International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 6, Issue 6, pp 68-84, June-2022

https://doi.org/10.47001/IRJIET/2022.606010

Comparing the Performance of Six Regional Climate Models and Their Ensemble over West Africa

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***Abstract* - This study assessed the ability of six CORDEX Regional Climate Models (RCMs) in comparison to their ensemble mean (ENSEMBLE) in reproducing rainfall distribution over West Africa from 1951 to 2005. Using annual and seasonal climatological and statistical description, all the RCMs and their ensemble were evaluated against Climate Research Unit (CRU) rainfall observational product. over three homogenous climatic zones of Guinea Coast, Savannah and Sahel. Results from annual rainfall evaluation indicated that most of the RCMs and ENSEMBLE captured the temporal and spatial distribution over West Africa as they simulates single rainfall peak over the Savannah and Sahel zones. Annual statistical evaluation performed shows that most of the RCMs and ENSEMBLE are in good agreement with the CRU. In particular, RACMO outperformed the ENSEMBLE in the Guinea Coast just as CRCM, HIRHAM, RCA and REMO did over the Savannah. Seasonally, the statistical performance of the six RCMs and the ENSEMBLE in DJF season is relatively poor while most of the individual RCMs performed better than ENSEMBLE in SON season over entire West Africa, Savannah and Sahelian zone. Spatial pattern also revealed that most of the RCMs replicated mean seasonal distribution in DJF and MAM season. The overall performance of all the RCMs and the ENSEMBLE varies in different climatic zones and from one season to the other. However, CRCM and RCA consistently performed better than others and can be used in place of the ENSEMBLE to study rainfall over West Africa.**

Keywords: West Africa, Climatic Zones, CORDEX, Regional Climate Model, Model Evaluation.

I. INTRODUCTION

At a global, regional and local level, the response of climate to increasing global warming level are observed in the rise of the magnitude and intensity of extreme events (Alexander, 2016; IPCC, 2014). As a result, this response has led to reduction in length of wet spell and light precipitation events in addition to increase in the length of dry spell that constitute a threat to livelihoods of people in the communities that depends on rainfall for various activities (World Bank, 2012). Spatial and temporal distribution of rainfall over West Africa is very important for many days to day activities like rain-fed system of agriculture, flood and drought forecasting, monitoring of water resources and generation of hydro-electric power (Ajayi and Ilori 2020; Akinsanola and Ogunjobi 2017; Omotosho and Abiodun 2007; Parry *et al*. 2007). Hence, spatiotemporal variations in amount of rainfall have significant effects on economic growth coupled with direct and indirect implications on West African populace. West Africa Monsoon (WAM) is one of the most dynamic and important phenomena of climate system in West Africa (Sultan *et al*. 2011) caused by seasonal reversal of the wind as a result of differential heating between ocean and land (Le Barbé et al. 2002; Sultan and Janicot 2000). The WAM plays a major role in producing more than 80% of the annual rainfall in West Africa (Fink et al. 2006; Omotosho and Abiodun 2007). Generally, WAM flow dynamics is been characterized by: intra-annual oscillation of the Inter-Tropical Discontinuity (ITD) that reaches it northernmost latitudinal position of 22-23 ºN in July/August and controlled by the position of the sun, inland moisture transport associated with the West Africa Westerly Jet (WAMJ), Tropical Easterly Jet (TEJ) located around 200 hPa level and African Easterly Jet (AEJ) within 600-700 hPa level (Jung and Kunstmann 2007; Sylla *et al*. 2013). The African Easterly Waves (AEWs) formed due to the combined barotropic and baroclinic instabilities of AEJ trigger the formation of Mesoscale Convective Systems (MCSs) and squall lines (Fink and Reiner 2003) that interact in a complex way to produce the monsoon rainfall (Sultan *et al.* 2011). The influence of some climate forcing and global teleconnections like Sea Surface Temperature (SST), Madden-Julian Oscillation (MJO), El~Nino Southern Oscillation (ENSO) and Northern Atlantic Oscillation (NAO) on inter-annual and inter-seasonal variabilities in the WAM have been documented by many researchers (Giannini *et al*. 2003; Lu and Delworth 2005; Ndehedehe et al., 2016; Vizy and Cook 2002). In providing helpful and accurate forecast of WAM variability and its impacts on West African rainfall, there are limitations due to inadequate ground observation datasets and insufficient knowledge and understanding of the complex scale interactions between hydrosphere, biosphere, and atmosphere that determine WAM nature (Redelsperger *et al*. 2006). To the policy makers, non-governmental organizations and climate scientists,

ISSN (online): 2581-3048
Volume 6, Issue 6, pp 68-84, June-2022
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providing lasting solution to this identified gaps have been a source of concern in order to initiate lasting action plans to adapt and mitigate against the socio-economic impacts of variability of WAM and projected climate change (Akinsanola *et al*. 2015; Ajayi and Ilori 2020). Hence, the development of climate models as the primary and fundamental tools that are used for investigating and analyzing the response of climate system to various atmospheric forcing, thereby, making climate predictions for different timescales possible.

For many decades now, numerous climate researchers have adopted the Global Climate Models (GCMs) to study climate pattern at regional and global level (Almazroui et al. 2017; Christensen et al. 1997; Maidment et al. 2015). However, one of the disadvantages of GCMs is the low horizontal resolution leading to inability of the model to capture and resolve the dynamics of ocean wave needed for correct representation of El~Nino development while the dynamics and physics of GCMs are incomplete (Akinsanola and Ogunjobi 2017). However, these above mentioned disadvantages of GCMs have necessitated the development and the use of dynamically downscaled and high resolution Regional Climate Models (RCMs) that are now being use by numerous institutions and climate scientist for different studies of climate related application (Giorgi and Gutowski, 2015; IPCC, 2004; Pal et al. 2007; Wilby and Fowler, 2010). This is so because new components have been added, widespread coordinated ensemble experiments have shown good realistic climate signal after they have been statistically compared to observations (Flato et al. 2013; Rummukainen 2010). The introduction of RCMs like Coordinated Regional Climate Downscaling Experiment Program (CORDEX; https://www.cordex.org) has helped in understanding extreme precipitation pattern, future precipitation trend in many regions of the world and other climate processes (Ajayi and Ilori 2020; Jacob et al. 2014; Nikulin et al 2012; Russo et al. 2015). CORDEX through World Research Climate Program (WRCP) downscaled GCMs dynamically to a higher resolution that are freely available for the public (Giorgi et al. 2009). Due to different lateral boundary conditions and parameterizations employed in running RCMs, studies conducted over Africa (Ajayi and Ilori 2020; Akinsanola et al. 2015; Endris et al. 2013; Gbobaniyi et al. 3013) have identified the need for in depth performance analysis and evaluations to determine limitation of each RCMs.

Over West Africa, different studies have evaluated the performance of CORDEX RCMs in reproducing pattern of climate (Ajayi and Ilori 2020; Akinsanola et al. 2015; Akinsanola and Ogunjobi, 2017; Diallo et al. 2012; Klutse et al. 2016) as it is observed over East Africa (Diro and Tompkins, 2012; Endris et al. 2015; Osima et al. 2018), central Africa (Fotso-Nguemo et al. 2017; Vondou and Haensler, 2017), North Africa (Tramblay et al. 2013) and South Africa (Maure et al. 2018). However, many of these mentioned studies were based on the first phase of the CORDEX when ERA-Interim re-analysis was used as driven runs by majority of the model centers (Dee et al. 2011; Akinsanola et al. 2017). GCMs that took part in Coupled Modelling Inter-comparison Project (CMIP5) were used in CORDEX second phase to downscaled future climate projection and the historical run (Taylor et al. 2012). Precisely, over West Africa, most studies have posited a good performance of ENSEMBLE mean of RCMs in replicating the spatial pattern of West African rainfall distribution, annual cycle and trend, inter-annual variability of West African climate features (Ayugi et al. 2019; Ilori and Ajayi, 2020; Sylla et al. 2016). It is worth mentioning that the general acceptability in the use of ENSEMBLE mean of many RCMs to study and analyze climate has over shadow the need to evaluate performance of individual RCM against ENSEMBLE mean and observations. This is important as potential uncertainties exhibited by different RCMs can be improve before each RCMs can be adopted for the impact of climate change analysis over West Africa.

The aim of this study is to evaluate the performance of six RCMs and their ENSEMBLE mean over West Africa that was dynamically downscaled from CMIP5 GCMs under CORDEX-Africa. In the present era of increasing magnitude and intensity of extreme climate events, understanding the performance and identifying the best models will help in exploring the projected climate change for mitigation and adaptation planning purposes. The later sections of this paper are structured as follow: section 2 presents material and methodology as section 3 discuss the results while conclusion and recommendation are found in section 4 of this paper.

