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Future shifting of annual extreme flows under climate change in the Volta River basin

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Abstract. Global warming is projected to result in changes in streamflow in West Africa with implications for frequent droughts and floods. This study investigates projected shifting in the timing, seasonality and magnitude of mean annual minimum (MAM) and annual maximum flows (AMF) in the Volta River basin (VRB) under climate change, using the method of circular statistics. River flow is simulated with the mesoscale hydrologic model (mHM), forced with bias-corrected climate projection datasets consisting of 43 regional and global climate model combinations under three representative concentration pathways (RCPs). Projected changes indicate that AMF increases between $+1\,\%$ and $+80\,\%$ across sub-basins, particularly in the near future (2021–2050), whereas MAM decreases between $-19\,\%$ and $-7\,\%$, mainly from the late century (2071–2100), depending on RCPs. The date of occurrence of AMF is projected to change between -4 and $+3$ d, while MAM could shift between -4 and $+14$ d depending on scenarios over the 21st century. Annual high flows denote a strong seasonality with negligible future changes, whereas the seasonality of low flows has a higher variation, with a slight drop in the future.

Keywords. Hydroclimatic extremes; modelling; West Africa; PUB; UPH 1; UPH 9; SDG 6.4; SDG 13.1

1 Introduction

Human-induced climate warming has significantly altered the magnitude of mean and extreme river flows globally (Gudmundsson et al., 2021). River flow is a key indicator of water availability for people and the environment. Fluctuations in river water availability can undermine water supply and profoundly affect water and food security. Therefore, knowing trends in river flows is crucial for preserving livelihoods and safeguarding ecosystems. In West Africa, global warming has induced a significant increase in extreme rainfall, thereby affecting river flows (Chagnaud et al., 2022; Rameshwaran et al., 2021). Streamflow extremes in West Africa are non-stationary and associated with devastating floods and droughts that are becoming persistent and widespread (Elagib et al., 2021; Wilcox et al., 2018). As flood and drought are two extremes of the same hydrological cycle, it is important to integrate them in disaster reduction strategies and measures to better cope with current and future risks (Ward et al., 2020; Brunner et al., 2021; Kreibich et al., 2022). Understanding future dynamics in the occurrence of annual extreme river flows is critical to guide adaptation measures (Lane and Kay, 2021). However, studies usually focus on assessing changes in the magnitude of river flows while timing and seasonality are also important for water planning and management.

This study investigates the shifting of annual minimum and maximum flows timing, seasonality and magnitude using a large ensemble of regional and global climate models under multiple climate change scenarios in the Volta River basin (VRB), where continuous updates on the state of water resources is essential to cope with persisting water-related risks. Here, annual minimum and maximum flows are analysed instead of flow percentiles as done by Dembélé et al. (2022).

2 Study area

The Volta River Basin (VRB) covers approximately 415 600 km^2 shared among six countries (Benin, Burkina Faso, Côte d'Ivoire, Ghana, Mali, and Togo) in West Africa (Fig. 1). The land cover is dominated by savannah, with a maximum altitude of 940 m a.s.l. Rainfall is characterized by interannual and multidecadal variabilities, and ranges between 570 and 1200 mm yr^{-1} from north to south. Actual evaporation exceeds 80 % of the basin annual rainfall. The Black Volta (152 800 km^2), White Volta (113 400 km^2), Oti (74 500 km^2) and Lower Volta (74 900 km^2) constitute the four sub-basins of the drainage system. The Volta River flows over 1850 km and fills in the Lake Volta formed by the Akosombo dam before draining into the Atlantic Ocean (Dembélé, 2020).

