Original Research Article

Evaluation of CMIP6 Models Skill in Representing Annual Extreme Precipitation over Northern and Southern Nigeria

Abstract

In this study, we evaluate the performance of 13 climate models from phase 6 of the Coupled Model Intercomparison Project (CMIP6) in simulating seven (7) extreme precipitation indices over Northern and southern Nigeria. The considered extreme indices designated in this study were, Total precipitation (PRCPTOT), maximum consecutive wet days (CWD), Heavy precipitation days (R10mm), Very heavy precipitation days (R20mm), Max-5 days Precipitation (RX5day), Extremely wet days (R99pTOT) and Very wet days (R95pTOT). The performance of these 13 climate models are assesed by comparing the model simulation to the observed dataset from the Global Precipitation Climatology Project (GPCP). The performance of CMIP6 models in capturing extreme precipitation characteristics is revealed through some selected multiple descriptive statistics: the normalized mean bias error, RMSE, NRMSE, and Taylor diagram. The descriptive statistics conclusively revealed the satisfactory performance of Cmip6 models in simulation of most extreme events over the north and southern region of Nigeria, as the selected 13 climate models showed a high statistical correlation of (~0.8) when compared with the observed GPCP data except for maximum consecutive wet days (CWD). Overall, majority of CMIP6 models were able to accurately represented only six (6) of the extreme indices, and a significant majority of CMIP6 models failed in simulating maximum consecutive wet days (CWD) in both northern and southern Nigeria.

Keywords: CMIP6, Climate change, Extreme events, GCMs, Rainfall, Nigeria

1. Introduction

Extreme precipitation events are visible manifestations of climate change, which have huge consequences on the environment, people's lives, and global economy. Modelling this incidence, magnitude, and geographical scope of such events is critical for preventing future damages, hence the need for climate models to improve their capacity to mimic these extremes. Therefore, climate model performance evaluation is critical for future climate extremes projections (Zhao et al., 2020). Numerous researchers have attempted to understand the visible impacts of climate change in various parts of the world under the lens of rising temperatures and unusual rainfall patterns (Khan et al., 2020a; Ilori and Ajayi, 2020). Nigeria remains vulnerable to the effects of climate fluctuation and change, owing to its reliance on precipitation for agricultural activities, as agriculture is the population' main and primary source of income. Adequate preparation is crucial to minimizing the economic consequences of climate extremes, specifically wet and dry precipitation extremes. Global climate models have widely been used to represent current and projected alterations in regional and global climate extremes, and their use for climate driven decision outside the scientific community is expanding as a result, a comprehensive examination of their performance is essential.

Many climate models have been developed over the years for the many scenarios in the IPCC assessment reports, including phase 3 of the coupled model inter-comparison project (CMIP), phase 5 of the CMIP, and the phase 6 of CMIP. Many studies have found that the CMIP5 is superior to the CMIP3 (Tanveer et al., 2016; Taylor et al., 2012; Zhou et al., 2017). Numerous studies have evaluated the performance of the CMIP5 Models to reproduce precipitation characteristics at global scales (Homsi et al 2020; Rivera et al 2020) and some at regional and local scales (Wainwright et al. 2019; Ajayi and Ilori, 2020; Monerie et al., 2020; Akinsanola et al., 2021).

The defining features between the CMIP6 simulations and the previous CMIP phases (CMIP3 and CMIP5) are the future scenario start years and new sets of criteria for concentration, emission, and land-use scenarios. Although CMIP6 does not yet contain all ensemble GCMs, several recent studies have shown that it is more resilient than CMIP5 in some locations, including South Asia (Zhai et al., 2020) and Africa (Akinsanola and Zhou 2018; Akinsanola et al., 2021; Faye and Akinsanola 2021). As a result, it is crucial to evaluate their effectiveness in other locations where they are not currently or have not been widely implemented.

The spatial performance of GCMs varies around the world (Chen et al., 2017; Akinsanola and Ogunjobi, 2017; Homsi et al., 2020; Khan et al., 2020b). There is also the difficulty of defining performance indicators that are suitably related to the models' prediction abilities, as well as the issue of a multifunctional overall model ranking technique in model subset selection. Using various statistical criteria, studies have been done in many regions of the world to examine the performance of GCMs (Rivera and Arnould, 2020; Akinsanola 2019).

Updates to current parameterizations, the addition of new physical processes, and somewhat greater resolution relative to CMIP5 are among the features of the newest edition of the Coupled Model Inter-comparison Project (CMIP6), Kluste et al 2021). It's critical to see how effectively CMIP6 models simulate precipitation extremes over Nigeria to see if the latest model development has improved their capacity to represent the key physics that drive convection and precipitation in the region.

2. Methodology

2. 1 Study Area

Nigeria is a West African country lying between 4–14 ° N and 3–14 ° E ((Gbode et-al 2019)). It covers an area of 923,000 km^{2,} to the north of the country is Niger, to the east are Chad and Cameroon, the Benin Republic borders it at the west while the stretch of the southern part is bordered by the Atlantic Ocean. The country can be divided into three different climatic zones (Figure **1**); Guinea coast (southern Nigeria) (4–8 ° N), Savannah (8–11 ° N) and Sahel (northern Nigeria) (11–14 ° N), based on similarities in land-use/land-cover, climate and ecosystems

