Hydroclimate Analysis Under 1.5 and 2 °C Global Warming in the Faleme River Basin

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Abstract. In this study, we analyze the hydroclimate of the Faleme basin which is a major tributary in the Senegal River Basin. This basin has faced hydrological droughts that have negatively affected rainfed agriculture, the economic development and have enhanced poverty. The main objective of this work is to investigate the variability and the changes of the basin hydroclimate during the past and the future under 1.5 and 2 °C global warming. Extreme precipitations analysis at Kidira (outlet of the basin) exhibit two noticeable periods 1950–1980 and 1981–2010; in the first period wet day's frequency and rainfall intensity decrease considerably. In the second period, the rainfall intensity, the consecutive dry days decrease while consecutive wet days, wet day frequency increase. Over the whole basin from 1901 to 2013, a general annual deficit is noticed with the simplified water balance, and the standardized precipitation from 1970 to 2010. As for the future changes over the basin by analyzing three regional climate models (RCA4, RACMO22, CCLM) simulations, rainfall is likely to increase under both warming conditions. Potential evapotranspiration from Penman is projected to increase with the highest magnitudes under 2 °C. Moreover, hydrological simulation with the GR4J model, project slight increase of river discharge in the coming decades. However, the simplified water balance shows drier conditions under both warming scenarios. Therefore, water saving technologies, crop resistant to higher evapotranspiration, and integrated water resources management should be developed and promoted in order to reduce the adverse effects of climate change.

Keywords: Hydroclimate · Faleme basin · Impacts · Global warming · Climate change

1 Introduction

The impact of climate change is already having an adverse effect on the stability of entire countries, regions, and continents. According to the fifth report of the Intergovernmental

J. P. R. Thorn et al. (Eds.): InterSol 2020, LNICST 321, pp. 121–133, 2020.
https://doi.org/10.1007/978-3-030-51051-0_9

Panel on Climate Change (IPCC), the impacts of extreme climate events have led to disruption of water supply and food production, alteration of ecosystems, mortality and morbidity, damage to infrastructure and settlements, and consequences human well-being and for mental health [1]. Furthermore, drought and flood are becoming more frequent worldwide. In addition, the potential changes in climate variability and in the frequency, intensity of extreme climate events are emerging as main determinants of future impacts and vulnerability [2]. In Africa, extreme weather and climate events including droughts and floods have considerable impacts on socio-economic sectors, natural resources and ecosystems, livelihoods, and human health [1].

Over West Africa, the recurrence of droughts has led to a significant decrease of streamflow in many river basins. Rivers are among the main water resources for drinking, irrigation, and industrial purposes in inland areas [3]. The Senegal River Basin has faced these conditions, its annual average flow at Bakel (reference station) has been reduced from an average of 840 $m^3.s^{-1}$ in the period 1950–1972 to only 419 $m^3.s^{-1}$ in the period 1973–2002 [4]. That hydrological drought has reduced rainfed agriculture, decreased the seasonal flooding of wetlands, limited economic development, and in the overall, enhanced poverty [5]. Such water shortage has obviously affected the main activities in the basin (agriculture, fishery, hydropower generation, etc.). Furthermore, it is well documented that hydro meteorological extremes [6, 7] will increase in the future and could have serious consequences on human societies and ecosystems. The Faleme River Basin (major tributary of the Senegal River Basin) is facing seriously the impacts of climate change and these are likely to be exacerbated in the future. It is in this context that our study aims to provide a better understanding of the potential impacts of 1.5 and 2.0 °C global warming levels (GWLs) on the hydroclimate of the basin. This will generate reliable climate change information for adequate adaptation measures in order to reduce the vulnerability of basin's people. Observed meteorological data and climate output from three regional climate models (RCA4, RACMO22, and CCLM) were used for analyzing the variability and the changes of the hydroclimate. In addition, the hydrological model GR4J has allowed us to simulate river discharge during the historical period (1984–2013), at 1.5 °C warming period (2017–2046) and at 2.0 °C warming period (2032–2061).

This paper is structured as following: after the Introduction, Data and Methodology are described in Sect. 2; the Results are presented in Sect. 3; Discussion and Conclusion are given in Sect. 4 and Sect. 5, respectively.

