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Change in Climate Indices Using Bias-Adjusted CMIP5 Models: The Case Study of the Fatick Region, Senegal

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Abstract

This study analyses change in rainfall and temperature indices by 2035 and 2050 in Senegal, with a focus on the Fatick region. These parameters are crucial for understanding the impacts of anthropogenic climate change on some vital socio-economic sectors such as agriculture and water resources in this region. To this end, a multi model ensemble mean of 21 bias-adjusted global climate models participating in CMIP5 has been used. We considered two Representative Concentration Pathways (RCP4.5 and RCP8.5). The results indicate an increase of 0.7˚C for maximum and minimum temperature by 2035 compared to the reference period (1976 - 2005). By 2050, an increase of 1.4˚C (2˚C) is projected for RCP4.5 (RCP8.5). These increases in temperature are statistically significant at the 90% confidence level. Conversely, the mean rainy season length decreases from 95 to 85 days by 2035 and less than 80 days by 2050. These decreases in rainy season length are mainly due to a delayed rainy season onset by 2035 and 2050, with the ensemble mean projecting an onset in the second half of July by 2050 instead of around the middle of June. The changes in both the onset and the length of the rainy season are significant at the 90% confidence level. Our results show a slight decrease in seasonal cumulated total rainfall by 2035 and 2050. However, we note a slight increase in seasonal cumulated extreme rainfall. These future changes in climate indices could induce yield reduction and water resources availability. To reduce yield losses, it would be interesting to adopt longer season varieties and also diversify income-generating activities. Concerning water resources, many actions could be done such as carrying out water retention works, treatment and reuse of non-conforming water for agriculture and livestock to reduce pressure on the resource.

Keywords

Climate Indices, CMIP5, Fatick (Senegal), RCP4.5 and RCP8.5

1. Introduction

Senegal, located in Western Sahel, is thus at high risk of climate change since the country is exposed to a combination of climate hazards of different natures: warmer temperatures, less annual rainfall, more intense rainfall. Many studies based on observations indeed show an increase in mean temperature, with an important variability (Bodian, 2014; Kosmowski et al., 2015; Sagna et al., 2015). An irregular onset and offset of the rainy season (Salack et al., 2012) and more intense rainfall events (Panthou et al., 2014; Maidment et al., 2015; Sanogo et al., 2015) For the near future, the different radiative forcing scenarios lead to temperature changes ranging between 1˚C and 2.5˚C in Senegal (Guichard et al., 2015; Tall et al., 2017). Moreover, Sarr & Camara (2017) analyzed the simulations by four Regional Climate Models (RCM) of the CORDEX (COordinated Regional climate Downscaling Experiment) program to characterize the extreme rainfall events in Senegal by 2100 under RCP8.5. Three of their models show a decrease in both rainfall and the number of wet days by 2100. This decrease in rainfall is conform with Tall et al. (2017) results, which also show a change of more than 50% in potential evaporation under RCP8.5 in the Lake of Guiers basin. When considering the evolution of some extreme rainfall events such as the highest one-day rainfall amount and the 99th percentile of daily rainfall, Sarr & Camara (2017) found (using four RCMs) an increase, which may translate, into strong floods in Senegal. This combination of climate events poses serious risks in Senegal for agriculture (which is mainly rain-fed), water resources as well as coastal areas, that is all already fragile. These three sectors occupy an important place in the national economy and their sensitivity to climate change is a serious challenge to the objectives of the Emerging Senegal Plan (CPDN, 2015) and has to be taken into account in the elaboration of adaptation strategies at the national level.

The above studies generally consider West Africa. Those focused on Senegal use either observations, e.g. (Descroix et al., 2015; Bodian, 2014) or a limited number of models (around 4), generally regional climate models, e.g. (Sarr & Camara, 2017). These studies focused on hydro-climatic parameters rather than on agronomic indices such as the onset, cessation and length of the rainy season. In addition, few studies focus on the effects of climate change at local scale, whereas there is an increased need for climate and weather information for decentralized technical services to better advise local populations in their activities. Finally, the time horizons used in above studies in Senegal are generally not useful for decision-makers who require climate information with a shorter time horizon that cover their plan and program. This study is in line with this need to provide information on agro-climatic indices changes in Senegal. It is part of the Scientific Support Project to National Adaptation Plans (PAS-PNA) processes in Senegal with a focus on the Fatick region. This project aims to examine the vulnerability to climate change of the agriculture, water resources and coastal sectors to climate change. The realization of a vulnerability study requires, among other things, the identification of exposure factors and thus of the past and future variability of climate parameters. To do so, we compute several impact indices that are relevant for the key sectors (agriculture, water resources) in 2035 and 2050 horizons by using 21 bias-adjusted global climate models. The choice of the 2035 and 2050 horizons is based on the Emerging Senegal Plan (PSE), which consists of several components including the Acceleration of the Senegalese Agriculture Rate (PRACAS in French) by 2035 horizon. The 2050 horizon takes into account the United Africa agenda 2063, which has as objectives, among others the economies and communities are environmentally sustainable and climate resilient (https://au.int/fr/agenda2063/objectifs). This article focused on the exposure factors in the framework of the PAS-PNA project. The data and methodology are described in section 2. The results are presented in section 3. The latter is divided into 3 subsections focusing on different metrics: mean states, spatial changes, and temporal evolution. The discussion and conclusion are presented in sections 4 and 5 respectively.

2. Data and Methods

2.1. Data

2.1.1. Global Climate Models

In this study, we used 21 bias-adjusted simulations of CMIP5 Global Climate Models (GCMs, Table 1). The bias correction is based on the cumulative distribution function transform (CDF-t) method. The later is based on the assumption that there exists a transformation T allowing to "translate" the cumulative distribution function (CDF) of a GCM variable (such as temperature, precipitation or wind intensity), i.e., the predictor, into the CDF representing the local-scale climate variable, i.e., predict and, at a given weather station (Vrac & Friederichs, 2015; Michelangeli et al., 2009). Overall, statistical downscaling methods with carefully chosen predictors and an appropriate model structure for a given application realistically represent many statistical aspects of present-day daily temperature and precipitation (Doblas-Reyes et al., 2021). Diakhaté et al. (2022) assessed the potential impact of bias-adjustment on Rainfall Annual cycle of GCM over the Senegal River Basin. Compared to the uncorrected ones, bias-adjustment reduced considerably the biases in the amplitude of the rainfall annual cycle. In this study, we have used the CMIP5 bias-adjusted results of Famien et al. (2018). The CDF-t has been applied over the period 1950-2099 by combining historical runs and climate change scenarios (Famien et al., 2018). The observation-based reference dataset used for bias-correction is WFDEI, the WATCH Forcing Data (Weedon et al., 2011) methodology applied to ERA-Interimdata, for the period from 1 January 1979 to 31 December 2013 on a 0.5° × 0.5° grid (Weedon et al., 2014). The GCMs data have been interpolated to the WFDEI grid before being bias corrected. We extracted model data for daily rainfall, maximum and minimum near surface temperature for a historical period (1950 - 2005) and for the future (2006 - 2067). The model projections include several scenarios called Representative Concentration Pathways (RCP), which explore the impact of climate policies (Van Vuuren et al., 2011; Collins et al., 2013). For our analyses, we re-gridded all extracted variables to a grid (0.25° × 0.25°) using a bilinear grid interpolation.

Table 1. CMIP5 models characteristics use in this study. All models have.

