The lack of observational data (both precipitation and river flow) during the late 1970s and 1980s is a constrain and a limitation in this region. We have discussed these limitations and constraints in the manuscript.

Specific comments

p. 4. Line 50. “require detailed information” – perhaps rephrase. If the information is not credible then details could be counterproductive. So I think better to say “would benefit from detailed information”

Revised

p. 4. Line 54. “predictive” and “forecast” – suggest change to “project” since we cannot forecast or predict on these timescales, only “project” what if under certain emissions scenarios. Suggest changing throughout.

Revised

p. 9. Line 162 – I am not sure what is meant by “medium mitigation” for RCP4.5.

The phrase is revised as “mid-range mitigation emission”. The paragraph is revised to make clear the two emission scenarios.

p. 11. Line 190 – does this refer to bias corrected precip? If so I think this should be highlighted. Does it mean much if bias corrected precip fits with observations? Since it has been corrected using these observations?

The GCM-simulated annual precipitation refers to the bias-corrected values. The paragraph has been revised to make this point clear. We used a statistical bias-correction method to correct monthly GCM-outputs [*Li et al.*, 2010]. The procedure is described in the methods section and in the SI.

p. 11. Line 193. “The modeled inter-annual variability among the climate models (vertical bars in Figure 2) lies within the range of the observed variability” – Looking at the figure I am not sure this is strictly true. I can see a few examples where the error bar for the models is larger than for the observed.

In Figure 2, we show, among the 25 GCM outputs, the largest (red vertical bars) and smallest (blue vertical bars) values. As noted, there are some GCM outputs that show larger variabilities.

Figure 2 – please clarify the meaning of the modelled error bar. The caption states that it is based on the minimum and maximum range of interannual variability from the models. Is there anything to show the range of mean/climatological values for the models? And how does this compare? (similar comment for Figure 3b)

The vertical bars show mean ± one standard deviation of GCM-simulated annual precipitation during the historical period (1950-2005). The red bars denote the largest variability (highest value of std. dev.) within the 25 GCM outputs, and the blue bars denote the smallest. The horizontal bars shows the mean ± one standard deviation for the observed precipitation during the same historical period. Each black point indicates the mean annual precipitation within the drainage areas at gage locations showed in Figure 1. The text and figure captions have been revised.

p. 13. Line 239 – why is the IQR used? What is the full range?

We chose to present the inter quartile range to highlight where the bulk of the projection values lie. The full range of precipitation projections varies between a 3% decrease to a 6% increase in the near-term (2016-2035). The mid-term (2046-2065) changes are -5% to 7.6% for RCP4.5 and -6% to 9% for RCP8.5, respectively.

Figure 7 – nice figure. Is there a way to make historical plot clearer?

Figure has been revised.

p. 16 Line 293 – I am not sure that MMEs reduce uncertainty. It’s more that they help explore and reveal uncertainty.

We have revised as per the reviewers suggestions.

p. 16 Line 304 – I think it is overstating it to say that these models reliably simulate regional climate. We don’t have good enough observations of the regional climate to judge this. And, in any region, subselecting models is usually about taking the ones which most reliably simulate regional climate, rather than being confident that they are good enough.

We evaluated the annual, seasonal and monthly simulations of precipitation and temperature by the 25 GCM in the Central African region in a separate manuscript [*Aloysius et al.*, 2016]. Previous works in the Central Africa region highlight that model skill in simulating precipitation are partly dependent on how they replicate teleconnections with sea-surface temperature (SST) departures, particularly in the North Atlantic and Indian Ocean sectors (e.g. *Balas et al.* [2007]; *Dezfuli and Nicholson* [2013]; *Hirst and Hastenrath* [1983]; *Suzuki* [2011]). Our companion manuscript [*Aloysius et al.*, 2016] explored the linkages between precipitation and SST departures, and identified a subset of GCMs that simulate precipitation well.

We revised the discussion taking into consideration i) the above points and ii) the reviewer’s comments.

p. 17 Line 326. This is quite an odd paragraph which starts of talking about implications of findings (from MM and SM?) and then finishes by saying we can reduce the range of projections from MMEs. Perhaps this should be reconsidered to suggest more nuanced conclusions about the implications of the findings which incorporate uncertainty? It is also not clear, when the author is discussing the potential to constrain model ensembles using knowledge of mechanisms that moderate the regional climate system, whether this is something they feel they have already done, or something that needs to be done. If the former, I'd suggest that their subselection procedure warrants further attention in the paper.

This section has been revised.

Figure 8 – quite a lot of information here. Could it be distilled to extract the main message?

Figure is revised.

p. 19 Line 363. "with sufficient details". I disagree. Providing details to planners may be misleading if there is too much uncertainty to give details. Better to help planners understand the uncertainty?

