

Assessment of Climate Change Impacts on Drought in the Okpara Basin at Nanon (Benin)

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Abstract

Droughts are among the extreme weather events that generate serious social, economic, and environmental consequences. This study aims to characterize historical (1951-2020) and projected (2031-2100) droughts in the Nanon Basin. To this end, we used observed and simulated daily rainfall data from three climate models (AWI CM, EC Earth, INM CM4) from five rain gauge stations located around the basin. The standardized precipitation index was used to define drought episodes and assess their duration, severity, intensity, and extent. We calculated the marginal probability of precipitation from the empirical position on the Gringorten diagram and then transformed it into a standardized precipitation index using a standard normal distribution function. The results reveal that over the historical period (1951-2020), the number of droughts varied from 17 to 28 with an average length of 7 to 14 months. Droughts maximum length varied from 10 to 110 months while droughts intensity and severity varied respectively from -1.5 to -0.5 and -120 to -20 . During the projected period, all climate models under SSP245 and SSP485 scenarios show increases in average drought durations (0 to 10 months), number of droughts (0 to 10 months), drought intensity (0 to 1), and drought severity (up to 10) compared to the reference period. It should be noted that these changes are not great compared to historical period. This situation could deteriorate the quality of natural resources in the Nanon Basin in the future if adaptation measures are not implemented.

Keywords

Drought Characteristic, Climate Change, Climate Models, Climate Scenarios,

1. Introduction

Water is essential for sustaining life and plays a critical role in the economic and social development of nations [1]. However, managing water resources faces significant challenges. These challenges stem from climate change, increasing demand for drinking water, agricultural and industrial needs [2].

Climate change and its impacts are widely recognized as one of the greatest challenges confronting humanity, the environment, and global economies [3] [4]. Globally, its direct effects include rising temperatures, shifts in precipitation patterns, rising in extreme weather events, and reduced predictability of water resources [5] [6].

Africa has been profoundly affected by drought, with its severity intensifying during the 1970s and 1980s. This prolonged drought resulted from significant climatic variability driven by disruptions in the West African monsoon system [7]-[10]. The consequences are stark, including a 20% to 40% reduction in mean annual rainfall between 1931-1960 and 1961-1990 [4] [11], along with a 40% to 60% decline in river flow [12]-[15]. Furthermore, numerous studies have highlighted that challenges related to water resource availability in West Africa arise not only from climate change impacts but also from increasing anthropogenic pressures on watersheds and lowland areas [16]-[18].

A reduction in dry conditions over the Sahel and Sahara, coupled with an increasing trend in wet indices over the Western and Southern Sahel, has also been documented [19] [20]. Reference [18] reported a statistically significant rise in wet days and a corresponding decrease in dry days across the Sahel. They also noted that while extreme summer rainfall events generally show significant decreases over West Africa, localized increases are observed in the western Sahel. In Ghana, [21] identified a marked downward trend in rainfall indices over Lake Volta and central regions, while weak positive trends were evident in the country's northern parts. Meanwhile, [22] observed no trend in the evolution of climatic indices over the upper Ouémé basin north of Benin.

Benin has experienced periods of severe rainfall decline, accompanied by a notable increase in the frequency of dry years [23] [24]. With rapid population growth and accelerating urbanization, water demands in developing countries, particularly in Benin, continue to increase and diversify. The Okpara basin in northern Benin faces additional challenges due to its specific hydrogeological characteristics, which further hinder access to water [25]. Climate change, marked by decreasing rainfall and rising minimum and maximum temperatures [26], exacerbates this already challenging situation for the inhabitants of the Okpara basin. These changes threaten to reduce the availability of water resources in the region, particularly those relied upon at the Okpara reservoir. The Okpara dam, which

serves as the sole source of drinking water for the city of Parakou, is currently grappling with significant challenges that demand urgent attention from all stakeholders involved in its management and sustainability [27].

In light of these concerns, this study aims to analyze recent and future drought indices in the Okpara basin at the Nanon outlet using CMIP6 scenarios. Understanding drought patterns is particularly important in this basin for defining sound water management policies and ensuring the supply of drinking water to the city of Parakou. Furthermore, the CMIP6 SSP scenarios are not yet being used in this region for future rainfall analysis.

2. Methods

2.1. Study Area and Data

The Okpara watershed at the Nanon outlet is characterized by a crystalline peneplain interspersed with hard-rock hills. It spans an area of 2070 km² and encompasses all or parts of five communes in the Borgou department: Tchaourou, N'Dali, Pèrèrè, Nikki, and Parakou [27]. Geographically, it is situated between latitudes 9°4'59"N and 9°52'40.61"N, and longitudes 4°6'49.5"E and 4°37'11.5"E (Figure 1).