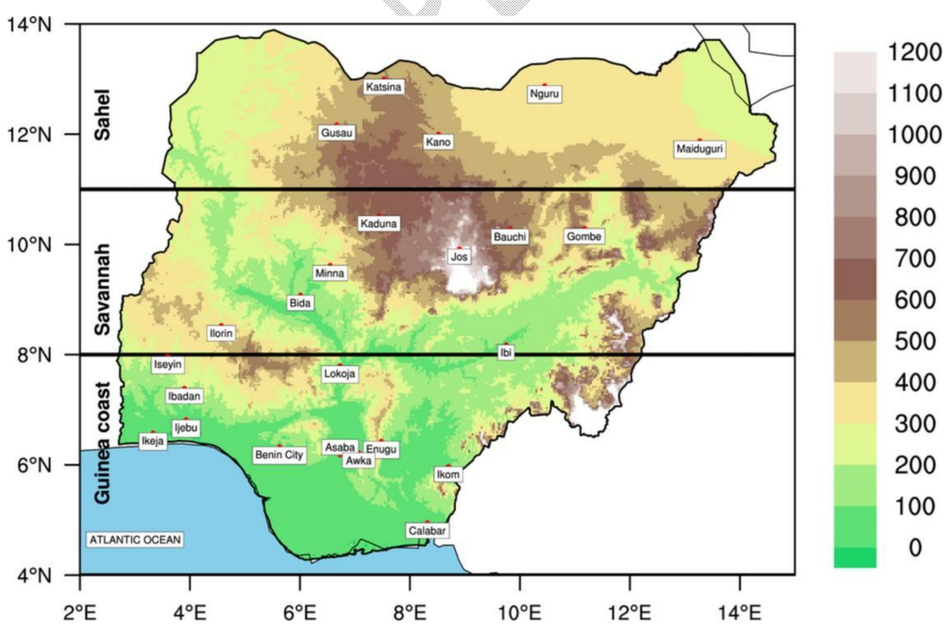

Fig. 1 Study domain showing Nigeria topography and the regions designated as Sahel and Guinea coast in the study (Gbode et-al 2019)

2.2 Observation and model data

Observation Data

The effectiveness of CMIP6 models in replicating precipitation events is evaluated employing gridded Global Precipitation Climatology Project (GPCP) datasets at 1° × 1° spatial resolution, satellite-derived products (Huffman and Bolvin 2013) from 1997 to 2014. GPCP has been shown in recent studies (e.g. Akinsannola 2021) to accurately describe mean precipitation variations as well as intense occurrences over Western Africa.

Model Datasets

We studied the effectiveness of thirteen CMIP6 models (first realization (r1i1p1f1)) in replicating extreme precipitation over Nigeria. The names of the models considered, along with their institutions and spatial precision, are described in Table 1. Because the observation (GPCP) and CMIP6 models simulations had different spatial and temporal resolutions, the assessment was conducted using a consistent timescale for both observations and models spanning from 1997 to 2014.

Table 1: Information of the thirteen CMIP6 climate models used in this study

S/N	Model	Institute	Resolution(lon × lat)	Reference
1	BCC-CSM2-MR	Beijing Climate Center (BCC) and China Meteorological Administration (CMA)	1.13 × 1.13	Wu et al. (2018); Zhang et al.(2018)
2	BCC-ESM1	Beijing Climate Center (BCC) and China Meteorological Administration (CMA)	2.81 × 2.81	Zhang et al. (2018)
3	CanESM5	Canadian Earth System Model	2.81 × 2.81	Swart et al. (2019)
4	CESM2	National Center for Atmospheric Research	1.25 × 0.94	Danabasoglu (2019)
5	CESM2-WACCM	National Center for Atmospheric Research	1.25 × 0.94	Danabasoglu et al. (2019)
6	EC-EARTH3	EC-EARTH consortium	0.70 × 0.70	EC-Earth (2019a)
7	EC-EARTH3-veg	EC-EARTH consortium	0.70 × 0.70	EC-Earth (2019a)

8	HadGEM3-GC31-LL	Met Office Hadley Centre	1.86 × 1.25	Ridley et al. (2019)
9	FGOALS-g3	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS, Tsinghua University, China	2.0 × 2.3	Pu et al. (2020)
10	MPI-ESM-1-2-HAM	Max Planck Institute for Meteorology, Germany	1.9° × 1.9°	Tegen et al. (2019)
11	MRI-ESM2-0	Meteorological Research Institute (MRI)	1.13 × 1.13	Yukimoto et al. (2019)
12	SAM0-UNICON	Seoul National University Atmosphere Model Version 0 with a Unified Convection Scheme	1.25 × 0.94	Park and Shin (2019)
13	UKESM1-0-LL	Met Office Hadley Centre	1.88 × 1.25	Tang et al. (2019)

2.3 Method

We evaluate the CMIP6 models' capacity to accurately simulate extreme precipitation indices as described by the ETCCDI. (http://www.cccma.ec.gc.ca/data/climdex/climdex.shtml). These extreme precipitation indices, which are presented in table 2 below, have been extensively used for climate extreme projection and simulation (Zhao 2019). The specific layout of these extreme indices is first examined by comparing model outputs (CMIP6 models) to gridded observations (GPCP). The model's performance is further measured using variety of evaluation metrics, including correlation, normalized bias error, and normalized root mean square error (Faye et al 2020). The findings are represented using a Taylor diagram TSS; (Taylor 2001; Wang et al. 2018), which provides a short overview of model performance relative to computed observed extreme precipitation indices designated for this study. A trend analysis is carried using the Mann Kendal sen slope test to measure magnitude of extreme indices as illustrated by (Mann 1945; Kendall 1975; Ilori and Ajayi 2020)

Table 2: Extreme precipitation indices used in this study

S/N	Extreme Indices	Name	Units
1	R10mm	Heavy precipitation days	days
2	R20mm	Very heavy precipitation days	days
3	R95pTOT	Very wet days	mm
4	R99pTOT	Extremely wet days	mm
5	PRCPTOT	Total wet-day precipitation	mm
6	RX5day	Maximum consecutive 5-day precipitation	mm
7	CWD	Consecutive wet days	days

3 Results and discussion

3.1 Extreme Precipitation Trend

Figure 2 presents the spatial trend of annual extreme precipitation indices. The Mann-Kendall trend test (Mann 1945; Kendall 1975; Ilori and Ajayi 2020) had a 95% confidence level. This is used to explore at the annual pattern of extreme precipitation over Nigeria. The extreme precipitation indices (Fig. 1) show an increasing trend over a larger part of Nigeria, with the exception of the South Eastern boundary, which reveals a statistically significant drop in PRCPTOT, R10mm, R20mm, R95pTOT, R99pTOT, and Rx5day, as well as a significant increase in consecutive wet days (CWD). During the reference period, the northern region of Nigeria, experienced a statistically significant trend of 0.24 and above, that further reflects a significantly increasing trend in annual extreme precipitation. The Northern and central regions of Nigeria have recovered from the severe droughts of the 1980s, as evidenced by this substantially rising trend (Nicholson 2013; Gbode et al 2019).