This section has been revised to highlight projection uncertainties between GCMs and emission scenarios.

p. 20 Line 377. "The analyses presented in our work increase the degree of confidence in using the results for policy and management." This is unsubstantiated.

References

Aloysius, N., J. Sheffield, J. E. Saiers, H. Li, and E. F. Wood (2016), Evaluation of historical and future simulations of precipitation and temperature in Central Africa from CMIP5 climate models, *Journal of Geophysical Research - Atmospheres*, *121*(1), 130-152, doi: 10.1002/2015JD023656.

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Simulated Hydrologic Response to Projected Changes in Precipitation and Temperature in the Congo River Basin

Abstract

Assessing the impacts of climate change on water resources of the Congo River Basin (CRB) has attracted widespread attention. Of particular interest to water resource planners~~ and policy makers~~ is the spatiotemporal variability of runoff due to the projected changes in climate. Here, with the aid of a spatially explicit hydrological model forced with precipitation and temperature projections from 25 global climate models (GCMs) under two greenhouse gas emission scenarios, we elucidate the variability in runoff in the near (2016-2035) and mid (2046-2065) 21st century compared to present. Over the equatorial, northern and southwestern CRB, models project an overall increase in precipitation and, subsequently runoff. A decrease in precipitation in the headwater regions of southeastern Congo, leads to a decline in runoff. Climate model selection plays an important role in precipitation projections, for both magnitude and direction of change. ~~Model c~~Consensus on the magnitude and the sign (increase or decrease) of change is strong in the equatorial and northern parts of the basin, but weak in the southern basin. The multi-model approach reveals that near-term projections are not impacted by the emission scenarios. However, the mid-term projections depend on the greenhouse gas emission scenario. The projected increase in accessible runoff (excluding flood runoff) in most parts of CRB presents new opportunities for augmenting human appropriation of water resources; at the same time, the increase in quick runoff poses new challenges. In the southeast, with the projected decrease in accessible runoff, the

challenge will be on managing the increasing demands with limited water resources. Uncertainties in precipitation and subsequently in runoff projections vary widely, and therefore adaptation and robust planning strategies will vary within the river basin, and will depend on the risk attitudes of resource planners.

1. Introduction

Sustainable management of water resources (e.g. water for food production, reliable and safe drinking water and adequate sanitation) presents immense challenges in many countries in Central Africa where the Congo River Basin (CRB) is located [*IPCC*, 2014; *UNEP*, 2011; *World Food Program*, 2014]. The economies of the nine countries that share the waters of the CRB are agriculture-based [*World Bank Group*, 2014] and, therefore, are vulnerable to the impacts of climate change. Despite the abundant water and land resources and favorable climates, the basin countries are net importers of staple food grains, and are far behind in achieving Millennium Development Goals [*Bruinsma*, 2003; *Molden*, 2007; *UNEP*, 2011]. Appropriation of freshwater resources is expected to dominate in the future as the CRB countries develop and expand their economies. At the same time, climate change related risks associated with water resources will also increase significantly [*IPCC*, 2014].

Historical, present and near-future greenhouse gas emissions in the CRB countries constitute a small fraction of global emissions; however, the impacts of climate change on water resources are expected to be severe due to the region’s heavy reliance on natural resources (e.g. agriculture and forestry) [*Collier et al.*, 2008; *DeFries and Rosenzweig*, 2010; *Niang et al.*, 2014]. The limited adaptation capacity in the CRB region is expected to cause severe water and food security challenges, which, in turn, can lead to ecosystem degradation and increased greenhouse gas emissions [*Gibbs et al.*, 2010; *IPCC*, 2014; *Malhi and Grace*, 2000].

Competing pressures on water resources in the CRB, including revival of rural economies (largely agriculture based), achieving millennium development goals and environmental conservation, would benefit from detailed information on the spatial and temporal variability of water balance components under different climate projection pathways. The effect of climate change on water resources can be investigated by incorporating climate change projections (e.g. precipitation and temperature) in simulation models that reliably represent the spatial and temporal variability of CRB's hydrology. Such a ~~predictive~~ framework could be applied to ~~forecast~~ project changes in storage and runoff, and hence freshwater availability, under different socioeconomic pathways that affect climate trajectories.

