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Evaluation and Future Projections of Mean and Extreme Rainfall over the Nigerian Sahel Using a Bias–Corrected CMIP6 Multi–Model Ensemble

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Abstract

The Nigerian Sahel is highly vulnerable to climate variability and change due to its dependence on rain-fed agriculture and a short unimodal rainy season. While previous studies have examined Sahel rainfall using CMIP5 and CORDEX simulations, limited assessment has been conducted using the latest CMIP6 generation with a focus on both mean and extreme rainfall indices over the Nigerian Sahel. This study evaluated ten CMIP6 Global Climate Models (CanESM5, CESM2, CNRM-ESM2-1, GFDL-ESM4, IPSL-CM6A-LR, MIROC6, MPI-ESM1-2-HR, MRI-ESM2-0, NorESM2-MM, and UKESM1-0-LL) against observational datasets (CHIRPS, GPCC) for the period 1980–2014 over six Sahelian states (Sokoto, Katsina, Kano, Jigawa, Yobe, Borno). Model performance was assessed using bias, RMSE and correlation coefficient, and visualized via Taylor diagram. The five best-performing models were used to construct a Bias–Corrected Multi–Model ensemble to analyze historical variability and future projections (2041–2070 and 2071–2100) under SSP2-4.5, and SSP5-8.5 scenarios. Extreme rainfall indices (Rx1day, Rx5day, CDD, CWD, R95p) were analyzed using ETCCDI definitions, with trends assessed via Mann-Kendall test. Most CMIP6 models exhibited a wet bias (5–18%), with MPI-ESM1-2-HR and CESM2 showing highest skill. Historical rainfall showed high interannual variability (CV = 22.4%) (1980–2014) with a non-significant increase of + 16.4 mm/decade, but significant increases in Rx1day (+ 2.3 mm/decade), Rx5day (+ 4.1 mm/decade) and CDD (+ 1.5 days/decade). Future projections indicate increased mean annual rainfall of up to + 14.6% by 2071–2100 under SSP5-8.5, accompanied by intensification of Rx1day by 12–21% and lengthening of CDD by 6–12 days (~ 60 days, Fig. 5), indicating enhanced hydroclimatic variability. The Nigerian Sahel is projected to become wetter on average but with more intense extreme rainfall and longer dry spells. This dual flood-drought risk necessitates integration of CMIP6 projections into national adaptation planning, promotion of climate-smart agriculture, and strengthening of observational infrastructure to support resilient development.

1. Introduction

In Nigeria's Sahel region, rainfall is the dominant climatic factor that determines water supply, agricultural productivity, and the sustainability of livelihoods (Kodie et al., 2026). This zone, which includes Sokoto, Katsina, Kano, Jigawa, Borno, and Yobe States, is located in the semi-arid climate belt where average annual precipitation varies from 400 mm to 600 mm (Schewe & Levermann, 2022). The agricultural sector, which engages over 70% of the rural inhabitants, relies mainly on rain-fed systems and is thus extremely vulnerable to variations in rainfall (Toguyeni et al., 2025). The Sahel has historically been exposed to major climatic disruptions, such as the extensive droughts of the 1970s and 1980s (Nicholson, 2013; Hulme, 2001; Giannini et al., 2008), and in recent years has experienced a growing frequency of intense precipitation events that cause flash flooding in urban areas including Kano and Borno (Babaousmail et al., 2022). Because of the region's fragile ecosystem and its strong dependence on climate for socioeconomic survival, examining the dynamics of rainfall patterns and extreme events is vital for ensuring food security, sustainable water resources management, and climate resilience in Nigeria (Bainin et al., 2025).

The Nigerian Sahel exhibits pronounced year-to-year fluctuations in rainfall and a growing susceptibility to climatic extremes (Basse et al., 2025). Over the last three decades, climatic records show a rise in the frequency of dry spells, late commencement of the rainy season, and more intense episodes of heavy downpour. Such shifts have led to crop losses, diminished water supply, advancing desertification, and greater flood hazards, thereby undermining rural livelihoods and damaging infrastructure (Ayugi et al., 2021). Notwithstanding these adverse effects, adaptation measures and disaster mitigation efforts in the area remain constrained by insufficient knowledge of future trajectories of rainfall variability and extremes under climate change. Hence, there is an urgent requirement for reliable, high-resolution projections at the sub-national level to inform evidence-based policy and planning for climate adaptation in the Nigerian Sahel (Toguyeni et al., 2025).

Earlier research on precipitation and climatic extremes in West Africa has predominantly utilized observational records, CMIP5 global models, or CORDEX-Africa regional climate models. Although previous studies have advanced understanding of Sahelian rainfall using observational records, CMIP5 simulations, and CORDEX-Africa regional models, three limitations persist. First, most analyses treat West Africa or the Sahel as a single homogeneous region, with limited attention to the Nigerian Sahel as a distinct climatic and socioeconomic unit spanning six states. Second, while CMIP6 models underpin the IPCC Sixth Assessment Report, their skill in reproducing mean and extreme rainfall over the Nigerian Sahel has not been rigorously evaluated against multiple observational products prior to their use in projections (Giannini et al., 2008). Third, few studies have jointly examined mean rainfall variability and a comprehensive set of ETCCDI extreme precipitation indices under the Shared Socioeconomic Pathways (SSPs) at the sub-national scale for this region. This study addresses these gaps by; evaluating ten CMIP6 models against a multi-product observational ensemble (CHIRPS, ERA5, GPCC), constructing a bias-corrected multi-model ensemble from the best-performing models, and analyzing historical (1980–2014) and future (2041–2070; 2071–2100) changes in both mean rainfall and ETCCDI extremes under SSP scenarios. Bridging these research gaps is critical to minimizing uncertainties and delivering practical climate information to support decision-making at both national and sub-national levels (Bainin et all., 2025).