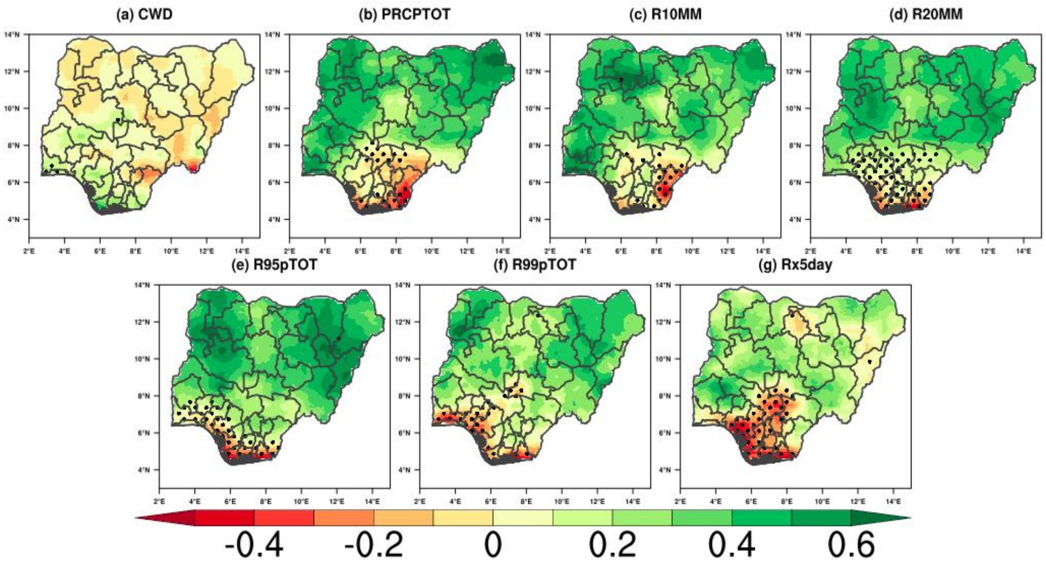

Fig 2: Trend of extreme Precipitation over Nigeria during Present day Period (1997 to 2019), (a) Dotted symbol indicate Regions that have statistically significant (95% level) Trend.

3.1 CMIP6 Representation of extreme Precipitation

The average distribution of days with heavy (R10mm) and extremely heavy precipitation (R20mm) is depicted in figures 3 and 4. Southern Nigeria is observed to have the highest number of days with rainfall over 10mm. When it came to representing the annual mean spatial pattern of heavy precipitation days (R10mm), the majority of the CMIP6 models performed similarly. Only few of model simulations accurately reflect R10 mm, with FGOALS-g3, HADGEM3, and Ukesm1 all severely underestimating R10 mm. The largest duration with rainfall greater than 20 mm is mostly concentrated towards the southern region of Nigeria as presented in Fig. 4. Beyond the fact that the vast majority of simulations underestimated R20mm, the CESM2 model had the closet annual spatial capture of extremely high rainfall days.

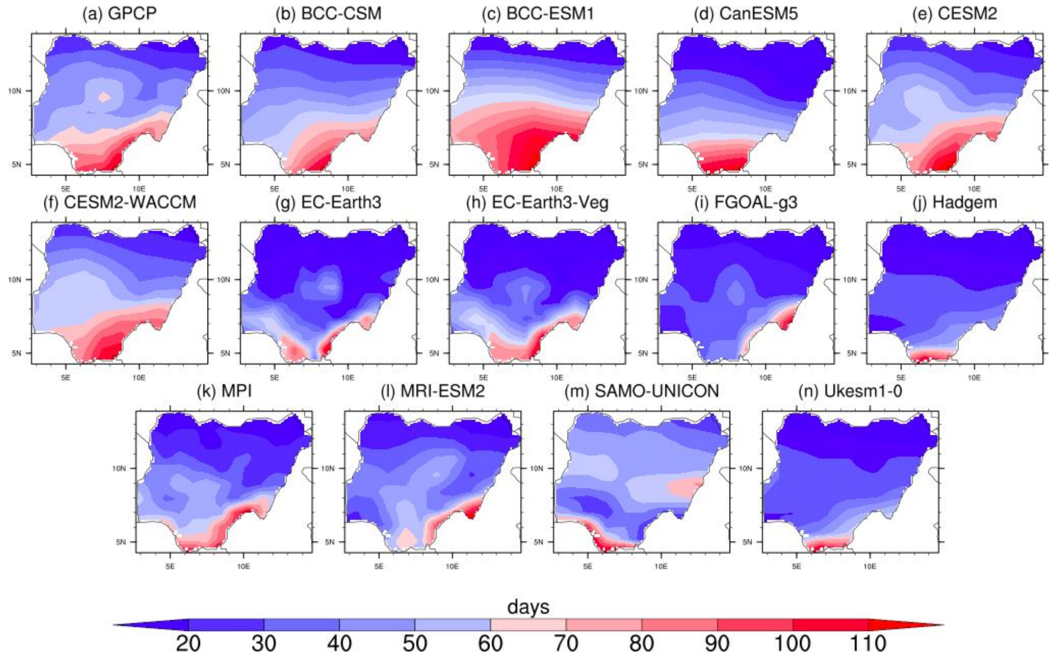

Fig 3. Heavy Precipitation days (R10mm), indicating observation a (GPCP) and b-n (CMIP6 Models) (1997 to 2014)