A predictive framework of CRB hydrology is hindered by insufficient data and too few evaluations of models against available data [*Beighley et al.*, 2011; *Wohl et al.*, 2012]. Basin scale water budgets estimated from land-based and satellite-derived precipitation datasets reveal significantly different results, and model-computed stream flows show only qualitative agreement with corresponding observations [*Beighley et al.*, 2011; *Lee et al.*, 2011; *Schuol et al.*, 2008]. *Tshimanga and Hughes* [2012; 2014] recently developed a semi-distributed hydrologic model capable of simulating surface-water runoff in CRB. This work crucially identified approaches suitable for approximating runoff generation at the basin scale, although the spatial resolution of the model predictions is rather coarse for supporting regional water management and regional-planning efforts. These regional planning efforts must take into account variablity and uncertainties stemming from climate-model selection and projected greenhouse gas emissions, but with respect to hydrological modeling of the CRB these issues have been incompletely addressed.

The goals of this study are to i) develop a spatially explicit hydrology model that uses downscaled output from general circulation models (GCMs) and is suitable for simulating the spatiotemporal variability of surface-water runoff throughout the CRB; ii) test the ability of the hydrological model to reproduce historical data on CRB river discharges using both observed and GCM-simulated climate fields; (iii) quantify the sensitivity of hydrologic-model runoff predictions to GCM selection; (iv) use the hydrologic model with individual GCMs and multi-GCM ensembles to forecast near-term (2016-2035) and mid-term (2046-2065) changes in surface-water flows for two greenhouse-gas emission scenarios. We focus on the runoff projections of the hydrologic model because streams and rivers will serve as the primary sources of freshwater targeted for human appropriation [*Burney et al.*, 2013; *Molden*, 2007].

We show that the hydrologic model that is forced with bias-corrected and downscaled outputs from an ensemble of 25 GCMs and two emission scenarios reveal a range of projected changes in precipitation and runoff, and that runoff yields and dynamics are highly sensitive to GCM-forcing. The multi-model mean (MM, unweighted average of all GCMs) and the select-model mean (SM, selected GCMs based on performance in the historical period and realistic representation of certain attributes in the climate system) reveal 1-3% and 4-9% increase in precipitation and runoff, respectively in the CRB in the near-term (2016-2035) relative to reference period (1985-2005). In the mid-term (2036-2065), on the other hand, projections are GCM and emission-scenario dependent, with the high emission RCP8.5 scenario showing the highest increases in precipitation (2-5%) and runoff (7-14%). However, both MM and SM show decreasing precipitation and runoff patterns in the southeastern headwater regions of Congo.

2. Materials and Methods

2.1 The Congo River Basin

The Congo River Basin, with a drainage area of 3.7 million km^2, is the second largest in the world by area and discharge (Figure 1, average discharge of ~41,000 m^{3}s^{-1}) [*Runge*, 2007]. The basin extends from 9^{o}N in the northern hemisphere to 14^{o}S in the southern hemisphere. The longitudinal extent is 11^{o}E to 35^{o}E. Nine countries share the water resources of the basin. Nearly a third of the basin area lies north of the equator. Due to its equatorial location, the basin experiences a range of climate regimes. The northern and southern parts have a strong dry and wet seasons, while the equatorial region has a bimodal rainy season [*Bultot and Griffiths*, 1972]. Much of the rain in the northern and southern CRB is received in Jun-Jul-Aug (JJA) and Dec-Jan-Feb (DJF), respectively. The primary and secondary rainy seasons in the equatorial region are Sep-Oct-Nov (SON) and Mar-Apr-May (MAM, see [*Bultot and Griffiths*, 1972] and Supplemental Information (SI) Figure S1). The mean annual precipitation is about 1,500 mm. Rainforests occupy nearly 45% of the basin and are minimally disturbed compared to the Amazon and Southeast Asian forests[*Gibbs et al.*, 2010; *Nilsson et al.*, 2005]. Grassland and savannah ecosystems, characterized by the presence of tall grasses, closed-canopy woodlands, low-trees and shrubs, occupy another 45% [*Adams et al.*, 1996; *Bartholomé and Belward*, 2005; *Hansen et al.*, 2008; *Laporte et al.*, 1998]. Water bodies (lakes and wetlands) occupy nearly 2% of the area, but they are concentrated mostly in the southeastern and western equatorial parts of CRB (Figure 1). Soil mapping reveals that soils in the CRB vary from highly weathered and leached Ultisols to Alfisols, Inceptisols and Oxisols [*FAO/IIASA*, 2009; *Matungulu*, 1992]. Most types are deep and well-drained, but they are very acidic, deficient in nutrients, have low capacity to supply potassium and exhibit a low cation exchange capacity [*Matungulu*, 1992].

In order to compare regional patterns in precipitation and runoff, we divided the basin into four regions: i) Northern Congo (NC), ii) Equatorial Congo (EQ), iii) Southwestern Congo (SW), and iv) Southeastern Congo (SE). The EQ region covers most of the rainforest. The SE region consists of many mostly interconnected lakes and wetlands. Most of the CRB's population is concentrated in the NC, SE and SW regions [*Center for International Earth Science Information Network (CIESIN) Columbia University et al.*, 2005].

