Journal of Environmental Science and Engineering B 11 (2022) 248-266
doi:10.17265/2162-5263/2022.06.004

The Projected Changes of Precipitations over Niger Under the Scenarios RCP 4.5 and RCP 8.5

Mounkaila Saley Moussa[1], Yacoubou Mahamadou[2] and Abdou Saley Inoussa[1]

1. Department of Physics, Faculty of Sciences and Techniques, Abdou Moumouni University, BP:10662, Niamey, Niger

2. Department of Physics, Faculty of Sciences of Education, Andre Salifou University, BP:656, Zinder, Niger

Abstract: The socio-economic activities of Niger rely on agriculture which is strongly affected by changes in precipitation during the rainy season. The ultimate aim of this study is to assess the projected changes of precipitation over Niger under the Representative Concentration Pathways (RCP) scenarios 4.5 (RCP 4.5) and RCP 8.5 using multi-RCM (Multi-Regional Climate) model approach. The observation data are from CHIRPS (Climate Hazards Group InfraRed Precipitation with Station) and the RCMs are from the SMHI (Swedish Meteorological and Hydrological Institute) model (RCA4) driven by ten (10) different GCMs (General Circulation Model) (e.g., CCCma, CSIRO, ICHEC, IPSL, MIROC, MOHC-HadGEM2, MPI, NCC-NorESM1, NOOA, and NRCM) within the framework of CORDEX (Coordinated Regional Climate Downscaling Experiment) Africa experiment. The reference and projections periods in this study are respectively 1981-2005 for the present and 2011-2100 for the near, medium and far future divided into three periods, 2011 to 2040 (P1), 2041 to 2070 (P2) and 2071 to 2100 (P3). The methodology used, consists of assessing the performance of the multi-RCMs of RCA4 model (with respect of CHIRPS) in simulating the precipitations changes by computing the spatial distribution and anomalies of precipitations; and their indices of RMSE (Root Mean Square Error), the bias, SPI (Standardized Precipitation Anomaly Index), correlation coefficient, statistical *t*-test, spatial evolution rate and the rate of temporal change. After the validation of the multi-RCMs RCA4 models, the ensemble mean of the models is used to assess the projected changes of precipitations over Niger in the future. The results show that most of the multi-RCMs capture the four climatic zone except for IPSL. While the ensemble mean of the models simulates (as compared to CHIRPS) more accurately the monthly, annual precipitations anomalies and their indices than individual's models in the reference period, some RCMs (e.g., CSIRO-IPSL and CCCma-HadGEM) poorly reproduce them. The projected changes of precipitations indicate for the scenario RCP 4.5 respectively a moderately surplus of precipitation years in the period P1 and moderately deficit years in the period P2 while the period P3 shows a small upward precipitation trend. In contrary, for the scenario RCP 8.5, all the three periods (P1, P2 and P3) indicate an intensification of precipitation leading to a longer wet period which may lead to extreme precipitations and flooding. Moreover, both scenarios have projected an increase of total monthly precipitation in May and September and a decrease in July and August respectively which will likely lead to an early onset and late cessation of the rainy season; and a shift of the peak of the rainy season. Therefore, this study shows the need of a monitoring system for the projected changes of precipitation in the near future to anticipate urgent action in wet/dry periods to adapt to a changing climate.

Key words: Climate projection, precipitation changes, anomaly scenarios RCP, Niger, Sahel.

1. Introduction

The 3rd IPCC (Intergovernmental Panel on Climate Change) report had revealed that global warming would induce an increase of temperature of nearly 0.7 ℃ over the entire African continent during the XXIe century with an increase of 0.05 ℃ per decade [1, 2]. Climate models have also predicted this temperature increase on a global scale with significant differences across climate regions varying between 1.5 ℃ and 2 ℃ [3, 4]. These differences are manifested by increases in mean temperature in most countries and ocean regions, extreme heat in most populated areas, intense precipitation in most regions with an increase in the number of high cumulative rainfall events, and risks of drought and precipitation deficits in some regions (e.g., [5, 6]). Since the mid-1990s, the central and eastern Sahel has experienced an increase in total annual

Corresponding author: Mounkaila Saley Moussa, Ph.D., research fields: Climatology, Meteorology and Energy.

rainfall accumulation, but this has not been caught up with the levels of the "wet" decades [7]. The republic of Niger (hereafter Niger), like other Sahelian countries, is experiencing a return to normal rainfall after the droughts of the 1970s to 2000 [8]. However, extreme precipitations events that cause flooding have been observed in recent years especially in high-risk areas such as towns along the Niger River. For example, in the year 2012, Niger and Burkina Faso have recorded in August at about 327 mm of rain in the first two dekads while the average for the month of August is 160 mm [9]. Therefore, Niger is facing the reality of climate change and the future change in precipitations variability is of most importance for populations, livelihood, stakeholders and decisions makers (such as governments) and socio-economic activities.

Many studies have investigated the projections of precipitations over Sahel using GCMs (General Circulation Models) or RCMs (Regional Climate Models) (e.g. [10-17]). For instance, Akinsanola et al. [12] have shown that GCMs have significant uncertainties about the intensity and direction of rainfall change in the Sahel while Kim et al. [13] have demonstrated that GCMs simulate better the average climatology of climate parameters but have significant biases in some regions. In this study, RCMs forced at lateral and boundary conditions by GCMs will be used to evaluate the projections of precipitations over Niger for a better understanding of climate change and its consequences in order to define mitigation and adaptation measures. Furthermore, climate projections over Sahelian regions, have faced particular difficulties for two reasons which are firstly, the higher climate variability observed in the 20e century and secondly, the divergent results of climate models in simulating precipitations [18]. Moreover, according to the IPCC report [1], the results of climate models output on precipitations variability over Sahel are contradictory, indeed despite the partial return of precipitation in the regions, some climate simulations have predicted a significant decrease in precipitations and/or an average of future trend towards increased precipitation [19]. The main reasons of these contradictions between simulation results over the Sahel are likely due to the difficulties of the climate models to accurately reproduce the African monsoon system. Thus, the multi-model approach using the ensemble mean will allow compensating the difference between models by considerably reducing the strong wet or dry biases of the individual models [10-16, 20, 21]. On the other hand, the main socio-economic activities of Niger are based on agriculture and agro silvo-pastoral which are strongly dependent on the amount, frequency, trend and variability of precipitation. Therefore, understanding the impact of climate change on precipitations projections over Niger is crucial for providing the right climate information on precipitations changes for planning measures to support the populations in their socio-economic activities. This study attempts to answer this question by using a multi-model approach to assess the future changes of precipitations over Niger through precipitation projections under the RCP (Representative Concentration Pathways) 4.5 and 8.5 scenarios. This paper is structured as follows: Section 2 presents the data and methodology of the study; Section 3 describes the results and discussion and Section 4 presents the conclusion of the study.

2. Data and Methodology

2.1 Presentation of the Study Area

Niger is located in the central part of West Africa region and is in the heart of the Sahelian zone, totally landlocked, with three quarters of its territory being desert. Niger covers a land area of 1,267,000 km^2 between the longitude 0°16′ and 16° East, and the latitude 11°01′ and 23°17′ North (see Fig. 1). Niger has two types of hot climates namely the desertic climatic conditions over most of its area in the northern part of the country and the tropical climatic ones in the southern part. Moreover, it has a single rainy season whose spatial distribution of precipitation divides the country into 4 climatic zones: the Sahelo-Sudanian zone (in blue) with an average annual total precipitation of 600 mm, the Sahelian zone (in green) with 300 mm, the Sahelo-Saharan zone (in orange) with 150 mm and the Saharan zone (in yellow) where precipitation is almost rare with a total of 150 mm (Fig. 1 on the left). According to the observation data of CHIRPS (Climate Hazards Group InfraRed Precipitation with Station) (with a spatial resolution 0.05°), the annual cycle of precipitation indicated that the rainfall starts in the Sahelo-Sudanian zone and the Sahelian zone from May but the season does not start until June. The Sahelo-Saharan zone receives their first precipitations from July but the peak of the rainy season is observed in August then it evolves over time to reach the end of the rainy season between September and October [16] (Fig. 1).

The total average annual precipitation over the southern part of Niger is around 435 mm with about 200 mm for the peak of the season, so most of the precipitation is observed in August. The total annual precipitation over the Sahelian zone is highly concentrated in the months of July and August [22].

2.2 Data

The data of precipitation used in this study are from the SMHI (Swedish Meteorological and Hydrological Institute) RCM (called RCA4) simulation outputs

