

Research

Projected near-future changes in precipitation extremes over Anambra-Imo River Basin inferred from CMIP6 HighResMIP

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Abstract

The southeastern region of Nigeria is susceptible to flood disasters primarily triggered by extreme precipitation with localized impacts. This study uses the output of High-Resolution Model Intercomparison Project (HighResMIP) of the Coupled Model Intercomparison Project Phase 6 (CMIP6) to investigate seasonal dependent changes in precipitation extremes in the near future (2031–2050) in the Anambra-Imo River Basin, in the southeastern region of Nigeria. Evaluating the models against observation for the 1995–2014 period, it is found that models reproduced the spatial pattern of the observed annual precipitation extremes over the river basin. Results show that in the near future, annual precipitation extremes will be characterized by a robust increase in annual total precipitation amount (PRCPTOT), maximum 5-day precipitation (RX5day), and heavy precipitation (R10mm). The models project a significant increase in PRCPTOT, RX5day, R10mm, and wet-day intensity (SDII) for the June–July–August (JJA) and September–October–November (SON) seasons. The results demonstrate a robust and higher magnitude increase in precipitation extremes during the SON season. Specifically, PRCPTOT, RX5day, R10mm and SDII are projected to increase by up to 46 mm, 24 mm, 1.2 days and 2.4 mm/day, respectively. Whereas during the March–April–May (MAM) season, the HighResMIP suggests that PRCPTOT, R10mm, and SDII will marginally increase over the eastern part of the Anambra-Imo River Basin. Besides, the December–January–February (DJF) season will be characterized by a marginal increase in the precipitation extremes, especially over the southern fringes of the river basin. We note that in the near future, precipitation extremes in the river basin will be characterized by more intense and less frequent precipitation extremes during the JJA and SON, potentially exacerbating flash flooding in the river basin. Hence, the results of this study may be vital for near-term socio-economic planning and policy decisions that will minimize the impact of flood disasters in the Anambra-Imo River Basin.

Keywords Precipitation extremes · CMIP6 · HighResMIP · Anambra-Imo River Basin · Nigeria

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1 Introduction

Precipitation is a key component of the hydrological cycle, which promotes socioeconomic activities and ecological stability in the Anambra-Imo River basin [1, 2]. The river basin is located in Nigeria's southeastern area and is distinguished by the complexity of its hydrological system [3], climate change has aggravated the basin's vulnerability to severe precipitation extremes [4, 5]. Meanwhile, precipitation extremes have maintained their capacity to exert a severe impact on Nigerian river basins in recent years [5, 6]. Torrential precipitation has caused disastrous floods that induced significant damage to the river basin, resulting in massive economic losses [5]. In this regard, the Nigerian Emergency Management Agency estimated that the 2012 flooding claimed over 400 individuals and triggered a 16 million US dollar damage to the economy, whereas the 2022 flood claimed over 600 people and impacted an estimated 3.2 million people [7]. Predicting the impact of potential extreme precipitation is critical for effective river basin management of water resources, infrastructure development, and climate adaptation measures [8–10].

With the increasing concern about the future impact of climate change and its effects on regional hydrology, it is critical to study the potential changes in precipitation extremes in the Anambra-Imo River Basin. In this context, the CMIP6-endorsed High-Resolution Model Intercomparison Program (HighResMIP; [11]) offers an effective tool for investigating the near-term precipitation changes using high-resolution climate projections [12, 13]. The HighResMIP project attempts to enhance our grasp of climate anomalies through the simulation of more precise and reliable projections [14]. Given the incorporation of more detailed topography, land surface processes, and atmospheric dynamics in these models and their high-resolution structure, it presents a special tool for the prediction of regional-scale extreme precipitation events [11, 15].

Several studies have reported the creditable performance of HighResMIP models in simulating mean precipitation and precipitation extremes in different regions across the world [15–19]. However, understanding the potential near-future changes in precipitation extremes will provide the crucial insight required to assist policymakers in establishing essential regulations that will forestall the impact of climate change and its implications on the population [8]. Recent studies have examined the impact of climate change on precipitation extremes in Nigeria [20–23]. For example, Salihu et al. [22], investigated projected changes in precipitation extremes over Nigeria using CMIP5 models and found a substantial increase in maximum 5-day rainfall and heavy rainfall days under high emission scenarios. While Hassan et al. [20], established that mean precipitation will increase by about 2.62%, implying a potential spike in the dangers associated with flooding, particularly in southern Nigeria. Despite the fact that these studies indicate an increase in precipitation in the river basin, Shiru et al. [23], found that drought will be frequent in most parts of the country. At the river basin scale, a consensus on the changes in precipitation extremes has not been reached based on a multi-model ensemble of high-resolution models. Therefore, this study focuses on the multi-model projection of near-term seasonal dependent changes in precipitation extremes in the Anambra-Imo River Basin.

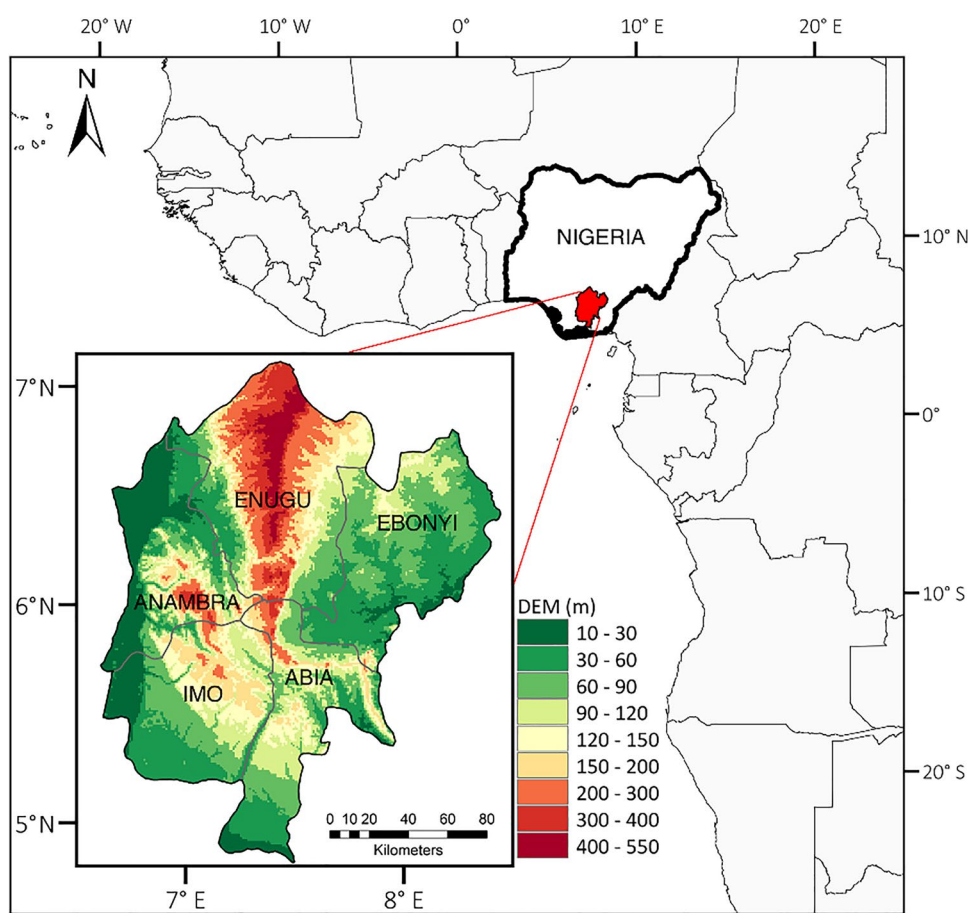
The primary objective of this study is to examine the projected near-future changes in extreme precipitation events using an ensemble of high-resolution models that participated in the HighResMIP project. This study will provide a comprehensive assessment of the uncertainties associated with future precipitation extremes over the Anambra-Imo River Basin. The multi-model approach offers insights into the range of possible outcomes, improving our understanding of the robustness and reliability of the projected changes. The rest of the study is presented as follows, the observation data, CMIP6-endorsed HighResMIP model data, and methods are discussed in Sect. 2, and the results and discussions are summarised in Sect. 3. Finally, Sect. 4 highlights our major conclusions.

2 Study area, data, and methods

2.1 Study area

Anambra-Imo River basin is located in southeastern Nigeria, within the geographic coordinate of Latitude 5–7°N and Longitude 6.5–8.5°E. Figure 1. The river basin is comprised of five States namely Anambra, Abia, Ebonyi, Enugu, and Imo states, with an estimated area of about 28,658.8 km². The tropical humid climate of southern Nigeria is regulated by the West African monsoon circulation, which supplies moisture to the region during the summer months [24, 25]. Annual precipitation in the river basin is characterized by a bimodal precipitation pattern due to the reversal of the

Fig. 1 Elevation map of Anambra-Imo River Basin. The black lines show the geographical locations of the five main sub-regions (Anambra, Abia, Imo, Enugu, and Ebonyi States) in the river basin. The topography is coloured based on a digital elevation map; the green colour indicates the low-level areas, while the red colour indicates higher elevation



monsoon front [24, 25]. The rainy season starts in March–April with the first peak in June–July and a second peak in September [6, 26–29]. In the region, annual total precipitation reaches 2800 mm [1, 5], with surplus rains during the rainy season.