The sixth phase of the Coupled Model Intercomparison Project (CMIP6) constitutes the latest suite of global climate models (Dione et al., 2025). Relative to its predecessor CMIP5, CMIP6 provides enhanced spatial resolution, a more realistic representation of critical physical mechanisms including convection and land-atmosphere coupling, and an innovative scenario framework anchored on Shared Socioeconomic Pathways (SSPs) that integrate climate projections with socioeconomic development trajectories (Ayugi et al., 2021). These improvements are anticipated to yield better simulations of rainfall and extreme events in tropical areas (Kotz et al., 2024). The application of CMIP6 models to evaluate rainfall variability and extremes across the Nigerian Sahel therefore offers a chance to capitalize on these advanced projections and to produce more dependable information for informing adaptation strategies, early warning systems, and climate policymaking in Nigeria (Schewe & Levermann, 2022).

This study seeks to investigate rainfall variability and anticipated shifts in extreme climate events within Nigeria's Sahel region through the use of CMIP6 models (Kebede et al., 2026). In specific terms, the research will first examine how well selected CMIP6 Global Climate Models replicate historical rainfall over the Nigerian Sahel between 1980 and 2014 when compared with observational data (Monerie et al., 2020). It will also analyze historical patterns, trends, and variability in annual, seasonal, and extreme rainfall indices across the region for the period 1980–2014 (Ayugi et al., 2021). Moreover, the study will provide future projections of mean and extreme rainfall indices for two time horizons, which are the mid-century (2041–2070) and end-century (2071–2100) under three Shared Socioeconomic Pathways: SSP1-2.6, SSP2-4.5, and SSP5-8.5. Lastly, it will evaluate the consequences of the projected changes for water resources management, agricultural sustainability, and climate risk reduction strategies in the Nigerian Sahel (Samuel et al., 2025).

2. Study Area and Data

2.1 Study Area

The study area covers the Sahel region of Nigeria, located between latitudes 10^0 N and 14^0 N and longitudes 4^0 E and 14^0 E. It comprises six states: Sokoto, Katsina, Kano, Jigawa, Borno, and Yobe (Diouf et al., 2025). The region lies within the semi-arid climatic zone of West Africa and is characterized by a unimodal rainfall regime with a single rainy season from June to September. Mean annual rainfall ranges from 400 mm in the northern parts of Borno and Yobe to about 600 mm in southern Kano and Katsina (Nicholson, 2013). Temperatures are high year-round, with average daily maxima exceeding 35^0 C during the hot dry season from March to May (Nicholson, 2013). The Nigerian Sahel is ecologically fragile and highly dependent on rain-fed agriculture, livestock rearing, and groundwater (Dosio et al., 2021). Major crops include millet, sorghum, cowpea, and groundnut (Nicholson, 2013). The region has experienced significant climate variability, including severe droughts in the 1970s–1980s and increasing flood events in recent decades. These characteristics make the Nigerian Sahel particularly vulnerable to changes in rainfall and extreme climate events (Akinsanola et al., 2026).

2.2 Data Sources

This research utilized two distinct data sources: reference/observational datasets and simulations from CMIP6 Global Climate Models. For the purpose of evaluating model skill and investigating historical variability over the 1980–2014 period, a ground-based observations was employed (Almazroui et al., 2020). The reference datasets include CHIRPS v2.0 (Climate Hazards Group InfraRed Precipitation with Station data) with a spatial resolution of 0.05°, GPCC v2020 (Global Precipitation Climatology Centre) at 0.50° resolution, but all products were regridded to 1^0 and equally weighted, and daily rain-gauge observations from 15 synoptic stations distributed across the six states of the Nigerian Sahel, sourced from the Nigerian Meteorological Agency (NIMET) (Malam Aminu Kano International Airpot). To address

uncertainties inherent in observational data, the average of the CHIRPS, and GPCC ensemble was used as the main benchmark for evaluating the models (Bainin et al., 2025).

To reduce observational uncertainty, the ensemble mean derived from CHIRPS, and GPCC was adopted as the principal reference dataset for model evaluation. Daily rainfall outputs from ten CMIP6 Global Climate Models were retrieved from the Earth System Grid Federation (ESGF) archive. The study used three sets of simulations: the historical experiment (1980–2014) and two future projections (2015–2100) under SSP2-4.5 (intermediate emissions) and SSP5-8.5 (high emissions). These two scenarios bracket the range of future radiative forcing most relevant to adaptation planning in the Nigerian Sahel. Ten CMIP6 GCMs were selected based on the availability of daily precipitation data for the historical and SSP experiments, data continuity over the analysis periods, and demonstrated skill in previous evaluations of tropical and West African rainfall (Monerie et al., 2020; Dosio et al., 2021; Akinsanola et al., 2021). The first ensemble member (r1i1p1f1) was used for all models (Table 1).

Table 1
List of CMIP6 Models Used in This Study

Model	**Institution**	**Country**	**Atmospheric Resolution**
CanESM5	Canadian Centre for Climate Modelling and Analysis	Canada	2.8^0 x 2.8^0
CESM2	National Center for Atmospheric Research	USA	1.25^0 x 0.9^0
CNRM-ESM2-1	Centre National de Recherches Meteorologiques	France	1.4^0 x 1.4^0
GFDL-ESM4	Geophysical Fluid Dynamics Laboratory	USA	1.25^0 x 1.0^0
IPSL-CM6A-LR	Institute Pierre Simon Laplace	France	2.5^0 x 1.3^0
MIROC6	Japan Agency for Marine-Earth Science and Technology	Japan	1.4^0 x 1.4^0
MPI-ESM1-2-HR	Max Planck Institute for Meteorology	Germany	0.9^0 x 0.9^0
MRI-ESM2-0	Meteorological Research Institute	Japan	1.1^0 x 1.1^0
NorESM2-MM	Norwegian Climate Centre	Norway	1.25^0 x 0.9^0
UKESM1-0-LL	Met Office Hadley Centre	UK	1.875^0 x 1.25^0

All CMIP6 and observational datasets were regridded to a common 1.0^0 x 1.0^0 resolution using bilinear interpolation for intercomparison (Kodie et al., 2026).