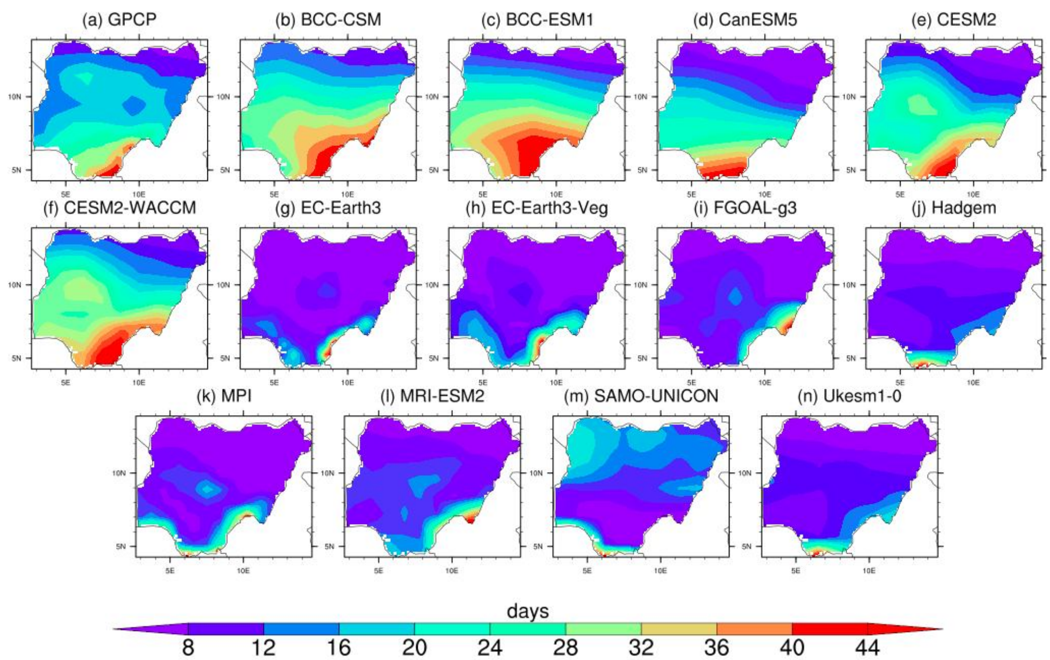

Fig 4. Very Heavy Precipitation days (R20mm), indicating observation a (GPCP) and b-n (CMIP6 Models) (1997 to 2014)

Geo-spatial pattern of annual cumulative wet-day rainfall total denoted as PRCPTOT over Nigeria is depicted in Figure 5. From the observation data (GPCP), the result indicated a declining spatial pattern of total wet-day presentation from the Guinea coast region (4–8 ° N) towards the Sahel (11–14 ° N) as seen in Figure 5 (a). Most GCMs (CMIP6) models, with the exception of FGOAL-g3, HADGEM3, and UKesm1-0, are relatively closer to the observed PRCPTOT spatial distribution. The CESM2 model simulation output outperforms the others (13 considered GCMs models) in terms of capturing both the mean annual pattern and variability of cumulative wet day rainfall across southern and northern Nigeria.

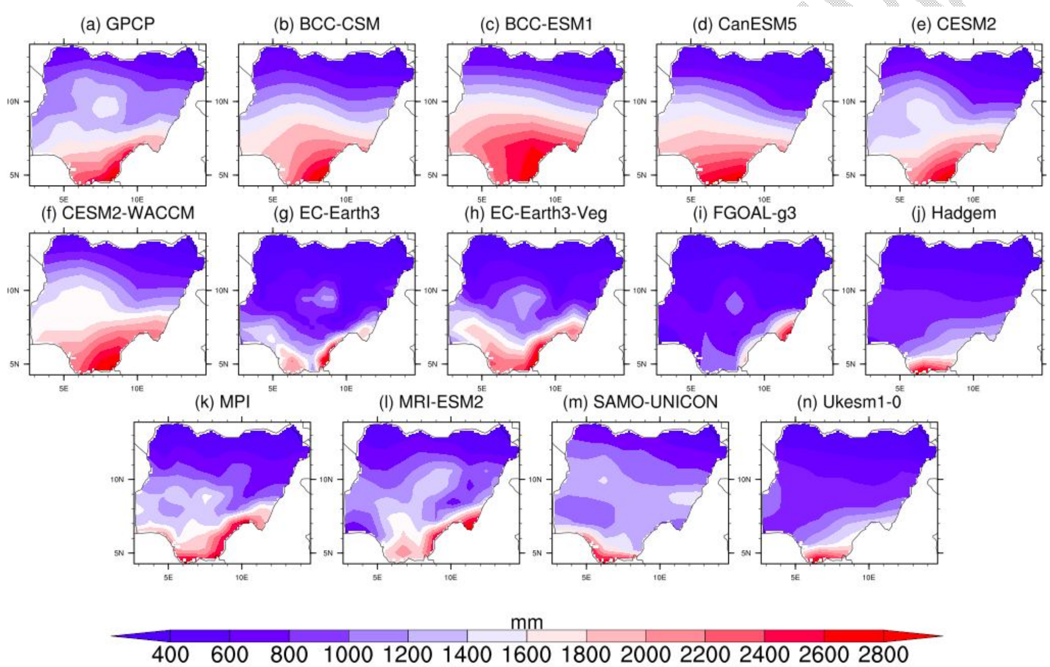

Fig 5. Total wet-day precipitation (PRCPTOT), indicating observation a (GPCP) and b-n (CMIP6 Models) (1997 to 2014)

Moreover, Fig. 6 presents the regional pattern of annual consecutive wet days (CWD) for the current period of 1997–2014. The Guinea coast region in Nigeria's southern region has by far the most rainy days. BCC-ESM1, CanESM5, CESM2, CESM2-WACCM, and SAMO-UNICON markedly overestimated CWD severity throughout the Southern region of Nigeria as compared to observation (GPCP). Conversely, the CMIP6 models were able to accurately mimic the geographical pattern of consecutive wet days over the northern region of Nigeria.