II. DATA AND METHODOLOGY

2.1 Locality of the study area

West Africa located within the longitudinal and latitudinal band of 20 ºW – 20 ºE and 0º – 20 ºN respectively as shown in Fig. 1. Bounded in the north by Mali and the Republic of Niger, in the east by Cameroon highlands and in the south by Atlantic Ocean that serves as sources of moisture transport into West Africa. Politically, West Africa includes sixteen countries: Benin, Burkina Faso, Cape Verde, Gambia, Ghana, Guinea-Bissau, Guinea-Conakry, Ivory Coast, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone and Togo covering an approximate area of 5 million km^2. Following Omotosho and Abiodun (2007) method

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of classification using climate and weather pattern, ecosystem and landuse/landcover similarity that was recently use by Ajayi and Ilori (2020), West Africa is divided into three climatic zones: Guinea Coast zone with latitudinal band of 4° – 8°N and annual average rainfall in the range of 1575 mm – 2533 mm (Oguntunde et al. 2011)), Savannah zone within 8° – 11°N and annual average rainfall between 879 – 1535 mm while the Sahel falls within 11 °N – 16 °N. Annual average rainfall over the Sahel zone ranges between about 433 mm to 969 mm. Rainfall distribution over West Africa follow the seasonal oscillation of the ITD zone that reaches it northernmost position of 21° – 23°N in August (Nicholson, 2013) together with southwesterly monsoon flow. ITD is associated with seasonal change in the wind direction from northeasterly during December – February season to southerly that transport moisture into the continent during boreal summer of June – July (Nicholson 2013). Savannah and Sahel have rainfall pattern that peaks in August while the Guinea Coast exhibits bi-modal rainfall pattern with little dry season (LDS) between its peaks which is the response to the seasonal migration of the ITD (Hagos and Cook, 2007; Le Barbe et al. 2002).

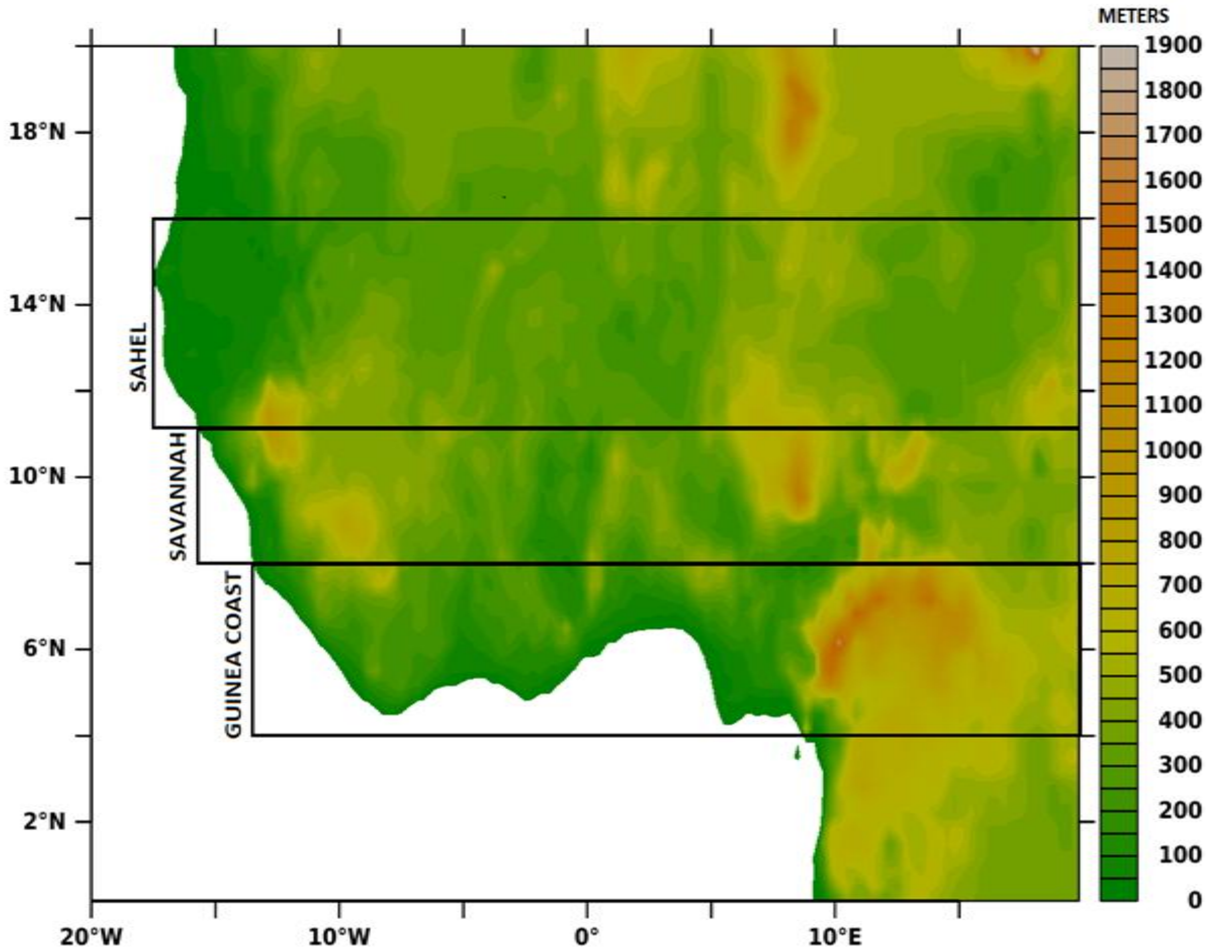

Figure 1: West Africa map showing the homogenous three climatic zones and elevation at interval of 50 meters (sourced from Ilori and Ajayi, 2020)

2.2 Reanalysis and Model datasets

Six different RCMs, their ENSEMBLE mean and observation datasets were used for this study. The monthly rainfall simulations dataset used in this study comprise of different RCMs that are driven by six GCMs from CMIP5 used in CORDEX second phase. Comprehensive list and detail information of all the RCMs and their driven GCMs from CMIP5 are presented in Table 1. All the RCMs are gotten from the archive of CORDEX-AFRICA through the Earth System Grid Federation (ESGF) at a horizontal resolution of 0.44 over Africa. The datasets span through a period of 55 years from 1951 to 2005 that covers decades of significantly dry and wet years over West Africa (Nicholson 2013) making it suitable for this study. In evaluating the performance of simulations across Africa, the required quality of observed data in time and spatial coverage has been a challenge (Nikulin et al. 2012). In this study, we adopted the precipitation datasets from the Climatic Research Unit (CRU TS v4.03) with a resolution of 0.5 ° x 0.5 (Harris et al. 2018) as observation dataset used in evaluating all the RCMs. Similar approach has been used in the past over West Africa (Ajayi and Ilori, 2020; Akinsanola and Ogunjobi, 2017). The rainfall estimates from all the six RCMs are

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provided in flux form (kg/m^{3}s) while the observed CRU rainfall estimate is in monthly accumulations (mm/month). This was addressed by converting the precipitation flux from all the RCMs into accumulated monthly rainfall by making use of every month's data matrix. Also, the difference in spatial resolution between the CRU and all the RCMs was addressed by re-gridding the CRU dataset to a spatial resolution of 0.44 (~ 50 km).

Table1: Detail description of the CORDEX dynamically downscaled RCMs used for this study

S/N	Institute	Driven GCM	RCM	Abreviation
1	Centre national de recherches météorologiques (France)	CNRM-CRAFACS-CNRM-CM5	CLMcom - CCLM4	CCLM
2	Consortium of european research institution and researchers	ICHEC-EC-EARTH	KNMI - RACMO22T	RACMO
3	Institut pierre-simon laplace, France	IPSL-IPSL-CM5A-LR	GERICS - REMO2009	REMO
4	Max planck institute for meteorology (Germany)	MPI-M-MPI-ESM-LR	UQAM - CRCM5	CRCM
5	Norwegian climate centre (Norway)	NCC-NorESM1-M	DMI - HIRHAM5	HIRHAM
6	National institute for environmental studies, and japan agency for marine-earth science and technology (MIROC), Japan	MIROC-MIROC5	SMHI - RCA4	RCA

2.3 Methodology

Different scalar accuracy methods were employed to evaluate the performance of all the RCMs and the ENSEMBLE in replicating the fundamental rainfall characteristics for the period of 1951 to 2005 over West Africa. Four seasons were used for comparative analysis in three climatic zones of West Africa: the dry season known as winter (December – February), the pre-rainy season being called spring (March – May), the rainy season (June – August) known as summer, and the post-rainy season (September – November) regarded as fall. The comparative analysis includes statistical and climatological description (Akinsanola and Ogunjobi, 2017; Ayugi et al. 2019). Inter-seasonal and inter-annual variability, spatial distribution pattern of rainfall and latitude-time cross-section were used to described the climatological performance of all the RCMs and the ENSEMBLE. Statistically, the performance of CORDEX RCMs in simulating rainfall were assessed using mean bias error (MBE), mean gross error (MGE), root mean square error (RMSE) and Taylor diagrams (Taylor 2001). Taylor diagram synthesize the degree of corresponding between CRU observation, CORDEX RCMs and ENSEMBLE graphically in terms of amplitude and phase of their evolution, determined by Pearson correlation coefficients (r), MBE, RMSE and Standard Deviation (SD). Many researchers have used Taylor diagram to evaluate and gauge the skill of different models (akinsanola and Ogunjobi, 2017; Kalognomou et al 2013).