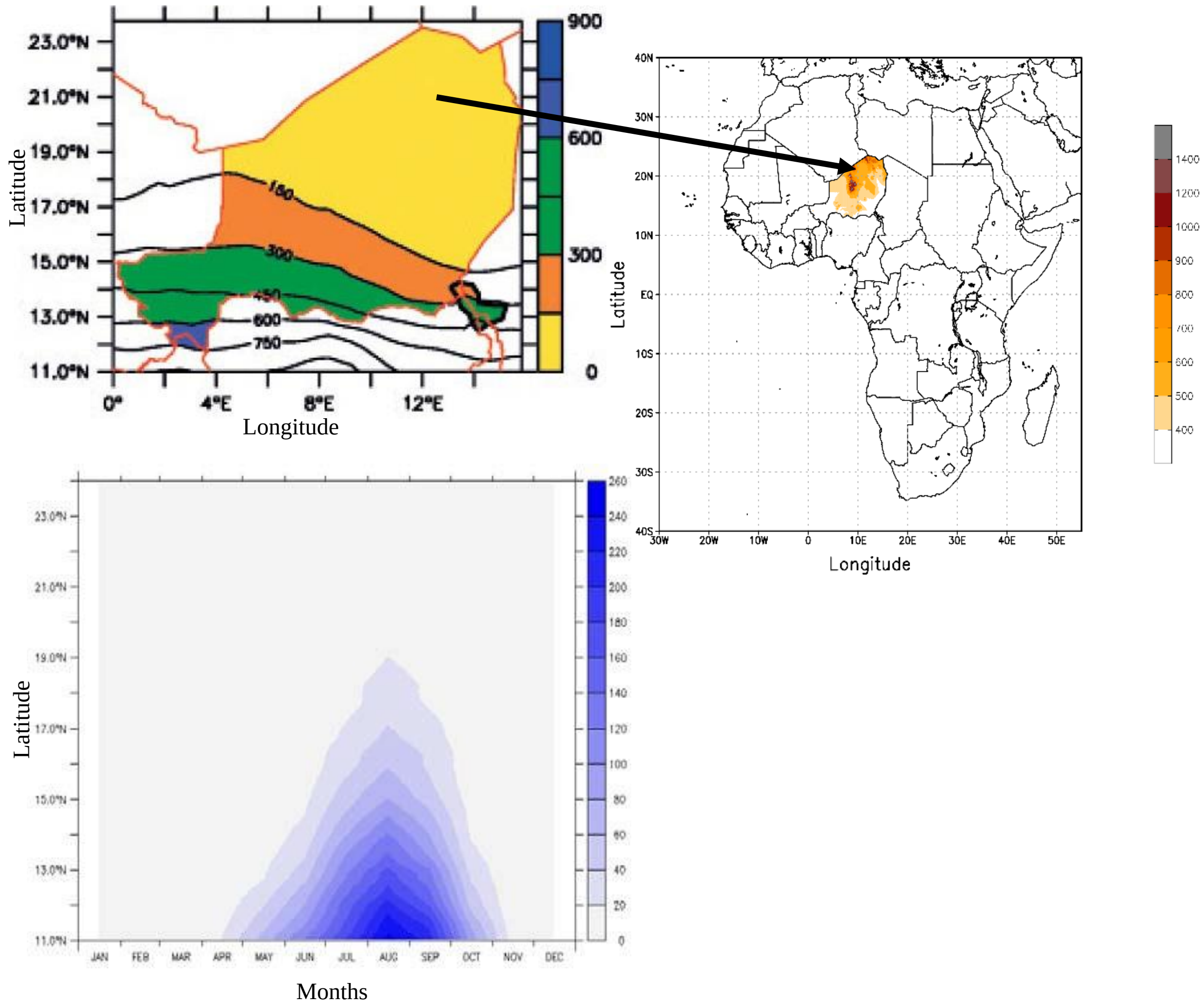

Fig. 1 Left panels: climatic zones and isohyets levels of precipitation over Niger (Climatic Research Unit (CRU) data from 1997 to 2008) and annual cycle of precipitations over the period 1997-2008 [16]. Right panel: the position (West Africa) and topography of Niger as seen in the map of African continent.

within the framework of the CORDEX (Coordinated Regional Climate Downscaling Experiment) Africa. Ten (10) categories of RC4 outputs obtained from 10 GCMs forcing: namely CCCma, CSIRO, ICHEC, IPSL, MIROC, MOHC-HadGEM2, MPI, NCC-NorESM 1, NOOA, and NRCM; were used to build the multi-RCM model approach. The 10 RCMs have the same spatial resolution of 0.44° (~50 km) and cover the entire African continent. The data were obtained freely at the SMHI at the International Conference on Regional Climate-CORDEX 2016 in Sweden.

The precipitations data of CHIRPS, spatial resolution 0.05° [23] are used as reference observation data to compare the RCMs with it. Therefore, the data of CHIRPS are remapped to the same spatial resolution of 0.44°(50 km) as the RCA4 models to facilitate the comparison.

The historical and projections data of RCA4 cover respectively the period 1951-2005 and 2006-2100 and the CHIRPS data are from the period 1981-2005. The choice of the CHIRPS and multi-RCMs of RCA4 model is basically due to the availability of the data and the lack of stations from the meteorological office. Moreover, the data of CHIRPS are used as reference because they reproduce better the spatial distribution of rainfall over Niger, although CHIRPS tends to overestimate rainfall over the Sahel zone [16].

Furthermore, the projections data of RCA4 are based under the RCPs scenarios 4.5 and 8.5 that reflect the trajectory of GHGs (Greenhouse Gases) responsible for global warming [24]. The RCP4.5 scenario is an ambitious scenario with pollution reduction policies. It is a scenario of average CO_2 emissions (650 ppm CO_2 equivalent) corresponding to a peak radiative forcing of 4.5 W/m^2 by 2100 [25]. Therefore, this scenario anticipates the implementation of public policies allowing strong mitigation of GHGs emissions and stabilization of atmospheric concentration without however preventing a global temperature increase of more than 2 ℃ [17]. On the other hand, the RCP8.5 scenario is the trend scenario corresponding to a radiative forcing of 8.5 W/m^2 which combines assumptions about high population growth, relatively slow income growth with modest rates of technological change and improvement of energy intensity with high energy demand and GHG emissions without policies of climate change [26]. These two scenarios represent the range of global trends in GHGs evolution that is most likely to be experienced [17].

2.3 Methodology

To evaluate the projections of precipitations changes and the impact of climate change on precipitation over Niger under the two previous scenarios, the performance of the multi-RCMs of RCA4 model forced with different GCMs will be assessed in simulating the precipitation by comparing the historical data of RC4 with CHIRPS observation from the period 1981-2005. Thus, this evaluation will be used for the RCA4 model validation in the reference period. Then, the projections of precipitations changes are conducted for three periods: the first period from 2011 to 2040 (hereafter P1), the second period from 2041 to 2070 (hereafter P2) and the third period from 2071 to 2100 (hereafter P3). The projections of precipitations are computed through the spatial distribution and anomaly of precipitations; and the following indices with respect to the average climatology calculated with the reference data of CHIRPS namely the RMSE (Root Mean Square Error), the bias, the SPI (Standardized Precipitation Anomaly Index), the correlation coefficient, the statistical *t*-test, the spatial evolution rate and the rate of change over time. Their description is as follow:

2.3.1 The Average Annual Precipitation

$$\bar{P} = \frac{\sum P_i}{n} \tag{1}$$

where:

P_i: the yearly accumulation of precipitation of a year I;

n: the total number of years in the series.

This index P_i is used to compare the cumulative rainfall for year i with the climate average and also to calculate the SPI.

2.3.2 *RMSE*

$$RMSE = \frac{\sqrt{\sum_{i=1}^{n} \frac{(M_i - O_i)^2}{n}}}{\overline{M}} \quad (2)$$

where:

M_i: the model's mean for year *i*;

O_i: the average of the reference data for year *i*;

$\overline{M}$: the climate average of the reference data;

n: the total number of years in the series.

The *RMSE* index provides an indication of the dispersion or variability of the prediction quality.

2.3.3 The Bias

$$Bias = \frac{100}{n} \sum_{i=1}^{n} \frac{M_i - O_i}{O_i} \quad (3)$$

where:

M_i: the model mean for the year *i*;

O_i: the average of the reference data for the year *i*;

$\overline{M}$: the climate average of the reference data;

n: the total number of years of the series.

The index Bias indicates the weakness/accuracy of the model in overestimating or underestimating predictions.

2.3.4 The SPI Anomaly

$$SPI = \frac{P_M^i - \overline{P_O}}{\sigma} \quad (4)$$

where:

P_M^i: the total precipitation of year *i* according to the model;

$\overline{P_O}$: climate average of reference data;

σ: standard deviation of the model.

The SPI index allows comparing the precipitations of different periods or different years, it also allows identifying the extreme years such as the severe deficit or surplus years.

2.3.5 The Correlation Coefficient:

$$R = \frac{\text{covariance}\left(M, O\right)}{\sigma_M \sigma_O} \quad (5)$$

where:

Covariance $(M, O) = \frac{1}{n}\sum_{i=1}^{n}(M_i - M)(O_i - O)$;

$\sigma_M = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(M_i - M\right)^2}$: the standard deviation of the model;

$\sigma_O = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(O_i - O\right)^2}$: the standard deviation of the observation.

The correlation coefficient gives an idea of the degree of confidence to be given to the models for a simulation of a parameter.

2.3.6 The Parameter *t* of the *t*-Test

$$t = \frac{\overline{P_i} - \overline{P_{reférence}}}{\frac{d}{\sqrt{N}}} \quad (6)$$

where:

$\overline{P_i}$: annual total precipitation of year *i*;

$\overline{P_{reférence}}$: annual total average precipitation over the reference period;

$d = \overline{P_i} - \overline{P_{reférence}}$: the difference between the two previous parameters;

N: the number of years of the study period;

If $t > t_0$ with t_0 the value corresponding to the distribution for the degree of freedom $dl = N - 1$; then there is a difference between the model and the observation.

For the projections, the analysis of the projected SPI anomalies under the two scenarios is done over three periods: the first period P1 from 2011 to 2040, the second period P2 from 2041 to 2070 and the third period P3 from 2071 to 2100.

The evolution of precipitation during each period is studied using the evolution rate defined by:

2.3.7 The Spatial Evolution Rate

$$\tau_s = \frac{P_i - \bar{P}}{\bar{P}} \times 100 \quad (7)$$

where:

P_i $(i = 1, 2, 3)$: Average precipitation over the considered period;

$\bar{P}$: Average precipitation over the reference period.

This parameter allows observing the spatial evolution of precipitations distributions.

2.3.8 The Rate of Change over Time

$$\tau_T = \frac{P_i - P_{-i}}{P_{i-1}} \times 100 \qquad (8)$$

where:

P_i: the average precipitation of the year i;

P_{i-1}: the average precipitation of year i-1.

The rate of change τ defined above allows analyzing the trend of the evolution of the parameter in time.