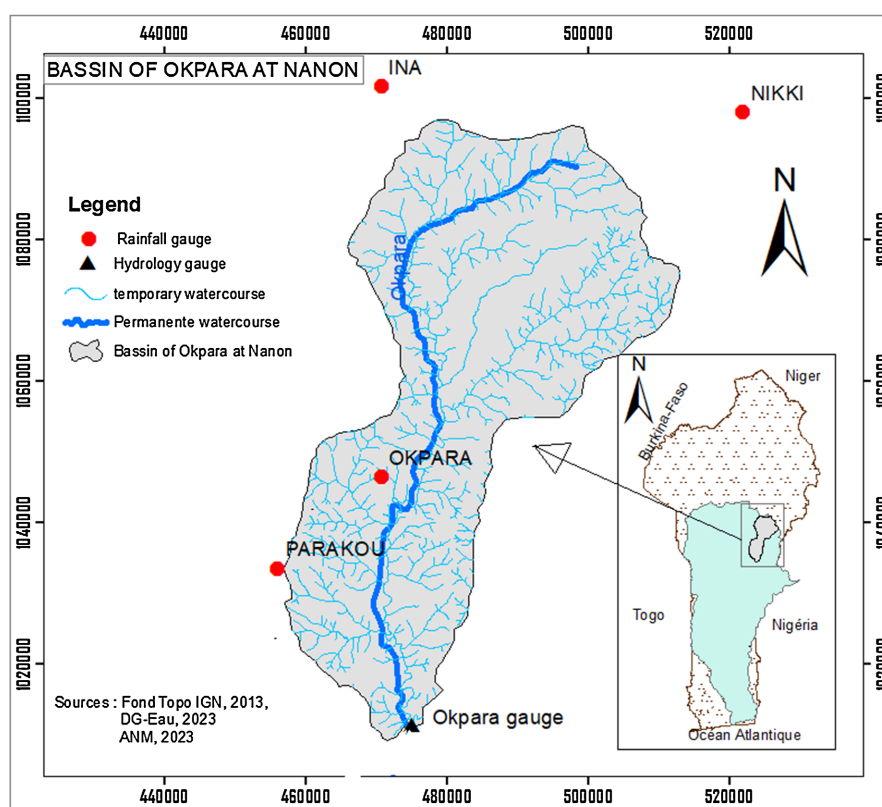


Figure 1. Geographical location of the Okpara basin in Nanon.

Observed daily precipitations (1951-2020) from five in situ stations (Ina, Nikki, Okpara, Parakou and Tchaourou) were obtained from the Agence Nationale de la

Météorologie (Météo-Bénin). The observed data are supplemented with simulations from climate models. In Inter-model comparison Project Phase 6 (CMIP6) a combination of Representative Concentration Pathway (RCP) and Shared Socioeconomic Pathway (SSP) scenarios [28] were developed. Among these scenarios historical, SSP245, and SSP58.5 simulations from the AWI-CM, INM-CM and EC-Earth3 climate models (Table 1) were used. These models were selected for their high spatial resolution and ability to reproduce extreme rainfall events in West Africa [29] [30].

Table 1. Characteristics of the climate models used.

CMIP6	Institution	Atmosphere lat/lon (°C)
AWI-CM-1-1-MR	Alfred Wegener Institute	0.9 × 0.9
INM-CM4-8	Institute for Numerical Mathematics (INM), Russia	1.5 × 2.0
EC-Earth3-CC	EC-EARTH consortium, The Netherlands/Ireland	0.7 × 0.7

2.2. Bias Correction Method

Applying bias correction to climate model data prior to use seems necessary at local scale [31]. Bias correction is made to address biases in model output that are the result of the way physical processes are captured in the original climate models, their boundary and initial conditions and the effects of the numerical algorithms used for solving the partial differential equations within the model [32]. Bias correction also removes errors due to the large spatial scale of grid cells models that can be different with local climate specificity [32] [33]. ISIMIP method [34] is used in this study to bias correct climate model simulations (historical, SSP245 and SSP585).

Bias correction with the ISI-MIP method is carried out in four steps. The first step adjusts for long-term differences between simulated and observed monthly average data over the historical period (Equation (1)).

$$\tilde{P}_{ij}^{hist} = C \times P_{ij}^{hist} \quad (1)$$

where P_{ij}^{hist} are the precipitations of a day j of a month i simulated by the climate model and \tilde{P}_{ij}^{hist} the corrected precipitations of the same day and the same month and C the correction factor given by the Equation (2)

$$C = \frac{\sum_{i=1}^m P_i^{obs}}{\sum_{i=1}^m P_i^{hist}} \quad (2)$$

with P_i^{obs} the observed monthly precipitation of month i over a period of m years and P_i^{hist} the simulated monthly precipitation of month i over a period of m years. The second step adjust the frequency of wet days by setting a wet day threshold from observed and historical precipitations. The third and fourth steps imply the correction of precipitation intensity on wet days. In the third step, the mean precipitations of a given month \hat{P}_i^{Obs} and \hat{P}_i^{hist} , is used to normalise ob-

served and simulated daily precipitation of the month (Equation (3)).

$$\delta P_{ij}^{data} = \hat{P}_{ij}^{data} / \hat{P}_i^{data} \quad (3)$$

The fourth step is based on a transfer function $g(\delta \hat{P}^{hist})$ derived using non-linear regression on the ordered sets of $\delta \hat{P}^{obs}$ and $\delta \hat{P}^{hist}$, which are the sets of normalized wet days of wet months during the reference period to correct precipitation intensity (Equation (5)). The lowest precipitation value $\delta \hat{P}_{min}^{hist}$ in this period is a parameter of the transfer function.

$$g(\delta \hat{P}^{hist}) = \left[a + b \cdot \left\{ \delta \hat{P}^{hist} - \delta \hat{P}_{min}^{hist} \right\} \right] \times \left[1 - \exp \left\{ - \frac{\delta \hat{P}^{hist} - \delta \hat{P}_{min}^{hist}}{\tau} \right\} \right] \quad (4)$$

The coefficients a , b and τ are obtained by adjustment. In this algorithm, the nonlinear regression is applied preferentially. If the nonlinear fitting procedure does not converge, a linear transfer function (Equation (5)) is used.

$$g(\delta \hat{P}^{MC}) = \left[a + b \cdot \delta \hat{P}^{MC} \right] \quad (5)$$

In both versions of this algorithm, when there are less than 100 wet days over the entire reference period or when the long-term monthly average is less than 0.01 mm/day, the precipitation intensity is not corrected due to insufficient statistical information. In this case, we consider a linear transfer function with $a = 0$ and $b = 1$.

2.3. Drought Characteristics

To define drought events and assess their durations, severities, intensities and extends, standardized precipitation index was used. To this end, we compute the marginal probability of precipitation [35] using the empirical Gringorten plotting position [36] (Equation (6)). The Gringorten plotting position method is used to directly determine Cumulative Distribution Function because it avoids predefining probability distribution, making it suitable for various dataset. It is also sensitive to extreme values, enhancing its ability to analyze severe drought events.

$$p(x_i) = \frac{i - 0.44}{n + 0.12} \quad (6)$$

where n is the sample size, i denotes the rank of non-zero precipitation data from the smallest, and $p(x_i)$ is the corresponding empirical probability. The outputs of equation 6 is then transformed into a Standardized Precipitation Index (SPI) as:

$$SPI = \phi^{-1}(p) \quad (7)$$

where ϕ is the standard normal distribution function, and p is probability derived from equation 6. A drought event is defined as a period over which SPI is continuously less than -0.5 . 12-months of SPI were investigated. The drought classification scheme used in this study is detailed in **Table 2**.