Model acronym	Modelling group	Initial resolutions (lonxlat)	Final resolutions (lonxlat)
ACCESS1-0 ACCESS1-3	Commonwealth Scientist and Industrial Research Organisation (CSIRO) and Bureau of Meteorology (BOM), Australia	1.25° × 1.875°	0.5° × 0.5°
CMCC-CM CMCC-CMS	Centro Euro-Mediterraneo per I Cambiamenti Climatici	0.748° × 0.75° 3.711° × 3.75°	0.5° × 0.5°
MIROC-ESM MIROC-ESM-CHEM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research, Institute (university of Tokyo) and National Institute for Environmental Studies	2.8125° × 2.8125°	0.5° × 0.5°
MRI-CGCM3	Meteorological Research Institute	1.12148° × 1.125°	0.5° × 0.5°
MPI-ESM-LR MPI-ESM-MR	Max-Plank-Institu fur Meteorologie (Max Plank Institute for Meteorology)	1.8653° × 1.875°	0.5° × 0.5°
bcc-csm1-1	Beijing Climate Center, China Meteorological Administration		0.5° × 0.5°
bcc-csm1-1-m		1.875° × 1.875°	0.5° × 0.5°
BNU-ESM	College of Global Change and Earth System, Beijing Normal University	2.81° × 2.81°	0.5° × 0.5°
GFDL-ESM2M GFDL-ESM2G GFDL-CM3	NOAA Geophysical Fluid Dynamics Laboratory	2° × 2.5°	0.5° × 0.5°
inmcm4	Institute for Numerical Mathematics	1.5° × 1.5°	0.5° × 0.5°
IPSL-CM5A-LR IPSL-CM5A-MR IPSL-CM5B-LR	Institute Pierre-Simean Laplace	1.9° × 3.75° 1.25° × 2.5° 1.9° × 3.75°	0.5° × 0.5°
MIROC5	Atmosphere and Ocean Research Institute (University of Tokyo), National institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	1.4° × 1.4°	0.5° × 0.5°
NorESM1-M	Norwegian Climate Institute	1.9° × 2.5° × 1	0.5° × 0.5° × 1

2.1.2. Observation

To evaluate the model rainfall, we used the Climate Hazards Group InfraRed rainfall with Station data (CHIRPS). The CHIRPS data are obtained from satellites recalibrated using rainfall stations on the ground (Funk et al., 2015). They have a horizontal resolution of 0.05˚ × 0.05˚, a daily temporal resolution and cover the period 1981-2015. For the evaluation of the representation of temperature we used the Climatic Research Unit (CRU) data, which are squared on a horizontal grid of 0.5˚ × 0.5˚ (Mitchell & Jones, 2005) at monthly temporal resolution, and start in 1901. Previous studies found big uncertainty on the quality of observed rainfall data over Africa, which may be largely due to with large areas over Africa scarcely covered with rain gauge (Morice et al., 2012; Sarr et al., 2015; Dosio et al., 2021b). However, some studies compared CHIPRS with other data (GPCP, ARC2.0, gauge data, TAMSAT…) and good performance depending on the indices (Dembélé & Zwart, 2016; Dinku et al., 2018; Shen et al., 2020, Fall et al., 2021).

2.2. Methods

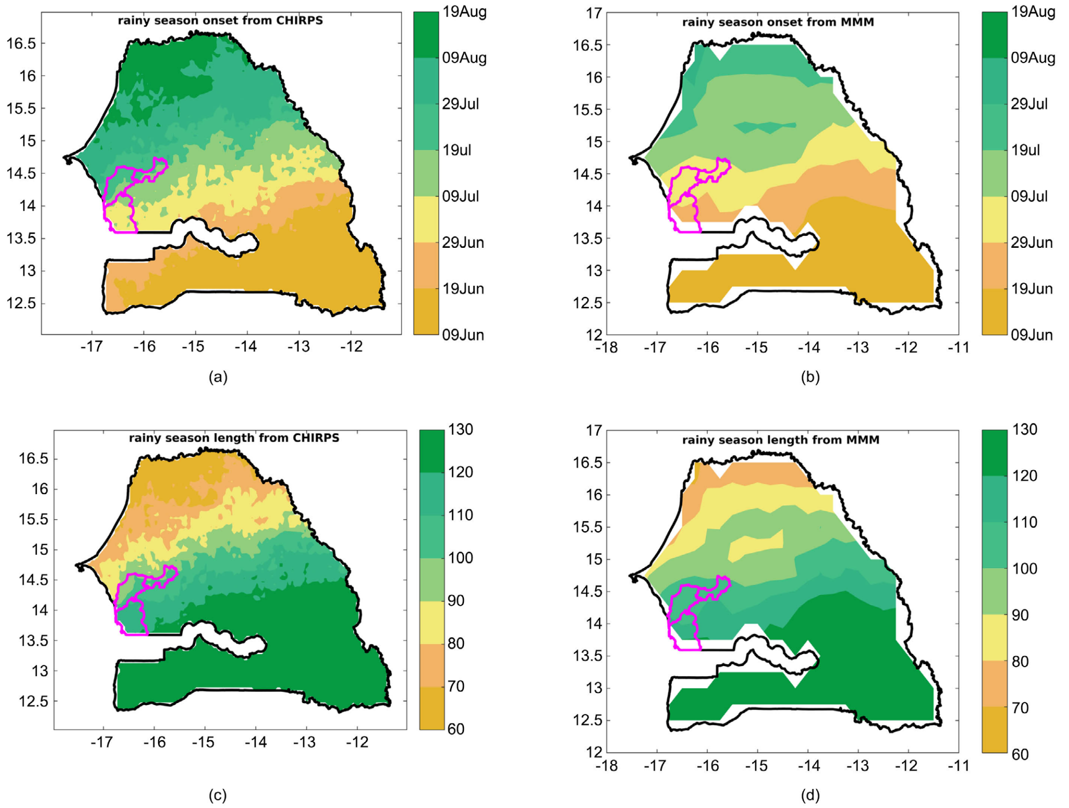
2.2.1. Study Area

The Fatick region (**Figure 1**; marked in magenta) is located in the groundnut basin, which is Senegal's largest agricultural region (MEDD, 2016). It is limited to the East by the Kaolack region, to the West by the Atlantic Ocean, to the North by the Diourbel region, to the North West by the Thies region, to the South by Gambia. The region has three departments (Fatick, Gossas, Foundiougne). The climate of the Fatick region is Sudano-Sahelian. Temperatures vary greatly from one zone to another, but also from one month to another, oscillating generally between 24˚C in January and 40˚C in April/May (CRF, 2001). The main winds that sweep the region are: the Harmattan which blows over the entire north and north-east, the southeastern wind present in the coastal area, and the monsoon blowing between April and October. Rainfall is relatively high and varies between 500 mm and 1000 mm (Sagna et al., 2015).

2.2.2. Climate Indices

In this study we consider agroclimatic indices (**Table 1** supplementary material), which were selected during a discussion with stakeholders involved in the development of the National Adaptation Plan of Senegal:

- Seasonal total wet days rainfall: we compute for each year the seasonal (June to September) total rainfall from days greater or equal to 1mm.
- Seasonal total extreme wet days rainfall: we compute for each year the seasonal (June to September) total rainfall from days greater or equal to the 99th percentile. The 99th percentile is computed over the historical period (1976 - 2005).
- Rainy season onset, cessation and length: The rainy season onset (RSO) is defined by the date after the 1st of May when we recorded at least 20 mm of rain over 3 days without any dry episode exceeding 7 days within 30 following



(a) (b) (c) (d)

Figure 1. Mean spatial distribution of rainy season onset for observation (a) and multi model mean (MMM) (b) over the period 1981-2005. (c) and (d) same as (a) and (b) respectively but for rainy season length. The Fatick region is marked in magenta.

days (Sivakumar, 1988). The rainy season cessation (RSC) is defined by the date, after September 1st, when there are at least 20 consecutive days with rainfall less than 1mm. The rainy season length (RSL) is obtained by subtracting RSC and RSO (RSL = RSC – RSO).