III. RESULTS AND DISCUSSION

3.1 Annual Climatology and Statistical Description

The ability of each of the RCMs and ENSEMBLE to replicate the pattern of annual average rainfall distribution compared to CRU over West Africa is shown in Fig. 2 from 1951 – 2005. From CRU rainfall pattern, a northward decrease in rainfall is observed over West Africa with the highest amount of rainfall higher than 2400mm domicile over the coast region of Sierra Leone and Liberia that extend to southeastern part of Nigeria. To the north of 14 °N exist a region of moderate to low amount of rainfall (less than 900mm). This pattern of rainfall distribution is consistent in most of the RCMs and the ENSEMBLE except in CCLM where region of highest rainfall localized over the coastal region of Nigeria and Jos Plateau. The region of moderate to low rainfall over the north of 14 °N in most of the RCMs and ENSEMBLE mean is slightly different in CCLM where it extends from the north of 14 °N to the southwestern part of West Africa. Also, there is variation in that amount of rainfall over the region of highest and low rainfall from one RCM to the other as the zone of highest rainfall further coincides with highlands of Cameroon Mountains, Jos Plateau, Fouta Djallon. This pattern of rainfall observed from CRU, ENSEMBLE mean, and all the RCMs is in agreement with results of Ajayi and Ilori (2020), Oguntunde et al. (2011), [45, 48]. Fig. 3 show the annual cycle of rainfall average overage the three homogenous climatic zones and the whole of West Africa for all the RCMs, ENSEMBLE and CRU from 1951 – 2005. This was done in order to evaluate the capability of each RCMs in simulating amplitudes and phases rainfall throughout the year in terms of peaks and minimum of the rainfall.

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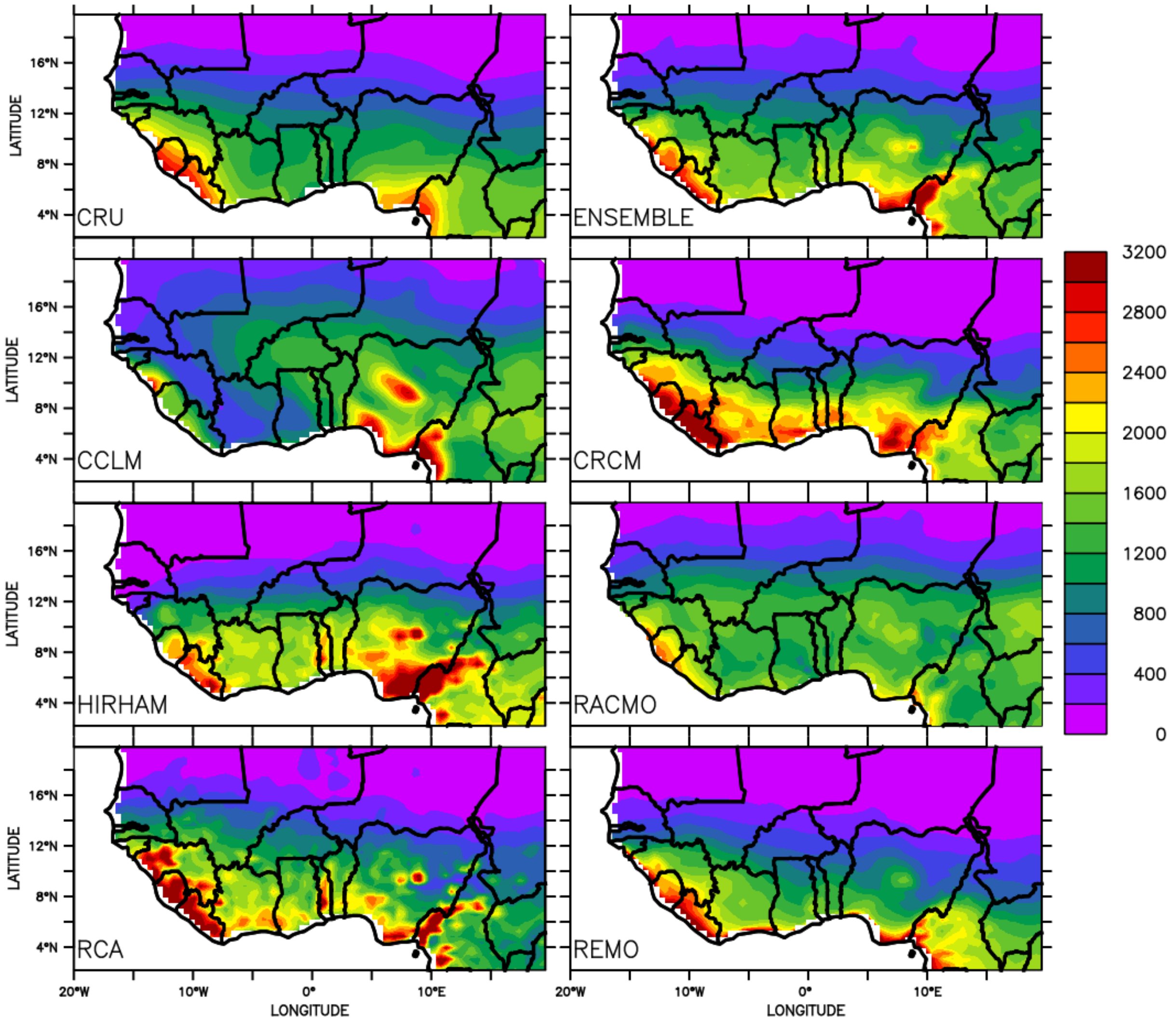

Figure 2: Spatial patter of annual average rainfall (mm/year) from 1951 – 2005 over for CRU, all the RCMs and their ENSEMBLE mean

Observed over the Guinea Coast, are two rainfall peaks with primary and secondary maximum in June and September respectively exhibited by CRU. Between the two peaks occur a deep (minimum rainfall) called little dry season (LSD) in August when the ITD is at its northernmost position (Dhonneur, 1970; Nicholson 2013) and as a consequence of monsoon rain band seasonal migration from north to south in the Guinea Coast. A noticeable difference in number of peaks and rainfall amount was observed in REMO, HIRHAM, CRCM and ENSEMBLE while RCA, RACMO and CCLM shows two maximum peaks as it is observed with the CRU but the timing of the peaks and LDS varies from one model to another. This has been previously reported by Akinsanola and Ogunjobi (2017) and was also attributed to differences in response and sensitivity of each of the RCMs and ENSEMBLE to Thorncroft et al. (2011) described sea surface temperature. Rainfall over the Savannah zone exhibits a single peak in August with length of the rainy season started in May and ends in September. Most of the RCMs and the ENSEMBLE overestimated and simulated the unimodal pattern of rainfall that attained their peak in August except RCA, RACMO and CCLM that peaks in July and underestimated rainfall over the Savannah during this period. RACMO and RCA captured two peaks over this zone. From the Sahel, most of the RCMs and ENSEMBLE mean replicate the observed single peak of the rainfall in August while only RCA show two peaks. RACMO and CCLM overestimated the peak rainfall amount as the rest of the RCMs underestimated the peak rainfall. The observed length of the rainy season is within four months between June and September. Over the whole West Africa, majority of the RCMs peak occur in August while it is July in CCLM and September in HIRHAM. It is important to point out that the period of minimum rainfall (LDS) in July/August coincides with the period of maximum (peak) over the Savannah Sahel. This is as a result of the occurrence of monsoon jump reported by Akinsanola *et al*. (2015) and Sultan and Janicot (2003). This monsoon jump is associated with the northward displacement of the monsoon rainfall front to about 10°N in late June and early July that resulted in a sudden cessation in rainfall over the Guinea Coast and high rainfall amounts in the

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Savannah and the Sahel (Akinsanola and Ogunjobi 2017; Gbobaniyi *et al*. 2013). The retreat of this above mentioned monsoon Jump leads to the second rainfall peak observed in the Guinea Coast.