We use 5 drought characteristics to analyze drought pattern in Okpara basin at Nanon. These drought characteristics are: the average number of drought events

Table 2. Drought severity information in both the original standardized scale and their corresponding drought scale [37].

SPI	Drought Scale	Description
-0.50 to -0.79	D0	Abnormally dry
-0.80 to -1.29	D1	Moderate drought
-1.30 to -1.59	D2	Severe drought
-1.60 to -1.99	D3	Extreme drought
-2.00 or less	D4	Exceptional drought

(N), the average length of drought events (DL), the length of the greatest drought event (MLD); the average of drought severity (DS) and the average of drought intensity (DI). The greatest drought is the drought event with the maximum length. DS was calculated as:

$$DS = \sum_i^n (\text{SPI} < -0.50) \quad (8)$$

n is the total length (in months) of drought events.

DI was calculated as mean drought severity over the greatest drought event.

$$DI = \frac{\sum_i^n (\text{SPI} < -0.50)}{n} \quad (9)$$

2.4. Change in Drought Characteristics

The rate of change is estimated following equation 10.

$$\text{Change rate} = \frac{\bar{X}_2 - \bar{X}_1}{\bar{X}_1} \times 100 \quad (10)$$

where \bar{X}_2 is the drought characteristics value over projected period (2031-2100), and \bar{X}_1 is the drought characteristics value over observed period (1952-2020).

3. Results

3.1. Performance of the Bias Correction Method

In this section, we assess the performance of AWI-CM, EC-Earth and INM-CM simulations to reproduce the observed precipitation in the study area. This step is very important because the accuracy and reliability of the future simulations of the meteorological drought index depend on how well the models capture the historical precipitation. **Figure 2** shows the performance of applied bias correction method on precipitation. All used Climate models perform well the seasonal precipitation pattern of Okpara basin. However, AWI-CM and EC-Earth over estimate precipitation of Jun to September and under estimate precipitation of other months. INM-CM under estimates precipitation from April to October but well estimate precipitation of other months. Correcting for bias brings the model simulations closer to the observed data. In this way, climate model projections can be used with a minimum of confidence to study the future drought in the basin. **Ta-**

ble 2 also presents the Mean Root Square Error (RMSE) and Percent Bias (Pbias) before and after bias correction. It clearly appears that bias correction improves the quality of simulations. Indeed, the RMSE decreased by 2 units after the bias correction while the Pbias which vary between -25% and 36% before the bias correction are estimated at between -5% and 5% after the bias correction.

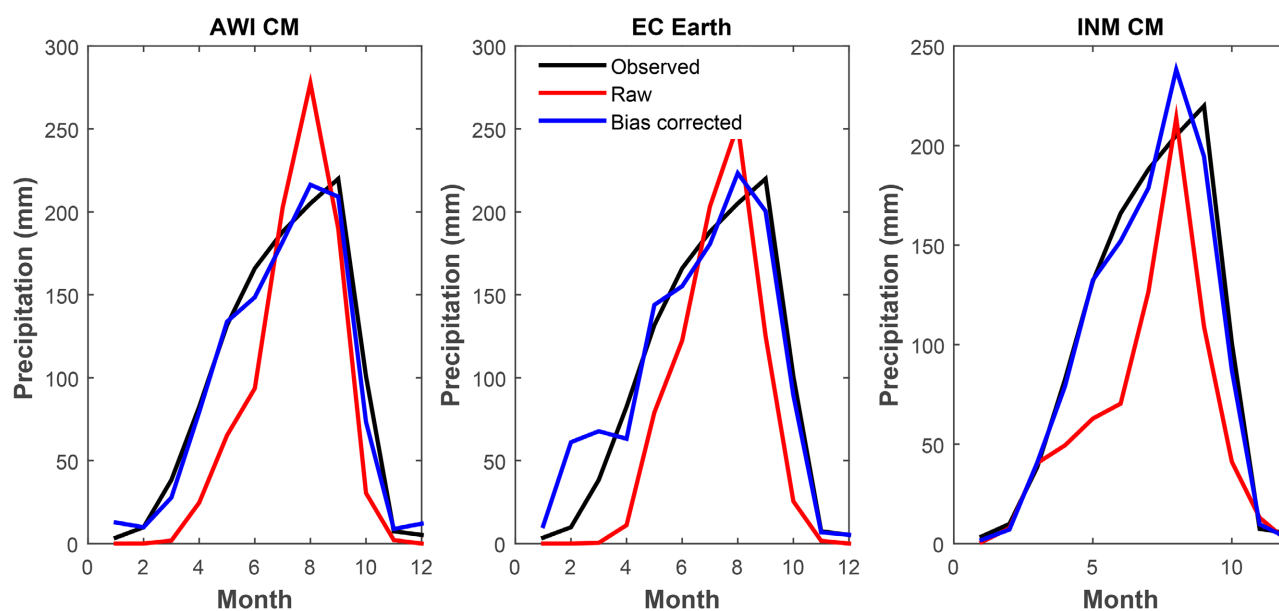


Figure 2. Performance of the bias correction method on monthly rainfall.

Table 3. Performances of bias correction.