- Seasonal mean maximum and minimum temperature: we compute for each year the seasonal (June to September) mean of daily maximum and minimum temperature.

2.2.3. Climate Change Scenarios

The analysis of the change in the agroclimatic indices is made in the context of national adaptation plan that is based on two horizons: horizon 2035 (2021 - 2050) and horizon 2050 (2038 - 2067). After defining both horizons, we defined a baseline, which expand from 1976 to 2005. In this study, two scenarios (RCP4.5 and RCP8.5) among the 4 of the 5th IPCC report (IPCC, 2013) described by Moss et al. (2010) were used to characterize future changes compared to the baseline. In fact, at the current rate of emissions, the global warming threshold of +1.5˚C compared to the pre-industrial period will be reached between 2030 and 2052 (Allen et al., 2018). Pathways reflecting the current national mitigation ambition up to 2030 are broadly consistent with cost-effective pathways that result in global warming of about 3˚C by 2100, with warming continuing thereafter (IPCC, 2021). This warming of 1.5˚C towards 2040 and 3˚C towards 2099 justify the choice of the two selected scenarios. The RCP4.5 scenario, here referred to as the low average scenario, indeed corresponds to the case where CO_2 emissions reach a maximum just before 2050. In contrast the RCP8.5 scenario, here referred to as pessimistic scenario (business as usual), corresponds to the case where the emissions of greenhouse gases effect intensify by the end of the century.

3. Results

3.1. Evaluation of the Present-Day Climate

3.1.1. Rainfall

Figure 1(a) and **Figure 1(b)** (in supplementary materials) show the mean over the period 1981-2005 of seasonal total wet days rainfall from CHIRPS data and the multi-model mean (MMM) respectively. The MMM succeeds in reproducing the observed spatial distribution of seasonal total wet days rainfall over Senegal, with higher rainfall amounts in the south of the country. This simulated spatial distribution is conforming to previous studies based on observations and models (Sagna et al., 2015; Bodian, 2014). The Fatick region is between the isohyet 500 mm and 700 mm according to the MMM (**Figure 1(b)** in supplementary materials). This is slightly higher than the observations (**Figure 1(a)** in supplementary materials) similarly to what Sagna et al. (2015) found and hereby placing this region in the North-Sudanian zone where the total varies between 500 mm and 1000 mm.

Regarding the rainy season onset and length (**Figure 1(a)** and **Figure 1(b)**), as in the observations, the MMM shows a north-south gradient for both indices. In the southern part of Senegal, the RSO is generally at the beginning of June or before while in the northern part it occurs at the end of July or later. In our study area, the MMM shows that the rainy season onset is between June 19 and July 9 (**Figure 1(b)**). This simulated RSO is 10 days earlier than the observed one. This shift could be due to overestimation of rainfall by the MMM (**Figure 1(b)** in supplementary materials). For the rainy season length (**Figure 1(c)** and **Figure 1(d)**), it varies between 80 and 100 days according to the MMM, which however overestimates this variable by ≈10 days in our study area.

3.1.2. Maximum and Minimum Temperatures

Figure 2 (supplementary materials) shows the JJAS mean of maximum and minimum temperature from observation data (**Figure 2(a)** and **Figure 2(c)**) and MMM (**Figure 2(b)** and **Figure 2(d)**). Maximum temperature varies between 29˚C and 38˚C in Senegal with lower values in the coastal region and higher values in the northeastern region. The MMM has the similar pattern, but the maximum temperature is overestimated (**Figure 2(b)**). The overestimation ranges between 0.1˚C to 0.9˚C with maximum bias located at the coast (not shown). Minimum temperature also presents a West-east gradient with strong temperature in the interior of the country (**Figure 2(c)** and **Figure 2(d)**). The minimum temperatures

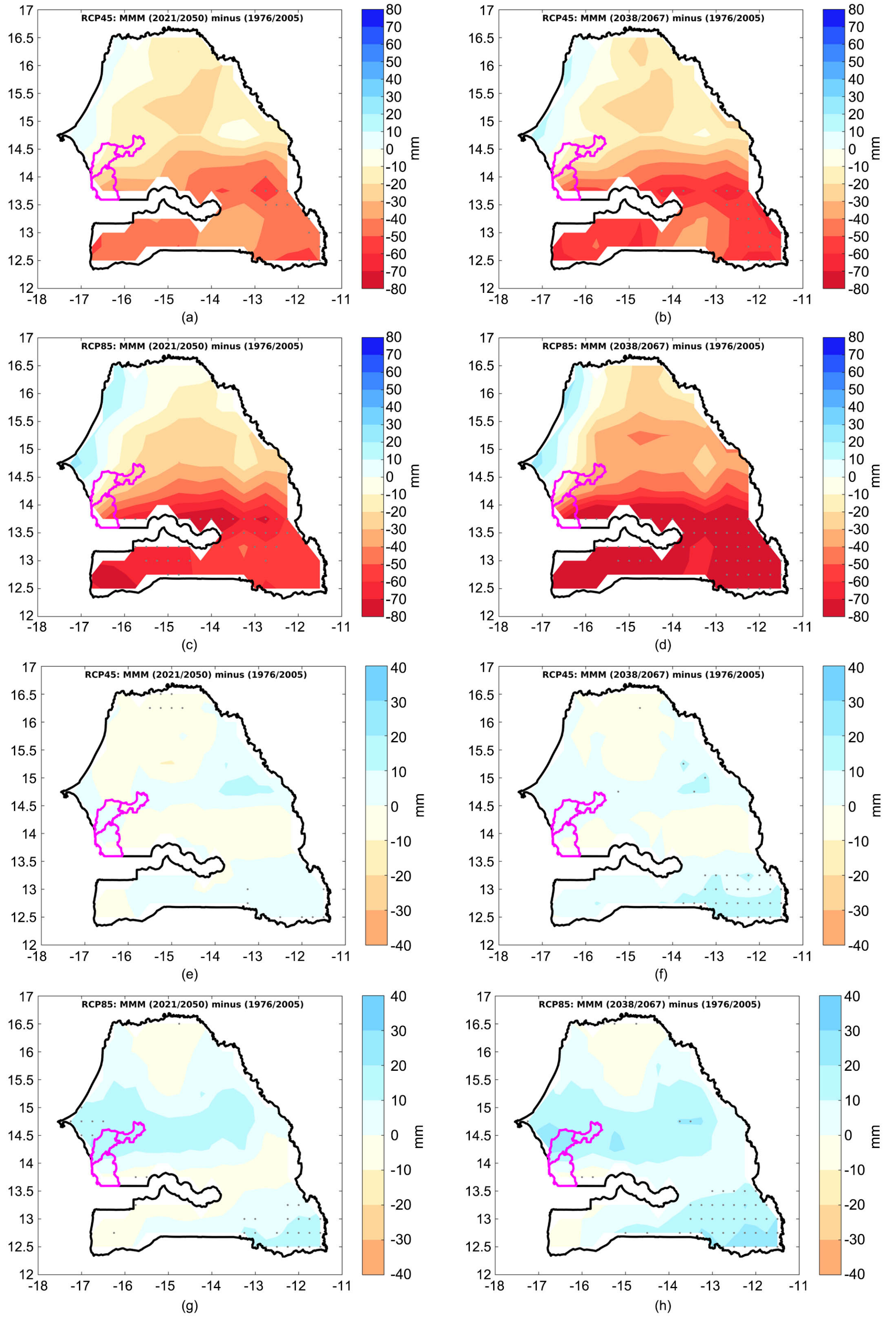


Figure 2. Climate changes (i.e. horizon minus reference period), of the multi model mean (MMM), of seasonal total wet days rainfall under RCP4.5: (a) is change by horizon 2035 and (b) is change by horizon 2050. Regions where the change is significant at 80% are indicated with gray dots. (c) and (d) are the same as (a) and (b) respectively under RCP8.5 scenario. (e), (f), (g) and (h) are the same as (a), (b), (c) and (d) respectively but for seasonal total extreme wet days rainfall. Extreme rainfall events are obtained by applying the 99th percentile threshold.