2 Data and Methodology

The Faleme basin is located in West Africa between longitudes 11°12′ and 12°15′0 W and latitudes 12°11 and 14°27 N. It is the main tributary of the left bank of the Senegal River Basin. The following stations (Fig. 1) were extracted from the Climatic Research Unit Time series (CRU TS) dataset (1901–2013) for monthly time series of precipitation and potential evapotranspiration; this dataset is gridded to 0.5×0.5 degree spatial resolution [8].

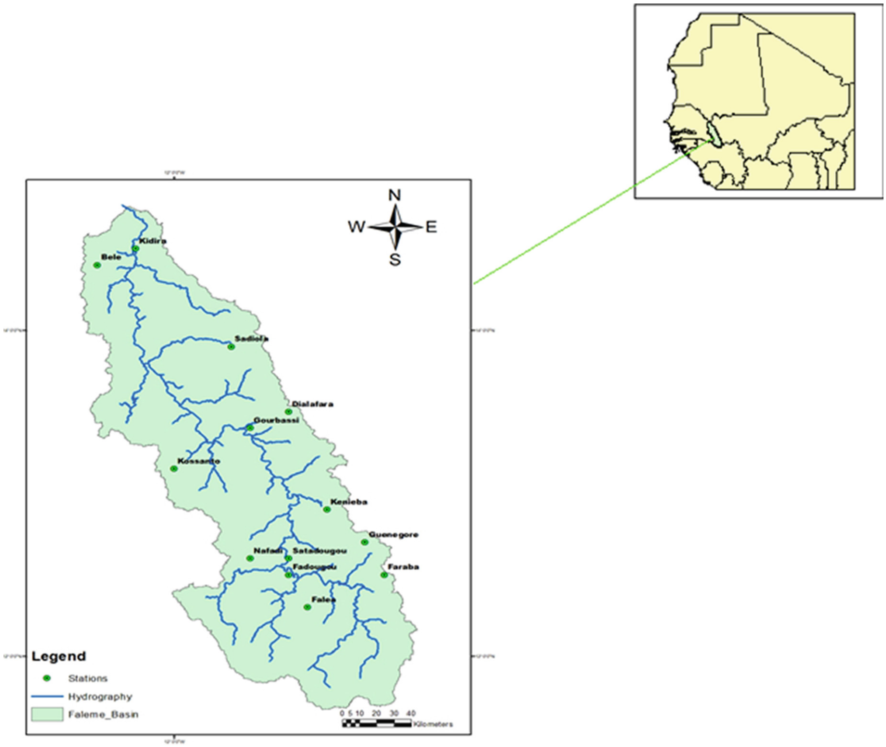

Fig. 1. Faleme river basin and its main stations

Then, we computed the mean values of precipitation and potential evapotranspiration over the whole basin by using the ensemble mean of all stations. We have used also daily observed rainfall at Kidira (1950–2010) from the National Agency of Civil Aviation and Meteorology of Senegal (ANACIM). Furthermore, daily climate simulations from three regional climate models (CCLM: Cosmo- Climate Limited-area Modelling Community Regional Climate Model, RCA4: Rossby Centre regional Atmospheric climate model, and RACMO22: Regional Atmospheric Climate Model) within the Coordinated Regional Climate Downscaling Experiment (CORDEX, [9]) are used. The spatial resolution of these climate models is 0.44° grid. One of the goal of CORDEX project, was to produce high regional climate simulations in order to better understand local and regional climate features over the world. These regional climate models (RCMs) are driven by the MOHC-HadGEM2 global climate model (GCM) following RCP4.5 Representative Concentration Pathways under 1.5 and 2.0 °C Global Warming Levels (GWLs). Three different periods were considered: historical (1984–2013), 1.5 °C warming period (2017–2046) and 2.0° warming period (2032–2061); these warmings are identified compared to the pre-industrial level [10]. Some characteristics of these RCMs are given in Table 1.

Table 1. Climate model data with the name of the driving global climate model (GCM), institute, regional climate model (RCM), and the different periods of simulations. The reference period is the historical period obtained with 0.5 °C warming, with respect to the preindustrial in the same way as both targets (1.5 °C and 2 °C) in the future.