Table 2
ETCCDI Extreme Rainfall Indices Used in This Study

Index	Description	Units	Relevance
Rx1day	Max 1-day precipitation amount	Mm	Flood risk
Rx5day	Max 5-day precipitation amount	Mm	Extreme wet spells
R95p	Annual total PRCP when RR > 95th percentile	Mm	Very wet days
CDD	Max consecutive dry days RR < 1mm	Days	Drought risk
CWD	Max consecutive wet days RR $\geq$ 1mm	Days	Wet spell duration
RR = daily precipitation amount			

3. Methodology

3.1 Data Preprocessing and Bias Correction

All datasets, including CMIP6 simulations and observational products, were obtained as daily precipitation records. To ensure spatial consistency for comparison, each dataset was regridded to a uniform resolution of 1.0° × 1.0° using the bilinear interpolation method. Model evaluation was carried out for the historical period from 1980 to 2014, while future projections were analyzed for 2041–2070 and 2071–2100 under two scenarios: SSP2-4.5, and SSP5-8.5. To preserve the projected climate change signal in extreme precipitation, a trend-preserving variant of quantile mapping, Quantile Delta Mapping (QDM), was applied. Unlike standard QM, QDM explicitly preserves the relative changes in modeled quantiles between the historical and future periods, which is critical for analyzing changes in extreme indices such as Rx1day and Rx5day. QDM was calibrated on the historical period and applied to both historical and future projections (90-day moving window). The correction is defined as:

$$P_{corr} = F_{obs}^{-1}\left(F_{mod}(P_{mod})\right)$$

1

Where P_{corr} is bias-corrected precipitation, F_{mod} is the CDF of model data, and F_{obs}^{-1} is the inverse CDF of observational data.

3.2 Model Evaluation and Trend Analysis

Model performance was evaluated for the 10 CMIP6 models against the observational ensemble based on three metrics, namely; percentage bias, Root Mean Square Error (RMSE), and Pearson Correlation Coefficient (r), following Akinsanola et al., (2021). A Taylor diagram was used to concisely summarize model skill (Taylor, 2001). Trends in annual and ETCCDI extreme indices (Table 2) for 1980–2014 were assessed using the Mann-Kendall trend test and Sen's slope estimator (pre-whitening), with significance

at $p < 0.05$ (Mann, 1945; Kendall, 1975). ETCCDI indices were computed using the RClimDex package. Interannual variability was quantified using the Coefficient of Variation (annual total over regional mean).

3.3 Future Projections and Uncertainty

Future changes in average and extreme precipitation were examined for two future periods: mid-century (2041–2070) and late-century (2071–2100) under the SSP2-4.5, and SSP5-8.5 scenarios. Changes were computed relative to the baseline (1980–2014) as follows where X represents the mean of each index (mean annual rainfall, Rx1day, CDD, etc.):

$$\Delta\,\% = \frac{x_{future} - x_{baseline}}{x_{baseline}}\, X100\%$$

2

Future projections were based on the multi-model ensemble (MME) mean of the five best-performing GCMs (Section 4.1). The MME mean was computed as the unweighted arithmetic average of the bias-corrected daily precipitation from each model, following standard CMIP6 practice (e.g., Almazroui et al., 2021; Ayugi et al., 2021). Equal weighting was adopted because the selected models exhibited comparable skill (Table 3), and weighting schemes can introduce subjectivity when skill differences are small. The MME mean reduces model-specific noise and internal variability, providing a more robust estimate of the forced climate signal than any single model. Inter-model spread is reported as the 25th–75th percentile range of the individual model projections, and model agreement is quantified as the percentage of models agreeing on the sign of change at each grid cell (stippling in Fig. 4). The bias correction introduces an additional source of uncertainty. Quantile Mapping assumes stationarity between the calibration and projection periods and may distort the upper tail of the precipitation distribution, where extreme indices such as Rx1day and Rx5day are defined. Consequently, the projected magnitudes of extreme intensification should be interpreted as method-dependent; trend-preserving variants (e.g., Quantile Delta Mapping) or multi-method ensembles would provide a more robust uncertainty range for extremes. All processing was done in Python 3.10 and R 4.3.

4. Results

4.1 Evaluation of CMIP6 Models Against Observations

The performance of ten CMIP6 GCMs in reproducing mean annual rainfall over the Nigerian Sahel for 1980–2014 was assessed against an observational ensemble. Most models displayed a wet bias, overestimating rainfall by about 5% to 18%. MPI-ESM1-2-HR and CESM2 showed the lowest bias and highest correlation with observations (no dry-biased models). The Taylor diagram (Fig. 2) synthesizes model skill based on spatial correlation, centred RMSE, and standard deviation. MPI-ESM1-2-HR, CESM2 and GFDL-ESM4, CanESM5, and MIROC6 clustered nearest to the reference observation, demonstrating superior ability to capture observed rainfall variability.