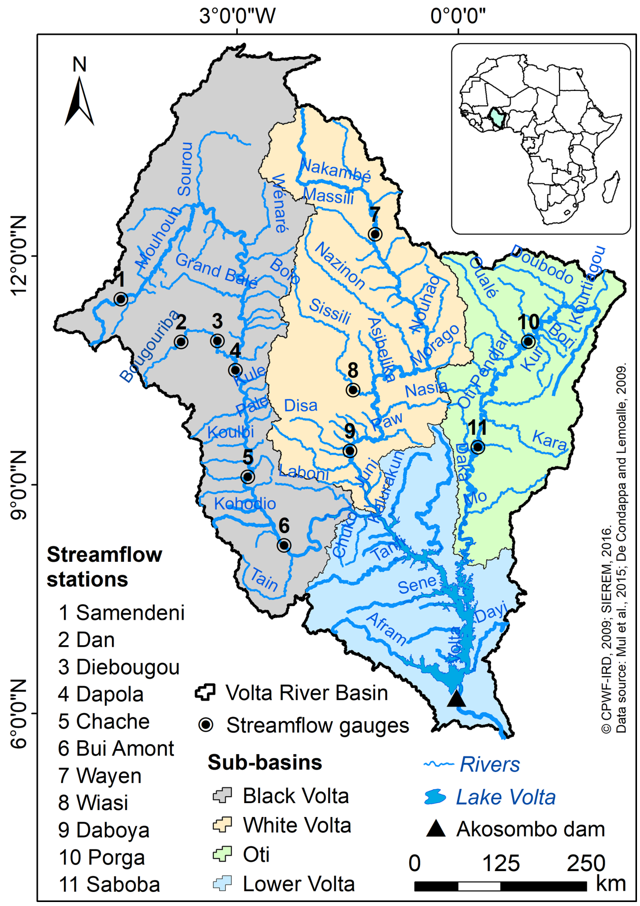

Figure 1. Hydrographic network of the Volta River basin. Adapted from Dembélé (2020).

3 Data and Methods

3.1 Climate projection data

Five Regional Climate Models (RCMs) from the Coordinated Regional-climate Downscaling Experiment (CORDEX) for Africa at a spatial resolution of 0.44° ($\sim$ 50 km) are considered with twelve General Circulation Models (GCMs) from the fifth Coupled Model Intercomparison Project (CMIP5; Taylor et al., 2012) under three Representative Concentration Pathways (RCPs; Van Vuuren et al., 2011), resulting in 43 RCM-GCM combinations. The daily data include rainfall and air temperature (average, maximum and minimum). The historical runs consider 21 RCM-GCM combinations, whereas the future projections involve 18 RCM-GCM combinations for RCP8.5, 16 for RCP4.5 and 9 for RCP2.6 (Table 1). The climate projection datasets are evaluated with the best-performing satellite and reanalysis rainfall and temperature products in the VRB (Dembélé et al., 2020c), after a multivariate bias correction with the Rank Resampling for Distributions and Dependences (R2D2) method (Vrac and Thao, 2020).

3.2 Hydrological modelling

The fully distributed mesoscale Hydrologic Model (mHM) (Kumar et al., 2013; Samaniego et al., 2010) is used to simulate daily streamflow, using the bias corrected climate projection datasets as input. The model configuration and performance are given by Dembélé et al. (2020b). The periods 2021–2050, 2051–2080 and 2071–2100, representing the near-term future, the long-term future and the late-century, are considered to assess the impact of climate change on streamflow, relative to the historical period or baseline (1991–2020). The detailed methodology and the bias-correction results are given by Dembélé et al. (2022).

3.3 Timing of high and low flows

The mean annual minimum flow (MAM) of seven consecutive days is considered as low flow, while high flow is the

Table 1. CORDEX-Africa Regional Climate Models (RCMs) and General Circulation Models (GCMs) per Representative Concentration Pathways (RCP).

RCP	RCM	GCM
RCP8.5	CCLM4-8-17	MPI-ESM-LR, HadGEM2-ES, CNRM-CM5
	RACMO22T	EC-EARTH
	RCA4	IPSL-CM5A-MR, EC-EARTH, CanESM2, CNRM-CM5, CSIRO-Mk3-6-0, GFDL-ESM2M, NorESM1-M, MPI-ESM-LR, HadGEM2-ES, MIROC5
	REMO2009	MPI-ESM-LR, HadGEM2-ES, MIROC5, IPSL-CM5A-LR
RCP4.5	CCLM4-8-17	MPI-ESM-LR, HadGEM2-ES, CNRM-CM5
	CRCM5	CanESM2, MPI-ESM-LR
	RACMO22T	EC-EARTH
	RCA4	IPSL-CM5A-MR, CanESM2, CNRM-CM5, CSIRO-Mk3-6-0, GFDL-ESM2M, NorESM1-M, MPI-ESM-LR, HadGEM2-ES, MIROC5
	REMO2009	MPI-ESM-LR
RCP2.6	RCA4	NorESM1-M, MPI-ESM-LR, HadGEM2-ES, MIROC5
	REMO2009	MPI-ESM-LR, HadGEM2-ES, MIROC5, IPSL-CM5A-LR, GFDL-ESM2G