Driving GCM	Institute	RCM	Reference period	1.5 °C warming period	2.0 °C warming period
MOHC-HadGEM2-ES	SMHI	RCA4	1984–2013	2017–2046	2032–2061
	KNMI	RACMO22T	1984–2013	2017–2046	2032–2061
	CLMcom	CCLM4–8–17	1984–2013	2017–2046	2032–2061

Hydroclimate indices are computed such as the maximum number of consecutive wet and dry days, frequency of wet and dry days, rainfall intensity, standard precipitation index (SPI), standard evapotranspiration index (SPEI), aridity index (P over PET), water balance/budget (P minus PET). The signification of these hydroclimate metrics/indices are summarized in Table 2. The changes in the basin hydroclimate are estimated by the difference between the future warming periods and the historical period.

We used the hydrological model GR4J (Génie Rural à 4 paramètres Journaliers) to simulate river discharge during the historical and future periods. GR4J is a simple rainfall-runoff model. It uses forcing data such as daily rainfall, temperature and evapotranspiration to simulate river flow at the outlet Kidira.

Table 2. Hydroclimate indices

Index name	Index signification	Unit
Simple daily rainfall intensity index (SDII)	Let PRwj be the daily precipitation amount on wet days, PR ≥ 1 mm in period j. If W represents the number of wet days in j, the rainfall intensity is given by the sum of PRwj divided by W	mm
Maximum number of consecutive dry days (CDD)	Let PRij be the daily precipitation amount on day i in period j. Count the largest number of consecutive days where PRij < 1 mm	day
Maximum number of consecutive wet days (CWD)	Let PRij be the daily precipitation amount on day i in period j. Count the largest number of consecutive days where PRij > 1 mm	day
Water balance	Difference between precipitation and potential evapotranspiration (P-PET)	mm

(*continued*)

Table 2. (*continued*)

Index name	Index signification	Unit
Aridity index	Fraction of precipitation over potential evapotranspiration	–
Standardized precipitation index (SPI)	In each rainfall time step, the rainfall mean over the whole period was subtracted, and after the difference was divided by the standard deviation	–
Standardized evapotranspiration index (SPEI)_	In each evapotranspiration time step, the evapotranspiration mean over the whole period was subtracted, and after the difference was divided by the standard deviation	–
Low flows (10P)	10th percentile of river flows means the value above which 90% of the daily flows are found	m^3/s

More details on the functioning of this model can be found in [11, 12]. Then, the climate output from the above three regional climate models are used by GR4J to simulate stream flows in the Faleme River during the historical and the future period.

3 Results

3.1 Interannual Variability of the Past Hydroclimate

Figure 2 shows the interannual variations of precipitation characteristics at Kidira (outlet of the Faleme basin) from 1950 to 2010. The years 1970s and 1980s have the highest number of consecutive dry days (Fig. 2a) and dry day's frequency (Fig. 2c) by contrast of the consecutive wet days (Fig. 2b) and the wet day's frequency (Fig. 2d). These years correspond to the periods where the Sahel region faced the most severe droughts. However, wet periods are relatively found during the 1950s and the 2000s, this later result is confirmed by the standard precipitation index (Fig. 2f) where blue color indicates an increase and red color exhibits water deficit. As for the rainfall intensity (Fig. 2e), the more heavy rainfall are found in the 1960s.

As for the mean over the whole basin by using CRU datasets, the standardized precipitation index (Fig. 3a) shows noticeably two different periods: a relatively wet period (1901–1970), and a water deficit period (1971–2013), with high interannual variability in both periods. Regarding the SPEI from 1901 to 2013 (Fig. 3b), higher potential evapotranspiration is noticed in particular periods such as 1907-1911, 1939-1945, 1969-1972, and 1990-2013; the other periods highlighted low potential evapotranspiration. Generally, the aridity indexes (Fig. 3c) are below one, this means that the annual PET is usually higher than the annual precipitation in this basin. This later result is well seen in the simplified water balance (P-PET) in Fig. 3d, where in the whole period, negative values are found which indicated more water losses through evapotranspiration.