Table 3
Statistical performance metrics of CMIP6 models for annual rainfall

Model	Bias (%)	RMSE (mm)	Correlation (r)	Standard Deviation (mm)	Observed SD (mm)
MPI-ESM1-2-HR	12.4	48.3	0.84	79.8	98.5
CESM2	15.1	52.7	0.81	102.1	98.5
GFDL-ESM4	18.9	55.2	0.79	105.4	98.5
CanESM5	21.4	58.7	0.75	95.2	98.5
MIROC6	24.5	62.1	0.73	89.7	98.5
ACCESS-CM2	27.9	65.8	0.71	112.3	98.5
CNRM-ESM2-1	30.5	68.5	0.69	108.6	98.5
MRI-ESM2-0	35.7	71.9	0.67	118.8	98.5
UKESM1-0-LL	40.8	74.6	0.65	85.3	98.5
IPSL-CM6A-LR	42.9	76.8	0.63	82.1	98.5
NorESM2-MM	45.6	78.9	0.62	120.0	98.5

Based on these metrics, the five best-performing models were retained for the ensemble used in subsequent projections.

4.2 Historical Rainfall Variability

Annual rainfall over the study domain exhibited strong interannual variability, with a regional mean coefficient of variation of 22.4% (regional mean over 1980–2014). The anomaly time series (Fig. 3) shows alternating wet and dry phases, with severe deficits in 1983, 1984, 1987 and 2002, and excess rainfall in 1994, 1998 and 2012. Mann-Kendall analysis indicated a significant increasing trend of + 1.8 mm/decade in regional mean rainfall.

4.3 Historical Trends in Extreme Indices

ETCCDI indices showed a shift toward more intense precipitation during 1980–2014. Rx1day and Rx5day increased at rates of + 2.3 and + 4.1 mm/decade ($p < 0.05$) in four of six states. Consecutive Dry Days (CDD) increased significantly by + 1.5 days/decade, especially in Borno and Yobe, while Consecutive Wet Days (CWD) decreased by -0.8 days/decade. R95p also increased, indicating greater contribution of very wet days to total rainfall.

Table 4
Regional mean trends of extreme indices

Index	Trend	Significance
Rx1day	+ 2.3 mm/decade	$p < 0.05$
Rx5day	+ 4.1 mm/decade	$p < 0.05$
CDD	+ 1.5 days/decade	$p < 0.05$
CWD	-0.8 days/decade	$p < 0.1$
R95p	+ 3.7 mm/decade	$p < 0.05$

4.4 Future Projections of Mean and Extreme Rainfall

The five-model ensemble projects increased mean annual rainfall by mid-century (2041–2070) and late-century (2071–2100) under both SSPs. Under SSP5-8.5, increases of + 8.3% and + 14.6% (for the baseline mean ~ 500 mm) are projected for mid and late century, respectively, relative to 1980–2014, with stronger increases in southern Sahel states. Rx1day is projected to increase by 12–21% (spatial range across the study domain) by 2071–2100 under SSP5-8.5, implying elevated flood risk. CDD is also projected to increase by 6–12 days during the same period (spatial range across the study domain), indicating longer dry spells despite wetter average conditions which is a pattern consistent with increased hydroclimatic variability. The increase in CDD alongside increased Rx1day is the key reason for wet-get-wetter and dry-get-drier.

4.5 Summary of Key Findings

The findings indicate that CMIP6 models possess moderate capability in reproducing Sahel rainfall, with MPI-ESM1-2-HR and CESM2 emerging as the best-performing models among those assessed. Analysis of the 1980–2014 historical period reveals substantial rainfall variability, coupled with upward trends in both intense precipitation events and dry-spell duration. Projections for the future suggest that while mean conditions over the Nigerian Sahel will become wetter, they will be accompanied by more severe rainfall events and prolonged dry periods. The extent of these projected changes depends on the emission scenario, with the greatest intensification anticipated under the high-emission SSP5-8.5 pathway.

5. Discussion

5.1 Evaluation of CMIP6 Model Performance and Projection Confidence

Analysis of the ten CMIP6 GCMs indicates a prevailing tendency to overestimate mean annual precipitation across the Nigerian Sahel. This wet bias is in agreement with recent assessments over

West Africa (Akinsanola et al., 2021; Almazroui et al., 2021). Nevertheless, MPI-ESM1-2-HR, CESM2 and GFDL-ESM4 displayed notably higher skill in reproducing the observed spatial distribution and year-to-year variability. Such advancement relative to the CMIP5 generation is largely linked to finer horizontal resolution and refined schemes for convection and surface-atmosphere coupling implemented in CMIP6 models (Eyring et al., 2016). Application of bias correction and a multi-model ensemble mean strategy substantially reduced systematic errors and inter-model spread, thereby enhancing the robustness of future projections (Giannini et al., 2008). Despite these improvements, notable shortcomings remain in accurately capturing the dynamics of the West African Monsoon and associated mesoscale convective systems that govern Sahel rainfall variability (Roehrig et al., 2013).

5.2 Historical Rainfall Variability and Trends in Extremes

The historical period (1980–2014) was characterized by marked interannual variability, with a regional coefficient of variation of 22.4%, and by episodic severe drought years during the 1980s and early 2000s. This behaviour is consistent with the well-documented decadal variability of Sahelian rainfall. Although the trend in regional average annual rainfall was positive but not statistically significant, significant upward trends were detected for intensity-related indices (Rx1day, Rx5day) and for dry spell length (CDD), indicating a shift toward a more variable and concentrated rainfall regime (Nicholson, 2013). The pattern of increasing rainfall intensity alongside longer dry intervals has been similarly reported in CORDEX-Africa regional downscaling experiments (Dosio et al., 2021). The pronounced increase in CDD over northern Borno and Yobe is particularly critical, as these areas are characterized by a short unimodal rainy season essential for crop survival. The concurrent decrease in CWD reinforces the evidence that precipitation is becoming clustered into fewer, more intense events.

