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ORIGINAL ARTICLE

# Evaluation of dry and wet spell events over West Africa using CORDEX-CORE regional climate models

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## Abstract
This study investigates the capability of regional climate models (RCMs) in simulating four extreme precipitation indices on an annual and monthly scale over West Africa during the period 1997–2014. Three global climate models (GCMs; HadGEM2-ES, NorESM1 and MPI-ESM) were dynamically downscaled using three high resolution (0.22°) regional climate models (RCMs; RegCM4, REMO2015 and CCLM5-0-15). These simulations were from the Coordinated Output for Regional Evaluations within the Coordinated Regional Climate Downscaling Experiment framework (CORDEX-CORE) publicly available through the Earth System Grid Federation (ESGF) web portals. The capabilities of the RCMs in the representation of maximum consecutive wet day (CWD), maximum consecutive dry days (CDD), number of dry days (NDD), and number of wet days (NWD) were compared with observation/satellites datasets obtained from the Global Precipitation Climatology Project (GPCP), Tropical Rainfall Measuring Mission (TRMM) and Tropical Applications of Meteorology using SATellite data and ground-based observations (TAMSAT). The reference datasets showed similar spatial pattern and magnitude of analyzed precipitation extremes but models exhibit different pronounced discrepancies relative to them. All RCMs consistently captured the spatial patterns of the indices but with some pronounced biases along the Guinean coast and northern parts of Niger. There exists little or no biases in the representation of annual cycle along the Guinea and Sahel for all the indices based on each of the RCMs ensemble, with the exception of RegCM4 which has a more pronounced bias in CWD. Statistical evaluation of the performance of the models over the entire West Africa with respect to the 4 indices revealed that REMO2015 models and its ensemble have overall lowest root mean square error followed by the choice of MPI-ESM GCM downscaled with either of the RCMs. REMO-HAD was found to have the best performance in the representation of consecutive dry days and number of wet days with RMSE values of 25.74 and 18.91 respectively. REMO-MPI has superior performance in the estimation of consecutive wet days and number of dry days with RMSE values of 5.38 and 20.51 respectively. Generally, REMO RCMs ensemble was found to be the best ensemble in all indices except consecutive dry days where REG4 ensembles had better performance. Operational use of these 3 RCMs are recommended with compensation for over-and underestimations.

**Keywords** CORDEX-CORE · West Africa · Dry spell · Wet spell · Climate change · Extreme precipitation

## Introduction

There are several indices developed to characterize excessive and deficit rainfalls. One of the commonly used indicators is the dry and wet spells. The maximum length of dry and wet spells are one of the 27 extreme climate indices proposed by the Expert Team on Climate Change Detection and Indices (Zhang et al. 2011). Wet (dry) spells are periods of continuous precipitation above (below) a given threshold. Consecutive dry and wet days have implications that extends to agriculture, health, and environment. Elongated wet spells will lead to flooding (Apurv et al. 2015; Khan et al. 2013),

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crop production (Fall et al. 2021), and the spread of diseases such as dengue fever (Khalid and Ghaffar 2015) and malaria (Macherera et al. 2017). The variability and characteristics of dry and wet spells have been the subject of several studies. Caloiero and Coscarelli (2020) studied the characteristics of dry and wet spells in a Mediterranean region over a period of 56 years using a yearly and a seasonal scale. Results indicated similarity in behaviour of dry and wet spells of the same spatial distribution. Also, higher values of dry spells were observed compared to the temporal distribution of wet spells throughout the year. Investigations on the variability of dry and wet spells has been carried out in Europe (Heinrich and Gobiet 2012), Ethiopia (Wondifraw et al. 2017; Adane et al. 2020), India (Atal and Zende 2015), South Africa (Cook et al. 2004). In 2013, (Ratan and Venugopal 2013) did an analysis of satellite based rainfall observation while juxtaposing it with the dry and wet spell characteristics of global tropical rainfall. It was observed that for the arid region, the major contribution to the seasonal rainfall comes from 1-5 day wet spell while for the humid region, the major contribution to seasonal rainfall comes from wet spells of as long as 30 days. Sivakumar (1992) studied the impact of dry spells on the agricultural productivity of several West African locations during the planting season. The characteristics of dry and wet spells within four regions of West Africa was examined. Of greater benefits to agriculture are shorter dry spell duration embedded in additional wet days during the season than an increase of dry days with less but longer duration dry spells (Osei et al. 2021).