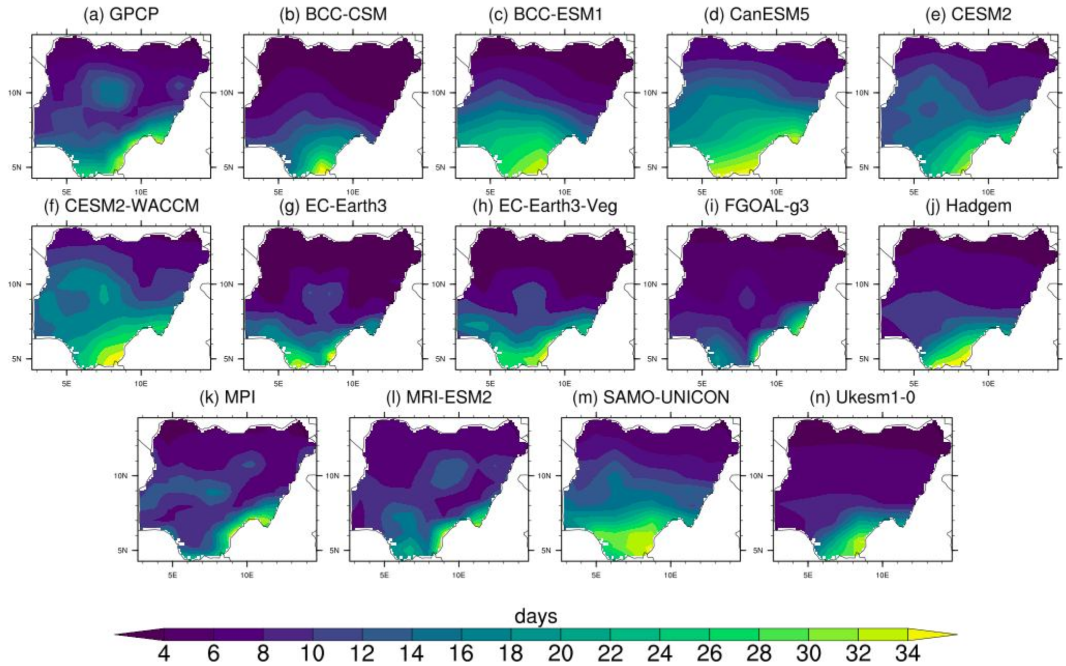

Fig 6. Consecutive wet days (CWD), indicating observation a (GPCP) and b-n (CMIP6 Models) (1997 to 2014)

Figure 7 depicts the extreme precipitation occurrences that exceeded the 95th percentile. The simulations of these models show significant discrepancies when compared to observations (GPCP). CanESM5 produces higher than expected estimates than the other CMIP6 models in southern region. The majority of models overestimated the occurrence of extreme rainfall across the jos plateau mountains. In comparison to GPCP, BCC-CSM, BCC-ESM1 CanESM5, and CESM2-WACCM, extreme precipitation events were recreated with higher estimates.

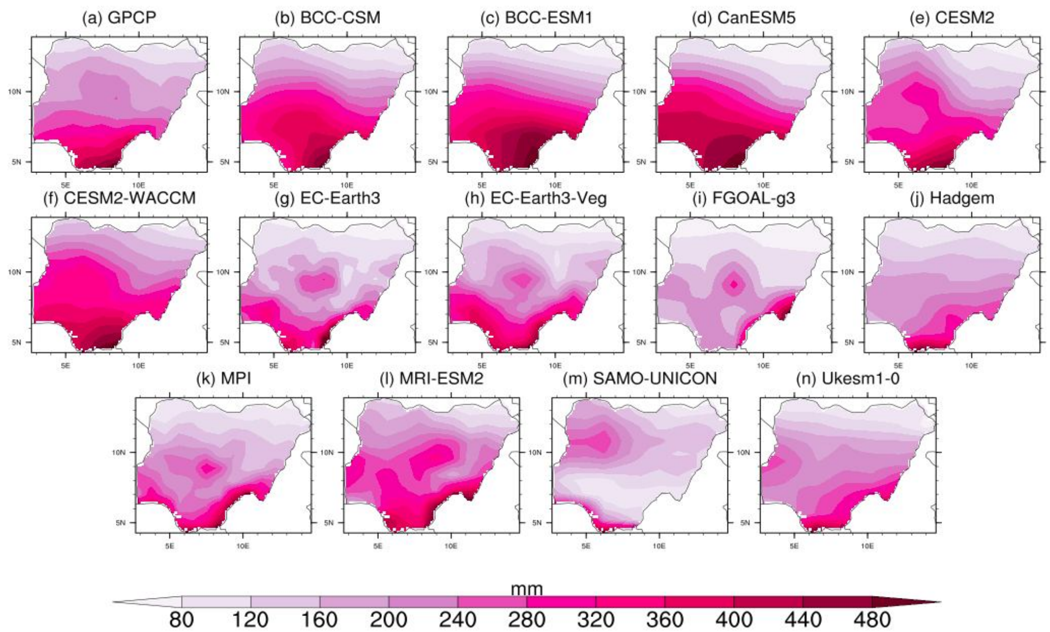

Fig 7. Very wet-days Total Precipitation R95pTOT, indicating observation a (GPCP) and b-n (CMIP6 Models) (1997 to 2014)

Figure 8 depicts extreme precipitation events that exceed the 99th percentile. Except for CanESM5, which failed extensively across the domain, the individual CMIP6 model members captured the geographic mean distributions of extremely wet days (R99pTOT).