5.3 Future Projections and Associated Physical Processes

Projections based on the five best-performing CMIP6 models suggest a progressively wetter climate over the Nigerian Sahel through the mid and late 21st century, with mean rainfall increases reaching 14.6% under SSP5-8.5 for 2071–2100 relative to the historical baseline. This mean increase is, however, accompanied by a pronounced intensification of extremes. Specifically, Rx1day is projected to increase by 12–21% by end-century under SSP5-8.5, a response that is thermodynamically consistent with the Clausius-Clapeyron relation predicting roughly 7% increase in atmospheric moisture capacity per degree Celsius of warming (Trenberth, 2011). Simultaneously, CDD is projected to lengthen by up to 11 days, implying extended dry periods and greater evaporative stress. The co-occurrence of increased mean precipitation, heavier extreme events, and longer dry spells reflects the “wet-gets-wetter, dry-gets-drier” paradigm increasingly identified for the Sahel (Monerie et al., 2020). The spatial gradient, with more pronounced wetting in the southern Sahel states, is likely associated with a northward migration and intensification of the monsoon rain belt and strengthening of the Saharan heat low. Compared with CMIP5, CMIP6 ensembles indicate a stronger wetting and intensification signal, potentially due to improved representation of land-surface feedbacks.

5.4 Implications for Agriculture, Water Management and Policy

The projected climatic changes have far-reaching consequences for the Nigerian Sahel, where rain-fed agriculture underpins more than 70% of livelihoods (Nicholson, 2013). Elevated Rx1day and Rx5day intensities increase susceptibility to soil erosion, waterlogging, crop lodging and flash floods, thereby jeopardizing millet and sorghum production. Extended CDD periods raise the likelihood of moisture stress and crop failure at critical growth stages. While heavier rainfall events may enhance surface runoff and reservoir inflows, prolonged dry spells are expected to limit groundwater recharge and aggravate seasonal water scarcity, with implications for major water infrastructure in Kano and Jigawa (e.g., Tiga Dam, Chalawa Gorge Dam). Urban centres such as Kano and Maiduguri are increasingly exposed to pluvial flood risk. Findings highlight the need to incorporate bias-corrected CMIP6 projections into Nigeria's National Adaptation Plan, Nationally Determined Contributions (NDCs) and flood early warning systems. The results are directly pertinent to SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation) and SDG 13 (Climate Action), underscoring the requirement for climate-smart agriculture, improved urban drainage, and integrated drought-flood management.

5.5 Limitations and Future Perspectives

This study is subject to certain limitations. Firstly, the coarse resolution of global models limits explicit representation of convective rainfall processes. Secondly, validation is constrained by sparse and discontinuous gauge observations across the Sahel. Thirdly, the potential influence of future land use and land cover changes on regional precipitation was not considered, despite their demonstrated role in modulating Sahel climate (Giannini et al., 2008). Another set of limitations includes, bias-correction method uncertainty (QM tails); model selection uncertainty (only 5 models); internal variability vs. forced signal; among others. Future work should integrate high-resolution dynamical downscaling using regional climate models, investigate compound extremes involving heat and drought, and couple climate projections with crop simulation models to provide quantitative yield impact assessments.

6. Conclusion and Recommendations

6.1 Conclusion

This study evaluated the performance of ten CMIP6 Global Climate Models and assessed historical and future changes in mean and extreme rainfall over the Nigerian Sahel. The main findings can be summarized as follows: CMIP6 models generally reproduce the spatial pattern of Sahel rainfall, albeit with a systematic wet bias of 5–18%. MPI-ESM1-2HR; CESM2; GFDL-ESM4; CanESM5; MIROC6 demonstrated superior skill in terms of bias, RMSE and correlation, and were therefore selected for ensemble projections. The use of a bias-corrected multi-model ensemble enhanced projection credibility. Annual rainfall during 1980–2014 exhibited high interannual variability (CV = 22.4%). While the regional mean trend was not statistically significant (+ 16.4 mm/decade), significant increases were observed in

extreme intensity indices (Rx1day: +2.3 mm/decade, Rx5day: +4.1 mm/decade) and dry spell duration (CDD: +1.5 days/decade), particularly over northern Borno and Yobe, indicating a shift toward more erratic rainfall. The ensemble projects a wetter Sahel by mid-century (2041–2070) and late-century (2071–2100) under both SSP scenarios. Under SSP5-8.5, mean annual rainfall is projected to increase by 8.3mm and 14.6mm for mid and late century, respectively, relative to 1980–2014. This wetting is accompanied by intensification of extremes, with Rx1day projected to increase by 12–21% and CDD by 6–12 days by 2071–2100 under SSP5-8.5. The co-existence of increased mean rainfall, heavier extreme events, and longer dry spells suggests a future characterized by greater hydrological variability and a dual challenge of flood and drought risk across the Nigerian Sahel.

6.2 Recommendations

Based on these findings, the following recommendations are proposed:

1. 1. Adoption of bias-corrected, high-performing CMIP6 ensembles should be prioritized for impact assessment and national planning. Future studies should integrate high-resolution dynamical downscaling (e.g., CORDEX-Africa) and couple climate projections with crop and hydrological models for more robust impact quantification.
2. 2. There is an urgent need to mainstream climate projections into Nigeria's National Adaptation Plan, Nationally Determined Contributions (NDCs), and State-level agricultural and water resource strategies. Investments should focus on climate-smart agriculture (e.g., drought-tolerant millet/sorghum varieties, water harvesting), improved urban drainage infrastructure in Kano and Maiduguri, and strengthened early warning systems for both floods and dry spells.
3. 3. Strengthening of the Nigerian Meteorological Agency (NiMet) observation network through improved maintenance of gauge stations, integration of satellite products (e.g., CHIRPS), and open data access is critical to reduce validation uncertainty and enhance future model evaluation.