2.2 Hydrologic model for the Congo River Basin

We used the Soil Water Assessment Tool (SWAT) [*Arnold et al.*, 1998; *Neitsch et al.*, 2011] to simulate the hydrology of the CRB for historical climate (1950-2008) and for two scenarios of future climate change. SWAT is a physically based, semi-distributed watershed-scale model that operates at a daily time step. The hydrological processes simulated include evapotranspiration (ET), infiltration, surface and subsurface flows, streamflow routing and groundwater recharge. The model has been successfully employed to simulate river basin hydrology under wide variety of conditions and to investigate climate change effects on water resources [*Faramarzi et al.*, 2013; *Krysanova and White*, 2015; *Schuol et al.*, 2008; *Trambauer et al.*, 2013; *van Griensven et al.*, 2012].

We delineated 1,575 watersheds within the CRB based on topography [*Lehner et al.*, 2008]. Watershed elevations vary between 15m and 2,700m with a mean value of 680m above mean sea level. Each watershed consists of one stream section, where near-surface groundwater flow and overland flow accumulate before being transmitted through the stream channel to the watershed outlet. Watersheds are further divided into Hydrologic Response Units (HRUs) based on land cover (16 classes) [*Bartholomé and Belward*, 2005], soils (150 types) [*FAO/IIASA*, 2009] and topography. The runoff generated within each watershed is routed through the stream network using the variable storage routing method. The average watershed size and the number of HRUs within each watershed are 2,300 km^2 and 5, respectively. We also included wetlands and lakes as natural storage structures that regulate the hydrological fluxes at different locations within CRB (Figure 1). Detailed information is not available for the all the lakes; therefore, we incorporated the largest 16 lakes (SI Table S1).

Runoff, estimated for each HRU and aggregated at the watershed level, is generated via three pathways: overland flow, lateral subsurface flow through the soil zone and release from shallow groundwater storage. The Curve Number and a kinematic storage routing methods are used to predict overland and lateral subsurface flows, and a nonlinear storage-discharge relationship is used to predict groundwater contribution (see *Arnold et al.* [1998]; *Neitsch et al.* [2011] and SI). A power law relationship is employed to simulate the lake area-volume-discharge (see SI and *Neitsch et al.* [2011]). The potential evapotranspiration is estimated using the temperature-based Hargreaves method [*Neitsch et al.*, 2011]. The actual evapotranspiration is estimated based on available soil moisture and the evaporative demand (i.e. potential evapotranspiration) for the day. Additional details on model development are provided in the Supplementary Information.

2.3 Model simulation of historical hydrology with observed climate forcings

We ran the hydrology model for the period 1950-2008. Estimates of observed daily precipitation, and minimum and maximum temperatures needed to calculate potential evapotranspiration were obtained from the Land Surface Hydrology Group at Princeton University [*Sheffield et al.*, 2006]. In addition, measured monthly stream flows were obtained at 30 gage locations (Figure 1) that had at least 10 years of records [*Global Runoff Data Center.*, 2011; *Lempicka*, 1971; *Vorosmarty et al.*, 1998].

The model was calibrated using observed streamflows for the period 1950-1957 at 20 locations. The number of model parameters estimated by calibration varied from 10 to 13, depending on the location of flow gages (e.g. gages with lakes within their catchment area have more parameters). The calibration involved minimizing an objective function defined as the sum-of-squared errors between observed and simulated monthly average total discharge, baseflows (estimated by applying a baseflow separation method [*Nathan and McMahon*, 1990]) and water yield. A Gauss-Marquardt-Levenberg algorithm as implemented in a model independent parameter estimation tool [*Doherty*, 2004] was used to adjust the fitted parameters and minimize the objective function. Parameter estimation was done at two stages. First, parameters for the watersheds in the upstream gages were estimated. Then the parameters for the downstream gages were estimated. To test the calibrated model, simulated stream flows were compared to stream flows measured at the same 20 locations, but during a period outside of calibration (i.e., 1958-2008), as well as at 10 additional locations that were not used in the calibration.

2.4 Hydrologic Simulations with Simulated Climate Forcing

Historical climate simulations for the period 1950-2005 and climate projections to 2099 for two greenhouse gas emission scenarios, mid-range mitigation emission (RCP4.5) and high emission (RCP8.5), were used as a basis to drive the hydrologic model. The RCP4.5 scenario employs a range of technologies and policies that reduce greenhouse gas emissions and stabilize radiative forcing at 4.5 W m^{-2} by 2100, whereas the RCP8.5 is a business-as-usual scenario, where greenhouse gas emissions continue to increase and radiative forcing rises above 8.5 W m^{-2} [*Moss et al.*, 2010; *Taylor et al.*, 2012]. We used monthly precipitation and temperature outputs provided by 25 GCMs (SI Table S2) for the Fifth Assessment (CMIP5) of the Intergovernmental Panel on Climate Change (IPCC).