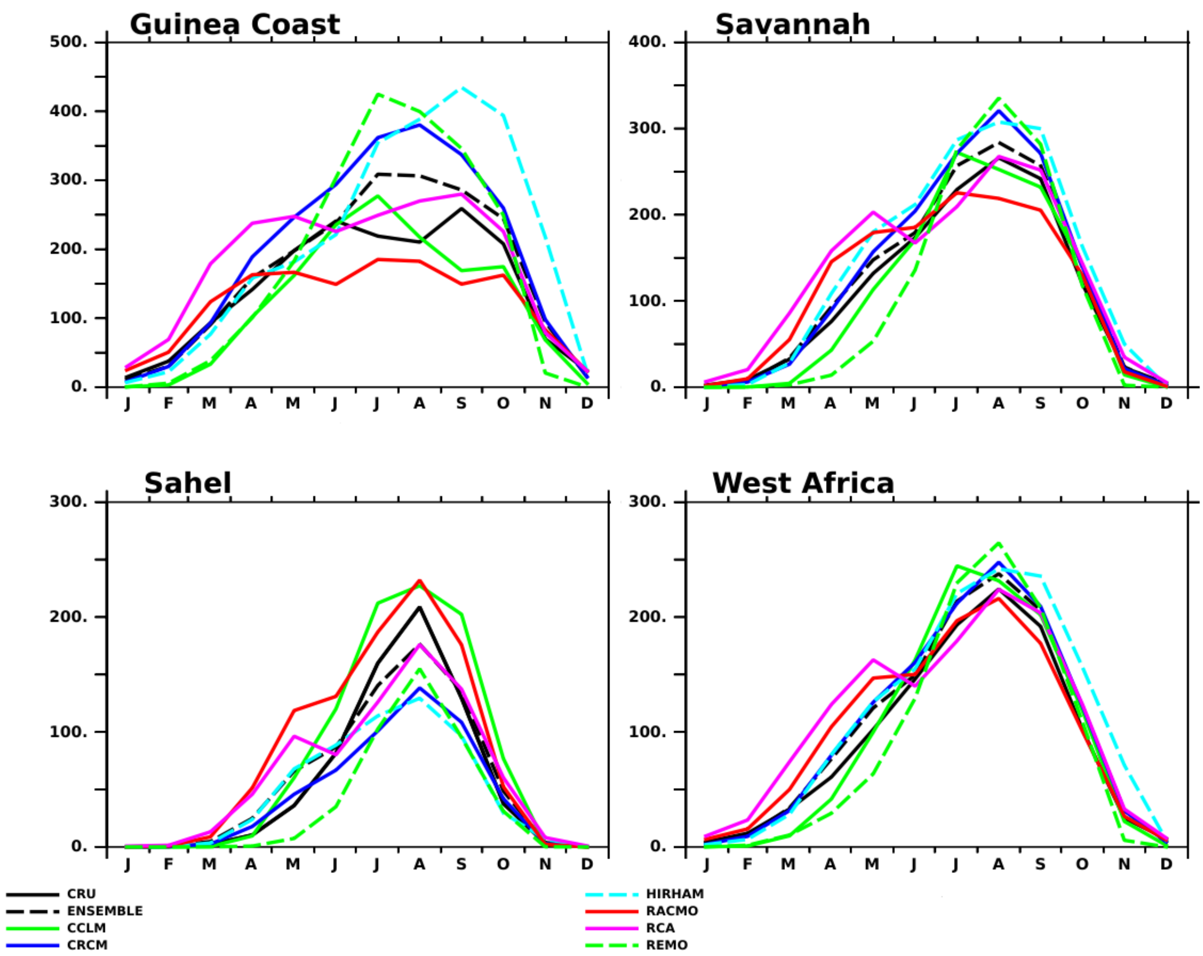

Figure 3: Zonal variation of monthly mean rainfall (mm/month) for the CRU, all RCMs and ENSEMBLE average over the Guinea Coast, Savannah, Sahel, and entire West Africa from 1951 to 2005

The correlation coefficient (*r*), root mean square error (RMSE), mean gross error (MGE), mean bias (MB) and normalized standard deviation (shown with Taylor's diagram) were used to performed annual statistical evaluation of all the RCMs and ENSEMBLE mean over the three homogenous climatic zones and entire West Africa. The results of all these statistical analyses are presented in Table 2. In the Guinea Coast, ENSEMBLE was observed to have about 70% agreement with the CRU data due to the correlation value of 0.70 and relatively low MGE and RMSE. RACMO slightly show a higher agreement with the CRU with a difference of 1% from the ENSEMBLE and correlation value of 0.71, HIRHAM and CCLM performed very low over Guinea Coast having lowest correlation coefficient and highest errors (MGE and RMSE). Over the Savannah, HIRHAM, CRCM and REMO performed better than the ENSEMBLE with a correlation of 0.88, 0.84 and 0.81 respectively while ENSEMBLE mean show an agreement of about 77% with the CRU over the Savannah. CCLM has the least performance over Savannah with highest MGE and RMSE values of 49.74 and 63.23 respectively. However, over the Sahel, correlation of all the RCMs and the ENSEMBLE are relatively higher as the MB, MGE, and RMSE are lower than other climatic zones. ENSEMBLE mean, CRCM and RCA show a higher agreement (more than 91%) with the CRU owing to their higher correlation values that are greater than 0.91. Overview of all the RCMs and the ENSEMBLE performance evaluation over West Africa (Table 2) show that ENSEMBLE mean and CRCM are in better agreement with the CRU data followed by RACMO, REMO and RCA while CRCM have a correlation coefficient of 0.63 as the least performing RCM averaged over the entire West Africa. Similar results for the performance of different models have earlier been reported by Akinsanola et al. (2015), [45, 48] and Akinsanola and Ogunjobi (2017) and over the great horn of Africa (GHA) by Ayugi (2019).

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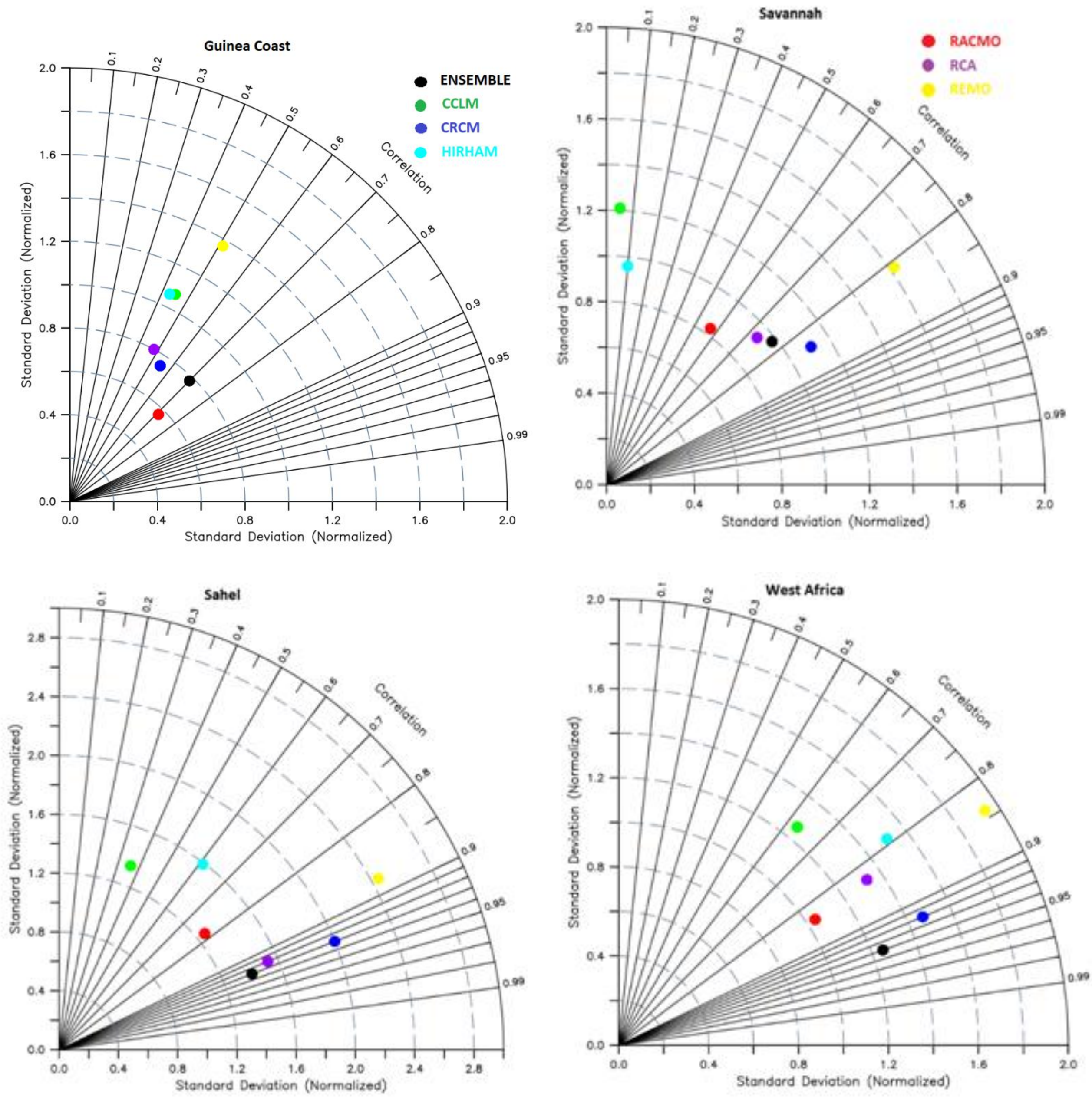

Figure 4: Taylor diagram for average annual rainfall over each climatic zone and whole West Africa from 1951 to 2005. Solid circles represent individual RCMs and ENSEMBLE while the radial arc show the normalized standard deviation

Table 2: Detailed output of annual statistical comparison between all the RCMs, ENSEMBLE and CRU datasets over the homogenous climatic zones and entire West Africa from 1951 – 2005