Station	Model	Raw_RMSE	Raw_PBIAS	Corr_RMSE	Corr_PBIAS
Ina	AWI_CM	11,944	-25.98	9.7975	-3.59
Nikki	AWI_CM	12,2019	-24.01	9.756	-2.29
Okpara	AWI_CM	12,2633	-22.1	9.8586	-2.04
Parakou	AWI_CM	11,9793	-23.9	9.9452	-4.56
Tchaourou	AWI_CM	11,6045	-4.94	9.7211	-3.89
Ina	EC_Earth3	12,6885	-42.8	10.1006	-1.71
Nikki	EC_Earth3	12,6508	-43.91	10.1042	-3.44
Okpara	EC_Earth3	12,8919	-27.64	10.0819	-1.23
Parakou	EC_Earth3	13,37	-29.63	10.2058	3.5
Tchaourou	EC_Earth3	12,6269	-21.5	9.9971	-0.29
Ina	INM_CM4	13,4704	38.48	10.216	3.52
Nikki	INM_CM4	13,3532	27.24	10.3464	3.97
Okpara	INM_CM4	13,1683	35.62	10.1584	4.11
Parakou	INM_CM4	13,9791	36.91	10.31	3.66
Tchaourou	INM_CM4	13,1771	8.11	10.2699	5.12

3.2. Recent drought Characteristics in the Nanon Basin

Figure 3 shows the spatial distribution of the average number of droughts, the average duration of droughts, and the maximum duration of droughts in the Nanon basin from 1952 to 2020. This figure indicates that the average number of droughts varied between 17 and 28 events. The highest values for this number are found in the far north of the basin, reflecting this area of frequent drought events. Average drought durations ranged from 7 to 14 months, with the lowest values localized in the far north of the study basin. Maximum drought durations in the study basin varied between 30 and 110 months. The centre of the basin experienced the highest maximum drought durations, while the highest values characterize the far north during the historical period. In summary, during the historical sub-period, the study basin exhibited a higher frequency of drought events in its far north, with shorter durations.

Figure 4 presents the severity and intensity of droughts. The analysis of this figure reveals that drought severity varied between -120 and -20 . Droughts were

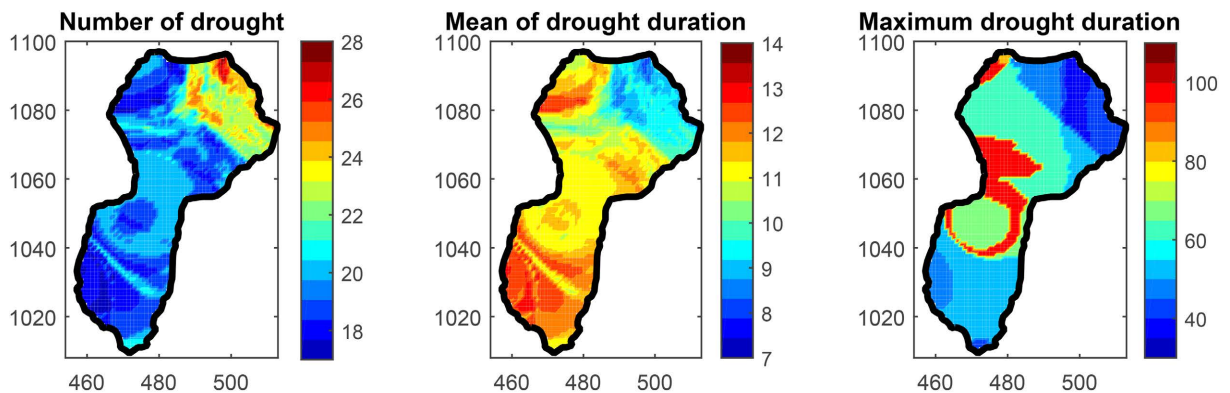


Figure 3. Spatial pattern of number of droughts, mean of drought duration and maximum drought duration in Nanon basin from 1952 to 2020.

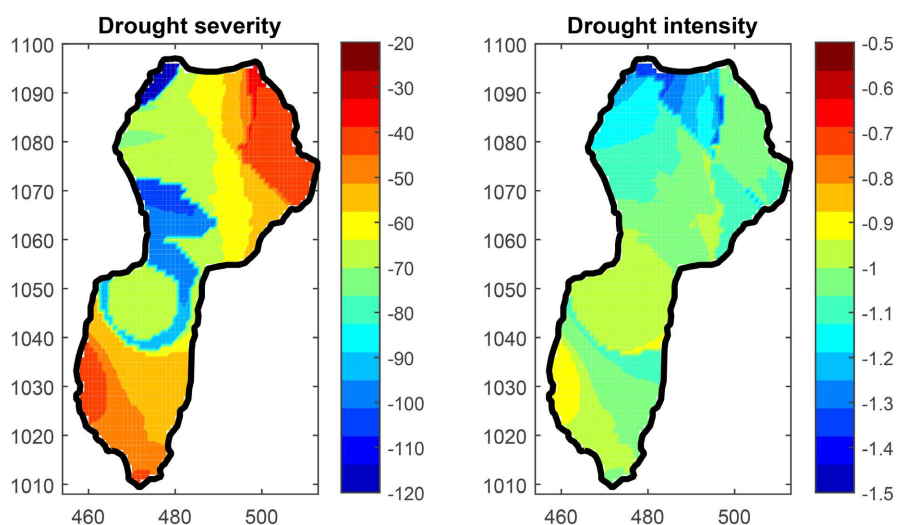


Figure 4. Spatial pattern of drought severity and intensity in Nanon basin from 1952 to 2020.

more severe in the central and northwestern parts of the basin, while they were less severe in the southern and northern parts. The intensity of droughts varied between -1.5 and -0.5 during the study sub-period in the Nanon basin. Drought scale varied from Abnormally drought to severe drought. Droughts were severe in the northern part of the basin (-1.5 to -1.2), while they were moderate, ranging between (-1.1 and -0.9) in most parts of the basin. In summary, during the historical period, only the northwestern part of the basin experienced severe droughts.