3. Results and Discussion

3.1 Validation of the Model RC4

3.1.1 Spatial Distribution of Precipitation over Niger

The performance of the model RC4 in simulating the present/actual precipitation pattern as in observation CHIRPS for each of the ten multi-RCM ensemble is presented in Fig. 2 (below). It shows that the RCMs models reproduce differently the spatial distribution of precipitation as compared to CHIRPS. The model IPSL reproduces very poorly the distribution over Niger; it captures only the pattern over the Sahelo-Sudanian zone with an average intensity of 150 mm per year. The CCCma model underestimates the distribution of precipitation over Niger and the model CSIRO overestimates the precipitation over the northern desertic part of Niger. As for the other models (CNRM, HadGEM, ICHEC, MIROC, MPI, NCC, NOOA), they simulate well the spatial distribution of precipitation over Niger but with much more intensity. All the models, expect CCCma and IPSL (as well as CHIRPS), show that the mountainous area of A ï r located in the desert zone

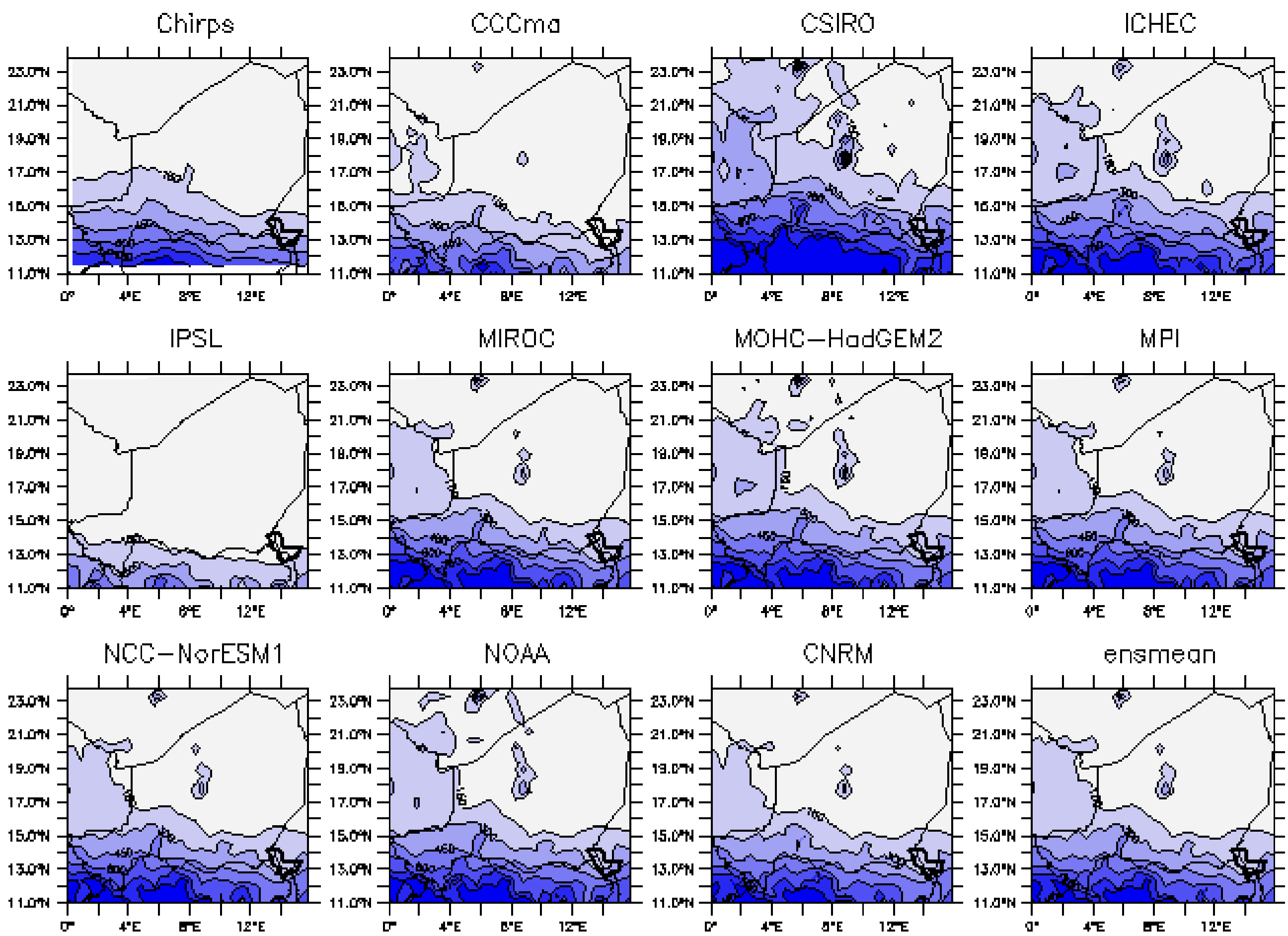

Fig. 2 Spatial distribution of precipitation with isohyets (different climatic zones) of the 10 multi-RCMs (CCCma, CSIRO, ICHEC, IPSL, MIROC, MOHC-HadGEM2, MPI, NCC-NorESM1, NOOA, and NRCM) and ensemble mean over Niger as compared to observation CHIRPS for the period 1981-2005.

shows an identic pattern of precipitation regime as in the Sahelian zone located to the south. However, the ensemble mean of the models reproduces better the spatial distribution of precipitation over Niger than any other individual models. These results are similar to previous studies (e.g. [10-17, 20-22]) that found that the ensemble mean of models compensates individual errors and uncertainties.

3.1.2 Interannual Variability of Precipitation in the Sahelian Part of Niger

The difficulty of RCMs models in simulating precipitations over the Sahelian zone is observed in Fig. 3 which shows how well the multi-RCMs RCA4 models forced with 10 different GCMs reproduce the interannual variability of precipitation over Niger. All the models show a scattered and diverse interannual variability with respect to CHIRPS. The annual total precipitations vary between 300 mm and 600 mm with CHIRPS. However, all models, except CCCma and IPSL, tend to overestimate CHIRPS at different magnitude of the annual total precipitations. In contrary, the representation (line plot) of the ensemble mean of the models reproduces better the interannual variability of precipitation over Niger but for certain extreme years, contradictions can be found where it slightly overestimates the annual total as compared to CHIRPS. These results are also seen in the previous cited references.

3.1.3 The SPI Anomaly

The SPI using CHIRPS indicates a decline of precipitation (dry conditions) in the 1980s and 1990s and return to wet conditions in the 2000s (Fig. 4). The reference CHIRPS data show well this evolution of precipitation over Niger as highlighted by Riahi et al. [27] and Le Barbé and Lebel [28]. The post-1990s period is characterized by an improvement in precipitation pattern over Niger but the persistence of deficit years is observed as indicated by Nicholson [29]. In contradiction for the same period, Ozer et al. [30] have claimed that the drought ended in the mid-1990s. The results obtained in this study with CHIRPS are more consistent with Ozer et al. [30] who have showed an attenuation of precipitation deficits after the year 1990 over central Sahel with high interannual variability and an average precipitation level which remains well below the wet period (1950-1970). Some others studies such as Ref. [17] have indicated that the period 1980-2010 was marked by an increase of precipitation at about 100 mm compared to the dry period of 1970-1990. Therefore, according to the data of CHIRPS

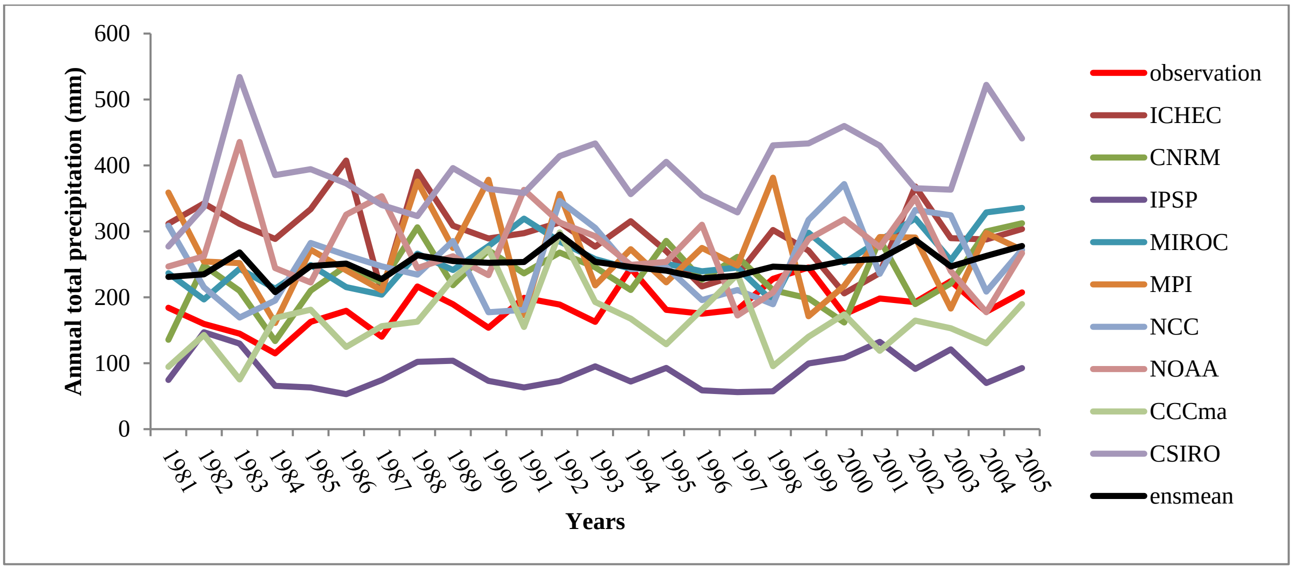

Fig. 3 Interannual variability of precipitation for the 10 multi-RCMs RCA4 models (CCCma, CSIRO, ICHEC, IPSL, MIROC, MOHC-HadGEM2, MPI, NCC-NorESM1, NOOA, and NRCM) and CHIRPS in southern part of Niger for the period 1981-2005.