DATA SET	GUINEA COAST				SAVANNAH			
	MB	MGE	RMSE	*r*	MB	MGE	RMSE	*r*
ENSEMBLE	-20.59	41.12	55.89	0.70	-9.14	22.62	27.62	0.77
CCLM	24.16	61.94	78.43	0.45	5.73	49.74	63.23	0.51
CRCM	-49.69	62.71	76.14	0.55	-16.25	30.80	36.86	0.84
HIRHAM	-63.61	97.38	147.40	0.44	-28.43	49.98	62.33	0.88
RACMO	21.31	49.49	60.75	0.71	-5.48	34.88	43.51	0.57
RCA	-33.33	67.02	97.84	0.48	-20.10	43.28	56.09	0.73
REMO	-22.36	81.27	123.50	0.51	9.69	43.80	58.02	0.81

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DATA SET	SAHEL				WEST AFRICA			
	MB	MGE	RMSE	r	MB	MGE	RMSE	r
ENSEMBLE	-1.99	11.71	15.87	0.93	-7.47	20.29	29.97	0.94
CCLM	-22.56	36.03	42.54	0.36	-6.45	44.51	56.76	0.63
CRCM	10.99	17.57	21.46	0.93	-7.78	29.95	40.79	0.92
HIRHAM	8.01	20.91	33.78	0.61	-15.12	43.38	71.68	0.79
RACMO	-20.60	26.85	33.60	0.78	-8.47	33.37	44.42	0.84
RCA	-4.88	19.32	28.82	0.92	-14.23	34.65	52.70	0.83
REMO	17.11	19.48	29.00	0.88	7.23	37.83	66.31	0.84

3.2 Seasonal Climatology and Statistical Description

The seasonal spatial variation of rainfall for all the RCMs, ENSEMBLE and CRU were assessed for four seasons of three months over West Africa. Shown in Fig. 5 is the December-January-February (DJF) mean seasonal rainfall spatial distribution from 1951-2005. It is observed that CRU, ENEMBLE and majority of RCMs have rainfall less than 20 mm over the north of 8°N as the region of highest to moderate rainfall confide to Guinea Coast (south of 8°N). CCLM and REMO were noticeably different as significantly low rainfall amounts were observed within the extremes of coastal region. However, the rainfall amount simulated by RACMO, CRCM and ENSEMBLE were very close to that of CRU in DJF season. All the RCMs and ENSEMBLE consistently captured northward decrease of rainfall. In a similar way, Fig.6 presents the obtained pattern of monthly mean rainfall (mm/months) for MAM season. Highest to moderate rainfall for the MAM season are found in the south of 12 °N while little rainfall amount (less than 20 mm/month) pre-dominant over the north of 12 °N (Sahel). This may be attributed to the extent of inland incursion of moisture from the Atlantic Ocean that is necessary for the activities of larger scale convective systems. Region of highest rainfall remained localized over the coastal part from the Sierra Leone to southeastern part of Nigeria and Cameron highland. This pattern of rainfall observed in CRU consistent with the rainfall distribution pattern of ENSEMBLE, RCAMO and CRCM in MAM season. Rainfall amounts of RCA, HIRHAM and CCLM are observed to be significantly low compared to CRU within the south of 12 °N.

Also depicted by REMO in Fig.6, rainfall remain restricted to the Guinea Coast while in RACMO, region having rainfall less than 30 mm extends beyond 12 °N to the far northern part of West Africa during MAM season. Moreover, the summer season of June-July-August (JJA) rainfall pattern from Fig. 7 show that significant rainfall amounts have spread over the whole domain of West Africa with the region of maximum rainfall found within the Guinea Coast and also localized over the major highlands of West Africa. These pattern of rainfall distribution are well capture by most of the RCMs except CCLM, observed amount of highest and lowest rainfall varies from one RCMs to the other and the ENSEMBLE. CCLM further show a distinct pattern from all other RCMs as the region of low rainfall extend from the Sahel to the Guinea Coast covering countries like Ivory Coast, Mali, Senegal, part of Ghana and Guinea-Conakry during JJA season. For the September-October-November (SON) season, there are discrepancies in the spatial pattern of SON rainfall as HIRHAM, RCA and REMO shows spatial pattern similar to that of DJF season but with larger bias. ENSEMBLE, CCLM, CRCM and RACMO spatial rainfall pattern are similar to JJA season (Fig. 7) but with varying amount of rainfall. It is worth mentioning that rainfall reduces from south to the southern fringe of Sahel region in all the season as local relief (orography) takes an important role in rainfall distribution over West Africa (Ajayi and Ilori, 2020; Akinsanola 2017; Jenkins et al. 2002; Jones et al. 2011). In the ENSEMBLE and all the RCMs, underestimation and overestimation observed over the local highlands of West Africa could be as a results of error incurred from the driven GCM, parameterization and convective scheme that failed to resolve topography accurately (Afiesimama et al. 2006) as model physics and dynamics cannot be left out (Ajayi and Ilori 2020).

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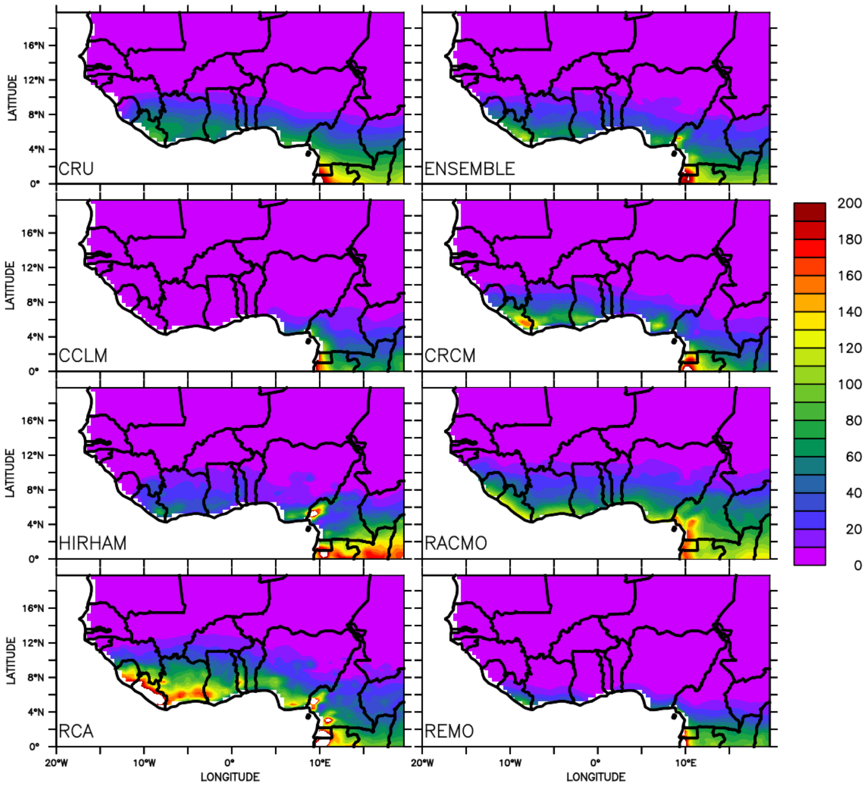

Figure 5: Spatial pattern of DJF mean monthly rainfall (mm/month) for CRU, ENSEMBLE and all the RCMs used from 1951 to 2005

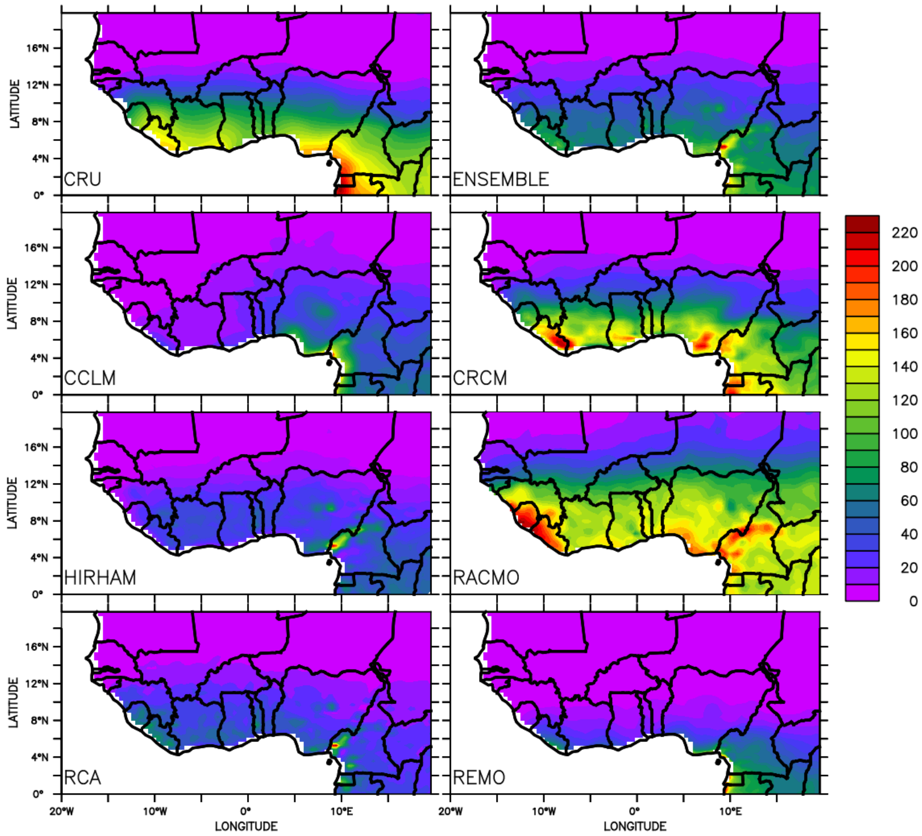

Figure 6: Spatial pattern of MAM mean monthly rainfall (mm/month) for CRU, ENSEMBLE and all the RCMs used from 1951 to 2005