3.3. Future Change in Drought Characteristics in the Nanon Basin

Figure 5 presents the potential rates of change in average drought durations between the reference period (1951-2020) and the projected period (2031-2100) under the SSP245 and SSP585 scenarios of the AWI CM, EC Earth, and INM CM4 climate models. This figure shows that the average drought duration could increase by approximately 5 months in the far north of the basin, while it could decrease in other parts of the basin under the SSP245 scenario of all used climate models. However, with the SSP585 scenario, all models predict increases in the average drought duration across the entire basin. For the AWI CM and EC Earth models, the rates of change range from 0 to 10 months, while they range from 5 to 10 months for the INM CM4 model. In conclusion, average drought durations are likely to increase in the Nanon Basin in the future under both SSP245 and SSP485.

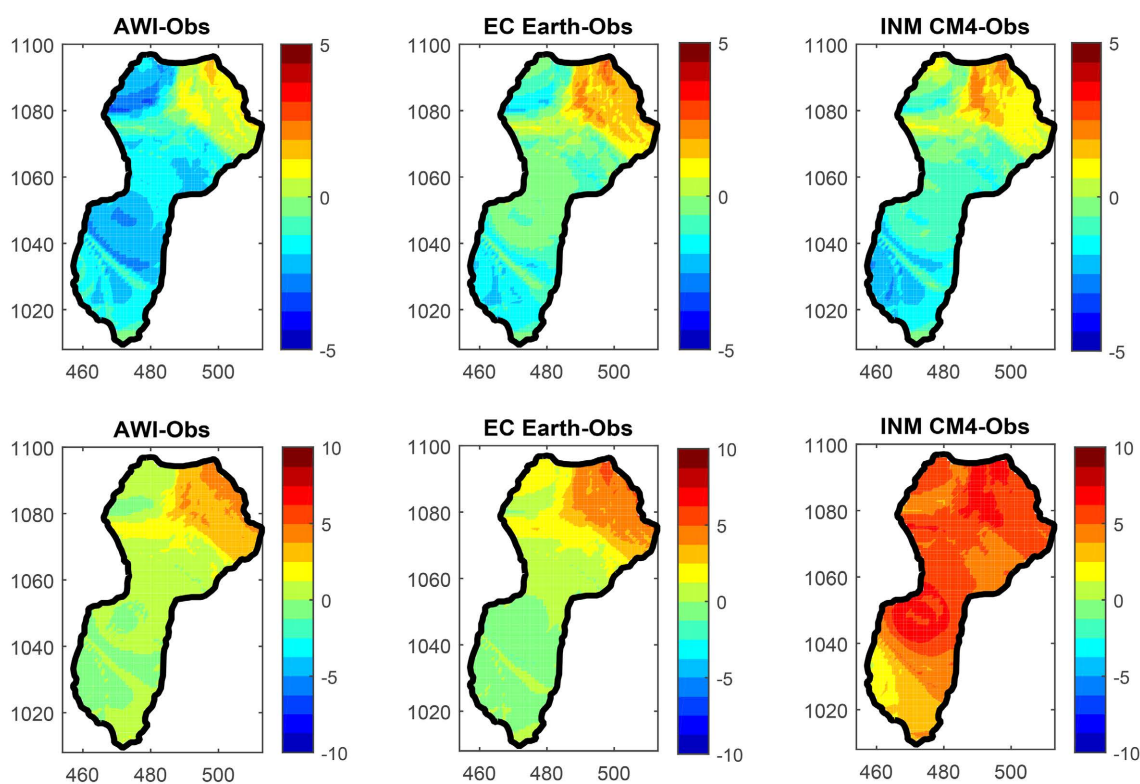


Figure 5. Spatial pattern of change in mean of drought duration in Nanon basin (first line SSP245-observed; second line SSP485-observed).

Figure 6 presents the projected rates of change in the average number of droughts between the reference period (1951-2020) and the projected period (2031-2100) under the SSP245 and SSP585 scenarios of the AWI CM, EC Earth, and INM CM4 climate models. This figure indicates that the average number of droughts could increase by 5 to 10 events across of the basin and by 2 to 5 in its far north under the SSP245 scenario of all climate models. In contrast, the AWI CM and EC Earth models predict increases ranging from 0 to 5 in the basin and lower increases for the far north under the SSP585 scenario. The INM CM4 model, predicts decreases in the average number of droughts ranging from -5 to 0 under the SSP585 scenario compared to the reference period. In summary, the average number of drought events is predicted to increase regardless of the model and scenario, except for the SSP585 of the INM CM4 model, for which this number decreases.