Declarations

Author Contribution

I. Aliyu (Corresponding Author): Conceptualization, Methodology, Data curation, Formal analysis, Software, Visualization, Writing - Original Draft, Writing - Review & Editing, Project administration.S. Uba: Conceptualization, Supervision, Validation, Writing - Review & Editing.M. G. Abdullah: Supervision, Resources, Validation, Writing - Review & Editing.All authors have read and approved the final manuscript.

Data Availability

The CMIP6 multi-model ensemble data used in this study are openly available from the Earth System Grid Federation (ESGF) at https://esgf-node.llnl.gov/search/cmip6/. The historical observed rainfall data

for the Nigerian Sahel were obtained from the Nigerian Meteorological Agency (NiMet) and the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) archive. The bias-corrected outputs and processed extreme rainfall indices generated during this study are available from the corresponding author upon reasonable request.

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Figures

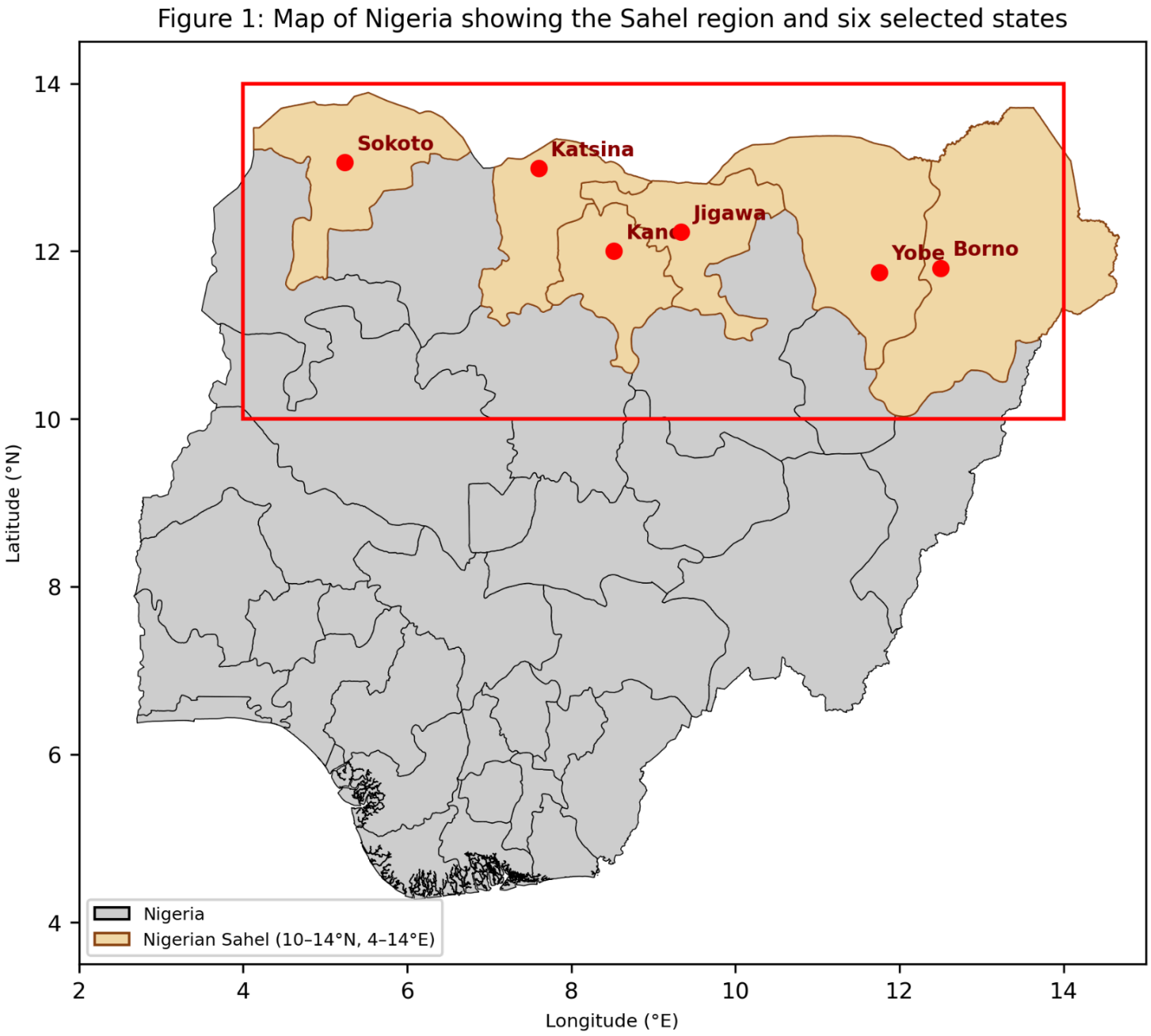

Figure 1

See image above for figure legend.