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https://doi.org/10.47001/IRJIET/2022.606010

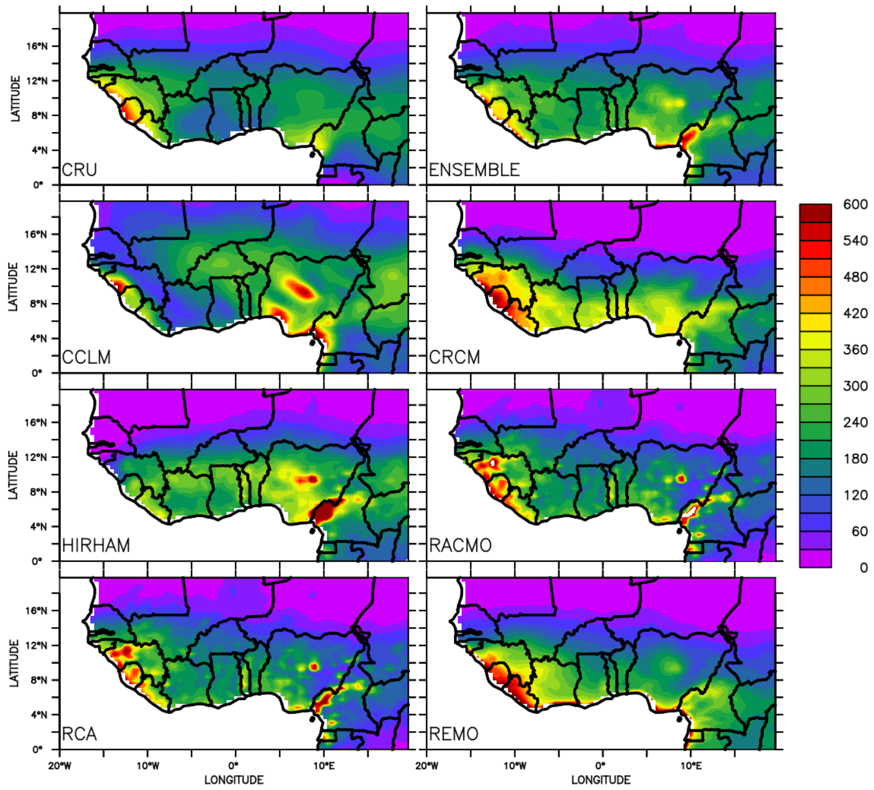

Figure 7: Spatial pattern of JJA mean monthly rainfall (mm/month) for CRU, ENSEMBLE and all the RCMs used from 1951 to 2005

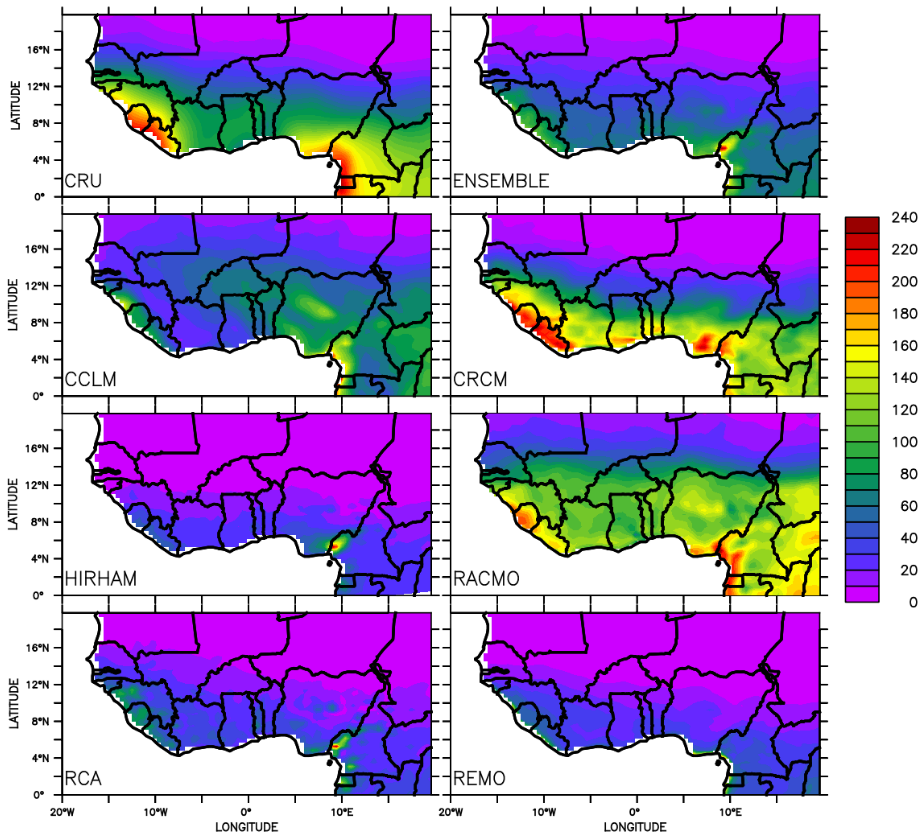

Figure 8: Spatial pattern of SON mean monthly rainfall (mm/month) for CRU, ENSEMBLE and all the RCMs used from 1951 to 2005

International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 6, Issue 6, pp 68-84, June-2022

https://doi.org/10.47001/IRJIET/2022.606010

Taylor diagram (Taylor 2001) was adopted to examine the performance of all the RCMs and ENSEMBLE in simulating seasonal rainfall over the three climatic zone and the whole West Africa. Graphically, Taylor's diagram summarizes the extent of agreement between the ENSEMBLE, all the RCMs and CRU seasonal rainfall. Correlation, centered root-mean-square difference and standard deviation that measures the amplitude of their variations were used to quantified the similarity between ENSEMBLE, all the RCMs and CRU. Based on seasonal mean inter-annual variation of rainfall, the results are shown for the period of 1951 to 2005. DJF season Taylor diagram over the three climatic zone and the entire West Africa are shown in Fig. 9. All the RCMs and the ENSEMBLE shows a less remarkable performance with $r > 0.6$ with varying degree of standard deviation and centered RMS difference during DJF season in all the three climatic zones and entire West Africa. In particular, ENSEMBLE, RCA and RACMO have r between 0.4 and 0.6 while other RCMs are less than 0.4 in all the climatic zones. For the pre-monsoon season of MAM (Fig. 10), there is general increase in the r values compared to DJF season but are more disperse over the Guinea Coast as CRCM and HIRHAM have r close to that of ENSEMBLE (0.8). Over the Savannah and Sahel during the MAM season, majority of the RCMs clustered around the same region of the Taylor diagram having correlation between 0.6 and 0.9 with varying degree of standard deviation and centered RMS difference (error). In particular, over West Africa during MAM (Fig. 10), most of the RCMs and ENSEMBLE have higher correlation values ($r \geq 0.8$) except CCLM and RCA. During the JJA monsoon season as shown in Fig. 11, a general poor performance from all the RCMs and ENSEMBLE was observed over Guinea Coast and the Savannah. However, relatively fair correlation results were being exhibited by all the RCMs and the ENSEMBLE over the Sahel and entire West Africa in JJA season. The difficulty in each of the models in simulating many features of WAM such as WAMJ, TEJ, AEJ and AEWs that contributes to inter-annual variation of mean seasonal rainfall in West Africa suspected to the major causes of the observed performance. Fig 12 shows Taylor diagram for the SON season, most of all the RCMs and the ENSEMBLE were able to simulate the observed rainfall in all the climatic zones and entire West Africa ($r \geq 0.69$). Although, the RCMs are more disperse over the Guinea coast while most of them clustered over the same part of the plot with the ENSEMBLE in Savannah and entire West Africa. This reveals that most of the RCMs performance is very close to that of ENSEMBLE during SON season. It has been shown that the performance of the RCMs and the ENSEMBLE varies from one season and climatic zone to another, implying that some RCMs performed as that of ENSEMBLE and can be used to investigate and analyze projected climate and their changes over West Africa.