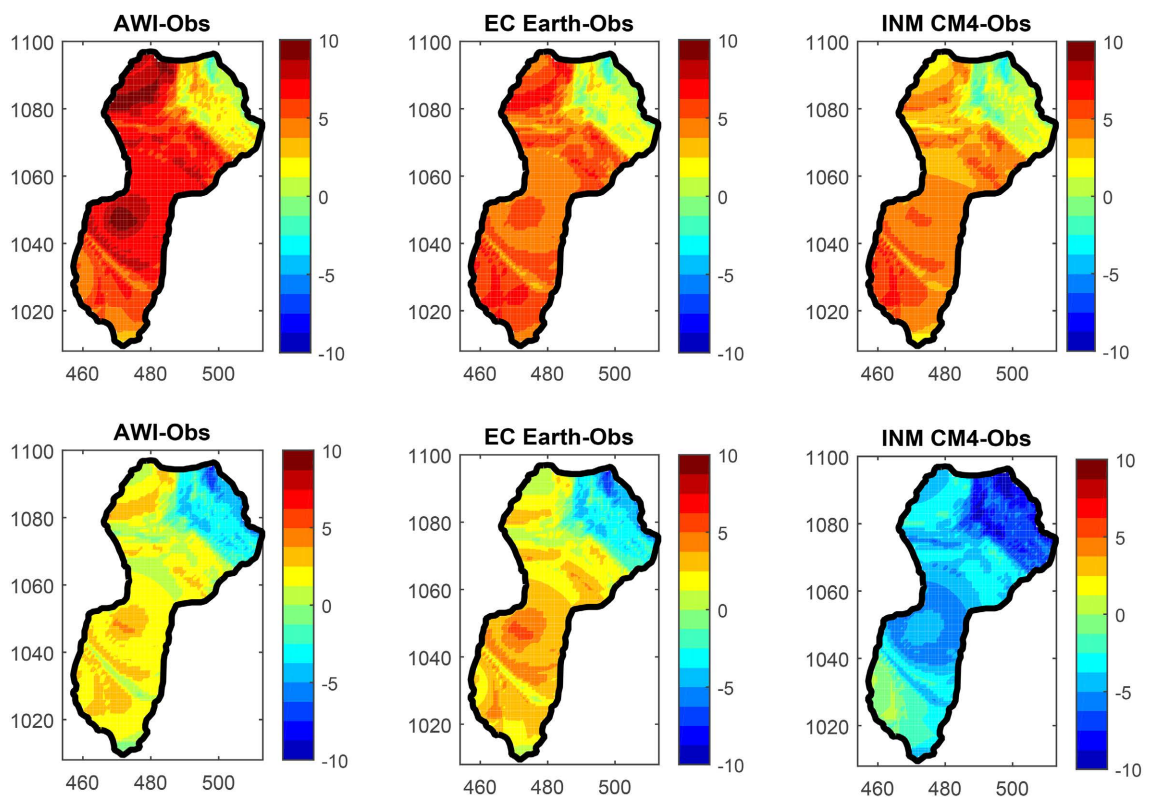


Figure 6. Spatial pattern of change in mean of drought Number in Nanon basin (first line SSP245-observed; second line SSP485-observed).

Figure 7 presents the potential rates of change in maximum drought durations between the reference period (1951-2020) and the projected period (2031-2100) under the SSP245 and SSP585 scenarios of the AWI CM, EC Earth, and INM CM4 climate models. This figure shows that the maximum drought duration could increase by 0 to 20 days across the entire basin, except in the central region where it could decrease by up to 40 days compared to the reference period under the SSP245 scenario of all climate models. However, under the SSP585 scenario, using

the EC Earth and INM CM4 models, these rates of increase vary between 0 and 60 days across the basin, with slight decreases of up to 40 days in the central region. The AWI CM model, predicts increases of up to 80 days under the SSP585 scenario compared to the reference period. In summary, in the future, maximum drought durations could increase in the Nanon basin.

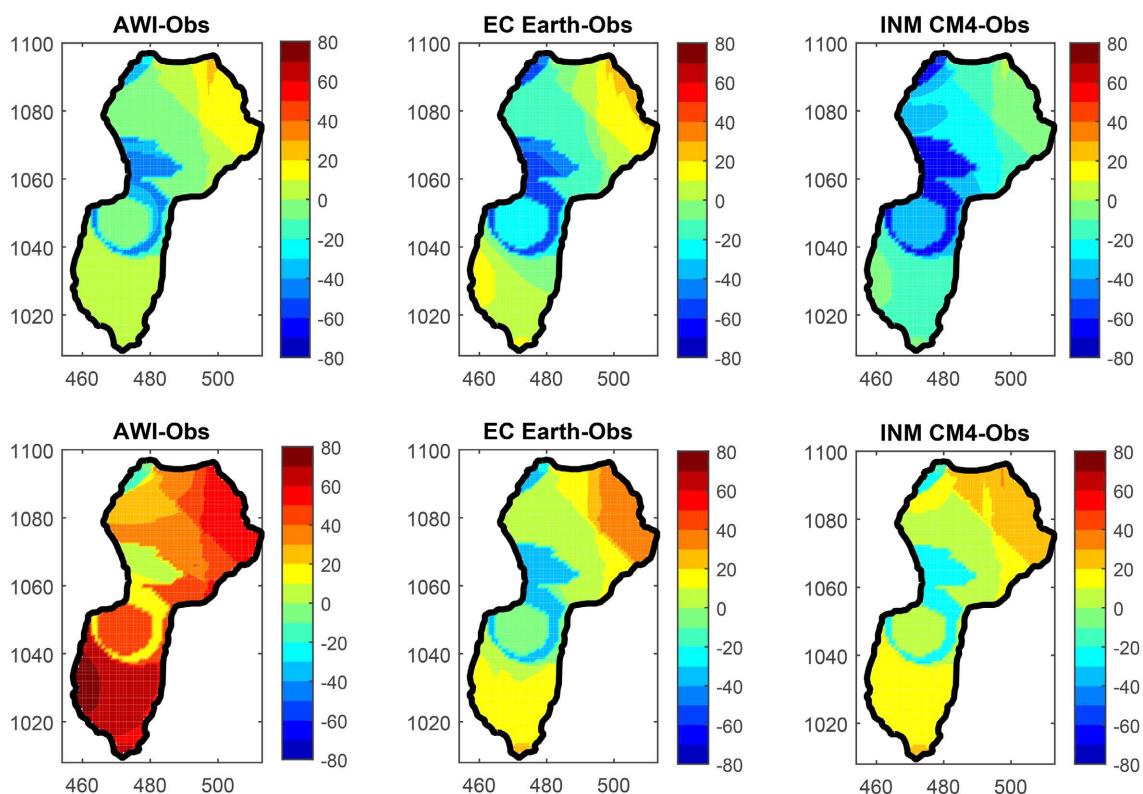


Figure 7. Spatial pattern of change in maximum drought duration in Nanon basin (first line SSP245-observed; second line SSP485-observed).

Figure 8 illustrates the potential rates of change in drought intensity between the reference period (1951–2020) and the projected period (2031–2100) under the SSP245 and SSP585 scenarios of the AWI CM, EC Earth, and INM CM4 climate models. This figure reveals that, regardless of the scenario, drought intensity could increase by a factor ranging from 0 to 0.5 (reaching 1 for SSP245) compared to the reference period with the INM CM4 model. In contrast, the rates of change range from -0.5 to 0.5 compared to the reference period for both the AWI CM and EC Earth climate model are projected. Overall, droughts are likely to be more intense in the coming years.