GCM outputs may exhibit biases in simulating regional climate. These biases, which are attributable to inadequate representation of physical processes by the models, prevent the direct use of GCM output in climate change studies [*Randall et al.*, 2007; *Salathé Jr et al.*, 2007; *Wood et al.*, 2004]. Hydrological assessments that use GCM computations as input inherit the biases [*Salathé Jr et al.*, 2007; *Teutschbein and Seibert*, 2012]. To mitigate this problem, we implemented a statistical method [*Li et al.*, 2010] to correct the biases in the monthly historical precipitation and temperature fields. In brief, the method employs a quantile-based mapping of cumulative probability density functions for monthly GCM outputs onto those of gridded observations in the historical period. The bias correction is extended to future projections as well.

In order to be used in the CRB's hydrologic model, the simulated monthly precipitation and temperature values must be temporally downscaled to daily values. We used the three-hourly and monthly observed historical data developed for the Global Land Data Assimilation System [*Rodell et al.*, 2004; *Sheffield et al.*, 2006] and the bias-corrected monthly simulations to generate three-hourly precipitation and temperature fields, which were subsequently aggregated to obtain daily values (see SI Methods). The hydrological model was forced with the bias-corrected and downscaled daily climate fields for the period 1950-2099. A total of 50 projections (25 RCP4.5 and 25 RCP8.5 projections) were compiled and analyzed. Results of individual and multi-model means (un-weighted average of all (MM) and selected (SM) GCM simulations) for the near-term (2016-2035) and mid-term (2046-2065) projections are presented.

3. Results and Discussion

3.1 Historical simulations

The bias-corrected GCM-simulated mean annual precipitation (1950-2005) of 1,450 mm in the CRB is in good agreement with observations. We compared the GCM-simulated annual precipitation with observations within the catchment areas of 30 streamflow gage locations in the historical period (Figure 2). The modeled inter-annual variability among the climate models (vertical bars in Figure 2) lies within the range of the observed variability (horizontal bars in Figure 2). The linear-regression slope of 1.16 ($p < 0.001$, Figure 2) between the annual observed and MM shows that bias-corrected precipitation is slightly over-estimated, but not significantly so. Similar conclusions are drawn for the seasonal precipitation (SI Figure S2) and within the four regions identified in Figure 1 (mean values within the regions are given in SI Table S3).

We compared the simulated streamflows at 30 locations with observations. The colored points (Figure 3A) compare observed mean annual runoff at the 30 gages with historical simulations (forced with observed climate), while the vertical bars show the modeled inter-annual variability. The shades of colors (from light-green to yellow and red) reveal the model's skill in simulating the monthly flows in the historical period. The Nash-Sutcliff coefficient of efficiency (NSE), a measure of relative magnitude of residual variance compared to the monthly observed streamflow variance [*Legates and McCabe*, 1999; *Nash and Sutcliffe*, 1970], varies between 0.01 and 0.86 (see color scale in Figure 3A). The NSE ranges between negative infinity to 1, with values between 0.5 and 1 are considered satisfactory [*Moriasi et al.*, 2007]. Seventeen of the 30 gages show NSE greater than or equal to 0.5, a subjective but commonly considered acceptable value for good model performance. Higher NSE values at locations on both sides of the equator, particularly at major tributaries (NSE ~0.60, gages 1 to 8 in Figure 1 and SI Figure S3) suggest that the model reliably predicts streamflows under different climatic conditions. High NSE values also indicate that the seasonal and annual runoff simulations, including the inter-annual variability in the historical period, are in good agreement with observations. The catchment areas of the 30 gages vary between 5,000 km^2 and 900,000 km^2 (excluding the last two downstream gages) and encompass a range of land cover and climate regions on both sides of the equator, which indicate the hydrology model's skill in simulating runoff satisfactorily over a wide range in watershed conditions.

Comparison of modeled runoff forced with GCM-simulated and observed climate (Figure 3B) reveals generally acceptable runoff simulations in the CRB. The black dots and red (blue) vertical bars in Figure 3B show multi-model mean and maximum (minimum) range of inter-annual variability in the 25 historical GCM simulations. The results suggest that model-data agreement in precipitation translates to similarly acceptable runoff simulations. The mean and the inter-annual variability of runoff within individual models generally lie within the variability of observed runoff.