One approach to mitigate the effect of sparse in-situ data is the use of reanalysis, satellite, and/or models. Regional and global climate models are used to simulate the climate for an improved understanding of the dynamics of climate in the historical and recent past as well as projected future scenarios under different forcing conditions. However, one of their limitations include the inability to represent the detailed processes of climate variability in regions whose complex topography influences climate on the local scale (Giorgi et al. 2009). Most times global climate models (GCMs) are downscaled using regional climate models in an attempt to improve the simulations from the GCMs. However, these sometimes does not necessarily produce a better simulation skill (Panitz et al. 2014) except in cases where the focus is on extreme events or with a higher resolution regional climate models (RCMs) (Dosio et al. 2015). There have been attempts to determine the efficiency of GCMs and RCMs in capturing the dynamics of precipitation over West Africa. Diallo et al. (2012) compared the performance of four RCMs and two GCMs in simulating June–September precipitation across the West African region. The best performance was obtained from an ensemble of the RCMs driven by the two GCMs. A similar research was conducted over Africa with four GCMs and one RCM during the months of June to August (Saini et al. 2015) while the RCM was found to have lower bias than the GCMs. However, these simulations were not considered for wet and dry spells.

There are several approach tailored towards enhancing the accuracy of climate information obtained from Global Climate Models (GCMs) which has a coarse resolution (1°) and therefore might not fully reproduce some regional and local climate features such as orography, coastline and changes in land-use. One of such approaches incorporate variable or high resolution GCMs at 0.2°–0.5° (Mizuta et al. 2012; McGregor 2015) while another effort is geared towards dynamically downscaling GCMs with regional climate models (RCMs) at higher resolutions (0.25°–0.6°, (Sylla et al. 2015; Steiner et al. 2009)). For instance, ensembles of regional climate models (RCMs) with similar experimental protocols participated in different projects aimed at providing improved information for climate impact and vulnerability studies. Some of these projects include the Coordinated Regional Downscaling Experiment (CORDEX, (Giorgi and Gutowski 2016)) under the auspices of World Climate Research Program (WRCP) at a horizontal resolution of $0.44° \times 0.44°$ and later icreased to $0.22° \times 0.22°$ in 2019; African Monsoon Multidisciplinary Analyses—Model Inter-comparison project (AMMA-MIP, Hourdin et al. 2010), West African Monsoon Modeling and Evaluation project (WAMME, GEWEX/CEOP initiative, Xue et al. 2010) and Ensembles-based Predictions of Climate Changes and Their Impacts (ENSEMBLES) projects (Paeth et al. 2011). Unfortunately,There exists pronounced discrepancies in climate simulations among the various RCMs which invariably contributed to the overall performance of the ensemble means. This discrepancies suggest the importance of improving the performance of individual RCMs configurations (e.g. lateral boundary conditions, grid resolution, and micro-physics option) before participation in similar ensemble project.

Over Africa domain, the CORDEX experiment at its initial phase produced many climate research outputs across the region and sub-regions (e.g. Hewitson et al. 2012; Mariotti et al. 2014; Kim et al. 2014). Also recently, the Coordinated Output for Regional Evaluations within the CORDEX framework (hereafter referred to as CORDEX-CORE) was setup to contribute and produce climate information at the regional scale using the same RCMs to downsacale similar GCMs at a higher resolution of 0.22°. As at the time of writing this article, there are three RCMs which has fully partcipitated in this initiative and some authors have been able to generate climate information from these simulations. The performance of two CORDEX−CORE RCMs in the simulation of seasonal precipitation over Africa was investigated by Gnitou et al. (2021)). They showed that CORDEX-CORE simulations over Africa could be sufficient for precipitation applications at a high resolution but the