Figure 9 shows the potential rates of change in drought severity over the Nanon Basin between the reference period (1951–2020) and the projection period (2031–2100) under the SSP245 and SSP585 scenarios of the AWI CM, EC Earth, and INM CM4 climate models. Analysis of this figure reveals that under the SSP245 scenario, drought severity could increase by a factor of 5 to 10 across most of the basin and by a factor of 2 to 5 in its northernmost reaches, according to all climate

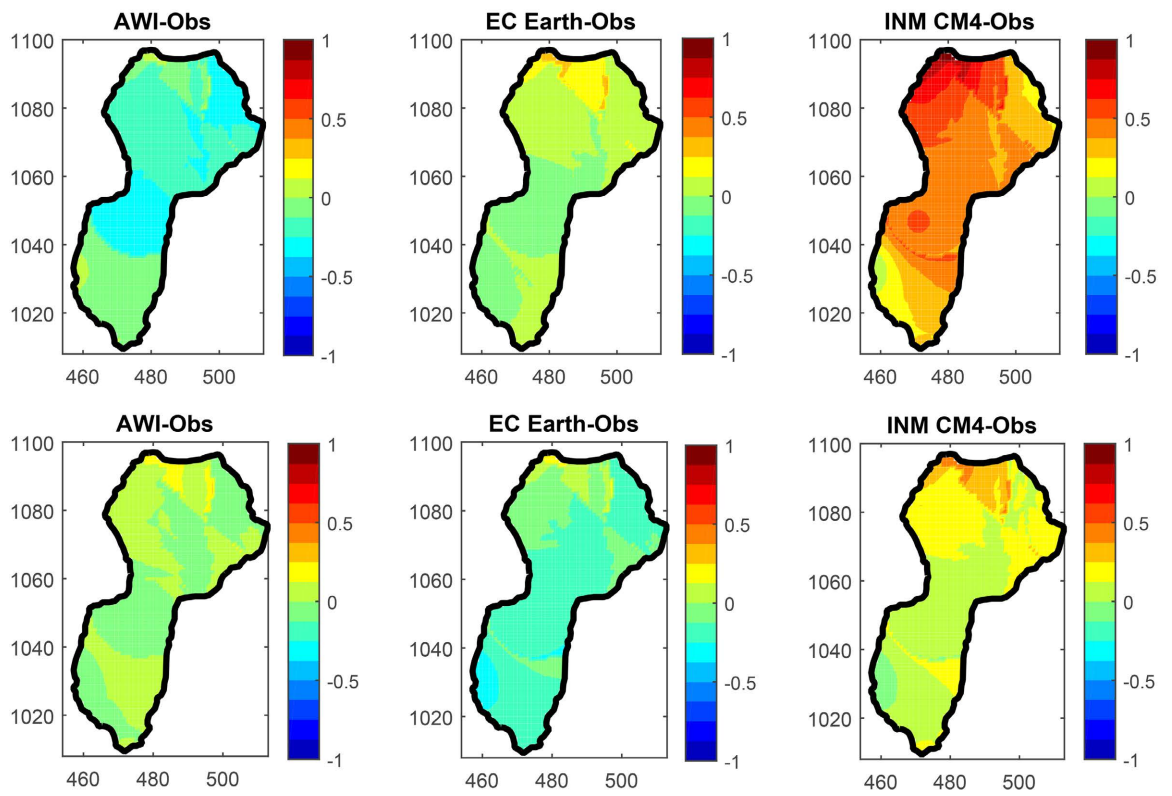


Figure 8. Spatial pattern of change in drought intensity in Nanon basin (first line SSP245-observed; second line SSP485-observed).

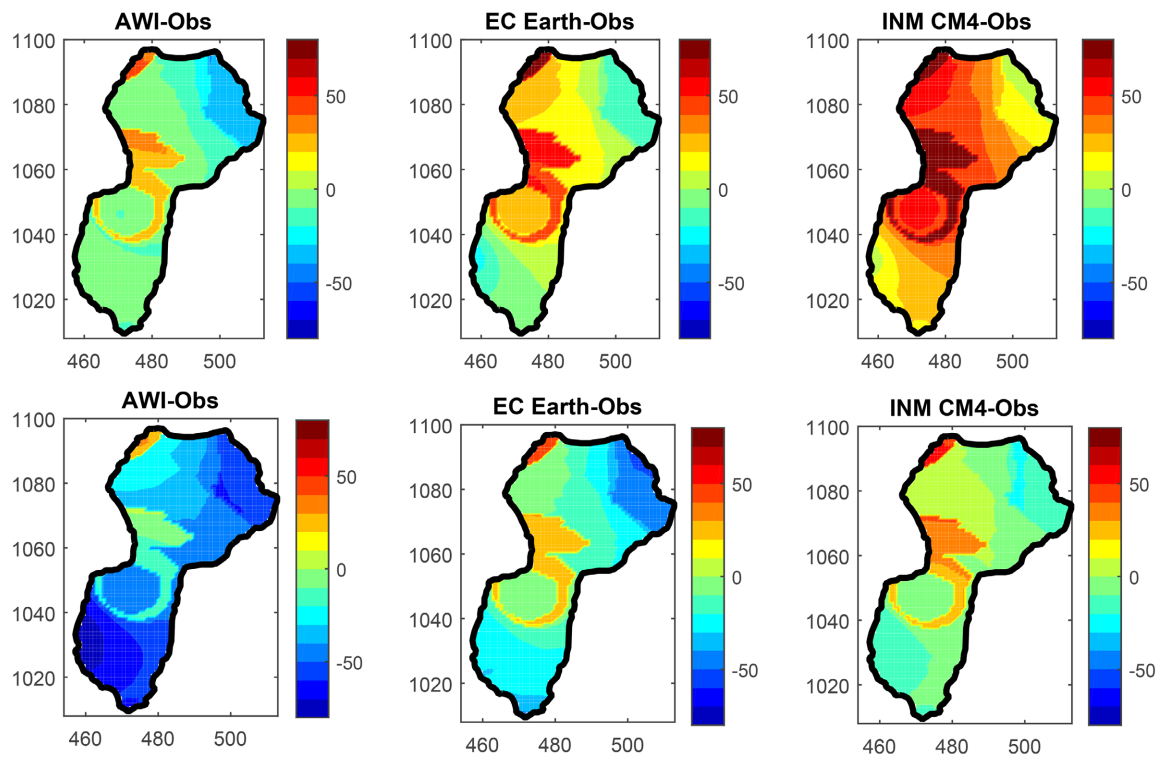


Figure 9. Spatial pattern of change in drought severity in Nanon basin (first line SSP245-observed; second line SSP485-observed).