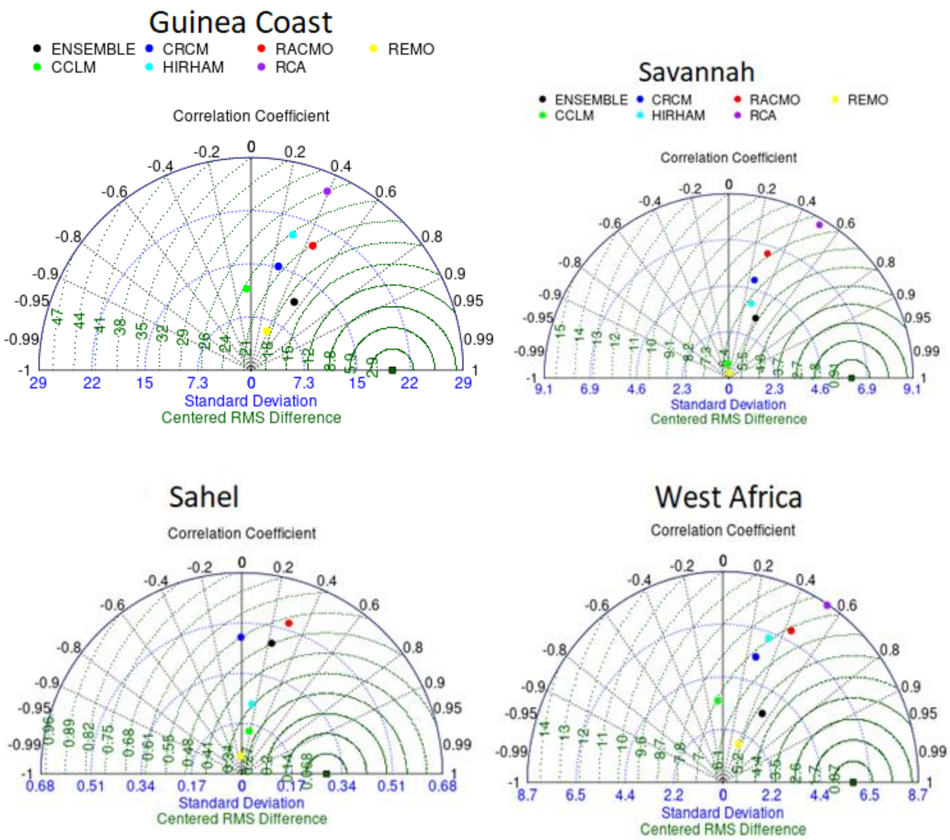

Figure 9: Taylor diagram for the DJF season over Guinea Coast, Savannah, Sahel and the whole West Africa from 1951 to 2005. The standard deviation is shown with radial coordinate as the green semicircle about the reference green square along horizontal axis indicate centered root-mean-square error

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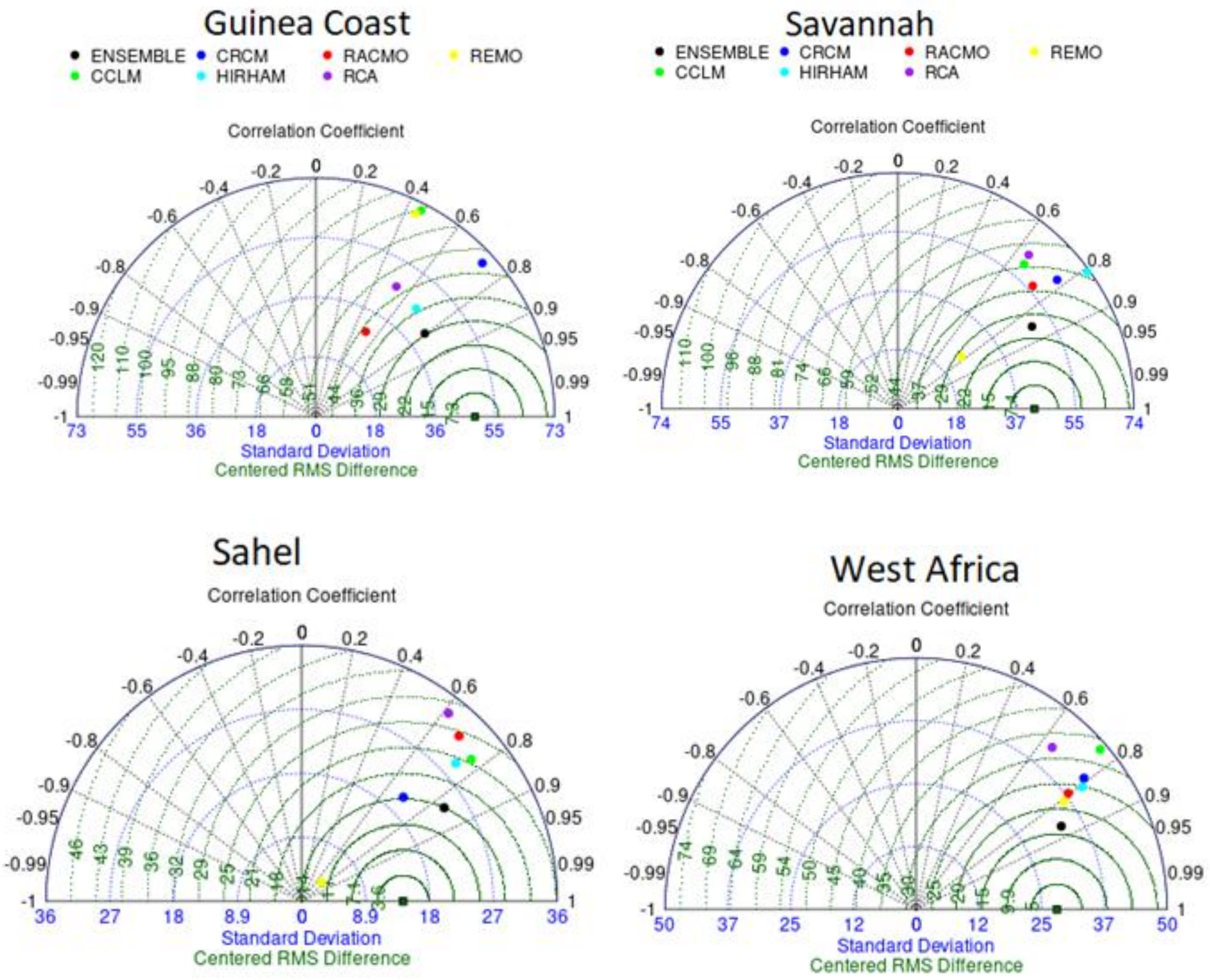
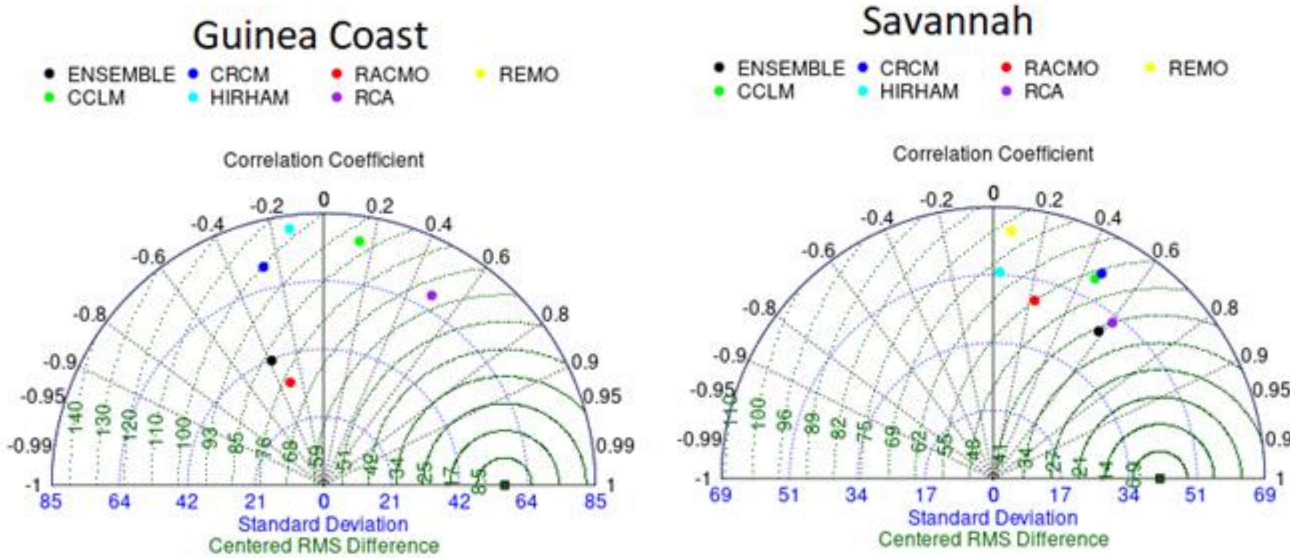


Figure 10: Taylor diagram for the MAM season over Guinea Coast, Savannah, Sahel and the whole West Africa from 1951 to 2005. The standard deviation is shown with radial coordinate as the green semicircle about the reference green square along horizontal axis indicate centered root-mean-square error