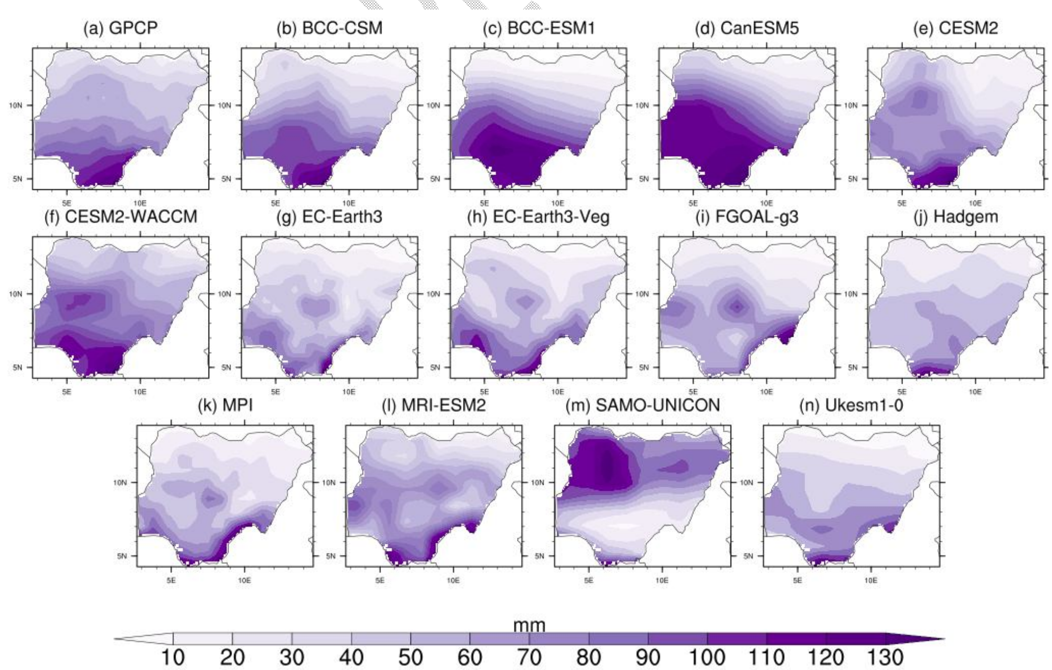

Fig 8. Extremely wet days (R99pTOT), indicating observation a (GPCP) and b-n (CMIP6 Models)

Lastly, Figure 9 presents the spatial pattern of the maximum consecutive 5-day precipitation (Rx5day). BCC-ESM1 and CESM2-WACCM grossly underestimated the RX5day in the Guinea coast, while HadGEM3-GC3 overestimated Rx5day

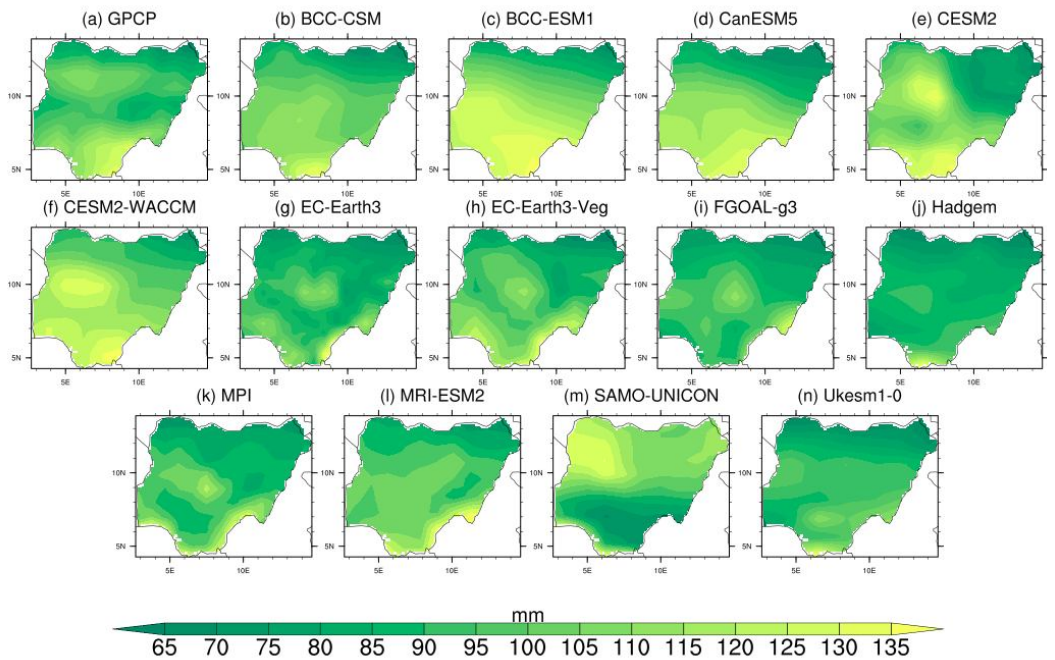

Fig 9. Maximum consecutive 5-day precipitation (Rx5day), indicating observation a (GPCP) and b-n (CMIP6 Models) (1997 to 2014)

3.2 Statistics of Model Skill

Several statistical techniques, such as the normalized mean bias error (NMBE), normalized root mean square error (NRMSE), and Taylor diagrams, are evaluated for the seven extreme precipitation indices in reference to GPCP, to measure CMIP6 models' skill to realistically capture extreme precipitation indices. Figure 10 provides a detailed analysis of CMIP6 models performance for simulating extreme precipitation as reflected in the Taylor diagram (TD) for all indices simulated in this study. The TD highlights the statistical feature of individual CMIP6 models in comparison to the reference observation (GPCP). Taylor diagram (TD) examination of extreme precipitation indicators across southern Nigeria as observed in figure 10 revealed that, with the exception of CWD, majority of CMIP6 models except for

BCC.CSM, Earth.CC CESM2.WACCM, FGOALS, MPI and MRI.ESM2 had excellent simulation of all indices with correlation values greater than 0.8 (r>0.8).