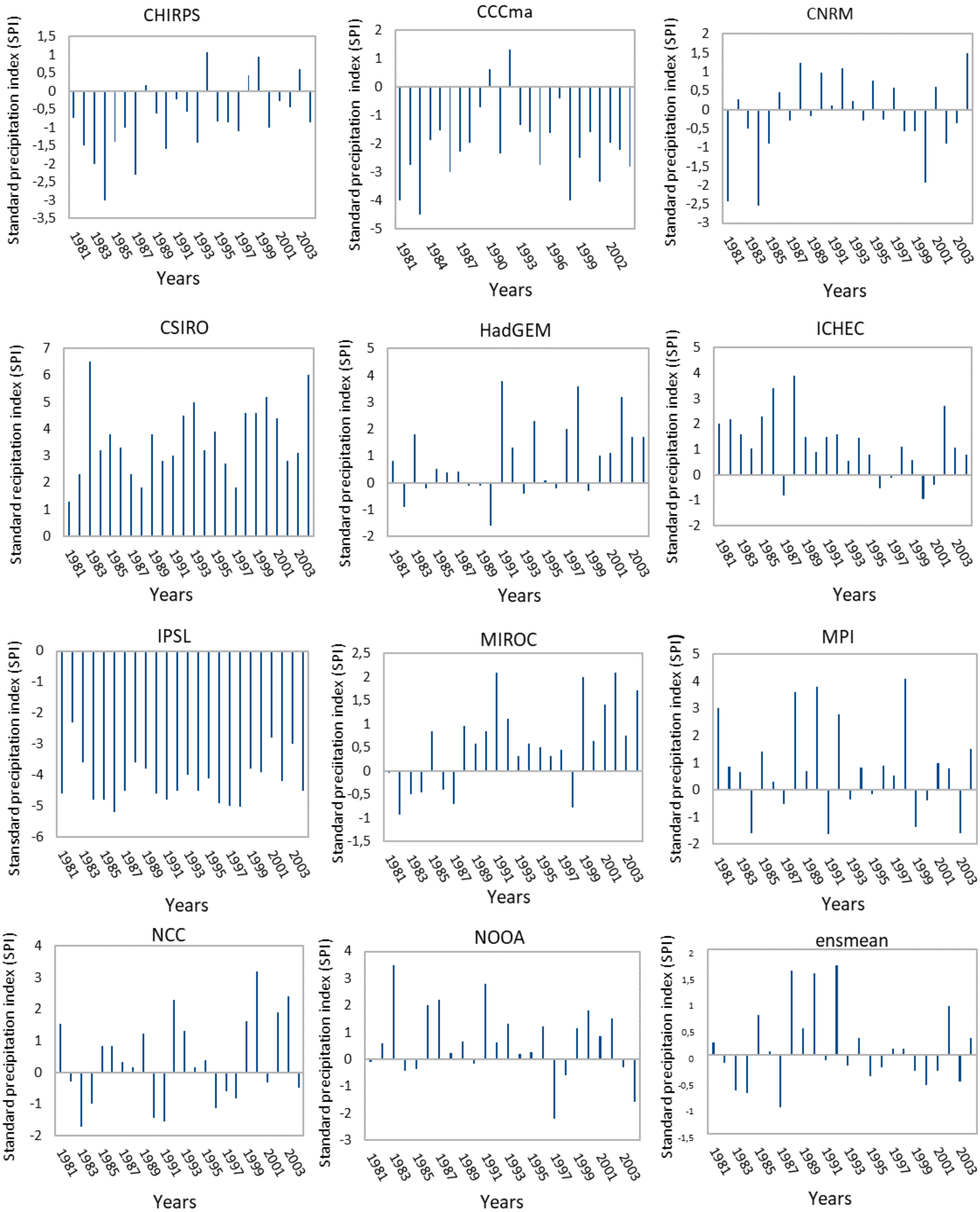

Fig. 4 SPI anomaly for CHIRPS and the 10 multi-RCMs (CCCma, CSIRO, ICHEC, IPSL, MIROC, MOHC-HadGEM2, MPI, NCC-NorESM1, NOOA, and NRCM) for the period 1981-2005.

used in this study (1981-2005), the period 1991-2005 (at about 195.2 mm/year over Niger) corresponding to the return of rainfall, has experienced an increase of about 20.3% compared to the dry period of 1981-1990 (162.3 mm/year).

None of the 10 RCMs simulate accurately the precipitation anomaly as observed in CHIRPS over the period 1981-2005. The RCMs CSIRO, ICHEC and IPSL reproduce very badly the temporal distribution of precipitation over Niger. For instance, the models CSIRO and ICHEC show that the entire period of 1981-2005 was very wet and without any deficit year, while the models CCCma and IPSL show the opposite pattern with the same totally dry period. Thus, the two models CSIRO and ICHEC largely overestimate the precipitation over Niger and IPSL with CCCma largely underestimates it over the country with respect to CHIRPS. As for the models CNRM, HadGEM and NCC, they indicate a strong interannual variability within the period with moderate wet and dry years marking a timid return of rainfall after the 1990s. The results of the remaining 5 models CNRM, HadGEM, MPI, NCC and NOOA are almost in agreement with previous studies from Lebel and Ali [31]. Lastly, the ensemble mean of the models simulates better the precipitation anomaly as compared to CHIRPS over Niger showing an improved precipitation pattern characterized by moderate deficit and surplus years respectively after the 1990s and between 1990 and 2000. These results of precipitations deficit are in agreement with the results of Lebel and Ali [31] who found that the Sahelian zone had faced droughts' episodes until the end of the 1990s. In the late 1990s, the Sahel has also experienced a timid return of precipitation to wet conditions [28] and from the 2000s onwards, a partial recovery of precipitation has been observed [32, 33].

3.1.4 Performance Evaluation of the MRCs and Statistical Significance Test

The performance comparison of the multi-RCMs RCA4 model is presented in Table 1 and shows a disparity between the annual means ($\bar{P}$) of precipitation simulated by the models with respect to CHIRPS (435 mm/year) for the historical period 1981-2005. Indeed, the models present different biases, thus the CCCma and IPSL models present a dry bias over Niger and the others models present wet bias. The CSIRO and IPSL models have respectively a strong wet bias (75%) and a strong dry bias (-55%) as observed in Fig. 4. Except the MIROC model, all the models show a low correlation coefficient with respect to CHIRPS. Although, the MIROC model overestimates CHIRPS (see section 2) but intends to correlate well in pattern with CHIRPS but the *t*-test score is slightly acceptable compared to the ensemble mean showing its performance as compared with CHIRPS.

The *t*-Test shows a significant difference between the models and CHIRPS. All the models including the ensemble mean have a *t*-statistic test greater than 2.042 which is the value of the distribution with a freedom degree of dl = 24. By comparing the different models, the ensemble mean has the smallest standard deviation. Except the CNRM model, all the other models (CCCma, CSIRO, HadGEM, ICHEC, IPSL, MIROC, MPI, NCC, NOOA) have greater biases than the ensemble mean

Table 1 Comparison of multi-RCMs of RCA4 models and observation CHIRPS.

RCMs/RCA4	CCCma	CNRM	CSIRO	HadGEM	ICHEC	IPSL	MIROC	MPI	NCC	NOOA	ensmean
$\bar{P}$	345	481	744	554	572	191	531	545	515	532	498
RMSE	0.34	0.22	0.44	0.27	0.30	1.34	0.22	0.30	0.24	0.29	0.19
σ	94	76	92	98	85	50	65,6	116	95	91	70
Bias (%)	-18.4	12.5	75.5	29.3	34	-55	24	27.7	20.4	26	17
R	-0.052	0.23	0.022	0.40	0.16	0.15	0.51	0.13	0.30	-0.14	0.27
t-test	4.69	2.96	16.43	5.95	8.05	24.4	7.38	4.74	4.21	5.32	4.5

(17%). The ensemble mean has also the smallest RMSE (0.19) and has a larger correlation coefficient ($R = 0.27$) than 7 of the models (CCCma, CSIRO, ICHEC, IPSL, MPI, NOOA, and NRCM). Therefore, through this comparison, the ensemble mean of the models reduces the discrepancies between models and observation as well as the errors related to individual models. Thus, the ensemble mean will be used to analyze the projections of precipitation changes over Niger during the three periods P1 (2011 to 2040), P2 (2041 to 2070) and P3 (2071 to 2100) under the two scenarios RCP 4.5 and RCP 8.5.

3.2 Projections of Changes in Precipitations over Niger

3.2.1 Projected SPI Anomaly under the Two Scenarios

The scenario RCP 4.5 predicts a higher interannual variability of precipitation over the three periods (P1, P2, P3) around the climate average calculated with the reference observation period 1981-2005 relative to CHIRPS (Fig. 5, first column). This interannual variability can be linked to several parameters such as ocean temperatures, monsoon intensity [22] and also to the Saharan heat low. The phenomena of El-NINO and La-NINA have a strong link to precipitation changes over Sahel and are correlated to ocean temperatures. For instance, the El-NINO phenomenon occurs when the temperature of the Atlantic Ocean rises, resulting in heavy precipitation over the Sahel in general and Niger in particular, whereas the La-NINA phenomenon corresponds to a cooling of the Atlantic Ocean, resulting in deficits of precipitation in the Sahel [34]. Under this scenario RCP 4.5, the period P2 is the wettest period with 60% of surplus years of precipitations. The period P3 is wetter than the period P1, with many years having totals of precipitations which are close to the average.

As for the scenario RCP 8.5, it projects that all the three periods (P1, P2, P3) will be wet, with only the first period P1 having a few deficit years (Fig. 5, second column first row). The scenario RCP 8.5 has projected wetter periods than the scenario RCP 4.5. Thus, the scenario RCP 8.5 is favorable for increasing precipitations over Niger. However, it will likely reflect an increasing trajectory of the concentration of GHGs in the atmosphere which could be beneficial in terms of precipitation in the agriculture sector over Niger in particular and for the Sahel in general. But these results are in contradiction with those of Carré et al. [19] who have shown that the precipitation over the Sahel is lower as the global temperatures are higher. Moreover, the consequences of very wet years could lead to extreme precipitations, flooding and human health damage for example in the heath sector.