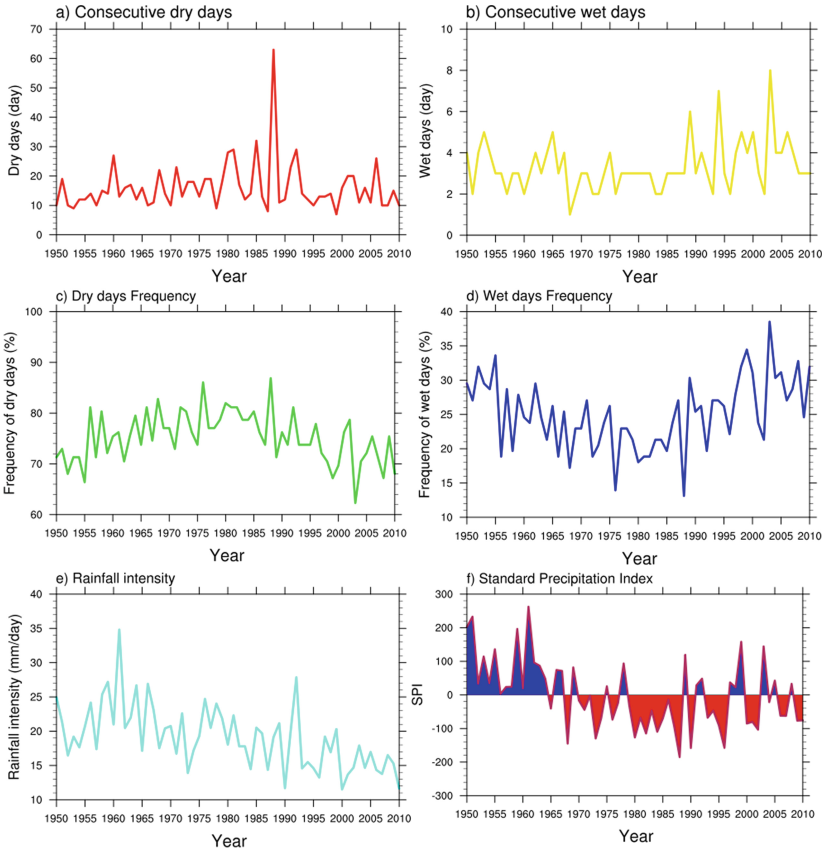

Fig. 2. Interannual variability of maximum number of consecutive dry days (a), maximum number of consecutive wet days (b), dry days frequency (c), wet days frequency (d), rainfall intensity (e) and standardized precipitation Index (f) at Kidira (1950–2010) (Color figure online)

3.2 Future Changes of the Basin Hydroclimate Under Global Warming Levels

With regard to the future hydroclimate of the basin under 1.5 and 2.0 °C global warming, the three RCMs (RCA4, RACMO22, CCLM) and their ensemble mean show mainly an increase of rainfall during the wet season (Fig. 4); even though in few months, precipitation could slightly decrease in the beginning and the end of the rainy season. This increase is more pronounced with 1.5 °C than with 2.0 °C, global warming. However, in the coming decades, potential evapotranspiration is likely to increase in all regional climate models and their ensemble mean (Fig. 5). The changes of PET are more substantial with 2.0 °C global warming. CCLM displays the greatest increase of water losses through the processes of evaporation and transpiration.