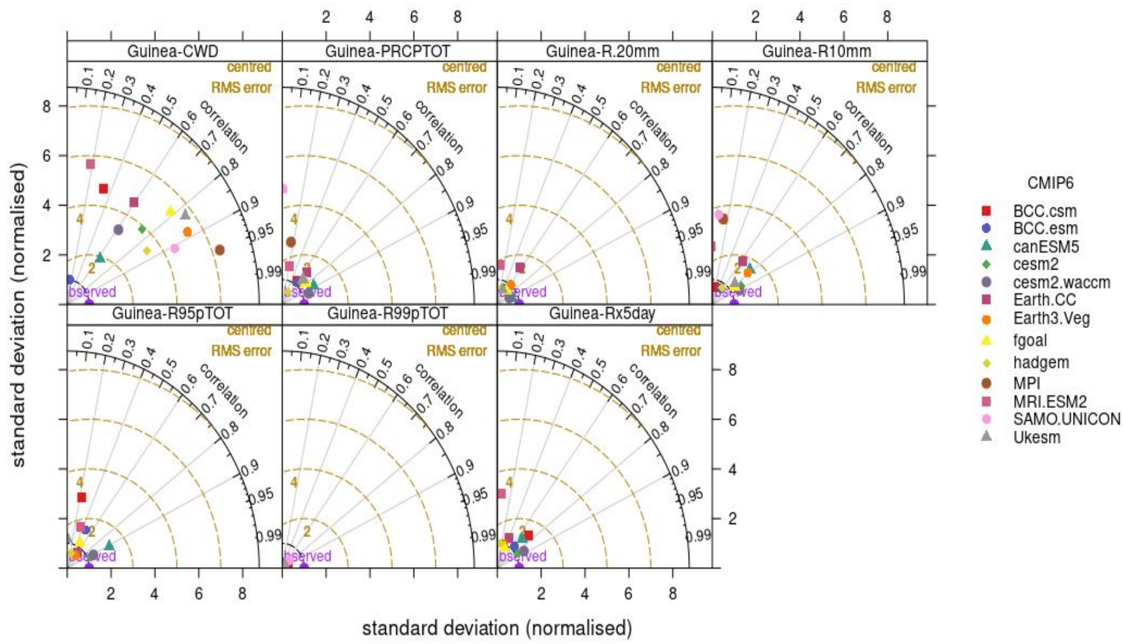

Fig 10. Taylor diagram showing the correlation between GPCP observations and CMIP6 Models (1997 to 2014).

In support to result in Figure 10, the normalized mean bias error (NMBE) and normalized root mean square error (NRMSE) of each model relative to the GPCP observation for all extreme precipitation indices is presented in figure 11. The findings indicated varying positive and negative biases for the majority of the indices. CWD, Rx5day, and PRCPTOT, for example, have positive biases in most models, whilst R20mm has negative biases in all models.

Except for the representation of CWD, the NRMSE given in Figs. 11 showed seemingly low values relative to GPCP observation for most models. The CMIP6 models and the reference observation have consistently high errors in CWD.

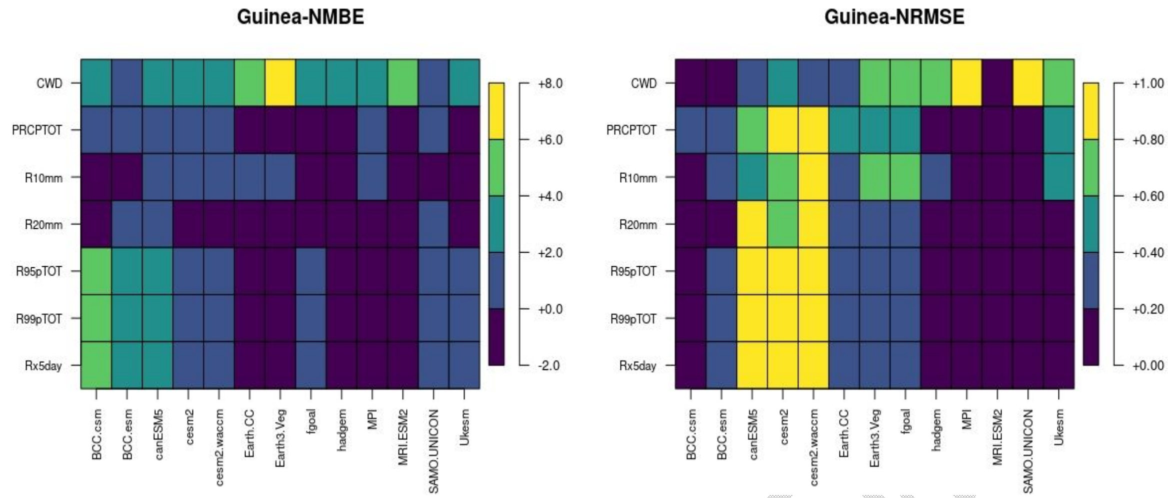

Figure 11. Portrait diagram of Normalized Mean Bias error and root mean square error for all selected indices over Southern Nigeria (1997 to 2014)

Figure 12 provides a summary of CMIP6 models accuracy skill for all indices simulation over Northern Nigeria in perspective of extreme precipitation as depicted in the Taylor diagram (TD). Relative to a reference observation (GPCP), the taylor diagram for northern Nigeria demonstrates an outstanding simulation of all indices for majority of the models with correlation values more than 0.8 (r>0.8) except in CWD, with BCC.CSM CanESM5, FGOALS and UKESM having correlation values less than 0.8 (r<0.8).