The asymmetric seasonality and magnitude in the rainfall regimes (see SI Figure S1) exhibit strong linkages with runoff. For example, the observed peak runoff at gages 2 and 6 (Figure 1) located north and south of the equator occur near the end of the rainy seasons – during Sep-Oct and Mar-Apr, respectively (Figure 4). Augmented by flows from northern and southern tributaries (e.g. gages 1, 2, 4 and 6) and by high precipitation in the tropical equatorial watersheds during the two wet seasons (MAM and SON), the main river flows (~ downstream of gage 3 in Figure 1) show low variability (Figure 4). For example, the coefficient of variation in observed (simulated) monthly flows at the basin outlet (gage 8), northern tributary (gage 2) and southern tributary (gage 4) are 0.23 (0.24), 0.77 (0.80) and 0.40 (0.48), respectively.

Regionally, runoff in the northern (NC) and southern (SW and SE) watersheds is strongly seasonal with long dry seasons, but this is not the case in the equatorial region (Figure 5). Average watershed runoff varies between 20-70 mm during dry seasons to 100-140 mm during wet seasons in the NC, SW and SE. In the equatorial region, seasonal runoff varies between 100-150mm with the highest in SON. Overall, the precipitation-runoff ratio is about 0.30 in the CRB. The accessible runoff (excluding runoff associated with flood events), which can be appropriated for human use, is about 70% of the total runoff.

3.2 Future projections in precipitation and runoff

The near-term (2016-2035) multi-model mean (MM) change in annual precipitation in the CRB is 1% relative to the reference period 1986-2005, irrespective of the emission scenario. The mid-term (2046-2065) MM projections of annual precipitation change are 1.7% and 2.1% for RCP4.5 and RCP8.5, respectively. The inter quartile range (IQR) between model and emission scenarios varies between 1.7-2.6% in the near-term and 2.6-5.8% in the mid-term, indicating considerable variability in rainfall projections across GCMs. The inter-model variability is larger in the mid-term, and even more so for RCP8.5 (SI Table S4). Although overall change in the CRB is positive, the multi-model ensembles reveal that the model agreement varies spatially (SI Figure S4 and ref. *Aloysius et al.* [2016]). Model agreement on increasing precipitation is greater in the equatorial, northern and southwestern CRB.

In general, the GCMs predict decreasing precipitation in the driest parts of the southern CRB (mostly in SE, but portions of SW as well). Under the RCP8.5 scenario, the northeastern CRB also experiences reduction in precipitation in the near-term. The areas of decreased precipitation shrink in the SE and SW in the mid-term; however, drying expands in parts of northern CRB under the two emission scenarios (SI Figure S4). Most GCMs (>15) predict an increase in the NC, EQ and most of SW, whereas majority of them predict a decrease in the SE.

We also examined the seasonal changes in the four regions (see SI Table S4). Except in the boreal summer (JJA), precipitation in the SE region is predicted to decrease under RCP4.5; the change is modest under RCP8.5. The actual increases in the north (south) during DJF (JJA) are modest (~1mm) as these are the dry seasons. The inter-model variability (SI Table S4) also exceeds the MM in all the seasonal predictions. Notably, the variability is larger in the dry seasons (e.g. DJF predictions in the NC and JJA predictions in the SE and SW). The temporal variation is further examined using monthly climatology in the reference and near- and mid-term projection periods in Figure 7A-D, which also shows the seasonal variations in the major climate regions (e.g. the bimodal rainy season in the EQ and unimodal, but asymmetric wet-dry seasons in the NC, and SW and SE). The inter-model variability is larger in the rainy seasons under RCP8.5, compared to RCP4.5. Larger variability under RCP8.5 highlight that GCMs may have limited skills in simulating precipitation under high greenhouse gas emissions.

The spatial pattern of runoff change in the near- and mid-terms ~~indicated by the MM~~ is similar to the precipitation changes, except in the northeastern CRB (3N-9N and 24E-30E) under RCP4.5 (Figure 6). The MM runoff projections show an increase of 5% (IQR 5-7%) and 7% (IQR 7-11%) in the near- and mid-terms under both RCPs. A reduction in runoff occurs in the SE and parts of the SW under both RCPs. The area of decreasing runoff expands in the NC under both emission scenarios in the mid-term. Although the northern and equatorial CRB show an overall increase in precipitation, the decrease in runoff in certain parts in the NC and EQ is caused by reduction in seasonal precipitation (i.e. limited moisture supply) rather than an increase in ET; changes in temperature associated with the two emission scenarios are relatively uniform within the GCMs (see *Aloysius et al.* [2016], and *IPCC* [2014]). Larger reduction – up to 15% – in the SE covering most of northern Zambia is due to an overall decrease in precipitation simulated by more the half of the GCMs (see SI Figure 4). The inter-model variability of runoff at monthly time scales in the four regions (Figure 7E-H) is similar to precipitation, but with a time lag. The runoff variability is larger in NC and SE compared to EQ and SW during the rainy seasons.