In the region, temperature and humidity remain relatively constant throughout the year in southern Nigeria, and the highest temperatures occur during the pre-monsoon season. Socio-economic activities are striving in the region, with massive infrastructural development for the growing population. However, the landscape of the river basin makes it vulnerable to flood disasters [5, 30] induced by torrential precipitation [6].

2.2 Data and method

2.2.1 Observational and CMIP6 HighResMIP data

Daily precipitation outputs from fifteen High-Resolution Model Intercomparison Project (HighResMIP; [11]) models were used in this study. The dataset consists of outputs of AMIP-style experiments, namely; highresSST-present and highresSST-future under the CMIP6 model experiment [31], designed to promote high-resolution simulations. The historical simulations run from 1950 to 2014, whereas the future climate simulations run from 2015 to 2050 period. Notably, near-future simulations are forced by high emission Shared Socioeconomic Pathway (SSP5-8.5; [32]). In this study, we set the baseline to cover the 1995–2014 historical period and 2031–2050 for the near-future period. The performance of the models was evaluated against an ensemble of two high-resolution daily gridded precipitation products from the Climate Hazard Group InfraRed Precipitation (CHIRPS version 2; [33]) and daily precipitation from Multi-Source Weighted-Ensemble Precipitation (MSWEP) dataset version 2 [34]. The observational datasets are produced at a higher spatial resolution of $0.05^\circ \times 0.05^\circ$ and $0.1^\circ \times 0.1^\circ$ for CHIRPS and MSWEP datasets, respectively. These observational datasets are acclaimed for

Table 1 Basic description of the 15 CMIP6 HighResMIP models used in this study

S/N	Modeling organizations	Model name	Atmospheric resolution	References for HighResMIP models
1	Euro-Mediterranean Center on Climate Change (Italy)	CMCC-CM2-HR4	1.00° × 1.00°	[38]
2		CMCC-CM2-VHR4	0.25° × 0.25°	
3	EC-EARTH consortium, (Sweden)	EC-Earth3P-HR	0.35° × 0.35°	[20]
4	Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences (CAS), China	FGOALS-f3-H	0.25° × 0.25°	[39]
5		FGOALS-f3-L	1.00° × 1.25°	
6	Geophysical Fluid Dynamics Laboratory/NOAA (U.S.)	GFDL-CM4C192	0.50° × 0.50°	[40]
7	The UK Met Office Hadley Centre for Climate Change (UK)	HadGEM3-GC31-MM	0.23° × 0.35°	[41]
8	Geophysical Fluid Dynamics Laboratory/NOAA (U.S.)	HiRAM-SIT-HR	0.25° × 0.25°	[42]
9		HiRAM-SIT-LR	0.50° × 0.50°	
10	Max Planck Institute MPI, (Germany)	MPI-ESM1-2-HR	0.94° × 0.94°	[43]
11		MPI-ESM1-2-XR	0.47° × 0.47°	
12	Meteorological Research Institute (Japan)	MRI-AGCM3-2-H	0.56° × 0.56°	[44]
13		MRI-AGCM3-2-S	0.19° × 0.19°	
14	Japan Agency for Marine-Earth Science and Technology (Japan)	NICAM16-7S	0.56° × 0.56°	[46]
15		NICAM16-8S	0.28° × 0.28°	

their robustness in representing precipitation over West Africa [35–37]. Both observational data and model outputs are aggregated into the same resolution (0.25° × 0.25°) for easy comparison. An ensemble of both the CHIRPS and MSWEP datasets was constructed hereafter OBS and used as reference data in this study (Table 1).

2.2.2 Extreme precipitation indices and model validation metrics

This study uses extreme climate indices described by the Expert Team on Climate Change Detection and Indices (ETC-CDI; [46]) to investigate future changes in precipitation extremes in the River Basin. The extreme precipitation indices are listed in Table 2 and have been widely applied to study changes in future precipitation extremes around the globe [6, 8, 9, 47–50]. In particular, this study uses the indices that mainly represent the intensity and frequency of extreme precipitation. These indices are employed herein to study the seasonally dependent near-future changes in precipitation extremes over the Anambra-Imo River Basin.

Furthermore, we used statistical evaluation metrics such as mean bias (MB), the normalized root mean square error (NRMSE) and the Pattern correlation coefficient (PCC). The mean bias for each model is calculated with respect to the observations as follows; $bias = \frac{(\bar{x} - \bar{y})}{\bar{y}}$ where $\mathbf{x}$ and $\mathbf{y}$ denote the map of each CMIP6 HighResMIP model and the observed field, respectively, and the over-bars (̄) indicate their means. The MB provides information on the difference in magnitude between observation and models.

The PCC between the model and observation is defined as follows.

$$PCC = \frac{1}{\sigma_x \sigma_y} \left[\frac{1}{N} \sum_{i=1}^N (x_i - \bar{x}) (y_i - \bar{y}) \right]$$

Sillmann et al. [51], used the normalized root-mean-square error (NRMSE), among other metrics to evaluate the performance of climate models. The NRMSE is also computed for the extreme precipitation indices following the same approach.

$$NRMSE = \frac{\sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - y_i)^2}}{\frac{1}{N} \sum_{i=1}^N y_i}$$

Table 2 Description and unit of extreme precipitation indices analyzed

ID	Name	Description	Units
PRCPTOT	Total wet-day precipitation amount	Total precipitation in wet days ($P \geq 1$ mm), defined as P_{ij} representing daily precipitation amount on day i in a period j . If the i denote the number of days in j , then, $PRCPTOT_j = \sum_{i=1}^j P_{ij}$	mm
RX5day	Maximum consecutive 5-day precipitation	Maximum rainfall sum for 5-day interval. Let P_{ij} be the precipitation amount for the 5-day interval i ending in period j . The maximum 5-day values are estimated for the period as: $RX5day_j = \max(P_{ij})$	mm
R10mm	Heavy precipitation days	Number of very heavy precipitation days ($P \geq 10$ mm). That is, let P_{ij} be the daily precipitation amount where $P_{ij} \geq 10$ mm	days
SDII	Wet-day intensity	Average precipitation from wet-days. This can be defined as P_{wj} be the daily precipitation amount on wet days, w ($P \geq 1$ mm) in period j . If w represents number of wet days in j , then $SDII_j = \frac{\sum_{w=1}^w P_{wj}}{w}$	mm/day
CWD	wet spells	Maximum number of consecutive dry days ($P \geq 1$ mm). Let P_{ij} be the daily precipitation amount on day i in period j . Count the largest consecutive days where $P_{ij} \geq 1$ mm	days
CDD	dry spells	Maximum number of consecutive dry days ($P \leq 1$ mm). Let P_{ij} be the daily precipitation amount on day i in period j . Count the largest consecutive days where $P_{ij} \leq 1$ mm	days

where N is the number of grid cells, x_i and y_i are the variable values to the i th grid cell of the models and the observed field, respectively. Whereas the $\bar{x}$ and $\bar{y}$ their mean values, φ_x and φ_y their standard deviations. Both NRMSE and PCC provide information on the model performance.

2.2.3 Analysis of the projected future changes

The projected near-future changes in precipitation extremes are quantified by the relative change between the projection (2031–2050) period and the baseline period (1995–2014). The future projections are considered for four seasons to obtain seasonal-dependent changes in precipitation extremes for the river basin. Moreover, we consider the projected changes robust when the ratio of the mean to the standard deviation of the climate change signals is equal to or larger than one. As such, when at least 70% of the models agree to defined metric, we consider the sign of the projected change in the precipitation extremes robust. We determined statistically significant projected change based on student's t test at 95% confidence level.

3 Results and discussions

3.1 Performance of the CMIP6 HighResMIP models in representing observed precipitation extremes

Figure 2 illustrates the spatial distribution of observed annual mean precipitation extremes, multi-model ensemble mean (MME) of HighResMIP models as well as their mean bias relative to the observation. The observation shows a high and low magnitude of annual total precipitation (PRCPTOT) over the lower reaches and upper part of the Anambra-Imo River basin, respectively, during the 1995–2014 period. Similarly, annual heavy precipitation days (R10mm), maximum 5-day precipitation (RX5day), wet-day intensity (SDII), and wet spells (CWD) follow the same pattern in the river basin (Fig. 2a–e). Conversely, it is found that the dry spell is more prevalent over the part of the river basin encompassing the