3.2.2 Projected Changes in Precipitations in the Different Regions of Niger

The two scenarios RCP 4.5 and RCP 8.5 predict similar results (in term of spatial distribution) of the changes in precipitation of the three periods in the northern part of Niger (region of Agadez). Indeed, the mountainous area of Aïr will experience positive changes in precipitations leading to a significant increase in rainfall over the three periods (Fig. 6). This increase is about 150 mm, i.e., a positive spatial evolution rate of 82% of the total annual precipitation average in the region of Agadez (180 mm according to CHIRPS for the period 1981-2005). As for the southern part of Agadez, it will experience an average precipitation decrease of about 50 mm, i.e., a decrease spatial evolution rate of $\tau_s = 27\%$. The region of Tahoua (located in the center and practically in the Sahelo-Saharan zone) will experience negative changes of precipitation leading to a decrease of about 50 mm in the eastern part corresponding to 15.1% decrease rate. The rest of the region will experience an average increase in precipitation ranging from 50 mm to 100 mm (i.e., an increase rate τ_s between 15.1% and 30.2%) over the three periods. Then, the central-eastern part of Niger which includes the regions of Maradi (in the center) and Zinder (in the center-east), will experience an average decrease of about 50 mm ($\tau_s = -13\%$) over the three periods for the scenario RCP 4.5.

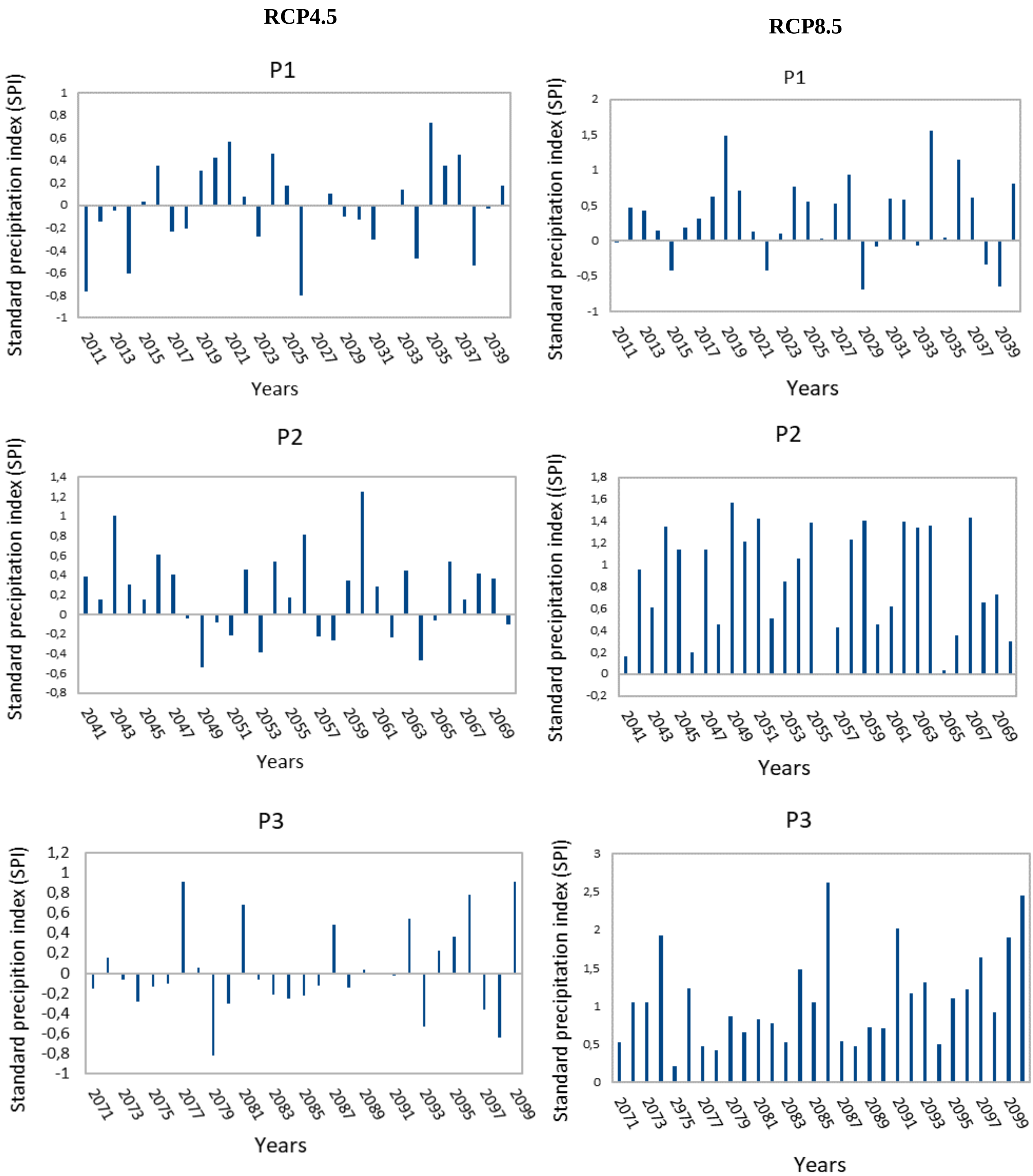

Fig. 5 SPI anomaly of precipitation for the three periods P1 (2011-2040), P2 (2031-2070) and P3 (2071-2100) under the scenarios RCP 4.5 and RCP 8.5 over Niger.

For the eastern part of the country (region of Diffa), the changes in precipitation will lead to an average increase of between 50 mm and 100 mm (i.e., an increase rate τ_s between 61% and 122%). As for the western part of Niger (regions of Tillabéry, Dosso and Niamey), the scenario RCP 4.5 will project an average precipitation increase of about 50 mm over Niamey and some part of Tillabéry (i.e., increase rates τ_s of 11.5% and 13%

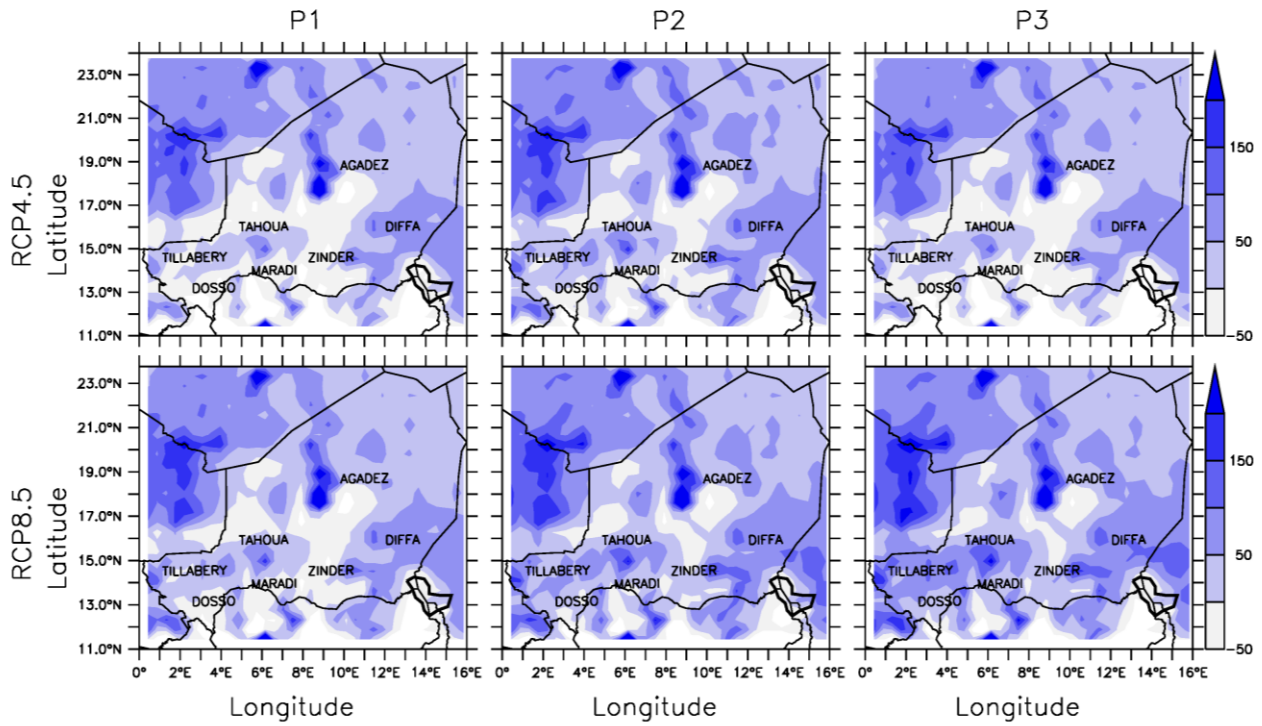

Fig. 6 Spatial distribution of the changes in precipitation of the ensemble mean of the models for the three periods P1 (2011-2040), P2 (2031-2070) over Niger under the two scenarios RCP 4.5 and RCP 8.5. The text in the figure represents the different regions of Niger namely Tillabery, Dosso, Maradi, Tahoua, Zinder, Diffa and Agadez.

respectively). But, the region of Dosso which is located in the Sahelo-Sudanian zone (southwest), will experience a slight precipitation decrease τ_s of about -9%.

Furthermore, the changes in precipitation for the scenario RCP 8.5 has also projected an increase of more than 50 mm in the northern part of the Agadez's region (i.e., an increase rate τ_s of 28%). where usually precipitation is very scarce and the southern part of Agadez will experience a decrease of more than 50 mm (i.e., a negative rate τ_s of -27%). The mountainous zone of Aïr will also experience an increase of more than 200 mm (i.e., an increase rate τ_s of more than 111%). For the western part of the region of Tahoua, this scenario projects a decrease in precipitation during the period P1 with a negative rate τ_s of less than -15.1%. The central part of Tahoua will again experience an increase in precipitation ranging from 15% to 31% for the periods P1 and P2 and from 31% to 45.2% for the period P3. This result confirms the Met Office report [18] which has found in their forecasts a decrease in rainfall ranging from -0.1 mm/day to -0.02 mm/day over the western part of the region of Tahoua and an increase of 0.1 mm/day in the central part over the period 2020-2049. The regions of Marada and Zinder will experience a decrease in precipitation during the period P1 (i.e., τ_s = -12.4% for Maradi and τ_s = -15.6% for Zinder respectively). The periods P2 and P3 will be marked by positive changes of precipitation leading to an increase rate τ_s of 24.8% for Maradi and 15.6% for Zinder. The Diffa region will also face a significant increase in precipitations over all the three periods with an average rate of τ_s ranging from 61% to 122%. Lastly, for the western part of Niger, the region of Dosso will have a slight decrease during the periods P1 and P2 and a slight increase during the P3 period. The region of Tillabéry will experience an average increase τ_s of between 13.1% and 26.2% during the P2 and P3 periods while the period P1 had a very low variation of precipitation around the climate average.