Runoff in the EQ region, which receives the highest precipitation is projected to increase between 4-7%; the increases are prominent in the secondary rainy season (MAM) than the primary (SON, Figure 7E-H, SI Table S5). However, runoff that can be appropriated for human use is generated mostly in the NC, SE and SW, which at present varies from 130mm/year in the SE to 250-400mm/year in the NC and SW (SI Table S3). Runoff in the SW is projected to increase by 6% and 10% in the near- and mid-terms. In the NC region, runoff is projected to increase by 2-4% in the near-term and decrease in the mid-term under RCP8.5, due to seasonal decreases (JJA and SON) in parts of NC (see Figure 6 and SI Tables S5 and S6). ~~. Runoff generated in populated areas in the CRB, excluding most parts of the EQ, has the potential to support human needs including water supply, sanitation, food production and hydropower; however, only a portion of the total runoff can be sustainably harnessed.~~

3.3 Role of multi-model ensembles

Extensive coordination provided by CMIP5 enabled all climate modeling groups to use a standard set of inputs, produce compatible historical and future model runs and provide their best outputs to the IPCC data archives; thus, the multi-model ensemble approach in climate change assessment presents an opportunity to examine outputs from a range of model structure biases, initial conditions, parameter uncertainties in climate model design, which vary within GCMs [*Stocker*, 2013; *Taylor et al.*, 2012]. Skill in simulating historical precipitation and temperature increases when outputs from different GCMs are added (*Pierce et al.* [2009] and *Pincus et al.* [2008]). At the same time, the range of projections presented here for the two emission scenarios also highlight the uncertainties planners will encounter when making climate-related decisions. For example, broader agreement on increase in runoff in parts of the CRB (see Figure 6) would help make robust decisions, whereas weaker agreement in the southern CRB calls for greater scrutiny of regional climate drivers and their representation in climate models (see *Weaver et al.* [2013] for further discussion). Along these lines, we argue that the MM approach help explore and reveal future projection uncertainties; however, we should be able to do better with a subset of models. How different are the projections if we use randomly selected subset of models or a subset that realistically simulates certain aspects in the region of interest? First, we examine the effect of MM projections based on outputs from randomly selected models out of the 25 simulations for each RCP (SI Figure S5). Projections under this random model selection method converge to MM projections as more models are added to the pool (compare values in SI Tables S4 and S5). However, with fewer models, projections vary widely and are highly dependent on the choice of GCMs.

GCMs generally have large uncertainties in simulating precipitation in the CRB region [*Aloysius et al.*, 2016; *Washington et al.*, 2013]. We examined a subset of models (SM – M6, M7, M18, M23 and M24, see refs. *Giorgetta et al.* [2013]; *Good et al.* [2012]; *Jungclaus et al.* [2013]; *Meehl et al.* [2013]; *Siam et al.* [2013]; *Voldoire et al.* [2012]; *Yukimoto et al.* [2006] and *Aloysius et al.* [2016] for further comparison of GCM performance) that reliably simulate regional climate as well as large-scale mechanisms that modulate regional climate. Based on diagnostic analyses to identify processes related to biases in atmospheric moisture and soil water balance in the CRB region, *Siam et al.* [2013] identifies few models in SM as good candidates for climate change assessment.

Focusing on the NC, SE and SW regions, where human appropriation of runoff is expected to increase, we find that the magnitude of annual projections (both precipitation and runoff) in SM are twice that of MM in the northern region; and the extent of drying in the south is concentrated in the southern upstream watersheds. From the viewpoint of water resources for human appropriation, the changes by seasons are also important. In Figure 8, we highlight the projections in precipitation and runoff for these regions for annual and four seasons in the form of box-and-whicker plots. Both MM and SM means reveal that the projections under RCP4.5 are slightly higher than RCP8.5 in NC region, and not so in other regions. Projection uncertainties are the largest in the dry seasons (DJF in the NC and JJA in SW and SE). Figure 8 also shows moderate increase in the SW and decrease or no-change in the SE during the rainy season (DJF). Our estimates also reveal that the upstream watersheds in the SE and parts of SW are projected to get drier with decreasing runoff (SI Table S6).