annual maximum flow (AMF) corresponding to the highest peak flow in a calendar year. High and low flows are estimated at Bui-Amont, Daboya and Saboba, which correspond to the outlets of the Black Volta, White Volta and Oti sub-basins (Fig. 1). The method of circular statistics (Mardia, 1972; Fisher, 1993) is used to estimate the timing of AMF and MAM based on the mean date of occurrence (D) and their seasonality based on the concentration of the dates of occurrence (R) for each of the 30-year historical and future periods (e.g., Blöschl et al., 2017; Hanus et al., 2021; Villarini, 2016). Julian dates are converted into angles that represent locations on the circumference of a circle to avoid concerns with calculating the mean when the day of occurrence comes around the start or end of a calendar year (Young et al., 2000). The angular value of the date of occurrence is obtained as follows:

$$\theta_i = D_i \cdot \frac{2\pi}{m_i}, \qquad 0 \le \theta_i \le 2\pi \tag{1}$$

Where D_i is the Julian date of occurrence of AMF or MAM varying between 1 and 365 (366 for leap years), m_i represents the number of days in a calendar year i, and θ_i is the angular date of occurrence in radians.

The mean date of occurrence $\overline{D}$ is calculated as:

$$\overline{D} = \begin{cases} \tan^{-1}\left(\frac{\overline{y}}{\overline{x}}\right) \cdot \frac{\overline{m}}{2\pi}, & \overline{x} > 0,\ \overline{y} \ge 0 \\ \tan^{-1}\left(\frac{\overline{y}}{\overline{x}}\right) \cdot \frac{\overline{m}}{2\pi} + \pi, & \overline{x} \le 0 \\ \tan^{-1}\left(\frac{\overline{y}}{\overline{x}}\right) \cdot \frac{\overline{m}}{2\pi} + 2\pi, & \overline{x} > 0,\ \overline{y} < 0 \end{cases} \tag{2}$$

with

$$(\overline{x}, \overline{y}) = \left(\frac{1}{n}\sum_{i=1}^{n}\cos\theta_i,\ \frac{1}{n}\sum_{i=1}^{n}\sin\theta_i\right) \tag{3}$$

$$\overline{m} = \frac{1}{n}\sum_{i=1}^{n} m_i \tag{4}$$

where $\overline{m}$ is the average number of days in a year, n represents the total number of years and $\overline{x}$ and $\overline{y}$ correspond to the cosine and sine components of the mean date, respectively.

The mean resultant R gives the concentration of the dates of occurrence around the average date as follows:

$$R = \sqrt{\overline{x}^2 + \overline{y}^2}, \qquad 0 \le R \le 1 \tag{5}$$

A small value of R close to 0 suggests a high interannual variability of the date of occurrence, whereas R values near 1 denote a high seasonality in the date of occurrence.

4 Results

4.1 Changes in the magnitude of annual extreme flows

Considering all RCPs over the historical period, the average multi-model ensemble medians of MAM and AMF vary across sub-basins in the VRB as follows (Fig. 2): Black Volta (AMF $= 88.6 \pm 17\,m^3\,s^{-1}$, MAM $= 1.4 \pm 0.1\,m^3\,s^{-1}$), White Volta (AMF $= 79.3 \pm 3\,m^3\,s^{-1}$, MAM $= 1.5 \pm 0.1\,m^3\,s^{-1}$) and Oti (AMF $= 176.1 \pm 12\,m^3\,s^{-1}$, MAM $= 3.1 \pm 0.2\,m^3\,s^{-1}$). However, large differences are found in AMF across RCPs,

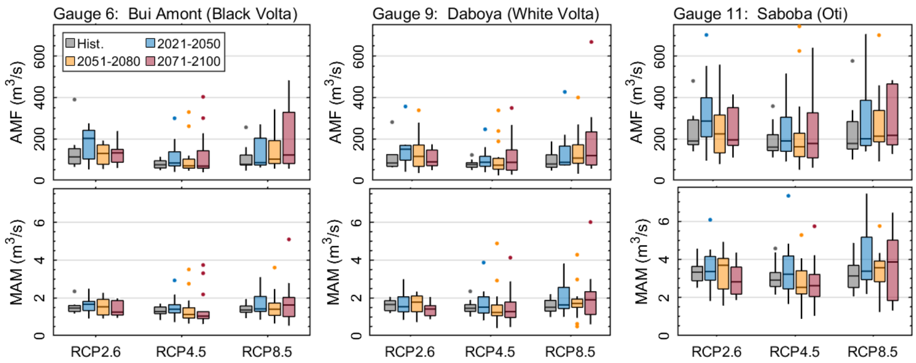

Figure 2. Mean annual minimum flows (MAM) and annual maximum flows (AMF) in the major sub-basins of the VRB (Black Volta, White Volta, Oti) over the historical (1991–2020) and future periods.