The analysis of the spatial evolution rate of precipitations shows positive changes of precipitations over the northern, western and eastern parts of both scenarios with the highest changes observed over the mountainous zone of Air. However, both scenarios show negative changes over central, some part of southern and east-southern part with the highest changes observed in the center of the country. Similar results have been obtained by Mouhamed and Toune [17] who have indicated that the increase in precipitation is expected to be greater respectively in the northern and eastern parts of the country and in the medium term for RCP 8.5 compared to the short term for RCP 4.5. According to Bodian [34], the projections of precipitation are uncertain and the results of some authors are consistent over the Sahel.

3.3 Temporal Analysis of Precipitation Projection Trends

The trend of precipitation obtained from the rate of change is given below where the period P1 (2011-2040) is characterized by a non-significant decreasing trend of precipitation (with a low regression coefficient R = 0.033) as compared to the reference climate average of CHIRPS for the scenario RCP 4.5 (Fig. 7, first row). The downward trend is not gradual and shows a disordered dispersion of wet and dry years in time which marks the randomness of the temporal distribution of precipitation. As for the period P3 (2071-2100), a weak upward trend (with a coefficient of regressions R = 0.16) is observed because of many years which tend towards the climatic average. A weak upward trend in precipitation is observed within each of the periods P2 and P3 with regression coefficients of 0.045 and 0.052 respectively, the trend is more noticeable for the period P3 than the period P2.

For the scenario RCP 8.5, the periods P1 and P3 are marked with a positive trend (P1: R =0.056; and P3: R = 0.035) and the period P2 by a negative trend (P2: R = 0.055) with low regression coefficients. The period P2 indicates almost a horizontal trend line and a low regression coefficient which is a non-significant positive trend although the period P2 is particularly wet compared to the reference period (1981-2005). So, the total annual precipitations are clustered around the climatic mean (P = 435 mm) with moderate surplus and deficit years. The analysis of the rate of change and trend shows the randomness of the annual total precipitation distribution over Niger in particular and the Sahel in general. Thus, the scenario RCP 8.5 as seen in previous results, is favorable for more precipitations over Niger and the Sahel in general.

3.4 Monthly Anomaly of Precipitation Projections

The monthly precipitation anomaly for the three periods P1, P2 and P3 for the months of MJJAS (May, June, July, August and September) under the two scenarios is evaluated to account for the changes during the seasonal monsoon variability over Niger and the WAM (West Monsoon African) in general (Fig. 8). The decrease of precipitation observed in August is similar to the results reported by Sultan and Janicot [35] where they found the persistent precipitation decrease until 2100 with the scenario RCP 4.5. Both scenarios have projected an intensification of precipitation in the month of May with an average increase between 20 mm and 40 mm which could favor an early onset of the rainy season. Moreover, the months of September and June will also experience an increase in precipitation which is less intense than the one of the months of May. It is also more significant with the scenario RCP 4.5 (with an average of about 30 mm) than the scenario RCP8.5 (with an average of about 10 mm). The intensification of precipitations in September could lead a delay cessation of the rainy season over Niger. Both scenarios have projected an increase in precipitation in the months of less rainfall (May and September) meaning very early onset; an average decrease of about 20 mm/month in the middle of the rainy season in the months of July and August (corresponding to the peak). In the scenario RCP4.5, July is more deficient in precipitation while with the scenario RCP 8.5, August will experience an improvement in precipitation.

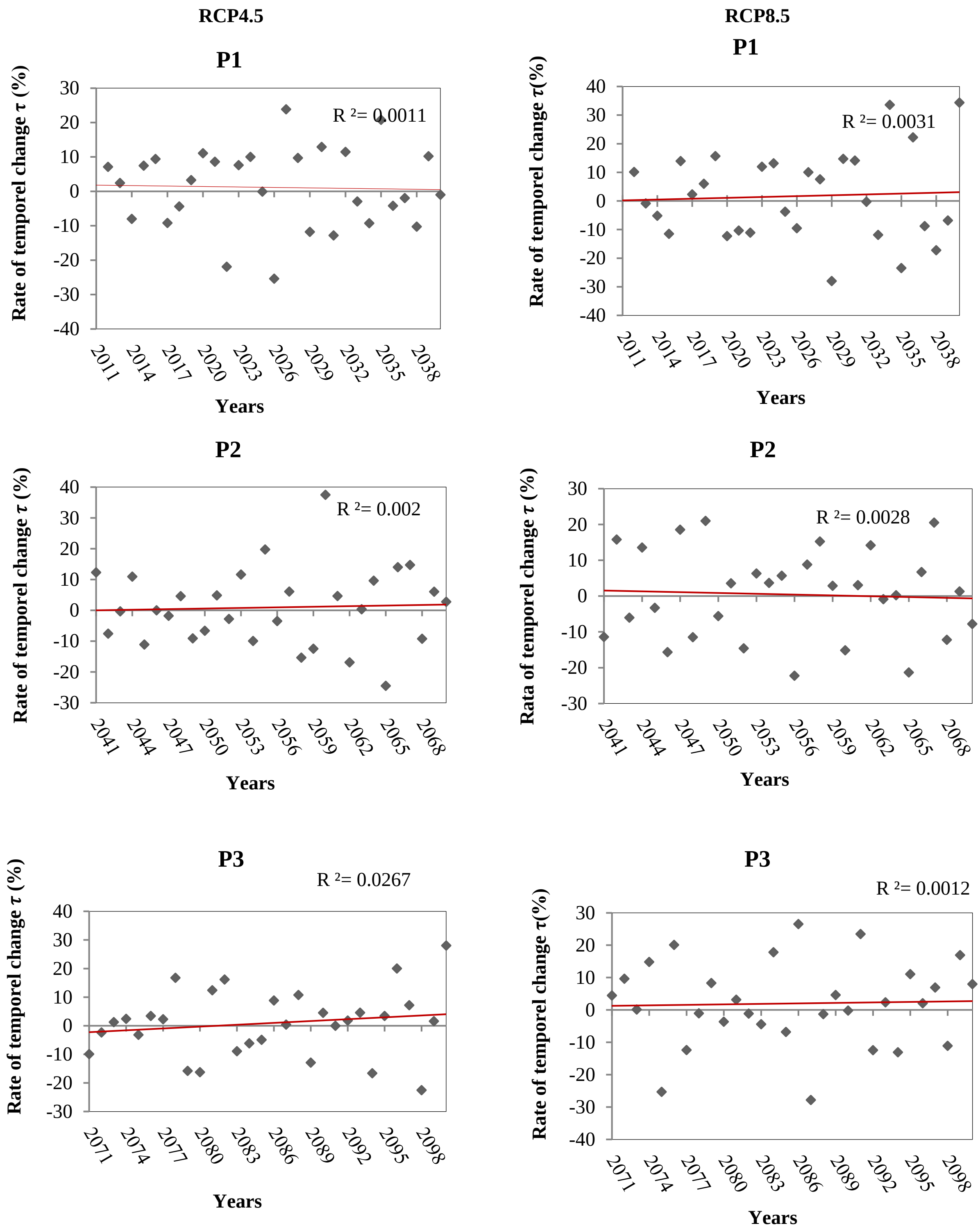

Fig. 7 Rate of temporal change and trend of precipitation of the model ensemble mean under the two scenarios RCP 4.5 and 8.5 for the three periods P1 (2011-2040), P2 (2031-2070) and P3 (2071-2100).

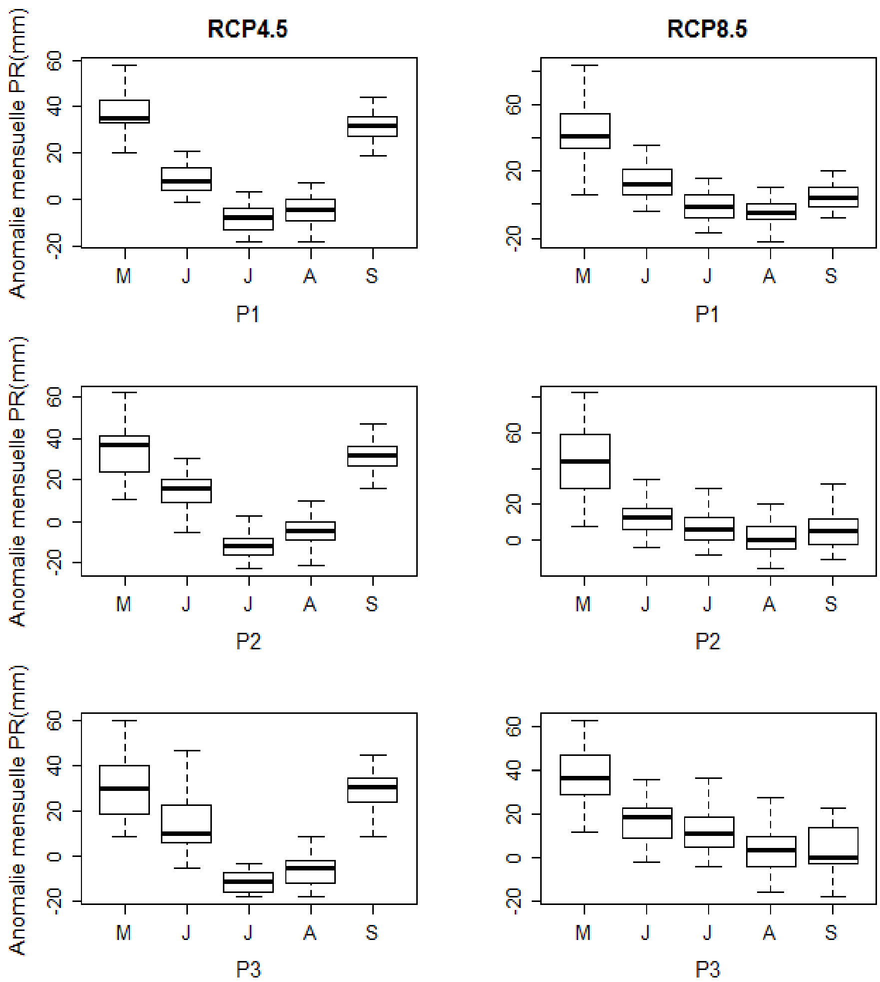

Fig. 8 Monthly precipitation anomaly for the three periods P1, P2 and P3 for the months of MJJAS under the two scenarios RCP 4.5 and RCP 8.5.