GCMs configurations relative to the high resolution RCMs is important for consideration too. Teichmann et al. (2020) also examined the climate change signal based on CORDEX-CORE and CMIP5 GCMs similations. They found that the spread of climate change signals in both temperature and precipitation are well presented in the CIRDEX-CORE simulations across all the nine CORDEX domains at an interquartile range. Also, Coppola et al. (2021) analysis of extreme precipitation and number of dry days from CORDEX-CORE, CORDEX, CMIP5 and CMIP6 simulations. The results from their research showed that the CORDEX-CORE ensemble improves on the performance of the driving GCMs for most of the temperature and precipitation extreme indices due to its higher spatial resolution.

In this study, we aim to investigate the performance of higher resolution CORDEX-CORE RCMs simulation for Africa in the representation of dry and wet spells across West African. Hence, we considered the ability of these RCMs to simulate the annual maximum consecutive dry and wet days and annual number of dry and wet days. The results from this study is expected to help in environmental planning for socio-economic development in the region.

## Data and methods

### Data sources

In this study, an investigation of wet and dry spells was carried out using 3 CORDEX-CORE RCMs simulations of daily precipitation over West Africa bounded by latitudes 4° N – 20°N and longitudes 16° W – 16° E (Fig. 1), a subset of the CORDEX Africa domain. The area averages were carried along designated Guinea (2° N – 12° N; 16° W – 16° E) and Sahel (12° N – 20° N; 16° W – 16° E ) zones. All model simulations output variables are freely avaialable at https://esg-dn1.nsc.liu.se/search/esgf-liu/ or https://esgf-data.dkrz.de/projects/esgf-dkrz/ or https://esgf-index1.ceda.ac.uk/search/esgf-ceda/. The data were obtained from the 3 high resolution CORDEX−CORE RCMs forced by 3 GCMs following the CORDEX-CORE protocol as described in Giorgi et al. (2012); Giorgi and Gutowski Jr (2015); Gutowski Jr et al. (2016). The selected RCMs are REMO2015 (Remedio et al. 2019) developed at the Climate Service Center Germany (GERICS); RegCM4 (Giorgi et al. 2012) developed at the Abdus Salam International Centre for Theoretical Physics (ICTP) and the COSMO-CLM developed and used by a community of scientists http://www.clm-community.eu/ (See Tables 1 and 2). REMO is a three-dimensional, limited-area hydrostatic, atmospheric circulation model (Jacob et al. 2012). Its physical parameterization is originally obtained from ECHAM4.5 (Roeckner et al. 1996) but there have been a lot of further improvements. Its dynamical core is from the German Weather Service (DWD) Europa-Modell (EM) weather prediction model (Majewski 1991) and uses a leapfrog time stepping with semi-implicit correction and an Asselin filter. Detailed description of REMO2015 configurations for CORDEX-CORE simulations is described in Remedio et al. (2019). RegCM4 model uses the hydrostatic dynamical core from the mesoscale model MM5 (Grell et al. 1994), split-explicit advection, sigma-p vertical coordinates and an Arakawa-b staggered horizontal grid. It has different options for physics parametrizations. Hence, optimum selection of physics options for each domain was used based on different ERA-Interim driven preliminary experiments. COSMO-CLM is a three-dimensional non-hydrostatic, limited-area atmospheric model with designed applications from the meso-$\beta$ to meso-$\gamma$ scales (Steppeler et al. 2003) which depends on primitive thermodynamical equations for the description of a compressible flow in a moist atmosphere. Detailed description of COSMO-CLM set-up and configuration are found in Sørland et al. 2021; Doms et al. 2011; Panitz et al. 2014.