models used. In contrast, under the SSP585 scenario, the AWI CM and EC Earth models predict increases ranging from 0 to 5 across most of the basin and lower increases in the northernmost reaches. The INM CM4 model, for its part, forecasts decrease in drought severity under the SSP585 scenario, ranging from -5 to 0 compared to the reference period. In short, drought severity is projected to increase across all models and scenarios, except for the SSP585 scenario in the INM CM4 model, for which this value decreases.

Regardless of the climate model and scenario considered, none of the assessed changes are significant. For the future period (2031-2100), while drought characteristics are indeed increasing, the values are not too critical. It would therefore be worthwhile to plan measures to adapt to these effects.

4. Discussion

The Nanon Basin has experienced frequent, short-duration drought events over the historical period (1951-2020). This pattern (high frequency but shorter episodes, and rarer but potentially more persistent episodes) is characteristic of what is observed in the Sudano-Sahelian climate, where interseasonal variability (season start/end dates, dry breaks) strongly controls the succession of deficit episodes, while interannual persistence depends more on large-scale forcings [4] [12] [13] [15]. Although dry periods are brief on average, the period from 1980 to 1990 was marked by a severe drought in West Africa [12] and [24]. This period undoubtedly explains the approximately 110-month drought observed in this study, which corresponds to the reality of the study area. While the changes remain weak, this phenomenon is projected to continue in the coming years (2031-2100). Thus, unlike the central Sahel, where some studies show a return to wetter conditions [16] [38], the Okpara basin appears to be maintaining a drier trend. Our results confirm the work of [26], which highlights that northern Benin remains vulnerable to a decrease in annual rainfall and an increase in extreme temperatures, and therefore in evapotranspiration. This situation could be very challenging for primary sector activities in the study area, especially given the high rainfall patterns that cannot tolerate prolonged periods of drought. These findings regarding future droughts appear to have global implications. For example, [39] predict an increase in extreme droughts in many regions of the world, with the risk sometimes tripling in some areas. According to [40], North America is expected to experience severe droughts over the next 100 years. Reference [41] also reach this conclusion but specify that if only rainfall is considered to predict droughts, the latter will decrease in North America, the Amazon, Central Europe and Asia, the Horn of Africa, India, and Central Australia. Conversely, if temperatures are taken into account, droughts will intensify.

The duration, intensity, and severity of droughts will vary considerably compared to the reference period. According to most models, these parameters increase. However, it should be noted that these short-term droughts will generally be accompanied by low intensity (not exceeding 2). These are the results obtained

by [42] for the Niger River basin in Benin. According to [43], the duration of meteorological droughts will be slightly less than or equal to that of the historical period in Kentucky, while the intensity of droughts will decrease in the same area. These results have also been obtained since 1995 for countries bordering the Gulf of Guinea by [44]. Reference [45] also showed that the Ouéme watershed at Beterou, in Benin, is characterized by droughts of varying intensity. What is interesting about our results is that the INM-CM4 model predicts a decrease in severity under SSP5-8.5. This divergence is quite common in West Africa, a region where general circulation models do not yet perfectly simulate the West African monsoon [10] [46]. This uncertainty highlights the need for multi-model approaches to hydrological planning. Unlike the work of [22] on the Upper Ouémé, which did not show a clear trend, our results suggest that the new CMIP6 scenarios capture an intensification of climate risk that previous models (CMIP5) may have underestimated for this area of interest.

The implications of these findings are critical for the Nanon basin and, more broadly, for the Parakou region. An increase in the duration and intensity of droughts could lead to severe water stress for a rapidly growing population [2] [27]. Furthermore, as the basin is dominated by agro-pastoral activities, more frequent droughts would reduce agricultural yields and could exacerbate conflicts between farmers and herders over access to water points, an issue that is already prevalent in Benin [23] [24]. Finally, groundwater recharge could also be severely impacted [47]-[49].

5. Conclusion

In this study, we characterized drought dynamics in the Nanon (Okpara) basin using the new CMIP6 scenarios (SSP24.5 and SSP58.5). The analysis was conducted over a historical period (1951-2020) and projected (2031-2100). The results suggest a persistence, or even worsening, of drought, even though the projected trends remain insignificant. Furthermore, the models generally agree on an increase in the frequency and duration of drought episodes. Under the SSP585 scenario, the spatial and temporal extent of rainfall deficits could reflect a shift towards more arid climatic conditions. This shift poses a direct threat to the Nanon basin: the foreseeable reduction in surface runoff and increase in evapotranspiration are likely to exacerbate the already water stress in this crystalline bedrock area. Beyond access to drinking water, an increase in the severity of droughts could have a lasting impact on agricultural productivity and food security, which are pillars of the local economy. These results show that there is an urgent need to implement adaptation strategies that explicitly integrate climate constraints. Even if certain change appears small, they should not obscure the reality of the physical processes at play and the vulnerability already observed in the basin. It is therefore imperative that decision-makers incorporate these projections into land use planning and water resource management plans. Finally, future research would benefit from combining these meteorological indices with hydrological models (flows, storage)

in order to more accurately quantify the water available in this context of extreme weather events.

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Conflicts of Interest

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

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