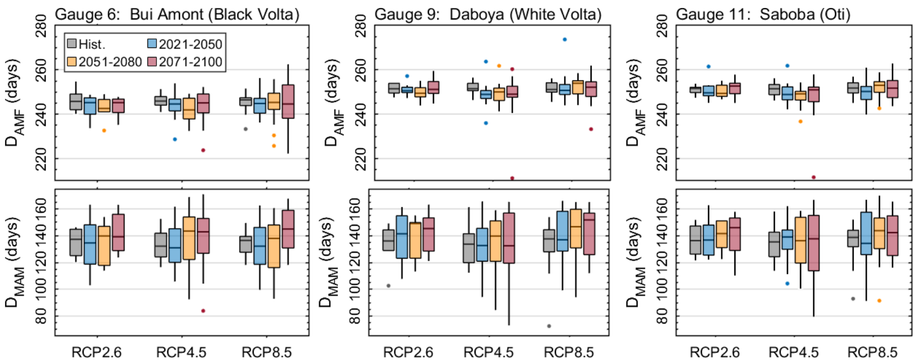

Figure 3. Mean Julian day of occurrence (D) of mean annual minimum flows (MAM) and annual maximum flows (AMF) in the major sub-basins of the VRB (Black Volta, White Volta, Oti) over the historical (1991–2020) and future periods.

with the highest values occurring under RCP2.6 and the lowest values under RCP4.5.

Future changes in annual high flows indicate an increase in median AMF in all the sub-basins under RCP2.6 and RCP8.5 over the 21st century, and also under RCP4.5 except over 2051–2080 in the White Volta and over 2051–2100 in the Black Volta. The increase in median AMF varies between +1 % in the Oti under RCP4.5 over 2051–2080 and +80 % in the White Volta under RCP2.6 over 2021–2050 with 56 % agreement on the direction of change among the RCM-GCMs. It is noteworthy, that AMF is projected to increase under all scenarios in the near future 2021–2050 in all sub-basins, with +11 % increase on average under RCP8.5, +15 % under RCP4.5 and +70 % under RCP2.6, with 76 %, 71 % and 59 % agreement on the direction of change of RCM-GCMs, respectively. An increase in flood occurrence is projected in all sub-basins under RCP2.6 and RCP8.5 over the 21st century, and mainly over 2021–2050 under RCP4.5.

For annual low flows, the projected decrease in median MAM varies between −19 % in the Black Volta under RCP4.5 over 2071–2100 and −7 % in the White Volta under RCP2.6 over 2021–2050. An overall median increase of MAM in all the sub-basins is projected under RCP8.5 by +16 % in the White Volta, +15 % in the Oti and +9 % in the Black Volta. Under RCP4.5, median MAM increases during 2021–2050 and decreases afterwards by −6 % on average in all sub-basins, whereas it increases until 2080 under RCP2.6 before decreasing by −15 % on average in the late 21st century. It is noteworthy that the median MAM increases under RCP2.6 by +8 % in the White Volta during 2051–2080. The agreement on the direction of change between the RCM-GCMs is on average 65 % for RCP8.5, 62 % for RCP4.5 and 59 % for RCP2.6. A higher likelihood for river droughts is projected from 2051 under RCP4.5 and from 2071 under RCP2.6 in all sub-basins.

4.2 Changes in the timing and seasonality of annual extreme flows

The median date of occurrence of AMF(D_{AMF}) varies on average between the Julian calendar days 246 and 252 (first dekad of September) over the historical period in all sub-basins, and it is projected to decrease by −2 d over the 21st century for all RCPs (Fig. 3). However, the highest reductions per sub-basin are −4 d in the Black Volta over 2051–2080 and −3 d in the White Volta and Oti over 2021–2050, all under RCP4.5. However, a rise by +3 d is projected in the White Volta over 2051–2080 under RCP8.5. Contrastingly,