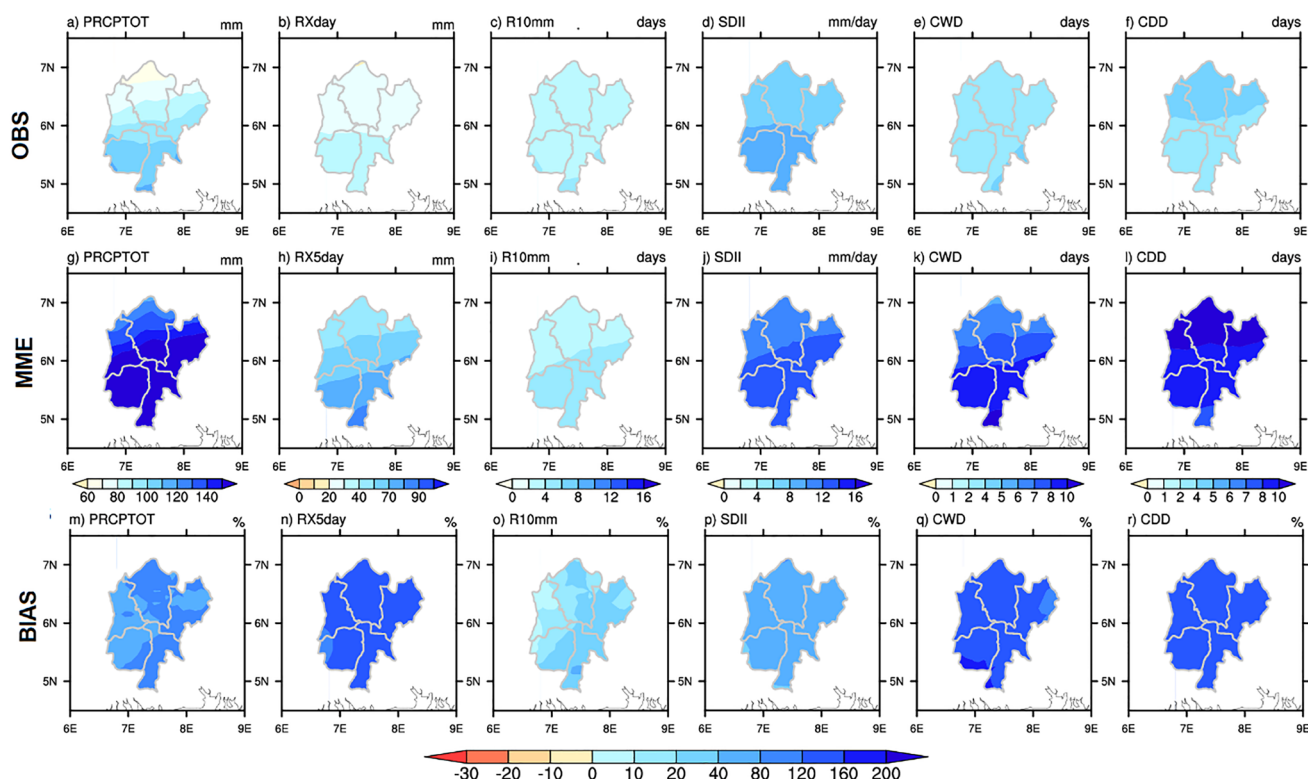


Fig. 2 Spatial pattern of Annual (ANN) precipitation extremes, PRCPTOT, RX5day, R10mm, SDII, CWD, and CDD. **a–f** ensemble of both CHIRPS and MSWEP, observation (OBS), **g–l** Multi-model Ensemble Mean (MME), and **m–r** percentage bias between the MME of HighResMIP models relative to the OBS for the present-day (1995–2014) period

northern extremities of Anambra, Enugu, and Ebonyi states (Fig. 2f). Interestingly, the MME reproduced the observed annual precipitation extremes (Fig. 2g–l), albeit indications that the models overestimated the magnitude of the observed annual precipitation extremes. The models overestimated RX5day, PRCPTOT, R10mm, CWD, SDII, and CDD (Fig. 2m–r). Specifically, it is found that the models overestimated PRCPTOT, R10mm, and SDII by 60%, 10%, and 40%, respectively, whereas the magnitude of the mean bias is about 80% for CWD, RX5day, and CDD during the 1995–2014 period. The foregoing indicates that biases known to exist in GCMs also persist in the HighResMIP simulation of precipitation extremes. The biases in the HighResMIP simulated precipitation extremes are perhaps related to the resolution of the models. Although the HighResMIP is acclaimed for its high resolution, nearly half of the models used in this study have a grid spacing larger than 0.5° , affecting the model's performance in the river basin.

Furthermore, we examine the performance of the models by considering the pattern correlation coefficients (PCC) and normalized root mean square errors (NRMSE) for the 35 grid cells within the river basin (Fig. 3a, b). Results show that the models creditably reproduced the spatial pattern of the annual precipitation extremes with $PCC > 0.8$ for MME. Particularly, FGOALS-f3-L, CMCC-CM2-HR4, HadGEM3-GC31-MM, MPI-ESM1-2-XR, NICAM16-7S, and NICAM16-8S performed better than other models with $PCC > 0.8$ for all the extreme precipitation indices. Meanwhile, some of the models show

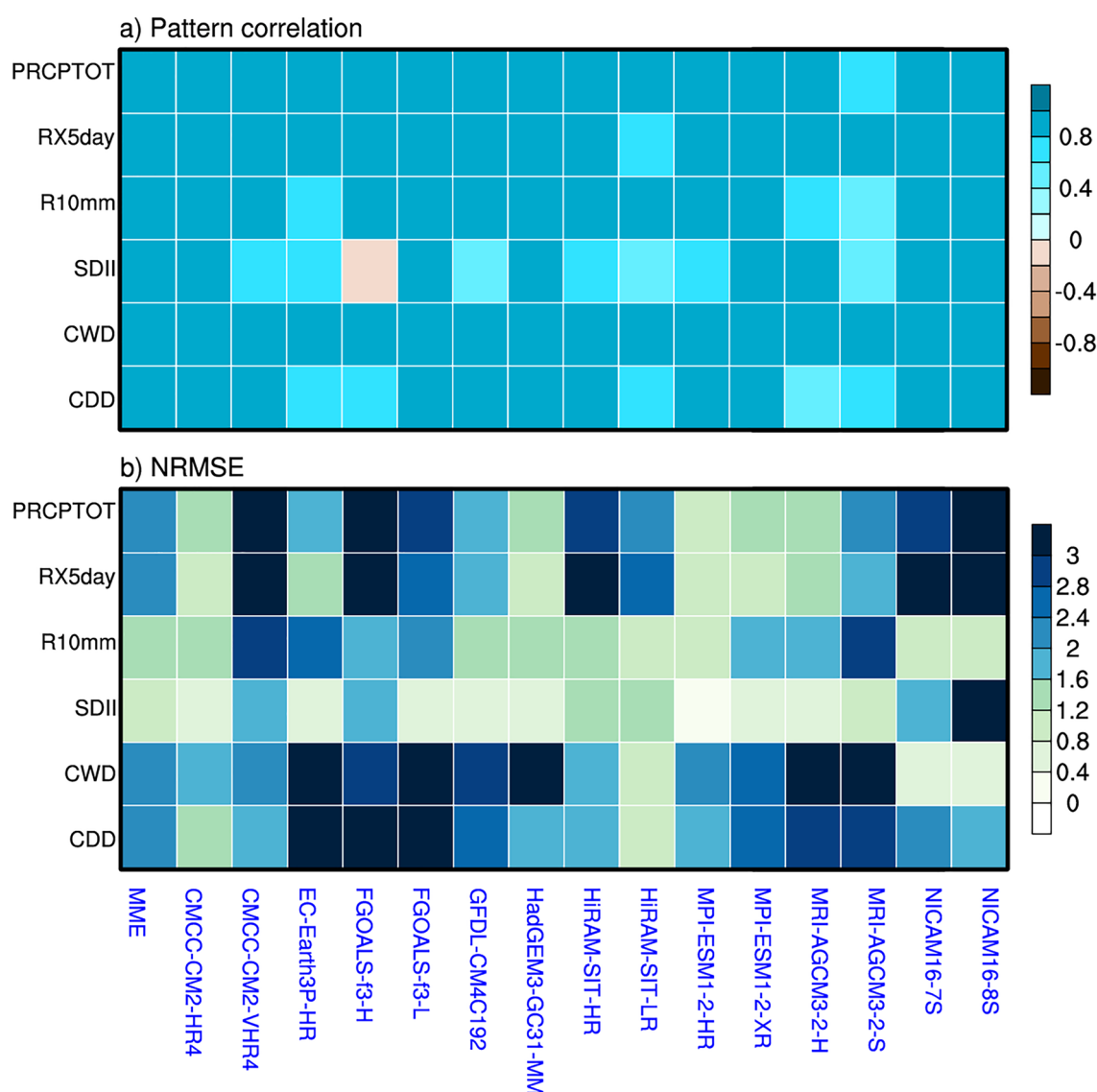


Fig. 3 Portrait diagram of spatially averaged of mean annual precipitation extremes relative to observation for the present-day (1995–2014) period **a** and **b** normalized root mean square errors

lesser performance in reproducing the spatial pattern of SDII over the river basin, with $PCC \leq 0.4$. It is also found that the models simulated the climatologies of annual mean precipitation extremes with minimum errors by CMCC-CM2-HR4, GFDL-CM4C192, HadGEM3-GC31-MM, HiRAM-SIT-HR, MPI-ESM1-2-XR, MPI-ESM1-2-HR, and NICAM16-7S (Fig. 3b). Meanwhile, the NRMSEs are consistently large for CWD and CDD, this is perhaps linked to the inability of the models in simulating the number of rainy days [50] and resolving the complex terrain over the Guinea coast [52]. Generally, the models captured the observed features of annual mean precipitation extremes over the Anambra-Imo river basin during the 1995–2014 period.