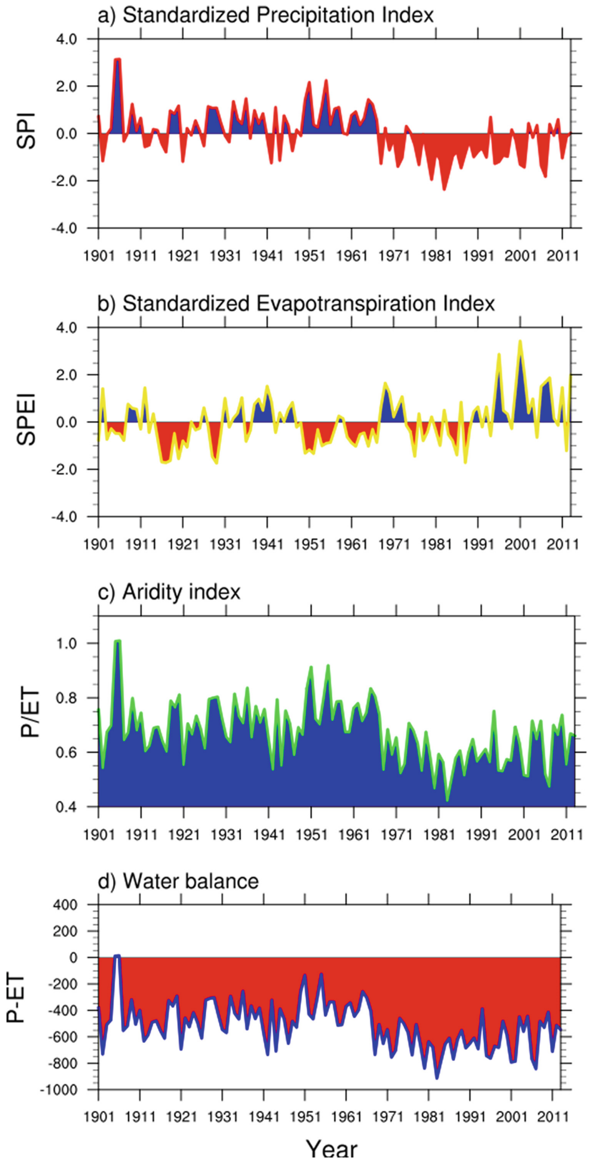

Fig. 3. Interannual variability of standardized precipitation index (a), standardized evapotranspiration index (b), aridity index (c) and water balance (d) over the whole basin (1901–2013)

3.3 Simulated River Discharge During the Past and the Future

Furthermore, we simulated river discharge at the main outlet of the basin (Kidira) by using the output of these regional climate models as forcing of the hydrological model GR4J during the historical (1984–2013), under 1.5 °C global warming (2017–2046), and under 2.0 °C global warming (2032–2061).

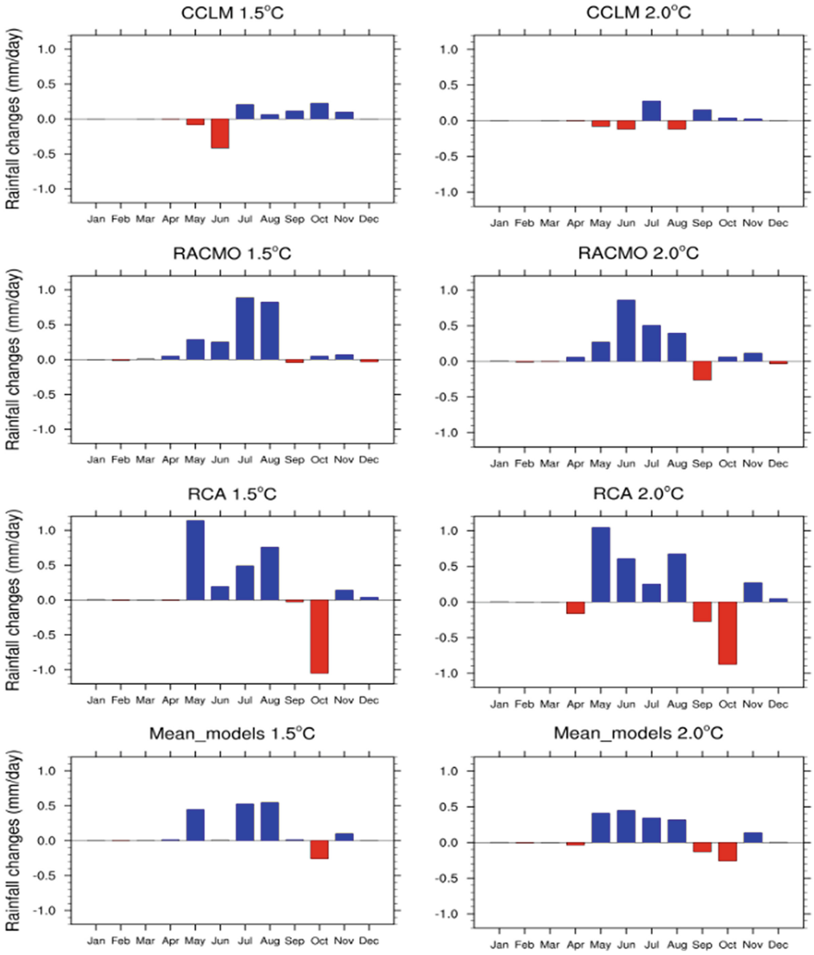

Fig. 4. Monthly changes of precipitation over the Faleme basin under 1.5 °C (left column) and 2.0 °C (right column) GWLs for the three RCMs and their ensemble mean. Red color indicates a decrease and blue color indicates an increase. (Color figure online)

The results are shown in Fig. 6 in the form of box-plots. It is clearly noticed that river discharge is likely to increase under both warming when compared to the historical period. This situation may be due to the probable increase of rainfall. The CCLM regional climate model exhibits the lowest increase of streamflow. The increase of river flow is highly linked to the input data, particularly precipitation that is relatively common in several rainfall-runoff models. Some characteristics of the basin hydroclimate are summarized in Table 3. The simple water balance (P-PET) is negative in all periods which means the basin may experiences in the future water stress up to −154.09 mm under 1.5 °C and −160.25 mm under 2.0 °C.