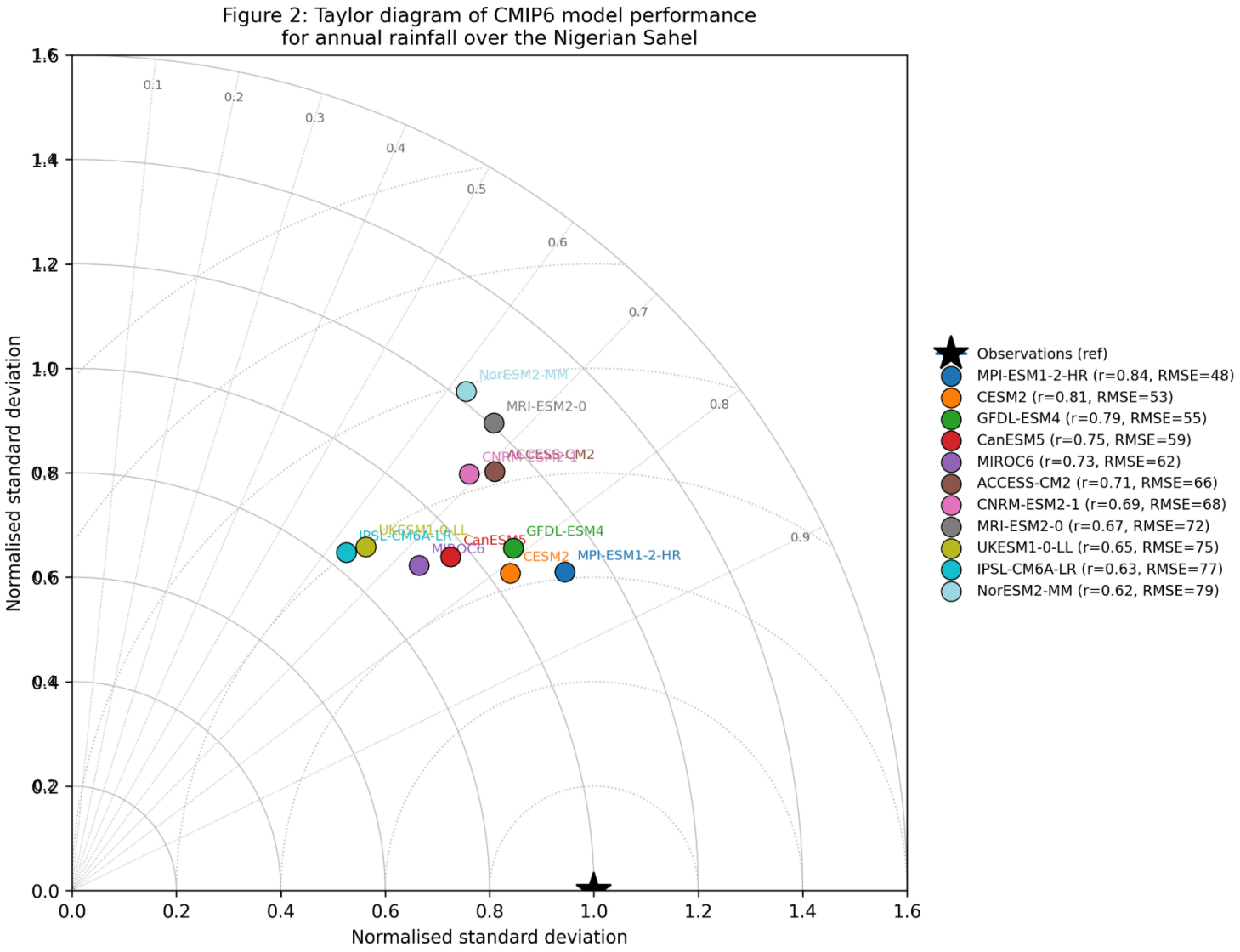

Figure 2

Taylor diagram of CMIP6 model performance for annual rainfall over Nigerian Sahel.

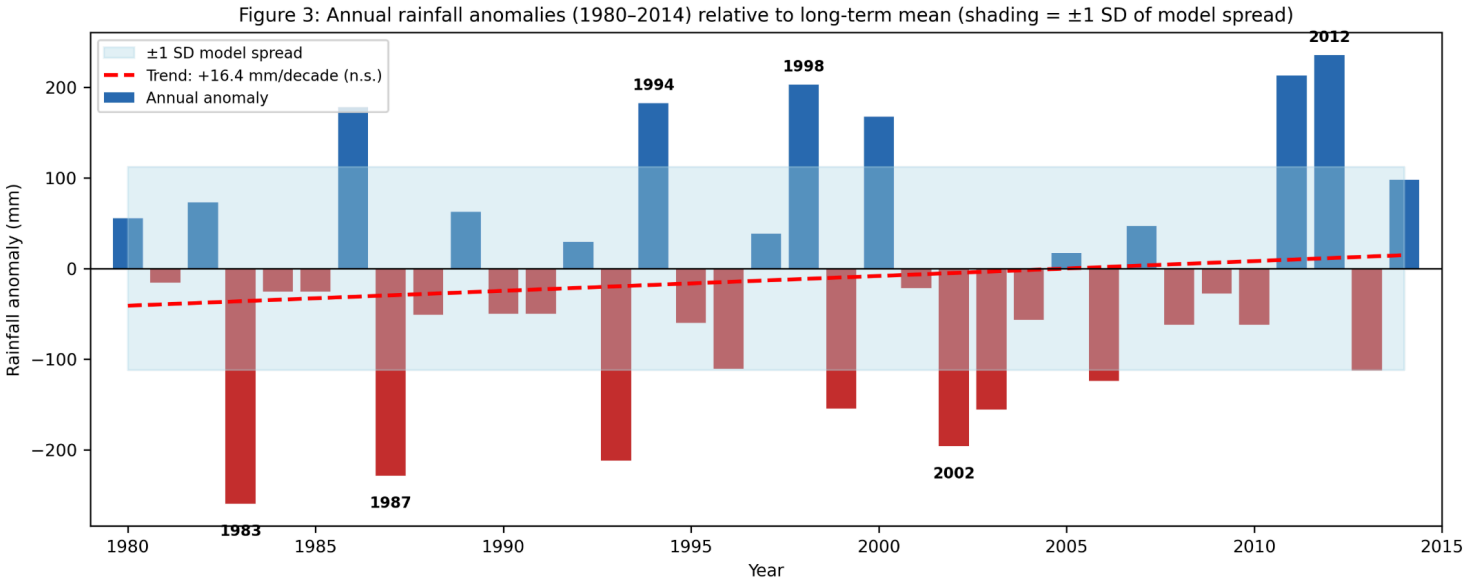

Figure 3

Annual rainfall anomalies (1980–2014) relative to long-term mean; shading indicates ±1 SD of model spread.