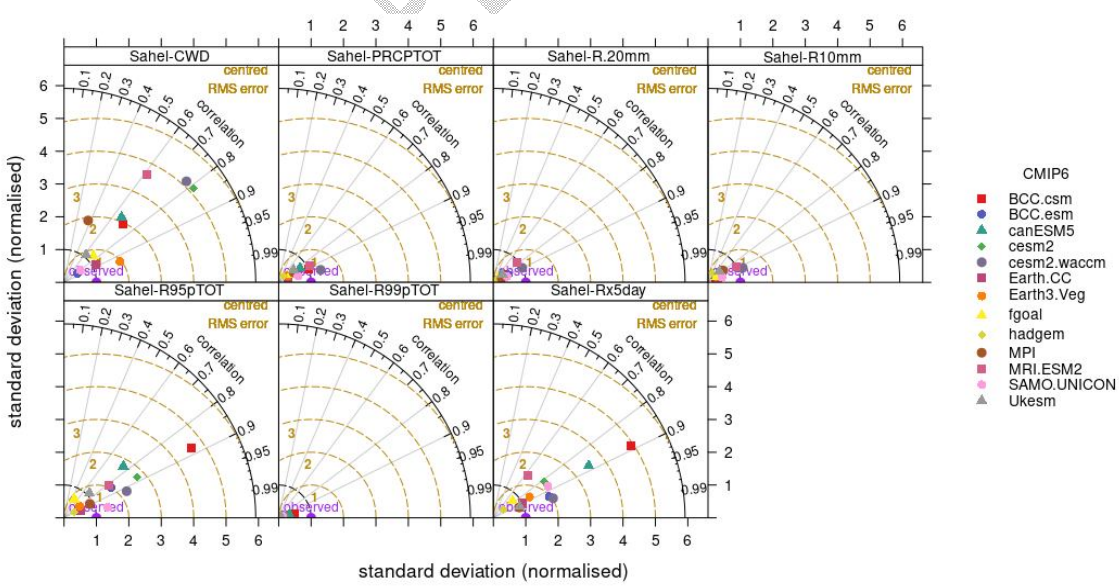

Fig 12. Taylor diagram showing the correlation between GPCP observations and CMIP6 Models(1997 to 2014).

Except for BCC.ESM, SAMO-UNICON, EC-Earth3, Hadgem, MPI, and Fgoal, most of the models had positive biases for CWD, Rx5day R95pTot, and PRCPTOT. When evaluated with the reference observation (GPCP), the NRMSE provided in figure 12 indicated an overall low scores for most models.

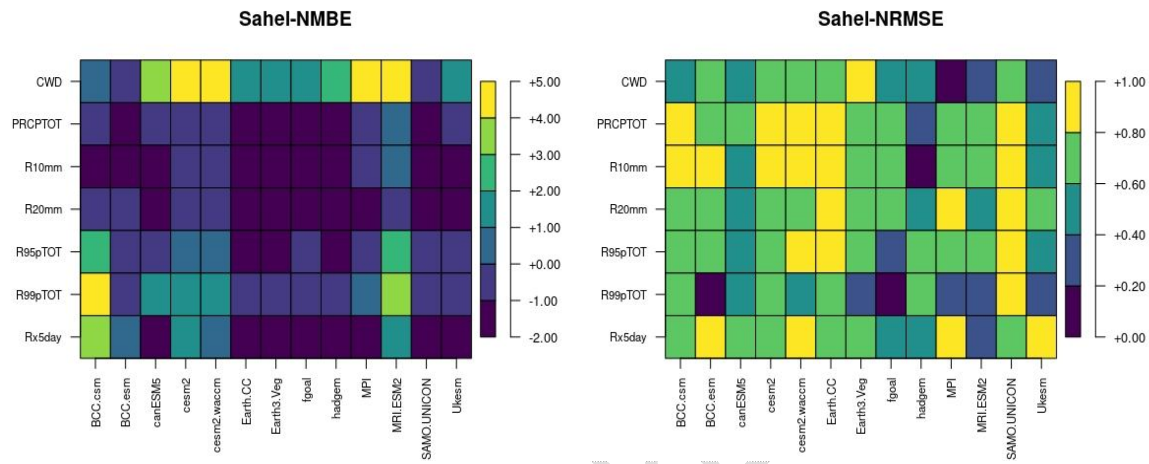

Figure 13. Portrait diagram of Normalized Mean Bias error and root mean square error for all selected indices over Northern Nigeria (1997 to 2014).

4 Conclusion

The skill performance of the CMIP6 model in reproducing extreme precipitation indices in northern and southern Nigeria is investigated in this paper. Overall, majority of the selected CMIP6 models accurately represented six (6) out of seven (7) of the extreme indices considered in the study, with majority of the CMIP6 models failing to replicate maximum consecutive wet days (CWD) in both northern and southern Nigeria. The selected CMIP6 performs relatively well in the northern region of Nigeria compared to southern region in repicating its spatial distribution of all seven extreme indices chosen in the study. The study also indicated that no single model can accurately predict all seven extreme precipitation indices in both southern and northern region of Nigeria. When compared to other models, each model has its own set of strengths and flaws. Climate model users seeking models best suited for their applications will benefit from this skill assessment of the model's effectiveness, as will climate model designers interested in understanding subregions and mechanisms (such as orographically linked extreme rainfall and related forced ascent) that are not yet adequately represented by present climate model configurations. This skill assessment is a guide for both users and developers. In order to improve regional climate forecast accuracy and to use these models in research using downscaling to study water resources, flooding, and drought projections, identifying and eliminating bias in the CMIP6 models is an essential next step.

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