3.2 Annual and seasonal dependent changes in precipitation extremes

Figure 4 depicts the spatial pattern of the projected changes in annual mean precipitation extremes during 2031–2050 compared to 1995–2014. The multi-model projection of near-term precipitation extremes indicates an increase in annual total precipitation (PRCPTOT), maximum 5-day precipitation (RX5day), and heavy precipitation days (R10mm); the results further indicate that the high-resolution models project shows a robust increase in extreme precipitation (Fig. 4a, c). Meanwhile, the HighResMIP models project no increase in annual wet-day intensity (SDII), whereas a non-significant increase is projected for wet spells over Enugu, Anambra, Ebonyi, and Abia states (Fig. 4d, e). Besides, Fig. 4f shows a non-significant decrease in dry spells over the river basin. The foregoing indicates that in the near-future, the annual increase in PRCPTOT is mostly associated with the projected increase in precipitation intensity rather than its frequency. The projected increase in RX5day is consistent with the results obtained by Salihu et al. [22], for the Guinea Coast region of Nigeria based on CMIP5 models. Besides, Salihu et al. [22], reported a significant increase in RX5day during

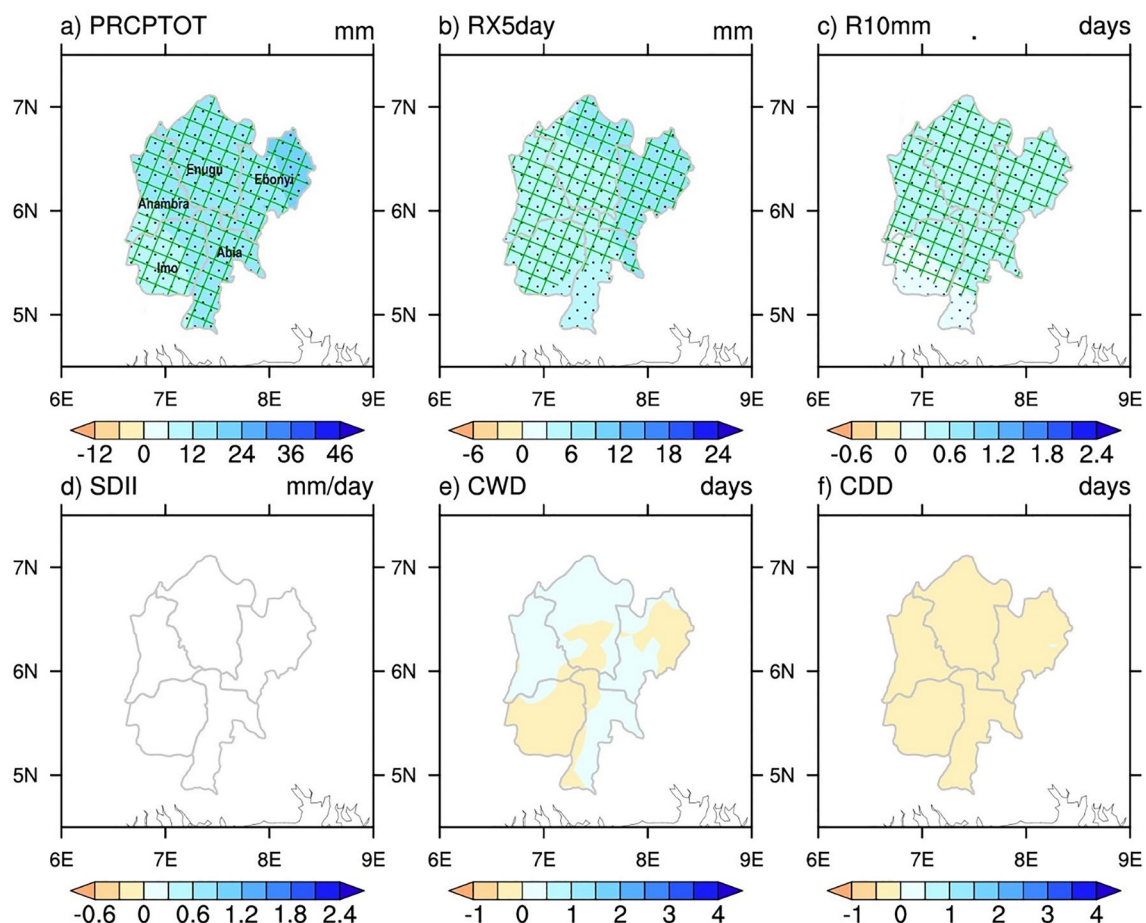


Fig. 4 Spatial pattern of the projected changes in Annual (ANN) precipitation extremes based on the SSP5-8.5 scenario for the near future (2031–2050) relative to the 1995–2014 period. **a** PRCPTOT, **b** RX5day, **c** R10mm, **d** SDII, **e** CWD and **f** CDD. The black stippling denotes statistically significant changes at the 95% confidence level, while areas with slanted green boxes indicate where at least 70% of models agree with the sign of projected future changes

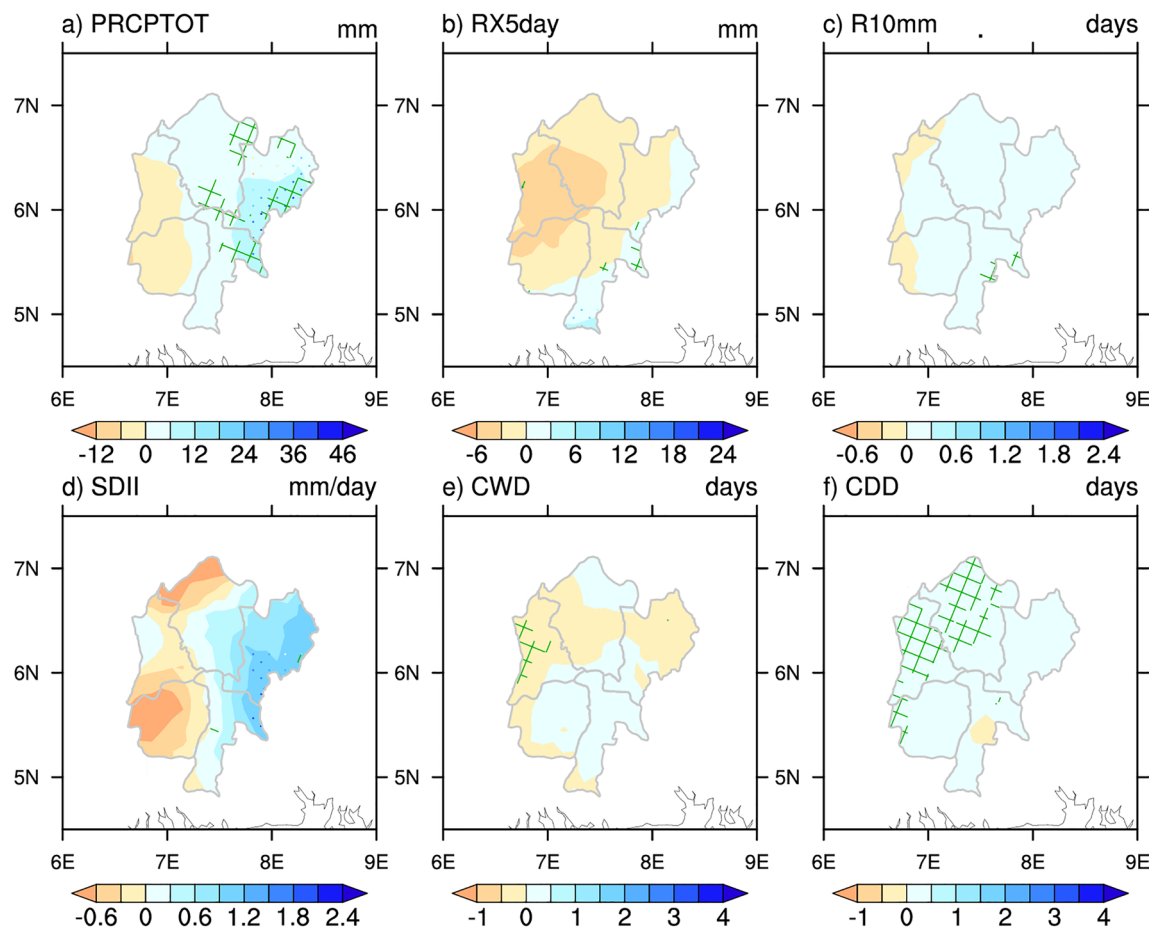


Fig. 5 Spatial pattern of the projected changes in March–April–May (MAM) precipitation extremes based on the SSP5-8.5 scenario for the near future (2031–2050) relative to the 1995–2014 period. **a** PRCPTOT, **b** RX5day, **c** R10mm, **d** SDII, **e** CWD and **f** CDD. The black stippling denotes statistically significant changes at the 95% confidence level, while areas with slanted green boxes indicate where at least 70% of models agree with the sign of projected future changes

the present-day period; this suggests that future increases in the precipitation extremes will trigger more disaster flood disasters in the region. Diba et al. [53], reported that the intensification of precipitation over West Africa is related to the warm extremes. According to the Clausius–Clapeyron equation, global warming has accelerated the local water cycle and increased advected moisture, leading to the intensification in precipitation extremes [54].

Next, we discuss the projected changes in precipitation extremes at seasonal timescales. Figure 5 shows the projected changes in March–April–May (MAM) precipitation extremes over the Anambra-Imo River basin. Figure 5a shows that the western parts of the river basin, specifically Anambra and Imo states, will experience a non-significant decrease in PRCPTOT during the spring season while other parts of the river basin will record a non-significant increase in PRCPTOT. A similar pattern will be recorded for RX5day, R10mm, SDII, and CWD (Fig. 5a–e). However, it should be noted that most parts of Enugu, Ebonyi, and Abia states will experience an increase in precipitation intensity (Fig. 5c, d), while a dry spell will increase during the MAM season (Fig. 5f).