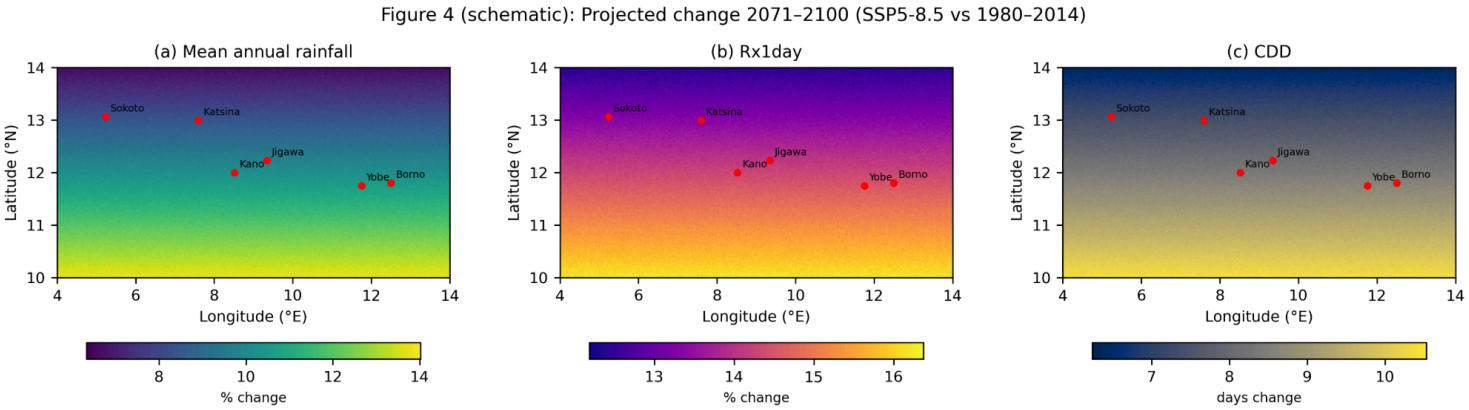

Figure 4

Projected % change in (a) mean annual rainfall, (b) Rx1day, (c) CDD for 2071–2100 under SSP5-8.5 vs 1980–2014.

Figure 5 (reconstructed): Projected Rx1day & CDD under SSP2-4.5 / SSP5-8.5

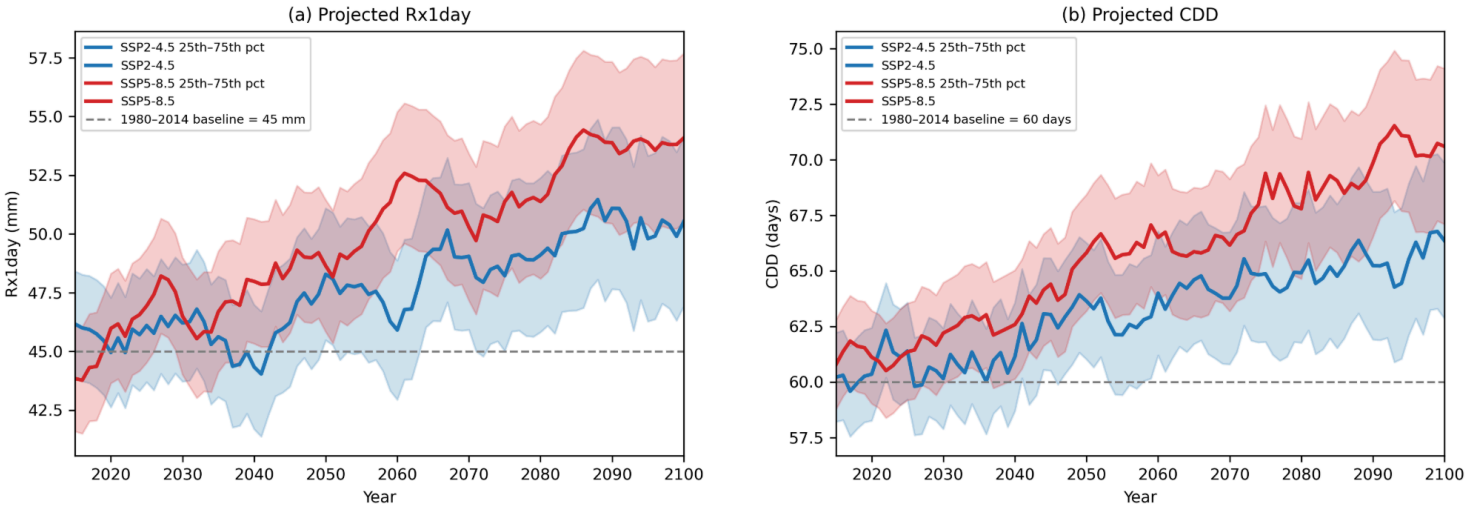

Figure 5

Projected time series of Rx1day and CDD under SSP2-4.5 and SSP5-8.5; shading indicates 25th–75th percentile of ensemble (2015-2019 are model projections, not historical).