All model simulations were compared with three gridded observation/satellite datasets (herefafter referred to as reference observations) to account for the uncertainty arising from the lack of continuous ground based measurements across the study area. The reference observation datasets used in this study are the Daily Global Precipitation Climatology Project One-Degree Daily product version v01r03 (GPCP; Huffman et al. 1997; Adler et al. 2017), the Tropical Applications of Meteorology using SATellite and ground-based observation (TAMSAT; Maidment et al. 2017) at $0.035° \times 0.035°$ resolution and the Tropical Rainfall Measuring Mission (TRMM; $3B-42$) product at $0.25° \times 1°$ grid spacing and at daily interval (Huffman et al. 2001). TRMM provides rainfall estimates using merged microwave infrared estimates at 3-h intervals (Huffman et al. 2007). Both GPCP and TAMSAT data used are for the period of 1997–2014 while TRMM covers the period of 1998–2014. Although these observation products also exhibit inherent uncertainties associated with their data sources and choice of processing algorithms, they nonetheless contribute significantly to regional climate studies in data-sparse region of West Africa.

### Data analysis

The variability in wet and dry spells across West Africa as simulated by the CORDEX-CORE RCMs is investigated using four selected hydro-climatic indices of the Expert Team on Climate Change Detection and Indices (ETCCDI: Zhang et al. 2011). The definitions of the four indices are presented in Table 3 according to definitions from http://etccdi.pacificclimate.org/list_27_indices.shtml. The selected indices is expected to give the overall behaviour of

**Table 1** Parameterizations of RCMs used in the CORDEX-CORE Africa domain

| Model | Driving GCMs/resolution | Parameterization | Schemes | References |
|---|---|---|---|---|
| RegCM4 | HadGEM2-ES (Jones et al. 2011) /1.25° × 1.85° | Boundary layer processes | Holtslag | (Holtslag et al. 1990; Holtslag and Boville 1993) |
| | MPI-ESM-MR (Stevens et al. 2013) /1.8653° × 1.875° | Interaction surface-atmosphere | Community land model version 4.5 (CLM4.5) | (Oleson et al. 2008) |
| | NorESM1-M (Iversen et al. 2013) /1.8947° × 2.5° | Turbulent fluxes over sea | Zeng scheme | (Zeng et al. 1998) |
| | | Cumulus convection | Tiedtke over the land and Kain-Fritsch over the sea | (Tiedtke 1989; Kain 2004) |
| | | Radiation scheme | NCAR community climate model 3 | (Kiehl 1996) |
| | | Large scale precipitation | Subgrid explicit moisture scheme (SUBEX) | (Pal et al. 2000) |
| REMO2015 | HadGEM2-ES (Jones et al. 2011) /1.25° × 1.85° | Boundary layer | Monin-Obukhov similarity theory | (Louis 1979) |
| | MPI-ESM-LR(Giorgetta et al. 2013)/1.8653° × 1.875° | Cumulus | Tiedtke with modifications | (Tiedtke 1989) |
| | | | | (Nordeng 1994) |
| | NorESM1-M(Iversen et al. 2013)/1.8947° × 2.5° | Microphysics | (Lohmann and Roeckner 1996) | (Lohmann and Roeckner 1996) |
| COSMO-CLM5 | HadGEM2-ES (Jones et al. 2011)/1.25° × 1.85° | Radiation scheme | Ritter and Geleyn | (Ritter and Geleyn 1992) |
| | MPI-ESM-LR(Giorgetta et al. 2013)/1.8653° × 1.875° | convection | (Tiedtke scheme being modified by the German Weather Service DWD) | (Tiedtke 1989) |
| | NorESM1-M(Iversen et al. 2013)/1.8947° × 2.5° | microphysics | Four category microphysics scheme that includes cloud water, rain wa- ter, snow, and ice | (Doms et al. 2013) |
| | | | | (Heise and Schrodin 2002) |
| | | Land surface | Soil-vegetation-atmosphere-transfer sub-model TERRA-ML | (Doms et al. 2011) |