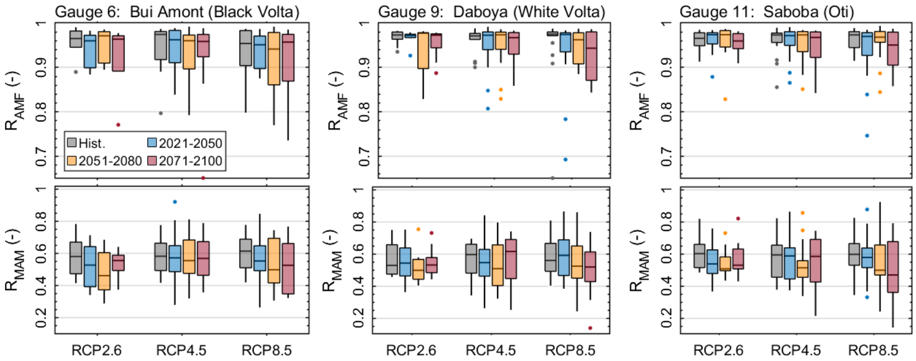

Figure 4. Concentration of the dates of occurrence (R) around the mean date for mean annual minimum flows (MAM) and annual maximum flows (AMF) in the major sub-basins of the VRB (Black Volta, White Volta, Oti) over the historical (1991–2020) and future periods.

the median D_{MAM} varies between 132 and 139 d (second dekad of May) over the historical period and increases on average by +6 d across sub-basins during the 21st century. However, notable rises in D_{MAM} are projected with +14 d under RCP8.5 over 2071–2100 in the White Volta, +11 d under RCP4.5 over 2051–2080 in the Black Volta and +10 d under RCP2.6 over 2071–2100 in the Oti, which might be the consequence of the forward shift of the rainy season (Dembélé et al., 2022). However, it is notable that D_{MAM} is projected to drop by −4 d over 2021–2050 under RCP8.5 in the Oti and the Black Volta.

The concentration of the date of occurrence (R) of D_{AMF} demonstrates a high seasonality in the occurrence of AMF ($R_{\mathrm{AMF}} = 0.97$) across sub-basins, and hardly changes over the 21st century (Fig. 4). The maximum change in R_{AMF} is −3 % over 2071–2100 in the White Volta under RCP8.5. The median R_{MAM} is 0.58 on average across sub-basins over the historical period and slightly decrease in the future, denoting a lower seasonality of MAM. A future reduction in R_{MAM} is observed in the Black Volta (−20 % to −2 %) and Oti (−22 % to −1 %) for all future climate scenarios, while changes are contrasted in the White Volta (−15 % to +6 %).

5 Limitations and future work

The large spread of AMF and MAM over 2071–2100 (Fig. 2), denoted by the moderate agreement on the direction of change of RCM-GCM combinations, can be explained by the limited capability of the models to project future trends, in addition to uncertainties associated with the hydrological model. Attention is solely given to climate-induced changes in river flow because climate was found to be the key driver in changes to global river flow (Gudmundsson et al., 2021). However, more local and regional changes in river flow might also result from other factors such as land and water management. Consequently, future studies in the VRB should also consider human interactions with the hydrological cycle (e.g. urbanization, agriculture, reservoirs) to better investigate the causes of changes in river flows (Yang et al., 2021; Yonaba et al., 2021). Furthermore, there is a need to improve hydrological modelling at large scale with earth observation data to better predict the spatial and temporal occurrence of extreme events (Dembélé et al., 2020a; Lindersson et al., 2020). Finally, uncertainties in hydrological modelling could be addressed by adopting multi-model approaches (Giuntoli et al., 2015; Vetter et al., 2017).

6 Conclusion

The analysis of projected shifting in timing, seasonality and magnitude of mean annual minimum flows and annual maximum flows in the Volta River basin under climate change reveals various changes over the 21st century. In general, projected annual high flows increase in all the sub-basins, particularly under RCP2.6 and RCP8.5, thereby leading to higher flood probability. Increase in river droughts are projected from 2051 under RCP4.5 and from 2071 under RCP2.6 in all sub-basins. High flows have a high seasonality with a mean date of occurrence that hardly changes in the future as opposed to low flows that show a future forward shift in time. These findings provide an important basis to inform research and climate change adaptation and mitigation strategies in the Volta River basin.

Code availability. The source code of the mHM model can be accessed at https://doi.org/10.5281/zenodo.1299584 (Samaniego et al., 2018).

Data availability. CORDEX data is available from the Earth System Grid Federation database at https://esgf-data.dkrz.de (ESGF, 2020). The database of the hydrological modelling is available at https://doi.org/10.5281/zenodo.3531873 (Dembélé, 2019).

Author contributions. MD designed the experiment, performed the analyses and drafted the paper. All co-authors contributed to the writing, review and editing.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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