vary between 22˚C and 26˚C according to the observations, but higher values are found in the models. The biases in the minimum temperature are identical (en terms of values and spatial distribution) to those in the maximum temperature. The bias between CRU and bias-adjusted data could be due to models themselves since some studies show little difference between CRU and WFDEI data (Aschenbrenner, 2019). The latter was bias-adjusted by the former (Weedon et al., 2014).

3.2. Future Changes in the Spatial Distribution of Climate Indices

3.2.1. Rainfall Indices

Figures 2(a)-(d) show the changes in the seasonal total wet days rainfall with respect to the reference period (1976-2005). For the RCP4.5 scenario, our results show generally a decrease in seasonal rainfall for the 2035 and 2050 horizons, except along the coast in the northern half of the country (**Figure 2(a)** and **Figure 2(b)**). The decrease is more important and significant at 80% confidence level in the southern regions, which experience higher seasonal cumulative rainfall. In the Fatick region our results show a decrease ranking between 20 and 60 mm with a maximum decline found in the southern part. The seasonal total extreme wet days rainfall, by 2035, could drop in the center-east and North of Senegal for both scenarios (**Figure 2(e)** and **Figure 2(g)**). However, by 2050 we find an increase in the major part of the country. This increase varies from 10 to 30 mm and is only significant at 80% in southeastern Senegal (**Figure 2(e)** and **Figure 2(g)** gray dots). In our study area, the total extreme wet days rainfall amount could generally increase with a maximum of 30 mm by 2050 under RCP8.5. The changes, due to half models, are more important in the north part of the Fatick region, but are not significant at 90% confidence level.

We find a delay in the rainy season onset in comparison with the reference period for both scenarios and horizons (**Figure 3**) with a confidence level of 90% except in the North-west of Senegal (see the black stippling in **Figure 3**). Under both scenarios the maximum delay is located in the southeastern region of Senegal. This maximum delay is about 12 and 15 days by 2050 under RCP4.5 and RCP8.5, respectively (**Figure 3(b)** and **Figure 3(d)**). In these regions, the mean RSO is between 19 June and 09 June (**Figure 1(b)**) meaning that by 2050 the RSO could be between the end of June and almost mid-July. In the Fatick region, the delay is around 6 days under RCP4.5. It can reach 10 days, mainly in the northern part of Fatick, by 2050 under RCP8.5 (**Figure 6(d)**), meaning that the RSO would occur at the end of July. The delay in the rainy season onset will impact its length. Under both scenarios, we see a reduction in RSL (**Figure 4**) of up to 15 days by 2050. By 2035, the maximum decrease is 9 days and is located in southeastern Senegal for RCP4.5, and 12 for RCP8.5. In the Fatick region, the RSL is around 95 days. It decrease is less important with a maximum of ≈6 days (≈12 days) for RCP4.5 and RCP8.5 respectively (**Figure 4**). These changes are significant at 90% confidence level. So by 2050 under RCP8.5, the RSL could be less than 3 months (around 80 days) while under RCP4.5 it could reach three months (**Figure 4(b)**, **Figure 4(d)** and **Figure 1(d)**). By 2035, the RSL could reach 3 months under both scenarios (**Figure 4(a)**, **Figure 4(c)** and **Figure 1(d)**).

3.2.2. Maximum and Minimum Temperature

Figure 5 shows the change in seasonal mean maximum temperature relatively to the reference maximum temperature. Under both scenarios and horizons we find an increase of maximum temperature with a 90% confidence level. Under RCP4.5 (RCP8.5), the increase in maximum temperature ranges between 0.5˚C and 1.5˚C (0.5˚C and 2˚C) by 2035 (**Figure 5(a)** and **Figure 5(c)**). By 2050 under RCP4.5, the maximum temperature increase intensifies, reaching between 1˚C to 2˚C. In our ROI, changes range between 1˚C and 1.5˚C (**Figure 5(b)**). In comparison, under RCP8.5 by 2050, the maximum temperature change reaches between 2˚C and 2.5˚C in the southeastern regions of Senegal. In the Fatick the increase is limited to about 1.5˚C to 2˚C (**Figure 5(d)**). Concerning seasonal mean minimum temperature, our results also show a similar increase in the future (not shown) with greater change values on minimum temperatures than on maximum temperatures (not shown).