**Table 2** List of AFR-CORDEX-CORE simulations used in this study at 0.22° × 0.22° spatial resolution

| Institute | RCM | Lateral boundary conditions | Reference | RCM/GCM abbreviation |
|---|---|---|---|---|
| IMK-TRO/KIT, Karlrushe* | CCLM5-0-15 | HadGEM2 | http://cordex.clm-community.eu | CLM-HAD |
| | | MPI-ESM-LR | | CLM-MPI |
| | | NorESM1-M | | CLM-NORE |
| Helmoholtz-Zentrum Geesthacht, Climate Service Center Germany | REMO2015 | HadGEM2 | http://www.remo-rcm.de | REMO-HAD |
| | | MPI-ESM-LR | | REMO-MPI |
| | | NorESM1-M | | REMO-NORE |
| Internation Centre for Theoretical Physics | RegCM4-7 | HadGEM2 | http://gforge.ictp.it/gf/project/regcm | REG4-HAD |
| | | MPI-ESM-LR | | REG4-MPI |
| | | NorESM1-M | | REG4-NORE |

*CORDEX CORE CCLM run driven by MOHC-HadGEM2-ES historical (CMIP5) performed by KIT Karlsruhe in collaboration with the CLM-Community

precipitation extremes for dry and wet conditions across the region as suggested in several research studies (e.g. Klutse et al. 2018; Akinsanola et al. 2015). In the analysis of wet and dry spells, all datasets from both model simulations and

**Table 3** Definition of the expert team on climate change detection and indices (ETCCDI) rainfall-based indices used in this study

| Indices | Definitions |
|---|---|
| Maximum consecutive wet days | Let infile be a time series of the daily precipitation amount RR, then the largest number of consecutive days where RR is at least 1 mm is counted |
| Maximum consecutive dry days | Let infile be a time series of the daily precipitation amount RR, then the largest number of consecutive days where RR is less than 1 mm is counted |
| Number of wet days | Let infile be a time series of the daily precipitation amount RR in (mm) [or alternatively in ($kgm^{-2}$)], then the number of days where RR is at least 1 mm is counted |
| Number of dry days | Let infile be a time series of the daily precipitation amount RR in (mm) [or alternatively in ($kgm^{-2}$)], then the number of days where RR is less than 1 mm is counted |