Interestingly, the models project a robust and statistically significant increase in summer (JJA) precipitation extremes over the river basin (Fig. 6a–d). The increase in summer PRCPTOT is mostly linked to intensity-related extremes viz RX5day and SDII, especially over Enugu, Ebonyi, and Abia states. Although the projected increase in R10mm and CWD is not statistically significant, the decrease in CDD suggests that the river basin will experience an increase in intensity and less frequent summer precipitation extremes. This is consistent with the findings by Dike, Lin and Ibe [6] for the sub-region in recent decades.

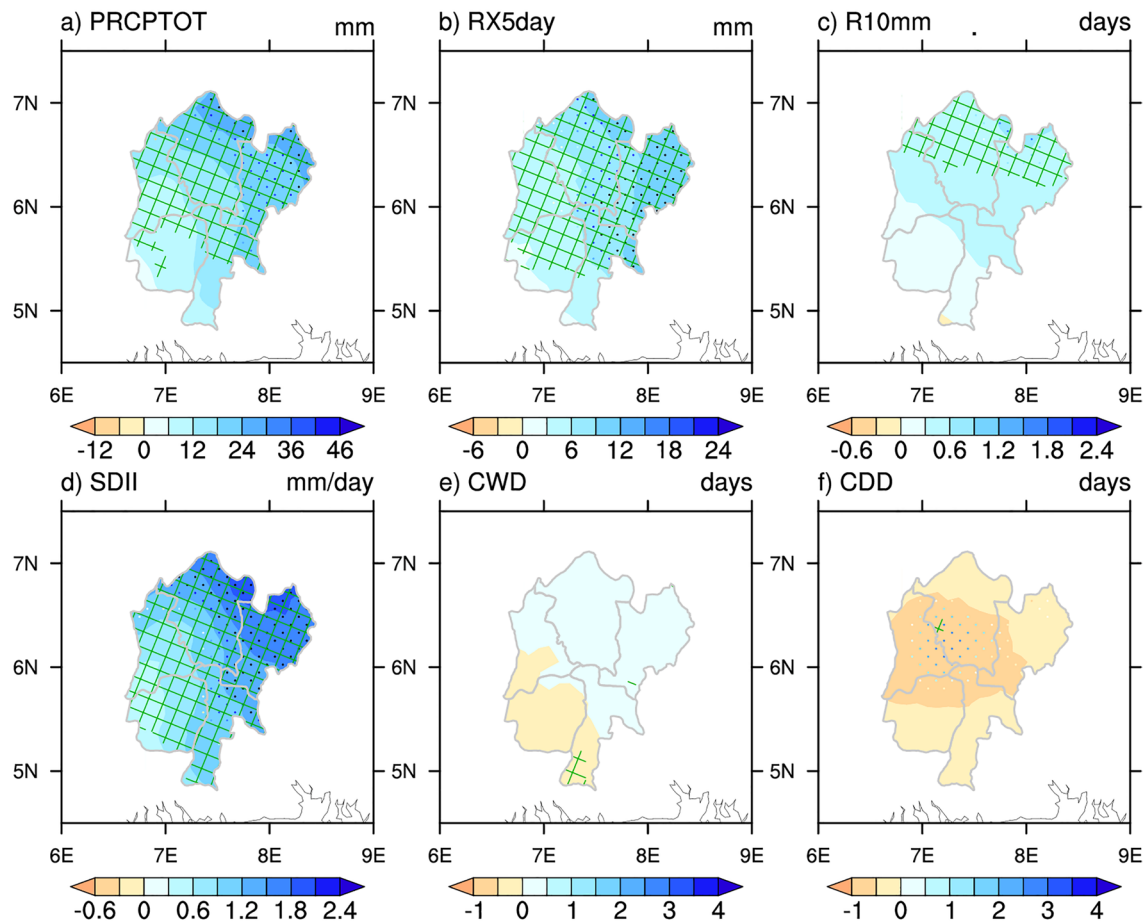


Fig. 6 Spatial pattern of the projected changes in June–July–August (JJA) precipitation extremes based on the SSP5-8.5 scenario for the near future (2031–2050) relative to the 1995–2014 period. **a** PRCPTOT, **b** RX5day, **c** R10mm, **d** SDII, **e** CWD and **f** CDD. The black stippling denotes statistically significant changes at the 95% confidence level, while areas with slanted green boxes indicate where at least 70% of models agree with the sign of projected future changes

Furthermore, the spatial distribution of the projected changes in September–October–November shows that in the near-future, the river basin will experience a greater magnitude of increase in precipitation extremes (Fig. 7). The models project a wide-spread, robust, and significant increase in PRCPTOT, RX5day, R10mm, and SDII (Fig. 7a–d). Essentially, the state in the northern fringes of the river basin (Anambra, Enugu, and Ebonyi) will record a notable increase in the precipitation extremes. The precipitation is projected to increase by up to 46 mm, 1.2 days, 24 mm, and 2.4 mm/day for PRCPTOT, R10mm, RX5day, and SDII, respectively. It is noteworthy to state that the projected changes are robust as more than 70% of the models herein considered agree with the projected significant increase in SON precipitation extremes over the river basin. This increases the vulnerability of the river basin to flood disasters in the future [7]. Meanwhile, the projected change in CWD shows a non-homogenous increase (decrease) in wet spells, whereas the projected decrease in CDD is widespread (Fig. 7e, f). As with the findings for the summer season, the projected increase in the extremes is also linked to the increase in the intensity and less frequent precipitation extremes [6, 50, 55]. Both the JJA and SON seasons will experience a significant and severe increase in precipitation extremes, with higher magnitude recorded in the SON season. Recently, Hassan et al. [20], used the downscaled CMIP5 model to demonstrate that mean precipitation will increase significantly in July–August–September in most parts of the Niger-Delta region. This indicates that water vapour will be more abundant during the July–August–September season in the near future. Meanwhile, previous studies have illustrated that future precipitation in the region will be characterized by intense precipitation extremes and highlighted the propensity of later wet seasons with more intense precipitation under future climate change [35, 56].

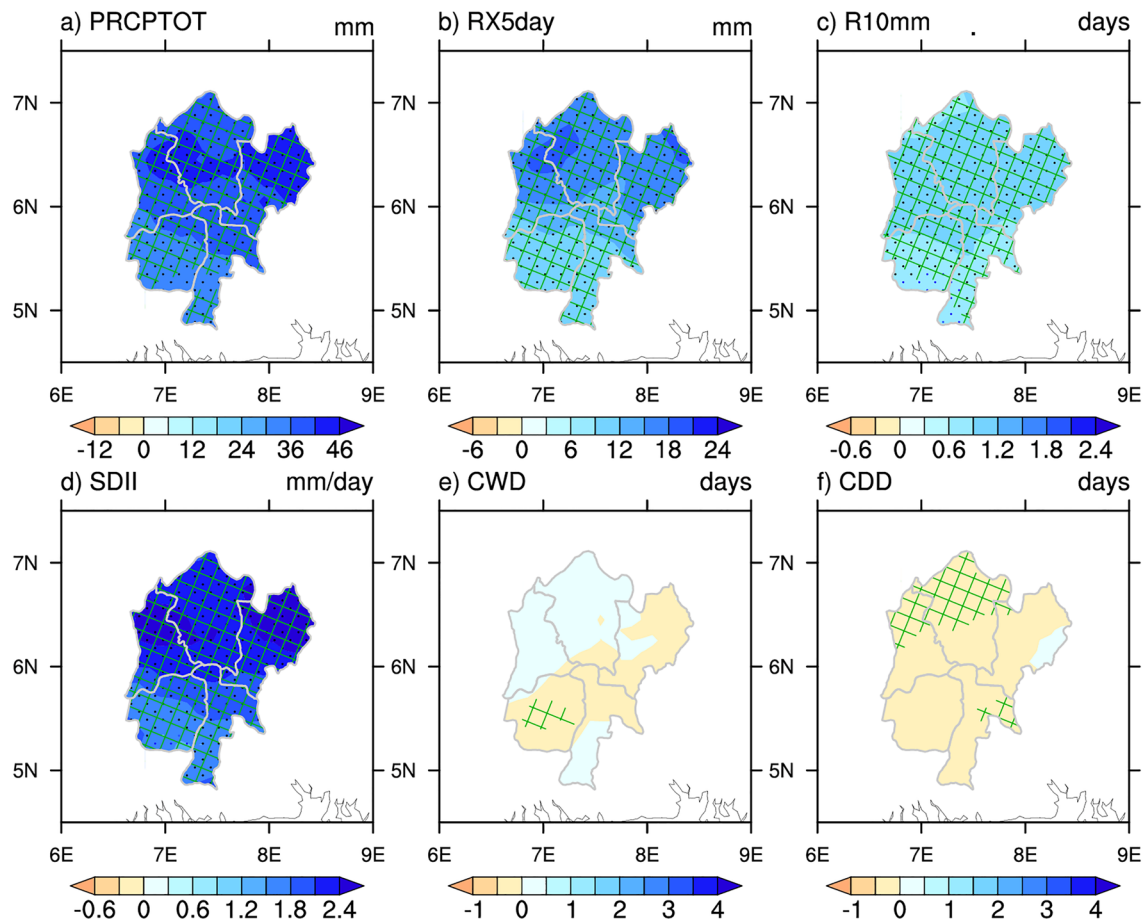


Fig. 7 Spatial pattern of the projected changes in September–October–November (SON) precipitation extremes based on the SSP5-8.5 scenario for the near future (2031–2050) relative to the 1995–2014 period. **a** PRCPTOT, **b** RX5day, **c** R10mm, **d** SDII, **e** CWD and **f** CDD. The black stippling denotes statistically significant changes at the 95% confidence level, while areas with slanted green boxes indicate where at least 70% of models agree with the sign of projected future changes