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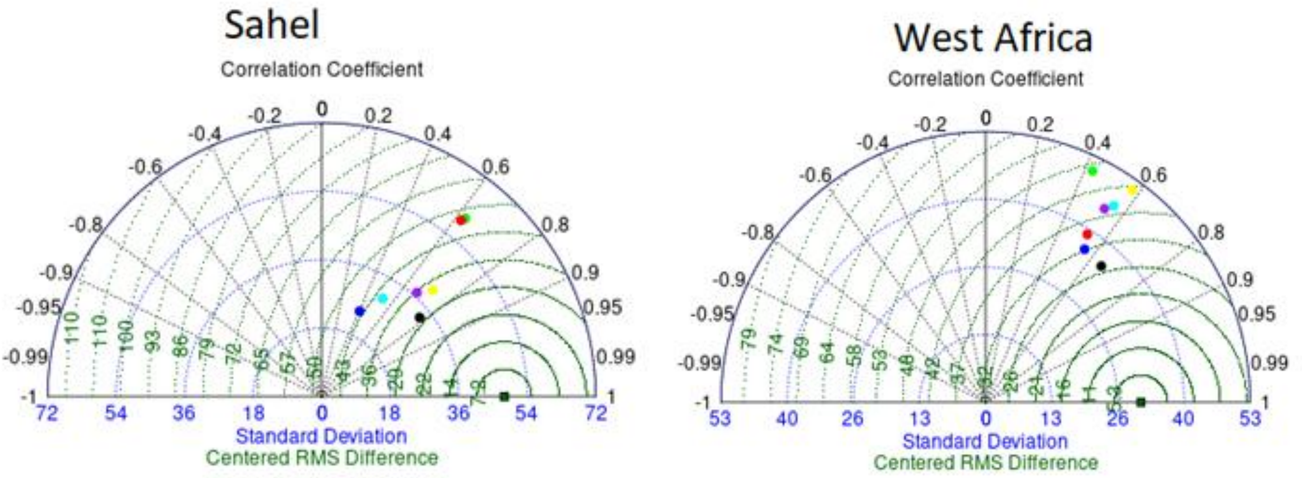

Figure 11: Taylor diagram for the JJA season over Guinea Coast, Savannah, Sahel and the whole West Africa from 1951 to 2005. The standard deviation is shown with radial coordinate as the green semicircle about the reference green square along horizontal axis indicate centered root-mean-square error

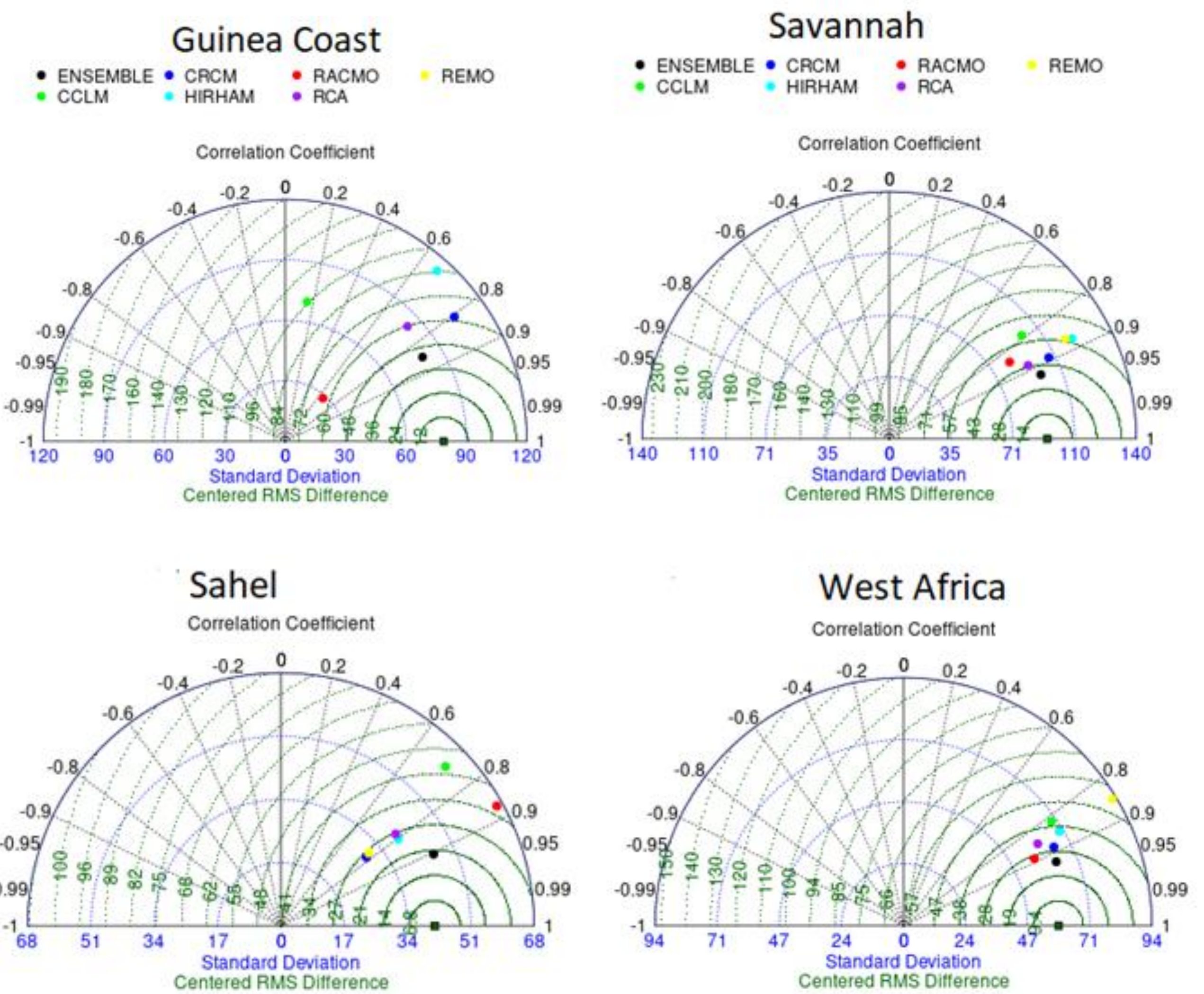

Figure 12: Taylor diagram for the SON season over Guinea Coast, Savannah, Sahel and the whole West Africa from 1951 to 2005. The standard deviation is shown with radial coordinate as the green semicircle about the reference green square along horizontal axis indicate centered root-mean-square error

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IV. CONCLUSION

The ability of six CORDEX RCMs (CCLM, CRCM, HIRHAM, RACMO, RCA and REMO) and their ensemble in replicating rainfall characteristics over West Africa has been evaluated in this study from 1951 to 2005. All these RCMs and their ensemble have been evaluated against CRU rainfall using both climatological and statistical description. The overall performance of most of the RCMs in simulating the annual spatial distribution of rainfall are relatively good as their ensemble except CCLM. Ensemble, CCLM, CRCM, and HIRHAM failed to simulate two rainfall peaks over the Guinea Coast unlike other RCMs that simulated two rainfall peaks. Most of the RCMs further simulated single peaked rainfall over the Savannah and Sahel in the month of August. Annual statistical evaluation performed over sub region and entire West Africa revealed that most of the RCMs are in good agreement with the CRU as that of the ENSEMBLE. In particular, RACMO outperformed the ENSEMBLE in the Guinea Coast as CRCM, HIRHAM, RCA and REMO did over the Savannah. The bias over West Africa are lower than other climatic zones with higer correlation values, this suggested that majority of the RCMs performed better over larger domain tha the climatic zones.

Seasonal evaluation shows that most of the RCMs simulate the mean seasonal spatial rainfall distribution properly except CCLM and REMO in DJF and MAM season. The seasonal statistical performance of the RCMs and the ENSEMBLE in DJF season are relatively poor while most of the RCMs performed better as the ENSEMBLE in SON season over West Africa domain and Savannah and Sahel climatic zones. This show that the performance of the RCMs and ENSEMBLE varies from one season and region to another which further reveal the relevance of performing the evaluation in sub-divided homogenous climatic zones. Moreover, base on the individual performance of each RCMs, CRCM and RCA consistently performed better than all other RCMs as they performed within the same level as the ENSEMBLE. Hence, this study supports and suggest their usage for any related climate change and variability studies over West Africa.

ACKNOWLEDGEMENTS

The author appreciate Climate Research Unit (CRU), University of East Anglia, for the observational dataset used in this study and also appreciate Coordinated Regional Climate Downscaling Experiment (CORDEX) for making the simulation dataset used in this study available to the general public.

CONFLICT OF INTEREST

The two authors declare that there is no conflict of interest in any form or so associated with the publication of this work.

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Volume 6, Issue 6, pp 68-84, June-2022
https://doi.org/10.47001/IRJIET/2022.606010

Citation of this Article:

Vincent O. Ajayi, "Comparing the Performance of Six Regional Climate Models and Their Ensemble over West Africa" Published in *International Research Journal of Innovations in Engineering and Technology - IRJIET*, Volume 6, Issue 6, pp 68-84, June 2022. Article DOI https://doi.org/10.47001/IRJIET/2022.606010

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