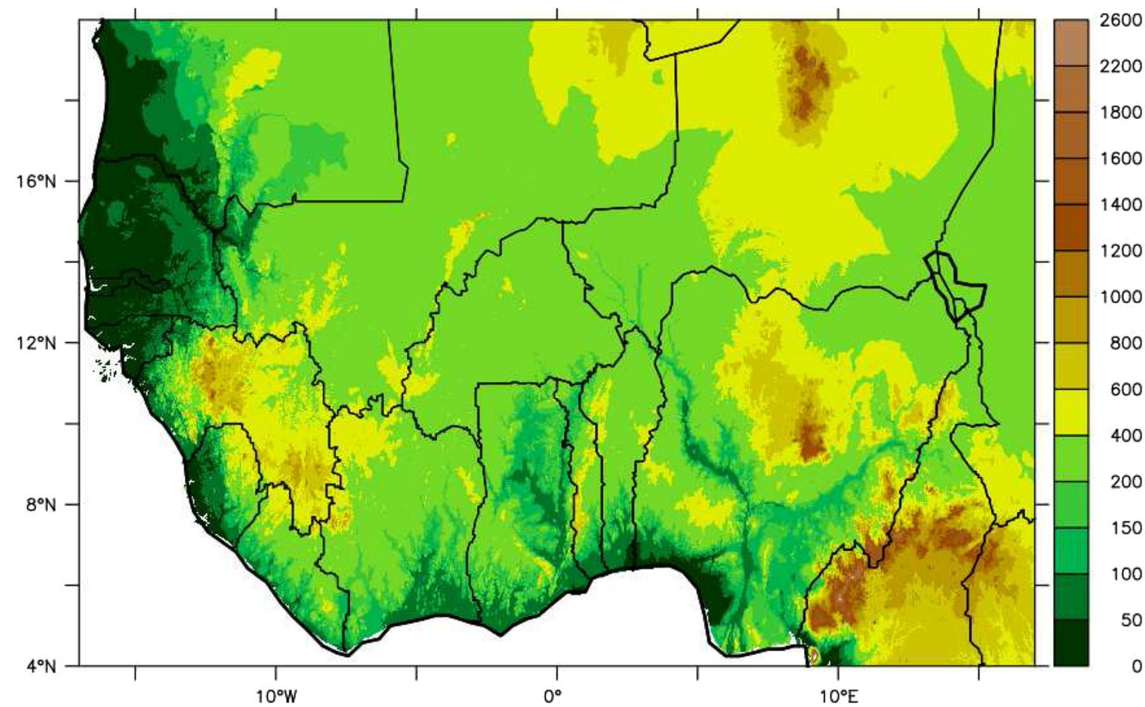


**Fig. 1** High resolution map of West Africa Region showing the elevation in meters. The data source is https://www.gebco.net

reference observation datasets were regridded to GPCP grid (which has the lowest grid size). We further investigated the root mean squared error (RMSE) with respect to GPCP only, using grid points over the land because it appears to have a good representation of the spatial patterns in the region with respect to the indices considered (e.g. in Table 3). The RMSE shows the error of the model in the prediction of the quantitative measurement and how the model data is concentrated around the line of best fit.

## Results

The RCMs were used to simulate mean values of maximum consecutive dry days (CDD), maximum consecutive wet days (CWD), annual number of dry days (NDD) and wet days (NWD) on an annual and monthly time scale. The results obtained are shown in Figs. 2, 3, 4, 5, 6 and 7. The maximum consecutive wet days over West Africa from the three reference observation data and nine RCMs are shown in Fig. 2. The reference observation data shows a strong agreement indicating that areas north of 12° N exhibits a maximum of 5 consecutive wet days per year in these locations. CWD values from TAMSAT captured the subtle vegetation changes expected in the savannah-desert transition zone between latitude 12° N and 14° NEklundh and Olsson (2003). Generally, the three observations appear to show similar pattern in the distribution of maximum consecutive wet days in most parts of West Africa except over Jos, Plateau in Nigeria and Cameroon's highlands where GPCP datasets reported lower values of CWD (10–40) days/year compared to TAMSAT but higher values compared to