Finally, Fig. 8 shows that during the December–January–February (DJF) season, PRCPTOT, RX5day, R10mm, and CDD will increase slightly. Specifically, Fig. 8a–c shows that winter PRCPTOT, RX5day, and R10mm will increase in most parts of the river basin. No notable change is projected for SDII for the DJF season over the river basin (Fig. 8d). However, RX5day will increase significantly by 10 mm over most parts of Imo state (Fig. 8b), while CWD will increase (decrease) by 1 day relative to the present-day levels in the southern (northern) parts of the river basin. Remarkably, CDD will increase slightly in the river basin as well, suggesting that both wet and dry precipitation extremes will increase in the future during the DJF season (Fig. 8a–f). More so, the increase in the precipitation extremes is projected to extend to the DJF season, which indicates a wet winter season in the river basin under SSP5-8.5 emission scenario. Studies have indicated the changes in precipitation seasonality over the region, especially under high-emission scenarios [35, 56, 57].

Meanwhile, the projected increase in the seasonal precipitation extremes, especially during the JJA, SON, and DJF seasons, contributes significantly to the projected annual precipitation extremes in the near future. The significant increase in the intensity-related precipitation extremes implies a potential risk of intensified extreme precipitation and the associated flood disasters [5, 8], which would increase the vulnerability of key socioeconomic sectors, such as agriculture and water management under SSP5-8.5 emission scenario [12, 48, 58].

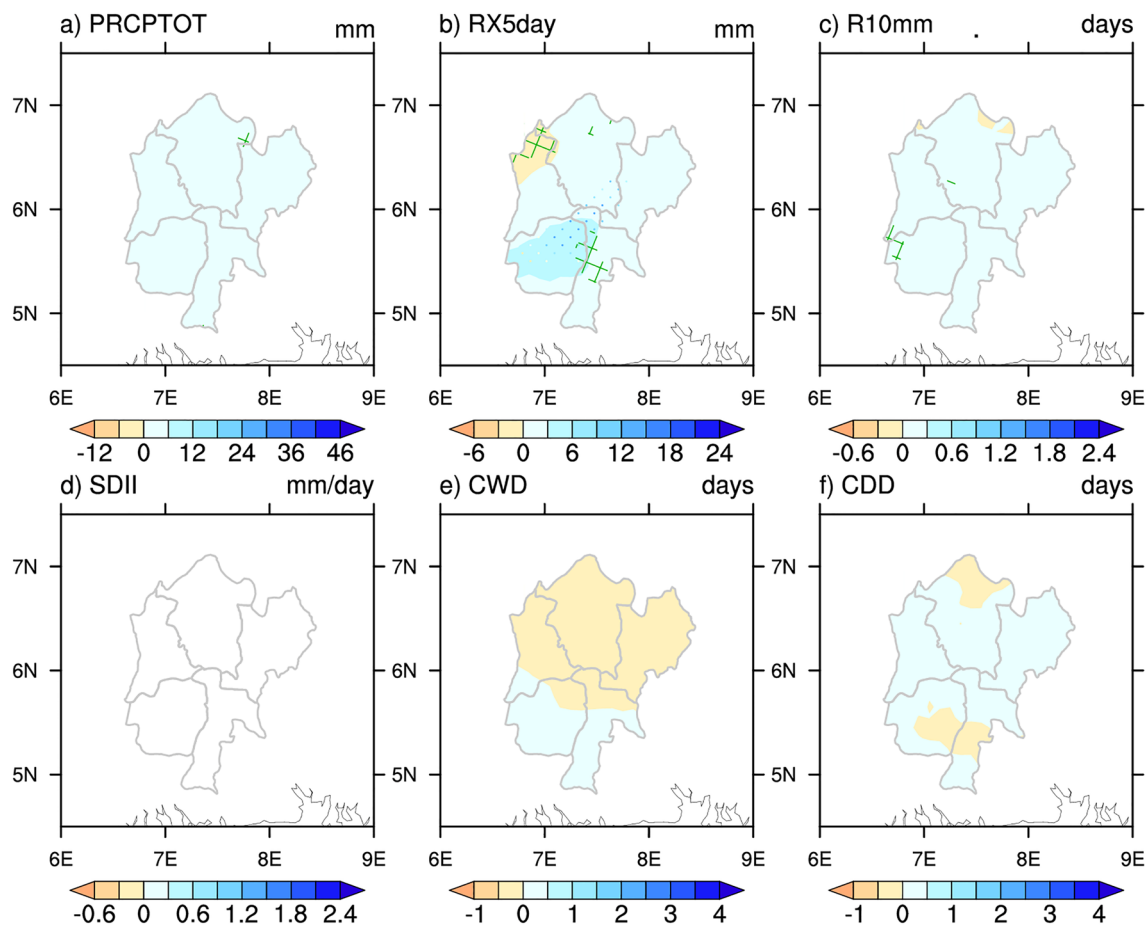


Fig. 8 Spatial pattern of the projected changes in December–January–February (DJF) precipitation extremes based on the SSP5-8.5 scenario for the near future (2031–2050) relative to the 1995–2014 period. **a** PRCPTOT, **b** RX5day, **c** R10mm, **d** SDII, **e** CWD and **f** CDD. The black stippling denotes statistically significant changes at the 95% confidence level, while areas with slanted green boxes indicate where at least 70% of models agree with the sign of projected future changes

4 Conclusion

This study investigates the projected future changes in seasonal precipitation extremes over Anambra-Imo River basin in southeastern Nigeria. Firstly, fifteen AMIP-type historical simulations of the CMIP6 HighResMIP were evaluated against an ensemble of two gridded observation products to assess the ability of the models to reproduce the observed precipitation extremes. The results show that the models reproduced the spatial distribution of the observed precipitation extremes. Specifically, CMCC-CM2-HR4, FGOALS-f3-L, HadGEM3-GC31-MM, MPI-ESM1-2-XR, NICAM16-7S, and NICAM16-8S performed better than other models with $PCC > 0.8$ for all the extreme precipitation indices. Consistent with the results obtained by Ajibola et al. [17], for the entire West Africa region. Although the models seemingly overestimated the precipitation extremes, it is also found that the models simulated the climatologies of annual mean precipitation extremes with minimum errors. Specifically, CMCC-CM2-HR4, GFDL-CM4C192, HadGEM3-GC31-MM, HiRAM-SIT-HR, MPI-ESM1-2-XR, MPI-ESM1-2-HR, and NICAM16-7S simulated the precipitation extreme with minimal errors. However, the NRMSEs are consistently large for CWD and CDD; this is perhaps linked to the inability of the models to simulate the number of rainy days over the river basin.

Furthermore, the HighResMIP models project a significant increase in annual total wet-day precipitation (PRCPTOT) for 2031–2050 relative to the 1995–2014 period under the SSP5-8.5 emission scenario. The projected increase in PRCPTOT is mostly linked to the increase in maximum 5-day precipitation (RX5day) and heavy precipitation (R10mm).

Consistent with the projected increase in these precipitation extremes indices, the future total annual dry spells will decrease in the river basin. It was also found that during the MAM season, most parts of Enugu, Ebonyi, and Abia will experience an increase in R10mm and SDII, leading to an increase in MAM PRCPTOT in these aforementioned areas. However, it should be noted that the projected increase in these extreme precipitation indices is not statistically significant and has notable uncertainty. Meanwhile, the models project an increase in dry spells during the MAM season, which indicates a drier spring over the river basin in the near-future.

Nonetheless, the HighResMIP models project a notable increase in summer precipitation extremes. Results further demonstrate that summer PRCPTOT, R10mm, RX5day, and SDII will increase in most parts of the river basin, especially over the northern reaches of the Anambra-Imo River Basin encompassing Enugu, Ebonyi and Abia state. The spatial distribution of consecutive wet days shows that wet spells will also increase over these areas, whereas dry spells will decrease. Relatedly, precipitation extremes during the September–October–November (SON) will be characterized by a similar pattern projected for the summer season but with a higher magnitude. This is an indication that the river basin will experience an increase in intensity and less frequent summer precipitation extremes in the near future, especially during the SON season. Similar results have also been obtained for other river basins worldwide [9, 12, 13]. We note that in the near future, the SON will be characterized by a higher magnitude increase in precipitation extremes, which will potentially exacerbate flash flooding in the river basin during the season. We highlight the need for a detailed analysis of the potential physical mechanisms driving the projected changes in the precipitation extremes in the river basin.