Hulme [36] has found over West Africa that the dry months (December to February) of the period 2010-2039 will experience an increase of at about 10% to 35% in total precipitations as compared to the reference period of 1961-1990. Then, the months of September and November will experience an increase of about 7% to 28% and the wet period from June to August a decrease of 10% to 25% will be observed. The projected changes in precipitation observed in this study for the months of September, May and June are in agreement with the results of Deme et al. [37] although the reference periods are different.

3.5 Seasonal Variability of Precipitation Projections

The seasonal variability of precipitation for CHIRPS shows the unimodal character of the rainy season over Niger after the monsoon settles at the end of June with the arrival of the ITD (Inter-Tropical Discontinuity) moist air/humidity in the Sudano-Sahelian latitudes between 5 ° N and 10 ° N around July and August (Fig. 9). Indeed, the installation of the rainy season is progressive from the Gulf of Guinea from May or June to the Sahelian latitudes between 15 ° N and 20 ° N around July and August as in the studies of sultan [35]). The retreat of the rainy season is announced from September towards the south [38].

According to CHIRPS, the month of June corresponds to the beginning of the rainy season over Niger in the reference period 1981-2005 (with an average total monthly precipitation of 56 mm that is more than double of the total of May. Then, the precipitation gradually evolves to reach the peak in August with a

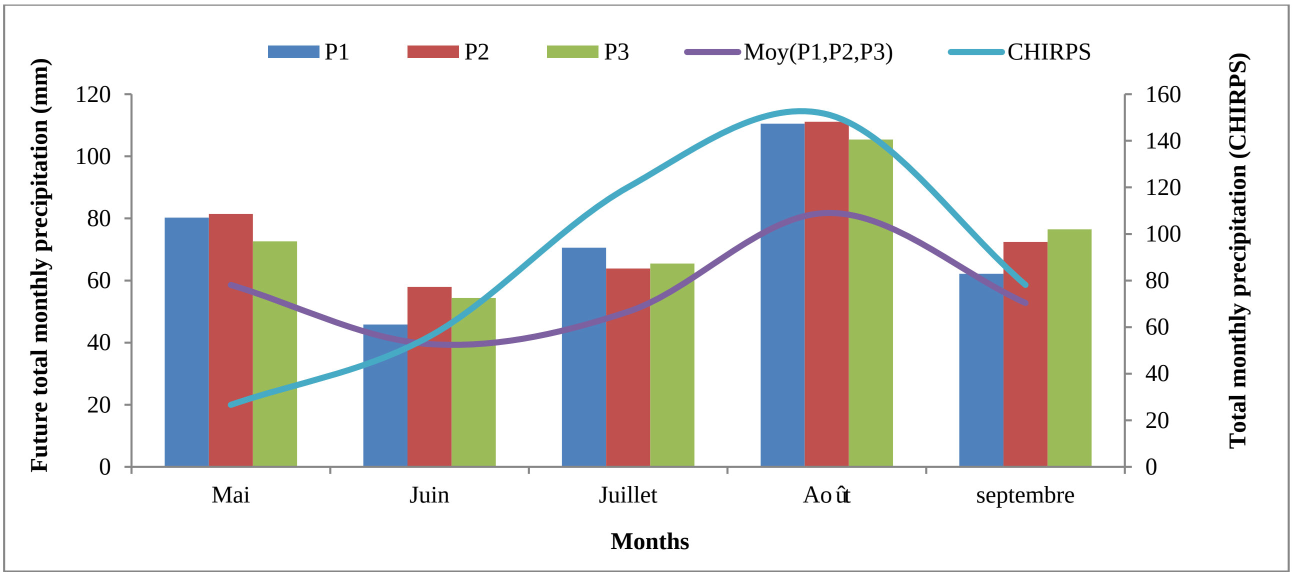

Fig. 9 Seasonal variability of precipitation for the mean ensemble model and CHIRPS in the three periods P1, P2 and P3 under the scenario RCP 4.5 over Niger.

total precipitation average of 160 mm, then it decreases with the withdrawal of the monsoon system in September. The scenario RCP4.5 projects an increase of precipitation in the month of May with a total precipitation average of 78 mm compared to 52 mm for the month of June.

This projected increase of precipitation in the month of May has already been observed in recent years in Niger corresponding to an early arrival of the ITD. The later gives a false onset of the rainy season which results in anticipating the agricultural planting period. The increase in the number of rainy days in May could lead to an early onset. Therefore, global warming could favor an early onset of the rainy season over Niger in particular and over Sahel in general from May. Although the scenario projects a decrease in monthly cumulative precipitation for August, August is still the peak of the season. The intensification of precipitation at the beginning of the season has caused a decrease in precipitation in the middle of the season. Thus, global warming could lead to changes of different magnitude in the temporal precipitation distribution over Niger.

The scenarios project precipitation's decrease in August and a heavy (peak) one in May as simulated by all models. Indeed, Niamey has experienced heavy precipitation event of more than 100 mm on May 5th, 2016 which has caused flooding and many damages, therefore, it is likely that such situations could probably occur again in the near or far future.

4. Conclusions

The aim of this work is to assess the projected changes of precipitations using multi-RCMs models over Niger under the scenarios RCP 4.5 and RCP 8.5. The data of CHIRPS are used as reference (1985-2005) and the SMHI's RCMs RCA4 is used with 10 different forcing GCMs as projections (1985-2005; 2005-2100). This study is divided into two-fold: the performance evaluation of the multi-RCMs through the validation of the model RCA4 in simulating the present climate on precipitation (period 1985-2005) over Niger and the projected changes of precipitation for the period 2011-2100) subdivided into three (3) periods P1 (2011-2040), P2 (2031-2070) and P3 (2071-2100) respectively in the near, medium and far future under the scenarios RCP 4.5 and RCP 8.5.

In the historical/present period, most of the RCMs capture well the spatial distribution of precipitation by highlighting the 4 climatic zones (the Sahelo-Sudanian zone, the Sahelian zone, the Sahelo-Saharan zone and the Saharan zone) as in observation CHIRPS. Only the RCM IPSL model fails to simulate the climatic zones because of its weakness in capturing the precipitation over the southern part of Niger. Some RCMs such as CSIRO-IPSL and CCCma- HadGEM models have very different and even contradictory biases. All the models poorly reproduce the annual precipitations anomalies for the historical period. However, the ensemble mean of the multi-RCMs models reproduces better the historical precipitations anomalies than the individual model with much more intensity towards the end of the first dekad.

The analysis of the correlation coefficient between the multi-RCMs models and CHIRPS gives very different and low correlation coefficients for most RCMs. The observed low correlation coefficient of RCMs indicates that the models have difficulties in simulating the precipitation pattern as in observation. The reason may be due to the models' physics, convection and parametrization schemes that describe the precipitation spatial, temporal distributions, accumulations and interannual variability, etc. The *t*-test of the RCMs also shows significant differences between the models with respect to CHIRPS. It indicates the difficulties of the RCMs models to correctly simulate precipitations over the study area and the Sahel in general. However, the ensemble mean of the multi-RCMs models gives again a better result than the RCMs taken individually. Thus, the ensemble mean of the RCMs will be used hereafter to assess and evaluate the projected changes of precipitation for the period 2011-2100 over Niger.

Under the scenario RCP 4.5, the periods P1 (2011-2040), P2 (2031-2070) have projected high interannual variability in the annual total precipitation with some years moderately respectively in surplus and deficit of precipitations compared to the reference period where a balance is shown between surplus and deficit years. The period P3 (2071-2100) has also projected high interannual variability but with a small upward trend of precipitations. As for the scenario RCP8.5, all the three periods have projected a significant increase in precipitations, especially after the first dekad. The scenario RCP8.5 seems to be favorable to a longer wet period over Niger whereas this scenario has projected an accentuated global warming level between 2.6 ℃ and 4.8 ℃ [4]. According to the results of this scenarios, global warming is likely to be favorable to extreme precipitations over Niger. This result is in contradiction on the finding research from historical water balance reconstruction that shows deficits of precipitation over Sahel under the higher global temperatures [19].

Both scenarios have projected an increase of precipitation during the months of May and September indicating respectively an early onset and late cessation of the rainy season. Unfortunately, these scenarios predict a decrease in the monthly totals of precipitations in the rainy months of July and August which correspond to the peak of the season. Therefore, this shifting in the rainy season observed in these scenarios will strongly affect the agriculture activities if an accurate monitoring of the season is not conducted to detect the dry spell within the monsoonal period. Moreover, global warming will likely result in a reorganization of the seasonal distribution of precipitation with significant changes in precipitations trend towards dry and/or wet periods over Niger leading to new measures of resilience and adaptation to climate change in the Sahelian regions and Niger in particular.

Acknowledgement

We thank the late Professor Fode MADE for his contribution in this work, may his soul stay in peace in paradise.

References

[1] IPCC. 2007. "Climate Change 2007. The Scientific Basis." In *Contribution of Working Group I to the Fourth Assessment Report on the Intergovernmental Panel on Climate Change*, edited by Solomon, S. D. Manning, Q., M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, R. L. United Kingdom and New York, NY, USA: Cambridge University Press.