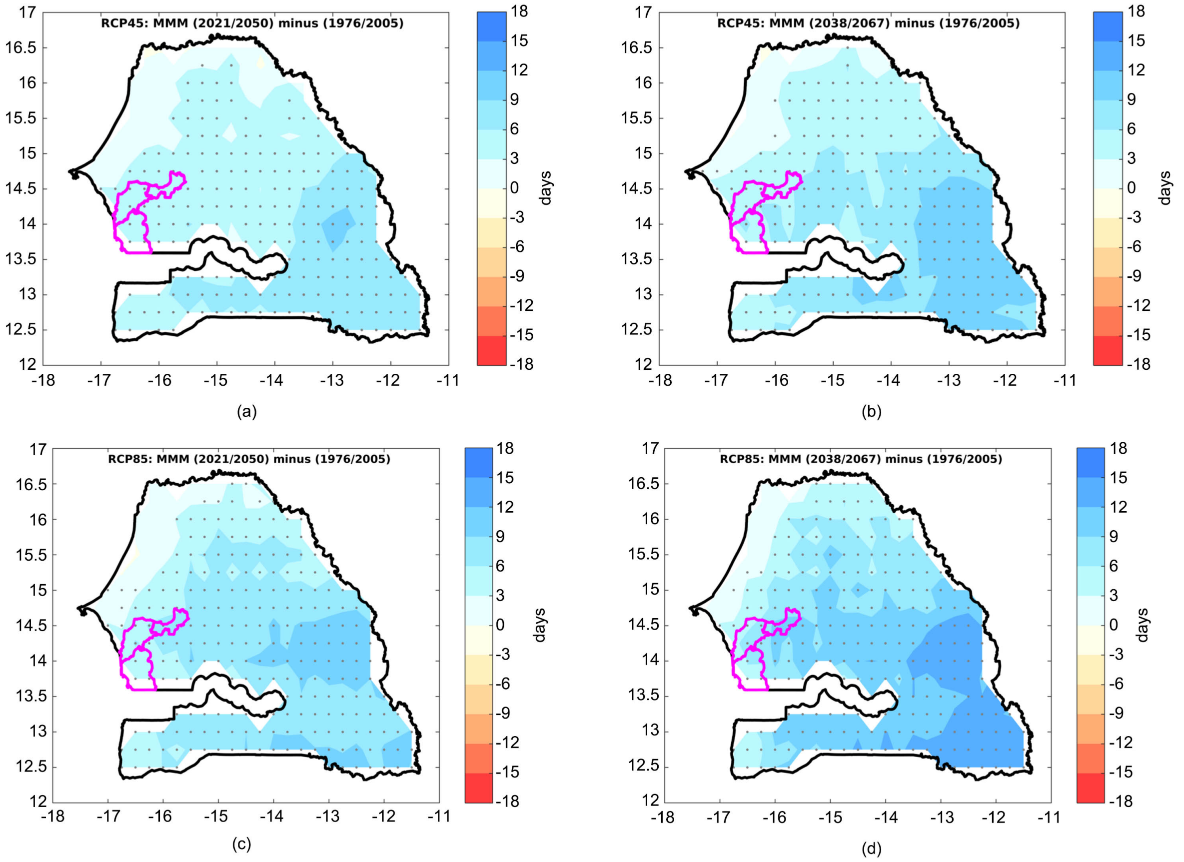


Figure 3. Climate changes (i.e. horizon minus reference period), of the multi model mean (MMM), of rainy season onset under RCP4.5: (a) is change by horizon 2035 and (b) is change by horizon 2050. (c) and (d) same as (a) and (b) respectively under RCP8.5 scenario. Regions where the change is significant at 90% are indicated with gray dots.

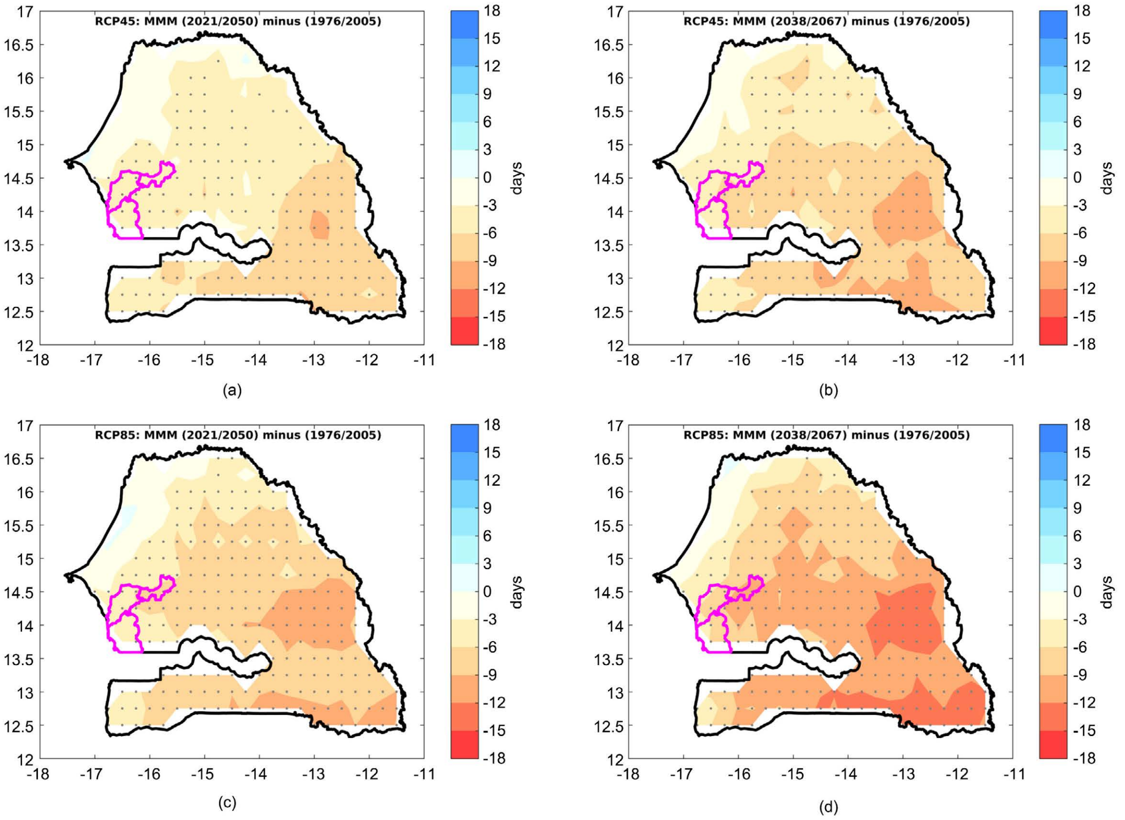


Figure 4. Climate changes (i.e. horizon minus reference period), of the multi model mean (MMM), of rainy season length under RCP4.5: (a) is change by horizon 2035 and (b) is change by horizon 2050. (c) and (d) same as (a) and (b) respectively under RCP8.5 scenario. Regions where the change is significant at 90% are indicated with gray dots.

3.3. Temporal Evolution

3.3.1. Rainfall Indices

The temporal evolution of the MMM rainfall and temperature indices averaged over the Fatick region is displayed in Figure 6. For the seasonal total wet days rainfall (Figure 6(a)), there is no clear tendency. However in comparison with the reference period value (580 mm; Figure 6(a) black horizontal line), for the historical period (1950-2005) the rainfall is more important from 1950 to 1970 and quasi-equal the rest year (Figure 6(a) black curve). In the future the rainfall decreases, in comparison with baseline value, under both scenarios (Figure 6(a) blue and red curve). However the interdecile model spread (range between the 10th and 90th percentile), indicated by the shading, is large. This decrease is estimated at 8.02 mm (4 mm) by 2035 (2050) horizon under RCP4.5 (Table 2). Under RCP8.5, we found a higher multi-model mean reduction equal to 11.7 mm and 15.4 mm by 2035 and 2050 respectively. So, by 2050 under RCP8.5 the seasonal total wet days amount could be around 560 mm (reference value minus the reduction). Under RCP8.5 61% (71%) of the model agree with the reduction by 2035 (2050) however these changes are not significance at 90% confidence level.