For the December–January–February (DJF) season, the models project a marginal increase in winter precipitation extremes like RX5day and R10mm, with a higher magnitude of RX5day over the Imo state. This suggests that the fundamentally dry season will be wetter in the near future. Additionally, the river basin will experience more intense precipitation during the JJA and SON seasons, contributing significantly to the projected increase in annual total precipitation in the river basin. It is also important to note that in the near future, precipitation extremes in the river basin will be characterized by more intense and less frequent precipitation extremes, potentially exacerbating flash flooding in the vulnerable river basin [3]. Notably, we presented the future changes in precipitation extremes in the river basin without analyzing the mechanism associated with these projected changes. Therefore, further analysis is needed to identify the circulation features associated with these projected changes. Besides, one notable limitation of this study is the horizontal resolution of some of the HighResMIP models used in this study. The spatial resolutions of the models are still coarse, considering the size of the river basin. Therefore, future studies over the river basin should consider higher resolution regionally downscaled models. Despite these limitations, the inferences drawn from this study will provide a vital resource needed for near-term socio-economic planning and adaptation measures that will minimize the impact of flood disasters in the Anambra-Imo River Basin.

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Author contributions ICC: Conceptualization; data curation; formal analysis; writing – original draft; writing – review and editing. DVN: Conceptualization; data curation; formal analysis; funding acquisition; methodology; writing – original draft; writing – review and editing. SKI and MJJ: Supervision; writing – original draft; writing – review and editing. IAA and ACM: Writing – review and editing.

Data availability The data that support the findings of this study are openly available at the following sources: HighResMIP: <https://esgf-node.llnl.gov/projects/cmip6/>. CHIRPS: http://data.chc.ucsb.edu/products/CHIRPS-2.0/global_daily/netcdf/p25/. MSWEP: <https://www.gloh2o.org/mswep/>.

Declarations

Competing interests No competing interests. All the authors agree with the content of this study.

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References

1. Ogungbenro SB, Morakinyo TE. Rainfall distribution and change detection across climatic zones in Nigeria. *Weather Climate Extremes*. 2014;5:6:1–6. <https://doi.org/10.1016/j.wace.2014.10.002>.
2. Ogunrinde AT, Oguntunde PG, Akinwumiju AS, Fasinmirin JT. Analysis of recent changes in rainfall and drought indices in Nigeria, 1981–2015. *Hydrol Sci J*. 2019;64:1755–68. <https://doi.org/10.1080/02626667.2019.1673396>.
3. Chukwuma EC, Okonkwo CC, Ojediran JO, Anizoba DC, Ubah JI, Nwachukwu CP. A GIS based flood vulnerability modelling of Anambra State using an integrated IVFRN-DEMATEL-ANP model. *Heliyon*. 2021;7:e08048. <https://doi.org/10.1016/j.heliyon.2021.e08048>.
4. Ahuchaogu E, Gift U, Ojinnaka O, Baywood C. Flood hazard analysis and damage assessment of 2012 flood in anambra state using GIS and remote sensing approach. *Am J Geographic Inform Syst*. 2022. <https://doi.org/10.5923/j.ajgis.20150401.03>.
5. Ekwueme BN. Quantification of effects of climate change on flood in tropical river basins. *Cogent Eng*. 2021;8:1986967. <https://doi.org/10.1080/23311916.2021.1986967>.
6. Dike VN, Lin Z-H, Ibe CC. Intensification of summer rainfall extremes over Nigeria during recent decades. *Atmosphere*. 2020. <https://doi.org/10.3390/atmos11101084>.
7. Echendu AJ. The impact of flooding on Nigeria's sustainable development goals (SDGs). *Ecosyst Health Sustain*. 2020;6:1791735. <https://doi.org/10.1080/20964129.2020.1791735>.
8. Dike VN, Lin Z-H, Wu C, Ibe CC. Chapter 3—advances in weather and climate extremes. In: Ongoma V, Tabari H, editors. *Climate impacts on extreme weather*. Amsterdam: Elsevier; 2022. p. 49–63.
9. Li C, Dike VN, Lin Z, Gao X. Projected changes in precipitation extremes over Jiulongjiang river basin in coastal southeast China. *Front Earth Sci*. 2021. <https://doi.org/10.3389/feart.2021.771592>.
10. Ologunorisa TE. An assessment of flood vulnerability zones in the Niger Delta, Nigeria. *Int J Environ Stud*. 2007;61:31–8. <https://doi.org/10.1080/0020723032000130061>.
11. Haarsma RJ, Roberts MJ, Vidale PL, Senior CA, Bellucci A, Bao Q, Chang P, Corti S, Fučkar NS, Guemas V, et al. High resolution model inter-comparison project (HighResMIP v1.0) for CMIP6. *Geosci Model Dev*. 2016;9:4185–208. <https://doi.org/10.5194/gmd-9-4185-2016>.
12. Avila-Diaz A, Torres RR, Zuluaga CF, Cerón WL, Oliveira L, Benezoli V, Rivera IA, Marengo JA, Wilson AB, Medeiros F. Current and future climate extremes over latin america and caribbean: assessing earth system models from high resolution model intercomparison project (HighResMIP). *Earth Syst Environ*. 2023;7:99–130. <https://doi.org/10.1007/s41748-022-00337-7>.
13. Liang J, Tan ML, Catto JL, Hawcroft MK, Hodges KI, Haywood JM. Projected near-term changes in monsoon precipitation over Peninsular Malaysia in the HighResMIP multi-model ensembles. *Clim Dyn*. 2023;60:1151–71. <https://doi.org/10.1007/s00382-022-06363-5>.
14. Haarsma R, Acosta M, Bakhshi R, Bretonnière PA, Caron LP, Castrillo M, Corti S, Davini P, Exarchou E, Fabiano F, et al. HighResMIP versions of EC-Earth: EC-Earth3P and EC-Earth3P-HR—description, model computational performance and basic validation. *Geosci Model Dev*. 2020;13:3507–27. <https://doi.org/10.5194/gmd-13-3507-2020>.
15. Akhter S, Holloway CE, Hodges K, Vanniere B. How well do high-resolution global climate models (GCMs) simulate tropical cyclones in the Bay of Bengal? *Clim Dyn*. 2023. <https://doi.org/10.1007/s00382-023-06745-3>.
16. Ajibola FO, Zhou B, Shahid S, Ali MA. Performance of CMIP6 HighResMIP simulations on west African drought. *Front Earth Sci*. 2022. <https://doi.org/10.3389/feart.2022.925358>.
17. Ajibola FO, Zhou B, Tchalim Gnitou G, Onyejuruwa A. Evaluation of the performance of CMIP6 HighResMIP on West African Precipitation. *Atmosphere*. 2020. <https://doi.org/10.3390/atmos11101053>.
18. Mishra AK, Jangir B, Strobach E. Does increasing climate model horizontal resolution be beneficial for the mediterranean region?: Multi-model evaluation framework for high-resolution model intercomparison project. *J Geophys Res Atmospheres*. 2023;128:e2022JD037812. <https://doi.org/10.1029/2022JD037812>.
19. You Y, Ting M. Improved performance of high-resolution climate models in simulating Asian monsoon rainfall extremes. *Geophys Res Lett*. 2023;50:e2022GL100827. <https://doi.org/10.1029/2022GL100827>.
20. Hassan I, Kalin RM, Aladejana JA, White CJ. Potential impacts of climate change on extreme weather events in the Niger delta part of Nigeria. *Hydrology*. 2020;7:19.
21. Ilori OW, Ajayi VO. Change detection and trend analysis of future temperature and rainfall over West Africa. *Earth Syst Environ*. 2020;4:493–512. <https://doi.org/10.1007/s41748-020-00174-6>.
22. Salihu AC, Abdulkadir A, Nsofor GN, Otache MY. Projected extreme rainfall indices in Guinea and Sudano-Sahelian ecological zones, Nigeria. *Int J Multidisciplinary Stud*. 2020;7:32–52. <https://doi.org/10.4038/ijms.v7i1.120>.
23. Shiru MS, Shahid S, Dewan A, Chung E-S, Alias N, Ahmed K, Hassan QK. Projection of meteorological droughts in Nigeria during growing seasons under climate change scenarios. *Sci Rep*. 2020;10:10107. <https://doi.org/10.1038/s41598-020-67146-8>.
24. Sultan B, Janicot S. Abrupt shift of the ITCZ over West Africa and intra-seasonal variability. *Geophys Res Lett*. 2000;27:3353–6. <https://doi.org/10.1029/1999GL011285>.
25. Nicholson SE. The intensity, location and structure of the tropical Rainbelt over west Africa as factors in interannual variability. *Int J Climatol*. 2008;28:1775–85. <https://doi.org/10.1002/joc.1507>.
26. Adefolalu DO. Rainfall trends in Nigeria. *Theoret Appl Climatol*. 1986;37:205–19. <https://doi.org/10.1007/BF00867578>.
27. Adejuwon JO, Odekunle TO. Variability and the severity of the “Little Dry Season” in Southwestern Nigeria. *J Clim*. 2006;19:483–93. <https://doi.org/10.1175/JCLI3642.1>.
28. Chineke TC, Jagtap SS, Nwofor O. West African monsoon: is the August break “breaking” in the eastern humid zone of Southern Nigeria? *Clim Change*. 2010;103:555–70. <https://doi.org/10.1007/s10584-009-9780-2>.
29. Omotosho JB. Spatial variation of rainfall in Nigeria during the ‘little dry season.’ *Atmos Res*. 1988;22:137–47. [https://doi.org/10.1016/0169-8095\(88\)90004-X](https://doi.org/10.1016/0169-8095(88)90004-X).
30. Umar N, Gray A. Flooding in Nigeria: a review of its occurrence and impacts and approaches to modelling flood data. *Int J Environ Stud*. 2022. <https://doi.org/10.1080/00207233.2022.2081471>.