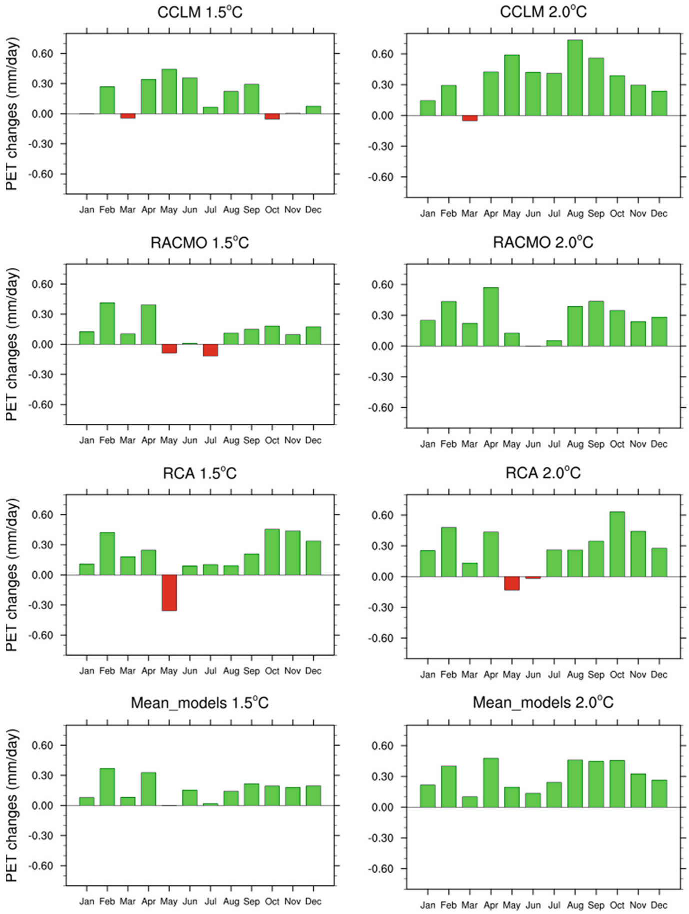

Fig. 5. Monthly changes of Potential Evapotranspiration over the Faleme basin under 1.5 °C (left column) and 2.0 °C (right column) GWLs for the three RCMs and their ensemble mean. Red color indicates a decrease and green color indicates an increase. (Color figure online)

Rainfall is projected to increase from historical to the future; an increase of 42.03 mm under 1.5 °C, and an increase of 36.85 mm under 2.0 °C. As well documented, temperature generally increases under both warming scenarios. Moreover, potential evapotranspiration follows obviously the same changes as temperature. However, the decline of the simple water balance while there could be a slight increase of precipitation may be due to an overestimation of the potential evapotranspiration. As found by these authors [13] smaller change is found under 1.5 °C scenario as the 2.0 °C scenario. Moreover, dry day's frequency might decrease under 1.5 °C global warming and increase under 2.0 °C global warming. In addition, the low flows characterized here by the 10th percentile, indicate a potential decrease of these river flows at 2046 and 2061 horizons.

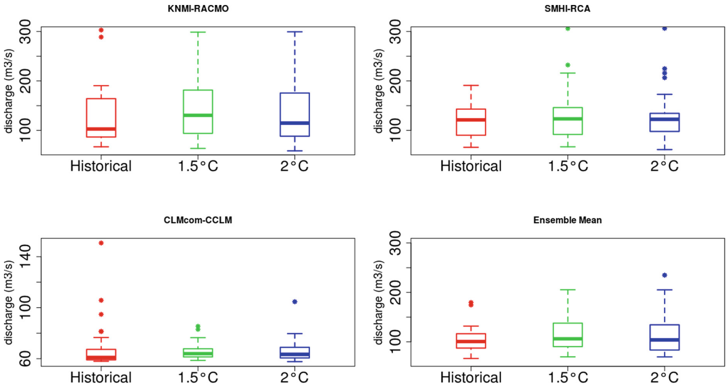

Fig. 6. Box plots of simulated river discharge under historical period (red color), under 1.5 °C (green color) and 2.0 °C (blue color) of the Faleme at Kidira outlet (Color figure online)