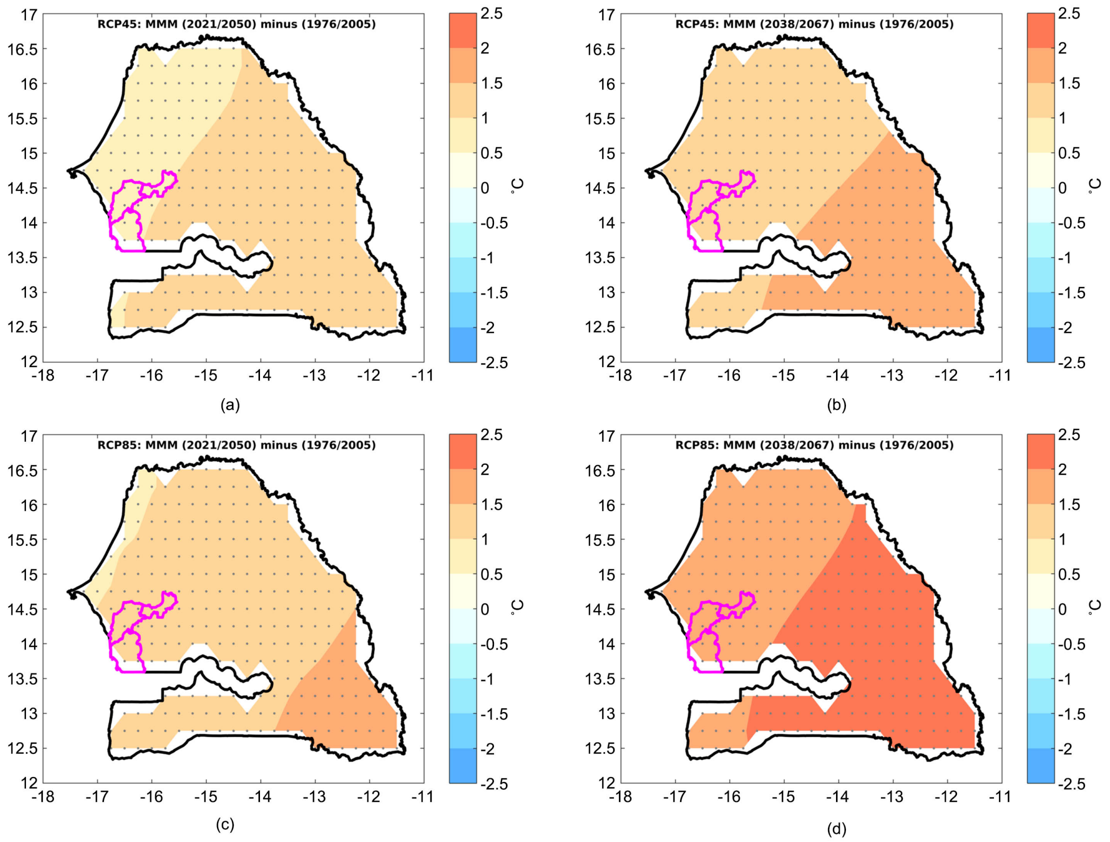
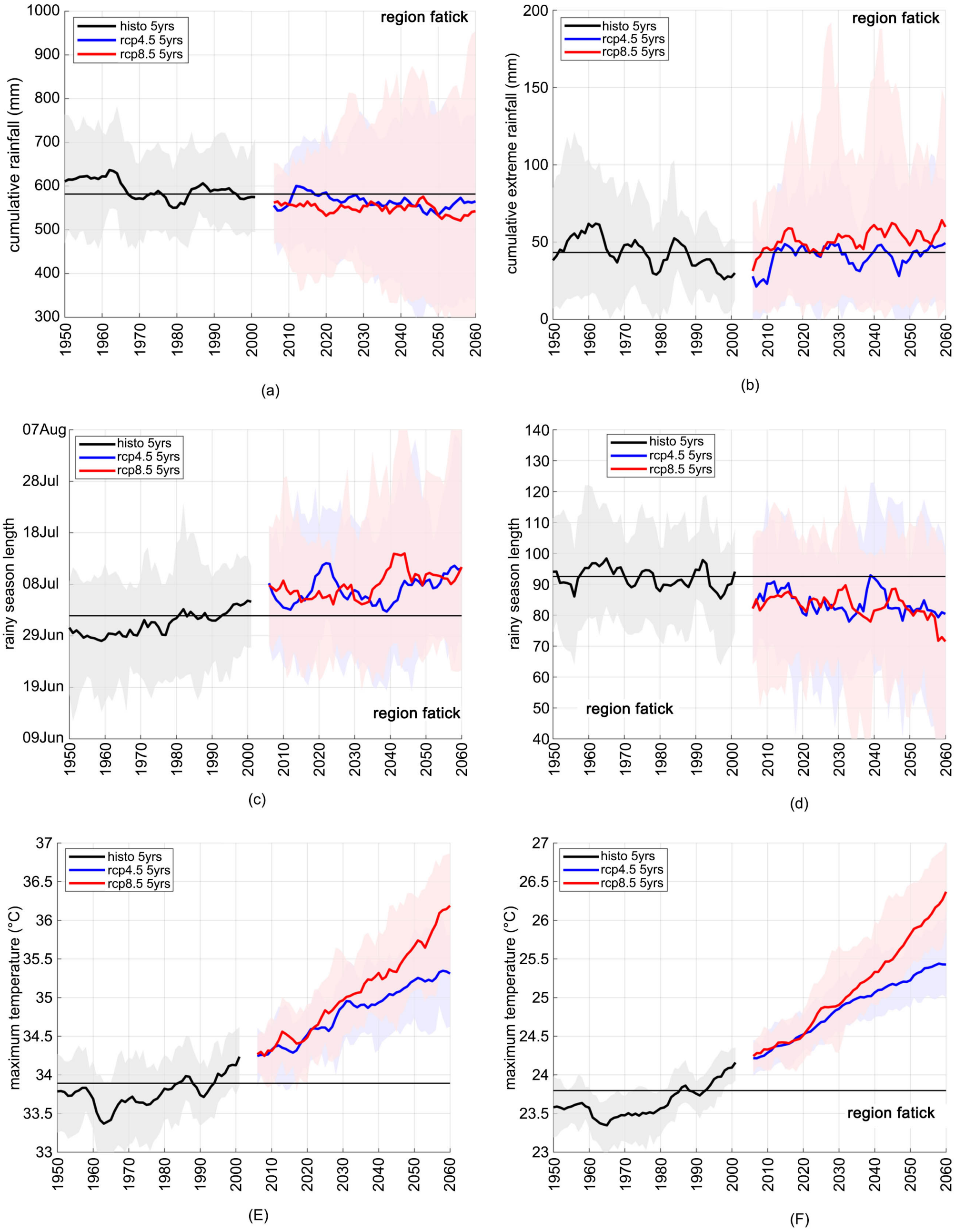


Figure 5. Climate changes (i.e. horizon minus reference period), of the multi model mean (MMM), of maximum temperature under RCP4.5: (a) is change by horizon 2035 and (b) is change by horizon 2050. (c) and (d) same as (a) and (b) respectively under RCP8.5 scenario. Regions where the change is significant at 90% confidence level are indicated with gray dots.

Table 2. Precipitation and temperature indices changes from the baseline (1976 - 2005) over Fatick region. Between bracket the number of models agree on the sign of the MMM. The ± values are relative standard errors.

Climate indices	Scenarios	Horizon 2035	Horizon 2050
rainfall cumulative (mm)	RCP4.5	−8.02 (11)	−4.00 (13)
	RCP8.5	−11.72 (13)	−15.37 (15)
extreme rainfall cumulative (mm)	RCP4.5	4.96 (11)	4.67 (10)
	RCP8.5	14.86 (08)	16.51 (10)
rainy season onset (days)	RCP4.5	4.63 ± 4.35 (14) **	6.06 ± 4.04 (17) **
	RCP8.5	6.32 ± 4.66 (18) **	9.31 ± 5.72 (17) **
rainy season length (days)	RCP4.5	−8.51 ± 6.45 (16) **	−12.31 ± 8.10 (18) **
	RCP8.5	9.58 ± 6.10 (18) **	−16.65 ± 8.79 (16) **
maximum temperature (˚C)	RCP4.5	0.95 ± 0.24 (21) **	1.26 ± 0.14 (21) **
	RCP8.5	1.15 ± 0.33 (21) **	1.78 ± 0.17 (21) **
minimum temperature (˚C)	RCP4.5	1.10 ± 0.24 (21) **	1.46 ± 0.12 (21) **
	RCP8.5	1.28 ± 0.34 (21) **	1.99 ± 0.16 (21) **

**: changes which are significant at 90% confidence level.



(a) (b)

(c) (d)

(E) (F)

Figure 6. Time evolution (from 1950 to 2060) of the multi model mean (MMM) over the Fatick region. Black thick curve is the historical period, blue curve is the scenario RCP4.5 and red curve is the scenario RCP8.5. A 5 years running mean is applied to the data. The shading indicates the interquartile ensemble spread (range between the 10th and 90th percentiles). Horizontal black thin line is the reference period (1976-2005) mean value. (a) and (b) are seasonal cumulative mean and extreme rainfall respectively. Extreme rainfall events are obtained by applying the 99th percentile threshold. (c) and (d) are rainy season onset and length respectively. (e) and (f) are maximum and minimum temperature respectively.