31. Eyring V, Bony S, Meehl GA, Senior CA, Stevens B, Stouffer RJ, Taylor KE. Overview of the Coupled model intercomparison project phase 6 (CMIP6) experimental design and organization. *Geosci Model Dev*. 2016;9:1937–58. <https://doi.org/10.5194/gmd-9-1937-2016>.
32. O'Neill BC, Kriegler E, Ebi KL, Kemp-Benedict E, Riahi K, Rothman DS, van Ruijven BJ, van Vuuren DP, Birkmann J, Kok K, et al. The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob Environ Chang*. 2017;42:169–80. <https://doi.org/10.1016/j.gloenvcha.2015.01.004>.
33. Funk C, Peterson P, Landsfeld M, Pedreros D, Verdin J, Shukla S, Husak G, Rowland J, Harrison L, Hoell A, et al. The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. *Scientific Data*. 2015;2:150066. <https://doi.org/10.1038/sdata.2015.66>.
34. Beck HE, Wood EF, Pan M, Fisher CK, Miralles DG, van Dijk AIJM, McVicar TR, Adler RF. MSWEP V2 Global 3-Hourly 01° precipitation: methodology and quantitative assessment. *Bull Am Meteorol Soc*. 2019;100:473–500. <https://doi.org/10.1175/bams-d-17-0138.1>.
35. Dunning CM, Black E, Allan RP. Later wet seasons with more intense rainfall over Africa under future climate change. *J Clim*. 2018;31:9719–38. <https://doi.org/10.1175/JCLI-D-18-0102.1>.
36. Kouakou C, Paturel J-E, Satgé F, Trambay Y, Defrance D, Rouché N. Comparison of gridded precipitation estimates for regional hydrological modeling in West and Central Africa. *J Hydrol Regional Stud*. 2023;47:101409. <https://doi.org/10.1016/j.ejrh.2023.101409>.
37. Nnamchi HC, Dike VN, Akinsanola AA, Okoro UK. Leading patterns of the satellite-era summer precipitation over West Africa and associated global teleconnections. *Atmos Res*. 2021;259:105677. <https://doi.org/10.1016/j.atmosres.2021.105677>.
38. Scoccimarro E, Peano D, Gualdi S, Bellucci A., Lovato T, Fogli PG, Navarra A. Extreme events representation in CMCC-CM2 standard and high-resolution general circulation models. *Geosci. Model Dev*. 2022;15:1841–1854. <https://doi.org/10.5194/gmd-15-1841-2022>.
39. Bao Q, Liu Y, Wu G, He B, Li J, Wang L, Wu X, Chen K, Wang X, Yang J, et al. CAS FGOALS-f3-H and CAS FGOALS-f3-L outputs for the high-resolution model intercomparison project simulation of CMIP6. *Atmospheric Oceanic Sci Lett*. 2020;13:576–81. <https://doi.org/10.1080/16742834.2020.1814675>.
40. Zhao M, Blanton C, John JG, Radhakrishnan A, Zadeh NT, McHugh C, Rand K, Vahlenkamp H, Wilson C, Ginoux P et al. NOAA-GFDL GFDL-CM4C192 model output prepared for CMIP6 HighResMIP highresSST-future. 2018. Earth System Grid Federation. <https://doi.org/10.22033/ESGF/CMIP6.8565>.
41. Williams KD, Copsey D, Blockley EW, Bodas-Salcedo A, Calvert D, Comer R, Davis P, Graham T, Hewitt HT, Hill R, et al. The met office global coupled model 3.0 and 3.1 (GC3.0 and GC3.1) configurations. *J Adv Model Earth Syst*. 2018;10:357–80. <https://doi.org/10.1002/2017MS001115>.
42. Tu C-Y. AS-RCEC HiRAM-SIT-HR model output prepared for CMIP6 HighResMIP. 2020. Earth System Grid Federation. <https://doi.org/10.22033/ESGF/CMIP6.13301>.
43. von Storch J-S, Putrasahan D, Lohmann K, Gutjahr O, Jungclaus J, Bittner M, Haak H, Wieners K-H, Giorgetta M, Reick C, et al. MPI-M MPI-ESM1.2-XR model output prepared for CMIP6 HighResMIP highresSST-future. 2019. <https://doi.org/10.22033/ESGF/CMIP6.10303>.
44. Mizuta R, Yoshimur H, Ose T, Hosaka M, Yukimoto S. MRI MRI-AGCM3-2-S model output prepared for CMIP6 HighResMIP. 2019. <https://doi.org/10.22033/ESGF/CMIP6.1625>, <https://doi.org/10.22033/ESGF/CMIP6.10942>.
45. Kodama C, Ohno T, Seiki T, Yashiro H, Noda AT, Nakano M, Yamada Y, Roh W, Satoh M, Nitta T, et al. The Nonhydrostatic ICosahedral Atmospheric Model for CMIP6 HighResMIP simulations (NICAM16-S): experimental design, model description, and impacts of model updates. *Geosci Model Dev*. 2021;14:795–820. <https://doi.org/10.5194/gmd-14-795-2021>.
46. Zhang X, Alexander L, Hegerl GC, Jones P, Tank AK, Peterson TC, Trewin B, Zwiers FW. Indices for monitoring changes in extremes based on daily temperature and precipitation data. *WIREs Clim Change*. 2011;2:851–70. <https://doi.org/10.1002/wcc.147>.
47. Ayugi B, Dike V, Ngoma H, Babaousmail H, Mumo R, Ongoma V. Future changes in precipitation extremes over east Africa based on CMIP6 models. *Water*. 2021;13:2358.
48. Ayugi B, Jiang Z, Iyakaremye V, Ngoma H, Babaousmail H, Onyutha C, Dike VN, Mumo R, Ongoma V. East African population exposure to precipitation extremes under 1.5 °C and 2.0 °C warming levels based on CMIP6 models. *Environ Res Lett*. 2022;17:044051. <https://doi.org/10.1088/1748-9326/ac5d9d>.
49. Ayugi B, Zhihong J, Zhu H, Ngoma H, Babaousmail H, Rizwan K, Dike V. Comparison of CMIP6 and CMIP5 models in simulating mean and extreme precipitation over East Africa. *Int J Climatol*. 2021;41:6474–96. <https://doi.org/10.1002/joc.7207>.
50. Dike VN, Lin Z, Fei K, Langendijk GS, Nath D. Evaluation and multimodel projection of seasonal precipitation extremes over central Asia based on CMIP6 simulations. *Int J Climatol*. 2022;42:7228–51. <https://doi.org/10.1002/joc.7641>.
51. Sillmann J, Kharin VV, Zwiers FW, Zhang X, Bronaugh D. Climate extremes indices in the CMIP5 multimodel ensemble: part 2. Future climate projections. *J Geophys Res Atmospheres*. 2013;118:2473–93. <https://doi.org/10.1002/jgrd.50188>.
52. Sylla MB, Gaye AT, Jenkins GS. On the fine-scale topography regulating changes in atmospheric hydrological cycle and extreme rainfall over west africa in a regional climate model projections. *Int J Geophys*. 2012;2012:981649. <https://doi.org/10.1155/2012/981649>.
53. Diba I, Diedhiou A, Famien AM, Camara M, Fotso-Nguemo TC. Changes in compound extremes of rainfall and temperature over West Africa using CMIP5 simulations. *Environ Res Commun*. 2022;4:105003. <https://doi.org/10.1088/2515-7620/ac9aa7>.
54. Wang X-Y, Bao X-Y, Huang Y, Li Z-W, Yong J-H, Wu Y-P, Feng G-L, Sun G-Q. Physical explanation for paradoxical climate change in semi-arid inland Eurasia based on a Remodeled precipitation recycling ratio and clausius-clapeyron equation. *Atmosphere*. 2023;14:376.
55. Bichet A, Diedhiou A. Less frequent and more intense rainfall along the coast of the Gulf of Guinea in West and Central Africa (1981–2014). *Climate Res*. 2018;76:191–201.
56. Ashfaq M, Cavazos T, Reboita MS, Torres-Alavez JA, Im E-S, Olusegun CF, Alves L, Key K, Adeniyi MO, Tall M, et al. Robust late twenty-first century shift in the regional monsoons in RegCM-CORDEX simulations. *Clim Dyn*. 2021;57:1463–88. <https://doi.org/10.1007/s00382-020-05306-2>.
57. Feng X, Porporato A, Rodriguez-Iturbe I. Changes in rainfall seasonality in the tropics. *Nat Clim Chang*. 2013;3:811–5. <https://doi.org/10.1038/nclimate1907>.
58. Liu Y, Chen J, Pan T, Liu Y, Zhang Y, Ge Q, Ciais P, Penuelas J. Global socioeconomic risk of precipitation extremes under climate change. *Earth's Future*. 2020;8:e2019EF001331. <https://doi.org/10.1029/2019EF001331>.