Only part of the runoff may be appropriated for human use. In the CRB, the accessible runoff, excluding runoff associated with flood events, is nearly 70%. Overall, the MM reveals a slightly higher increase in accessible runoff (5% and 7% for near- and mid-terms for both RCPs), compared to quick/flood runoff (3% in the near-term and 5-7% in the mid-term); the increase in the SM are nearly twice that of MM. However, increase in flood runoff is nearly twice that of accessible runoff in the NC region. On the other hand, both SM and MM consistently project drying in the southeastern and northeastern headwater regions (see SI Table S6).

The impacts on rural livelihoods due the changes in runoff are multifaceted. On the one hand, the increases in accessible runoff enhance access to water resources; on the other hand, the increases in quick/flood runoff present additional adaptation challenges. With reduced access to water resources, the impacts on rural livelihoods and the environment in the SE and parts of NC will be severe. Further, we emphasize that GCM-related variability in regional climate change predictions can be constrained by a subset of models based on attributes that modulate large-scale circulations which, in turn affect regional climate (see *Knutti and Sedlacek* [2013] and *Masson and Knutti* [2011]). This approach is particularly useful, since regions like the CRB lack complete coverage of observational data; however, the mechanisms that moderate the climate system, particularly precipitation are fairly well understood [*Hastenrath*, 1984; *Nicholson and Grist*, 2003; *Washington et al.*, 2013].

3.4 Variability in accessible flows

Accessible flows (AF), which exclude flows associated with flood events (see SI Methods), are largely under-utilized in the CRB, but their appropriation is expected to increase in the future, mostly in the NC, SW and SE. We attempt to elucidate the uncertainty associated with climate model and scenario selection by quantifying seasonal and inter-model variability in AF. The seasonal variation of AF at eight major tributaries (identified in Figure 1) reveals substantial inter-model spread in the near-term (Figure 9); the model spread widens in the mid-term (SI Figure S6). The inter-model spread is large during the rainy seasons, in some cases the increase/decrease is over 50% compared to the reference period. The inter-model consensus is strong in most of the northern and southwestern tributaries (e.g. gages 1 and 6) where majority of the GCMs predict increasing precipitation. In contrast, the consensus is weak in the southeastern tributaries (e.g. gage 4). The AF in the main river (gages 3 and 8) is projected to increase in the two rainy seasons and as well as in the dry season (JJA). A close look at tributaries in the NC and SW reveals a weaker agreement on increased AF in the wet season, but a stronger agreement in the dry season (compare gages 1, 2, 6 and 7 in Figure 8). Our results also show that the decrease in precipitation and AF in SE will have marginal effect on downstream flows in the main river.

The spatial and temporal variations in the projected AF will have consequences in water resources development and management. For example, uncertainty in predicting the AF near the proposed Grand Inga Hydropower project (near gage 8, *Showers* [2009]) is low compared the predictions near the proposed trans boundary water diversion in the southeast (near gage 5, *Lund et al.* [2007]). Reductions in high and low flows in streams in the SE region will have implications on aquatic life, channel maintenance and lake and wetland flooding.

4. Conclusions

From the point of view of climate change adaptation related to water resources, agriculture, land and ecosystem management, the challenge faced by CRB countries is recognizing the value of making timely decisions in the absence of complete knowledge. To be of use to planners, the spatial and temporal variability of hydro-climatic change in the CRB is presented with appropriate details. The results presented here show a range of runoff projections under two broad assumptions, that i) individual GCM biases will cancel and that MM mean projections are more likely correct and ii) selection of GCMs that simulate mechanisms reliably is a better option for climate change assessment.

Our analyses highlight that precipitation and runoff changes under business-as-usual and avoided greenhouse gas emission scenarios (RCP8.5 vs. RCP4.5) are rather similar in the near-term, but deviate in the mid-term, which underscores the need for rapid action on climate change adaptation. Development and implementation of adaptation strategies are often connected with large investments. Precipitation projections by GCMs, and subsequently runoff projections reveal considerable differences, which necessitate the need for multi-model evaluations of climate change impacts. With the focus on runoff – often the primary and easily accessible source of water, we show that accessible water resources increases in most parts of the CRB, with the exception in the southeast and parts of northeast.

Comparing the MM and SM projections, the increase in runoff in the mid-term are higher under RCP8.5 (7-14%) than RCP4.5 (6-10%), however, both accessible and flood runoffs are increasing. The projected increases in accessible runoff present new opportunities to meet the increasing demands (e.g. drinking water, food production and sanitation), while the enhanced flood runoff poses new challenges (e.g. flood protection and erosion control). On the other hand, water managers will face different challenges in the southeast where precipitation and runoff are projected to decrease. Projection uncertainties vary widely by region within the CRB, and therefore adaptation and robust planning strategies will vary within the river basin, and will depend on the risk attitudes of resource planners. ~~The analyses presented in our work increase the degree of confidence in using the results for policy and management.~~

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