For the seasonal total extreme wet days rainfall, it would increase under RCP8.5 scenario (**Figure 6(b)** red curve) in comparison with the reference period value mainly after 2030 (48 mm; **Figure 6(b)** black horizontal line). However, the future values under RCP4.5 revolve around the reference value. The increase in the extreme rainfall reaches 14.9 and 16.5 mm under RCP8.5 by 2035 and 2050 respectively (**Table 2** row 3). Under RCP8.5, by 2035 (2050) 8 (10) models agree on the sign of change, which is not significant at 90% confidence level.

Concerning rainy season onset and length, the interdecile model spread is large. However contrary to the seasonal cumulative rainfall, we found a clear tendency for RSO and RSL (**Figure 6(c)** and **Figure 6(d)**). Concerning the projections (2006-2067), the RSO date would be later than the baseline onset value (**Figure 6(c)** blue and red curve, **Figure 6(a)** black horizontal line). Consequently, we found in the future a decrease in rainy season length (**Figure 6(d)** blue and red curve). Under RCP4.5 the RSO date delay is 4.6 ± 4.3 and 6.1 ± 4.0 days by 2035 and 2050 respectively (**Table 2** line 3). Under RCP8.5 the delay is 4.3 ± 3.5 and 8.7 ± 4.9 by 2035 and 2050 respectively. So under RCP8.5 by 2050 the rainy season onset date could be at the second half of July. At least, 66% of the models are agreed on the delay. This delay in RSO date induced a decrease of 12.3 ± 8.1 and 16.6 ± 8.8 in RSL by 2050 under RCP4.5 and RCP8.5 respectively. The delay in RSO date and the decrease in RSL could impact strongly agriculture sectors. In fact by 2050, the rainy season onset date could be in the second half of July and the RSL could be less than 80 days. So, crops that need more than 80 (e.g. long-cycle 120 days of Millet and Sorghum) for maturation could have some problem. The above RSO date and RSL changes are significant at 90% confidence level for both scenarios and horizons.

3.3.2. Temperature Indices

Figure 6(e) and **Figure 6(f)** shows the temporal evolution of the MMM seasonal mean maximum and minimum temperature averaged over the Fatick region. All models agree on the sign of change for these variables, in contrast with rainfall indices. We found an upward trend more marked from 1965 (**Figure 6(e)** and **Figure 6(f)**). From 1950 to 1995, the maximum and minimum temperatures are lower than their reference values (35.8˚C and 23.8˚C; **Figure 6(e)** and **Figure 6(f)** respectively black horizontal curve). For the future, maximum and minimum temperatures are higher than their reference values. By 2035 the increase is estimated around 1.1˚C ± 0.3˚C (1.3˚C ± 0.3˚C) for maximum (minimum) temperature under RCP8.5 scenario. By 2050, the increase for maximum temperature is estimated at 1.3˚C ± 0.1˚C and 1.9˚C ± 0.2˚C under RCP4.5 and RCP8.5 respectively (**Table 2**). For minimum temperature the increase could be 1.5˚C ± 0.1˚C and 2˚C ± 0.2˚C under RCP4.5 and RCP8.5 respectively. This means that by the horizon 2050, under RCP8.5 the mean seasonal maximum (minimum) temperature could reach 37.7˚C (25.8˚C).

4. Discussion

Analyses of rainfall indices change by 2035 and 2050 horizons, with respect to the present day baseline value, in Senegal show a decrease while an increase is found for metrics based on temperature. These changes are in good concordance with previous studies in Senegal and more largely in West Africa (Dosio, 2017; Dosio et al., 2020; Tall et al., 2017). For example, for the seasonal cumulative rainfall, Kouakou et al. (2014) found a decrease of around 12.6% by 2100 in western Sahel. In Senegal, some studies show also this decrease in rainfall (Tall et al., 2017; Sarr et al., 2015) under RCP8.5. However our results differ slightly from those of Tall et al. (2017) by 2041/2060. The latter authors found an increase in the whole country under RCP4.5. In RCP8.5 the increases are confined to the northern and central regions of Senegal while the southwestern coast and the southern region of Senegal undergo rainfall decrease (Tall et al., 2017). These differences could be due to models used. Tall et al. (2017) used two CMIP5 models downscaled by RegCM4 while we used 21 bias-adjusted CMIP5 models. The difference in the type of model (RCM vs. GCM) and also the number of model (2 vs. 21) could be the causes of the disagreement. Furthermore, Tall et al. (2017) did not bias-adjusted their outputs while those used in this study were bias-adjusted. Mbaye et al. (2018) assessed the potential impact of bias-adjustment on extreme precipitation and temperature of the REMO RCM over the Senegal River Basin. Compared to the uncorrected ones, bias-adjustment affected mainly the magnitude of the climate change signal, which was lower in the bias-adjusted data. However, Dosio et al. (2022) found that bias-adjusted results of CORDEX-Africa RCM for precipitation indices are usually consistent with the original results. The decrease of the rainfall found over the Senegal could probably be induced in part by a weakening of the humidity from local sources, which slows down the hydrological cycle (Diallo et al., 2016). A large intermodel spread is found mainly for the seasonal cumulative rainfall. This large spread could modify future changes in cumulative rainfall by intensifying or weakening these changes (or even modify the sign of the changes). This marked spread is consistent with previous studies (Klutse et al., 2021; Gnitou et al., 2021; Dosio et al., 2021a). This large variation in model individual seasonal cumulative rainfall in the future could be due to the type of forcing or the use of different parametrization scheme by climate models (Sylla et al., 2010; Biasutti & Sobel, 2009; Druyan, 2011; Fontaine et al., 2011; Roehrig et al., 2013). Concerning seasonal total extreme rainfall, our results show an increase under both scenarios. This increase should also be taken with caution due to the numbers of models in disagreement. However it is important to note that previous studies, based on both GCM and RCM, also found an increase in rainfall extremes (Sylla et al., 2016; Sarr & Camara, 2017; Diatta et al., 2020). Locally, in the Fatick region, our results show a downward (upward) trend of cumulative rainfall (extreme rainfall). The seasonal rainfall decline is more pronounced in the Fatick region's southern reaches, with values as high as 60 mm, which could be explained by the fact that there is more rain in the south, therefore the decrease in rainfall would be felt more strongly there. The rainy season length decrease (**Figure 4(c)**) can mainly be related to the delay in rainy season onset, because projected variations in the rainy season cessation were found to be weak (Balme et al., 2005). The delay in RSO by one to two weeks is conforming to some previous studies (Balme et al., 2005; Biasutti & Sobel. 2009; Dunning et al., 2018; Dieng et al., 2018). According to the latter authors, the delay in the annual cycle of Sea Surface Temperature, particularly in the tropical Atlantic, may be the proximate cause of the delay in the annual cycle of rainfall in the Sahel. The projected rainy season length, for our two horizons, could be less important in the Fatick region mainly in the northern part. In fact, our results show an overestimation of simulated RSL for the historical period in this part of the region meaning that by 2050 (RSL is found to be around 80 days) the RSL could be less than 80 days.