Table 3. Summary of the mean characteristics of the basin's hydroclimate (water balance, Rainfall, Evapotranspiration, Temperature, dry day's frequency, low flows) of the ensemble mean of all RCMs during the reference period (1984–2013), 1.5 °C warming period (2017–2046), and 2.0 °C warming (2032–2061)

Indicators	Reference period (1984–2013)	1.5 °C warming (2017–2046)	2.0 °C warming (2032–2061)
Water balance (mm)	−154.09	−155.38	−160.25
Rainfall (mm)	689.77	731.8	726.62
Evapotranspiration (mm)	843.86	887.18	886.87
Temperature (∘C)	27.74	28.901	29.514
Dry day's frequency (%)	10.889	10.75	10.917
Low flows (10th percentile)	1.019	0.999	0.971

4 Discussion

This water shortage (Fig. 2 and 3) is within the period when the Sahel experiences its severe droughts in the 20th century which was a result of the cooling of the North Atlantic relative to the South Atlantic [14] However, some heavy rains were found in particular years; this kind of rainfall causes usually floods which affect human societies and their socio-economic activities. Substantial water is lost through evapotranspiration which is generally the most significant component of the water budget, acting to recycle much of rainfall, in particular, over the Sahel region [15]. In the coming decades, the RCA4 and RACMO22 models exhibit the most considerable changes in the future. This increase could be the result of moisture supply for convection from the North

Atlantic Ocean due the global warming which increases the atmospheric water vapor that in turn can leads to substantial precipitation over the basin. Temperature (not shown here) has similar changes that potential evapotranspiration. It generally increases in all climate models, and obviously in their ensemble mean. This is a well-known situation, as in the literature, the climate models in several studies agree in a general increase of temperature in the future due to anthropogenic greenhouse gases [16, 17]. The increase of evapotranspiration will lead to more atmospheric water vapor which generate cloud by condensation; the increase of cloudiness could in turn generate considerable rainfall. Additionally, it should also be taken into account the influence of the global tropical oceans and the North Atlantic SSTs that highly influence the Sahel rainfall [18]. In the ensemble mean, lower values of evapotranspiration during the rainy season can be explained by the fact that PET is moisture limited during the dry season and energy during the wet season. The differences in the models projections are mainly due to the physical parametrization and the convection scheme used to simulate the hydroclimate processes of the basin. The slight increase of streamflow found in the future can be explained by an increase of precipitation resulting from more atmospheric cooling due to high evaporation and an increase of the atmospheric water holding capacity [7].

5 Conclusion

This study analyses the past and the future variations of the hydroclimate of the Faleme basin under 1.5 and 2.0 °C global warming. In the past, the analyses show a higher interannual variability of precipitation, potential evapotranspiration, their indexes and the water balance. Generally, wet period (1901–1970), and dry period (1971–2013), were identified. The annual water budget shows a water deficit over the whole basin. Furthermore, the years 1950s and the 2000s, are wetter than those in the 1970s and the 1980s. In the future, the basin is likely to experience relatively slight increase of precipitation, and considerable increase of temperature and potential evapotranspiration in the coming decades. Water losses through evaporation and transpiration are more pronounced under 2.0 °C global warming. It is projected also an increase of streamflow in future under both warming, particularly with 1.5 °C global warming. Moreover, low flows could decrease in future. These results show also that the level of warming that is related with the greenhouse gases emission, has an important impact on the projected climate change signals. According to these findings, the riparian people of the basin should develop and use water saving technologies, crop resistant to higher evapotranspiration, and integrated water resources management, smart agriculture. However, due to uncertainties related to climate simulations and the hydrological model, further investigations are needed with more regional climate simulations and uncertainty analysis. Bias correction techniques on climate model output may improve the quality of the hydrological simulation. Instead of using a simple rainfall-runoff model, physically-based hydrological models may offer better representation of the hydrological processes.

Acknowledgments. The authors thank the Laboratoire d'Océanographie, des Sciences de l'Environnement et du Climat (LOSEC) of the University of Assane Seck, Ziguinchor were the work has been mainly done. The authors would like to thank also Babacar Faye and the anonymous reviewers for their valuable suggestions and comments to improve the quality of the paper. We are further thankful to AWARD and the One Planet Fellowship for the scientific skills acquired during the science week in Morocco.

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