[2] IPCC. 2014. "Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects." In *Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by Barros, V. R., Field, C. B., Dokken, D. J., Mastrandrea, M. D., Mach, K. J., Bilir, T. E., Chatterjee, M., Ebi, K. L., Estrada, Y. O., Genova, R. C., Girma, B., Kissel, E. S., Levy, A. N., MacCracken, S., Mastrandrea, P. R., White, L. L. Cambridge, UK and New York, NY, USA: Cambridge University Press, pp. 1199-265.

[3] Déqué, M., Calmantis, S., Christensen, O. B., Dellaquila, A., Maule, C. F., Haensler, A., Niulin, G., and Teichman, C. 2017. "A Multi-model Climate Response over Tropical Africa at + 2°C." *Climate Services* 7: 87-95.

[4] AR5 (5th Assessment Report). 2014. *Climate Change 2014*. Report and synthesis, Summary for policy makers.

[5] Panthou, G. 2013. "Analysis of Rainfall Extremes in West Africa and Their Evolution over the Last 60 Years." PhD thesis, UJF-Grenoble 1.

[6] Descroix, L., Niang, A. D., Dacosta, H., Panthou, G., Quantin, G., and Diedhou, A. 2013. "Evolution of High Cumulative Rainfall and Flood Resurgence since 1951 in the Middle Niger Basin (Sahel)." *Climatology* 10: 37-49.

[7] Ali, A., and Lebel, T. 2009. "The Sahelian Standardized Rainfall Index Revisited." *Int. J. Climatol*. 29: 1705-14. doi: 10.1002/joc.1832.

[8] Ozer Pierre., Manzo, O. L., Tidjjani, A. D., Djaby, B., and De Longueville, F. 2017. "Recent Evolution of Rainfall Extremes in Niger (1950-2014)." *Geo-Eco-Trop* 41 (3): 375-83.

[9] Bahari Ibrahim Mahamadou, Ibrahim Bouzou Moussa et Oumarou Faran Maiga. 2018. "Evolution of Rainfall Characteristics and Recrudescence of Floods in Localities along the Niger River." VertigO - the electronic journal in environmental sciences [Online], Regards / Terrain, online 25 May 2018, accessed 24 December 2022. URL : http://journals.openedition.org/vertigo/19891 ; DOI : https://doi.org/10.4000/vertigo.19891.

[10] Endris, H. S., Omondi, P., Jain, S., Lennard, C., Hewitson, B., Chang'a, L., Awange, J. L., Dosio, A., Ketiem, P., Nikulin, G., Panitz, H. J., Büchner, M., Stordal, F., and Tazalika, L. 2013. "Assessment of the Performance of Cordex Regional Climate Models in Simulating East African Rainfall." *J. Clim*. 26: 8453-75. doi: 10.1175/JCLI-D-12-00708.1

[11] Gbobaniyi, E., Sarr, A., Sylla, M. B., Diallo, I., Lennard, C., Klutse, N. A. B., Dosio, A., Diedhiou, A., Kamga, A., Hewitson, B., Nikulin, G., and Lamptey, B. 2013. "Climatology, Annual Cycle and Interannual Variability of Precipitation and Temperature in Cordex Simulations over West Africa." *Int. J. Climatol*. 34: 2241-57. doi: 10.1002/joc.38B4.

[12] Akinsanola, A., Ajayi, V., Adejare, A., Adeyeri, O., Gbode, I., Ogunjobi, K., Nikulin, G., and Abolude, A. 2017. "Evaluation of Rainfall Simulations over West Africa in Dynamically Downscaled CMIP5 Global Circulation Models." *Theoretical and Applied Climatology* 132: 437-50.

[13] Kim, J., Waliser, D. E., Mattmann, C. A., Goodale, C. E., Hart, A. F., Zimdars, P. A., Crichton, D. J., Jones, C., Nikulin, G., Hewitson, B., Jack, C., Lennard, C., and Favre, A. 2014. "Evaluation of the CORDEX-Africa Multi RCM Hindcast: Systematic Model Errors." *Climate Dynamics* 42 (5): 1189-202.

[14] Mounkaila, S. M., Abiodun, B. J., and Bayo Omotosho, J. 2014. "Assessing the Capability of CORDEX Models in Simulating Onset of Rainfall in West Africa." *Theoretical and Applied Climatology* 119: 255-72. doi: 10.1007/s00704-014-1104-4.

[15] Klutse, N. A. B., Sylla, M. B., Diallo, I., Sarr, A., Dosio, A., Diedhiou, A., et al. 2013. "Climate Projections over Cordex Africa Domain Using the Fifth Generation Canadian Regional Climate Model (CRCM5)." *Clim. Dyn*. 41: 3219-46. doi: 10.1007/s00382-012-1651-2.

[16] Mahamadou, Y., Mounkaila, S., and Fodé, M. 2018. "Multi-model Analysis of Rainfall and Temperature Patterns in Niger." *La Météorologie* 101: 50-61. doi: 10.4267/2042/67430.

[17] Ly Mouhamed, and Toune, N. 2019. *Elaboration of Disaggregated Climate Projections for Niger*. Technical Report No. 1.

[18] Met Office. 2010. *Sahelian Climate, Retrospective and Projection*. Report, p. 20.

[19] Matthieu Carré, Moufok Azzoug, Malick Wade, (2019). Moderne drought condition in western Sahel unprecedented in the past 1600 years. Climate Dynamics 52,1949-1964.

[20] Kalognomou, E.-A., Lennard, C., Shongwe, M., Pinto, I., Favre, A., Kent, M., Hewitson, B., Dosio, A., Nikulin, G., Panitz, H. J., and Büchner, M. 2013. "A Diagnostic Evaluation of Precipitation in Cordex Models over Southern Africa." *J. Clim*. 26: 9477-506. doi: 10.1175/JCLI-D-12-00703.1.

[21] Ly, M., Segnon, A. C., D'haen, S., Totin, E., Noblet, M., Camara, I., and Pfleiderer, P. 2019. "Understanding and Interpreting Climate Model Outputs for Conducting Vulnerability Studies: A Guide for Practitioners." In *Climate Analytics*. Berlin: gGmbH.

[22] Bouali Lofti, 2009. "Predictability of West African Rainfall (Intra-seasonal and Seasonal Scales) through DEMETER Simulations and Observations."

[23] Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., and Michaelsen, J. 2015. "The Climate Hazards

Infrared Precipitation with Stations—A New Environmental Record for Monitoring Extremes." *Sci. Data* 2: 150066. doi: 10.1038/sdata.2015.66.

[24] Sylvain, M., and Maurice, I. 2013. "Discovering the new RCP and SSP scenarios urilized by the IPCC."

[25] Thomson, A., Katherine, V. C., and Jae, A. 2011. "RCP4.5: A Pathway for Stabilization of Radiative Forcing by 2100." *Climatic Change* 109 (1-2): 77-94. doi: 10.1007/s10584-011-0151-4.

[26] Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fisher, G., Kindermann, G., Nakicenonic, N., and Rafaj, P. 2011. "RCP8.5—A Scenario of Comparatively High Greenhouse Gas Emissions." *Climatic Change* 109: 33-57. doi: 10.1007/s10584-011-0149-y.

[27] Le Barbé, L., and Lebel, T. 1997. "Rainfall Climatology of the HAPEX-Sahel Region during the Years 1950- 1990." *J. Hydrol.* 188-189: 43-73.

[28] Nicholson, S. E. 2013. "The West African Sahel—A Review of Recent Studies on the Rainfall Regime and Its Interannual Variability." *Meteorol.* 2013: 1-32. doi: 10.1155/2013/453521.

[29] L'Hote, Y., Mahé, G., Some, B., and Tribouelet, J. P. 2002. "Analysis of a Sahelian Annual Rainfall Index from 1896 to 2000: The Drought Continues." *Hydrol. Sci.* 47 (4): 563-72.

[30] Ozer, P., Erpicum, M., Demarée, G., and Vandiepenbeek. 2003. "The Sahelian Drought May Have Ended during the 1990s." *Hydrol. Sci. J.* 48: 489-92. doi: 10.1623/hysj.48.3.489.45285.

[31] Lebel, T., and Ali, A. 2009. "Recent Trends in the Central and Western Sahel Rainfall Regime (1990-2007)." *J. Hydrol.* 375: 52-64.

[32] Camara, M., Diedhou, A., Sow, B. A., Diata, S., and Mbaye, I. 2012. "Intra-seasonal and Diurnal Rainfall Variability Simulated by the Cordex Program Climate Models in West Africa." Presented at the 25th Colloquium of the International Climatological Association, Grenoble, pp. 159-64.

[33] Descroix, L., Diongue-Niang, A., Dacosta, H., Panthou, G., Quantin, G., and Diedhiou, A. 2013. "Evolution of Extreme Rainfall and Flood Resurgence in the Sahel." *Climatology* 10: 37-40.

[34] Bodian A. 2014. "Characterization of Recent Temporal Variability of Annual Rainfall in Senegal (West Africa)." *Physio-Geo* 8: 297-312. doi: 10.4000/physiogeo. 4243.

[35] Sultan, B., & Janicot, S. (2004). The West African monsoon dynamics. Part 2: The 'preonset' and 'onset' of the summer monsoon. J. Climate 16, 3407-3427.

[36] Hulme, M., Doherty, R., Ngara, T., New, M., and Lister, D. 2001. "African Climate Change: 1900-2100." Climate Research 17: 145-68.

[37] Deme, A., Gaye, A. T., and Hourdin, F. 2015. "Climate Projections in West Africa, Evidences and Uncertainties." In *Les sociétés rurales face aux changements climatiques et environnementaux en Afrique de l'Ouest.* Marseille: IRD, pp. 61-87.

[38] Poan, D. E. 2013. "Documentation and Physical Interpretation of the Intra-seasonal Variability of the African Monsoon; Application to Forecasting." PhD thesis, University of Toulouse.