Our results in terms of cumulative seasonal rainfall and total extremes rainfall trend over the Senegal are in agreement with trend found by recent studies made throughout West-Africa based on CMIP6 ensemble mean (Dosio et al., 2021a). This could be justified by the fact that Dosio et al. (2021a) stated that there is no clear difference between CMIP5 and CMIP6 over Africa. In fact, Dosio et al. (2021a) assessed the future daily characteristics of African precipitation by explicitly comparing the results of large ensembles of global (CMIP5, CMIP6) and regional (CORDEX, CORE) climate models. Their results showed that all ensembles project an increase in maximum precipitation intensity during the wet season over all regions and emission scenarios (except the West Sahel for CORE) and a decrease in precipitation frequency (under the Representative Concentration Pathways RCP8.5) especially over the West Sahel, the Atlas region, southern central Africa, East Africa and southern Africa. Similarly, a regional study conducted using CMIP6 across 41 sub-regions globally reveals limited improvements compared to the CMIP5 models (Kim et al., 2020). Ayugi et al. (2021) show that CMIP6 models simulated large biases in total rainfall and extremes wet days over East Africa.

The mean seasonal maximum and minimum temperature upward trend in our region of interest is in agreement with previous studies (Dosio, 2017; Sarr et al., 2015; Diallo et al., 2012). These changes in temperature could be due to reduced evaporation over the western Sahel, which would enhance the sensible heat, fluxes thereby raising the surface air temperature (Diallo et al., 2012). Using CMIP6 multi-model mean over all Africa, Almazroui et al. (2020) and Li et al. (2021) found a continuous increase in annual temperature with the largest warming projected over the Sahara and adjacent parts of northern Africa. They also compared CMIP5 and CMIP6 ensembles and found enhanced warming by CMIP6. For the 2035 horizon, the changes in all indices are quasi-equal in both scenarios except for extreme rainfall. This indicates that natural variability plays an important role when the greenhouse gas forcing is low (i.e., by 2035). By 2050 horizon, the model ensemble mean showed a clear distinction in the projected changes for each scenario. This could be due to the fact that the total radiative forcing under RCP4.5 varies slightly while under RCP8.5 it varies strongly (Van Vuuren et al., 2011) hence the difference in terms of changes between both scenario by 2050.

The combined effects of the seasonal total rainfall decline, the rainy season length decreases and the temperature increase could affect negatively the Fatick region. In fact, this region as many regions of Senegal depends strongly to rainfed agriculture and the main subsistence crops are Millet, Sorghum and maize. Sultan et al. (2015, 2013) found that climate conditions alterations have led to regional average (over West Africa) yield reductions of 10% - 20% for millet and 5% - 15% for sorghum (Sultan et al., 2013). Moreover, Faye et al. (2018) have highlighted a yield loss for maize and sorghum in West African Sudan Savanna. The yield reductions under 2.0˚C global warming could be greater than the 1.5˚C warming scenario (Faye et al., 2018). These authors also identified the shortening of crop duration as an important cause of the reduced yields. More locally, in the Fatick region, a short-cycle variety with 90 days maturation time and long-cycle variety with 120 days maturation time were considered for Millet and Sorghum (Faye et al., 2022). They found a downward trend of crop yields for both considered varieties by 2030 and 2050 horizons. The downward is more pronounced for short-cycle varieties and is due to temperature increases. Hence, the major future impact of climate change on these cereals would hence mainly be a yield losses induced by rising temperatures (Faye et al., 2022). Thus, a thorough consideration of temperature effects will be essential for better adapting cereal production to future climatic conditions in the Fatick region. To reduce yield losses, it would be interesting to adopt longer season varieties and also diversify income-generating activities. Water resources could be also affected. The recurrence of droughts in Sahel (Giannini et al., 2008; Biasutti & Giannini, 2006), has led to a significant decline of water flows in many river basins (Mbaye et al., 2018), which constitute the main water resource for drinking, irrigation, and industrial purposes in inland areas (Mouri et al., 2011). A decrease insoil moisture triggered by the projected decrease in rainfall could even be amplified by the warming, as Tall et al. (2017) showed in Senegal it would lead to an increase of potential evapotranspiration. In the Fatick region, a decrease is found in continental inputs of around 14% by 2050 under RCP4.5 (Bah et al., 2019) due to seasonal cumulative rainfall drop. This flow deficit combined with an increase in evaporation could result in an increase in fresh water salinity (Bah et al., 2019). Moreover, (Bah et al., 2019) found also an increase in water demand estimated to 15 million m^3 by 2035. The decline in renewable reserves and the tendency to overexploitation to meet water demand may contribute to an irreversible degradation of the water quality through the inflow of salt water from the sea and river water by 2050. To reduce climate change threat on water resources, many actions could be done such as carrying out water retention works adapted to the irrigation sector (e.g. retention basins, impluvium); Sanitation, treatment and reuse of non-conforming water for agriculture and livestock to reduce pressure on the resource. It would be also important to involve more women and youth in the management and planning of water resources at the local level. Note that for a better acceptance of mitigation and adaptation options, populations must be included from the beginning to the end of the exercise.

5. Conclusion

We have investigated the change of some agro-climatic indices in Senegal with a focus on the Fatick region from multi-model mean of 21 bias-adjusted CMIP5 simulations. The results indicate that the different GHG forcings produce different magnitudes of the seasonal total wet days rainfall decrease ranging from 10 mm by 2035 horizon under RCP4.5 to more than 60 mm by 2050 under RCP8.5. The increase in seasonal total extreme wet days rainfall could range from 2 mm by 2035 under RCP4.5 to more than 16 mm by 2050 under RCP8.5. Concerning the rainy season onset, we found a minimum delay of 3 days located in the northwestern region of Senegal and a maximum delay of two weeks in the southeastern region of the country by 2050 under RCP8.5. For the Fatick region, the delay ranges from 6 to 12 days. Consequently, the RSO could be in the second decade of July by 2050 horizons. The impact of such delay in rainy season length is a decrease. The RSL could be less than 80 days in the Fatick region by 2050 under both scenarios. For the minimum and maximum temperature, we found warming ranging from 0.5˚C by 2035 to more than 2˚C by 2050 under RCP8.5. For the Fatick region, the maximum temperature would rise between 1.5˚C to 2˚C. Interpretation of these results, mainly those on rainfall indices, should be cautious due to large intermodel spread. Another limitation could be linked to bias-adjustement due to the effect of mismatch between model and observations (*downscaling* effect) and the sensitivity to the observational reference used to calibrate the bias-adjust method.

In terms of tendency, there are no significant discrepancies between our findings and those of recent research utilizing CMIP6 models. The CMIP6 model ensemble projects more precipitation over western West Africa as compared with CMIP5, whereas CMIP6 projects reduced precipitation over Southern West Africa (Almazroui et al., 2020). Concerning temperature, the CMIP6 climate models simulate higher temperatures over large parts of Africa (Almazroui et al., 2020). What about Senegal? It would be important to pursue this study using both CMIP5 and CMIP6 model in the others region of Senegal.

Based on our results, it is certain that climate change will substantially affect the agro-climatic parameters in Senegal which could result in significant socio-economical fallout for the country's agricultural and water resources sectors. It is therefore important (even crucial) for policy-makers and decentralized technical services to appropriate these results to put in place adaptation and mitigation strategies aimed at improving the well-being of populations. Taking these results into account in adaptation policies, in Senegal, should facilitate the achievement of certain sustainable development objectives such as: establishing sustainable consumption and production patterns; taking urgent action to combat climate change and its repercussions; ending hunger, achieving food security, improving nutrition and promote sustainable agriculture.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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