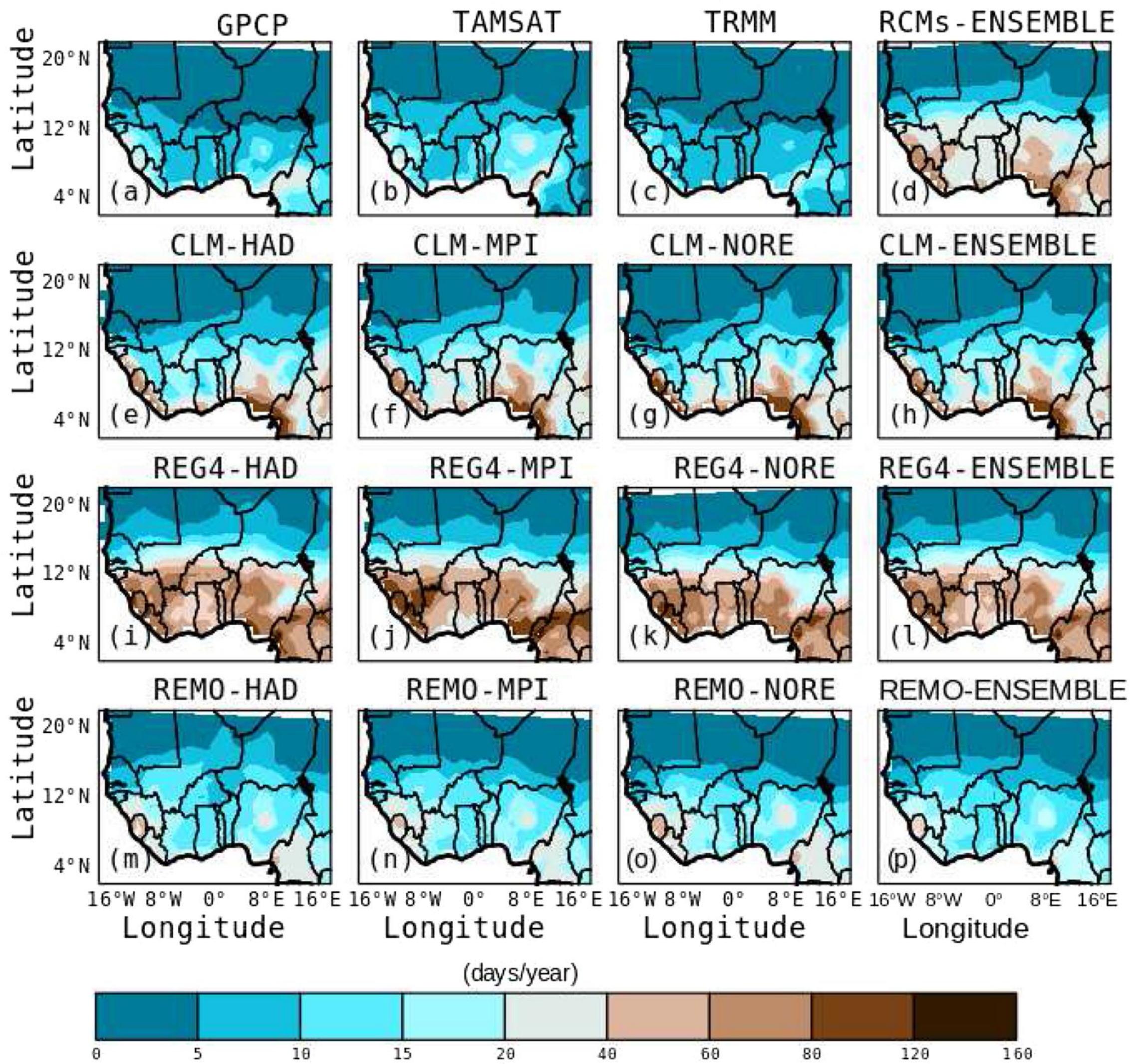


**Fig. 2** Maximum consecutive wet days (days/year) from different observations (**a–c**), all RCMs ensemble (**d**), CLM RCMs (**e–g**), CLM RCMs ensemble (**h**), REG4 RCMs (**i–k**), REG4 RCMs ensemble (**l**), REMO RCMs ensemble (**m–o**), REMO RCMs ensemble (**p**) across the West African region all averaged for the period 1997-2014 with the exception of TRMM which is 1998–2014

TRMM dataset over the region. TAMSAT generally show higher magnitude of precipitation in areas of complex orography. The similar pattern among the reference observation datasets in the representation of precipitation climatology was also reported in Klutse et al. (2021b). The CCLM5-0-15 based RCMs simulations (CLM-HAD, CLM-MPI, CLM-NORE) were in strong agreement in identifying the highest maximum consecutive wet days over West Africa irrespective of the driving GCMs. These simulations also compared favourably with the reference observation data for most parts of the region north of 12° N with minimal bias (less than 2 days/year). However, south of 12° N, the CWD values are higher relative to the observed datasets. The RegCM4-7 based RCMs (REG4-HAD, REG4-MPI, REG4-NORE) showed higher values of maximum consecutive wet days from the coastal regions up to 12° N. The intensity is much more in the MPI-ESM driven model compared to the HADGEM2 and NORESM driven models. Also, the models were found to grossly overestimate the maximum consecutive days relative to the reference observations/satelite data across most parts of West Africa irrespective of the driving GCMs. On the other hand, the REMO2015 based models (REMO-HAD, REMO-MPI, REMO-NORE) generally gives a better performance in the representation (spatial and magnitude) of CWD. The overall best performance of the RCMs is REMO which has the lowest RMSE of 7.40, 5.38 and 6.11 in REMO-HAD, REMO-MPI and REMO-NORE simulations respectively. The overall quantitative measurement of the models root mean square error is presented in Table 4.

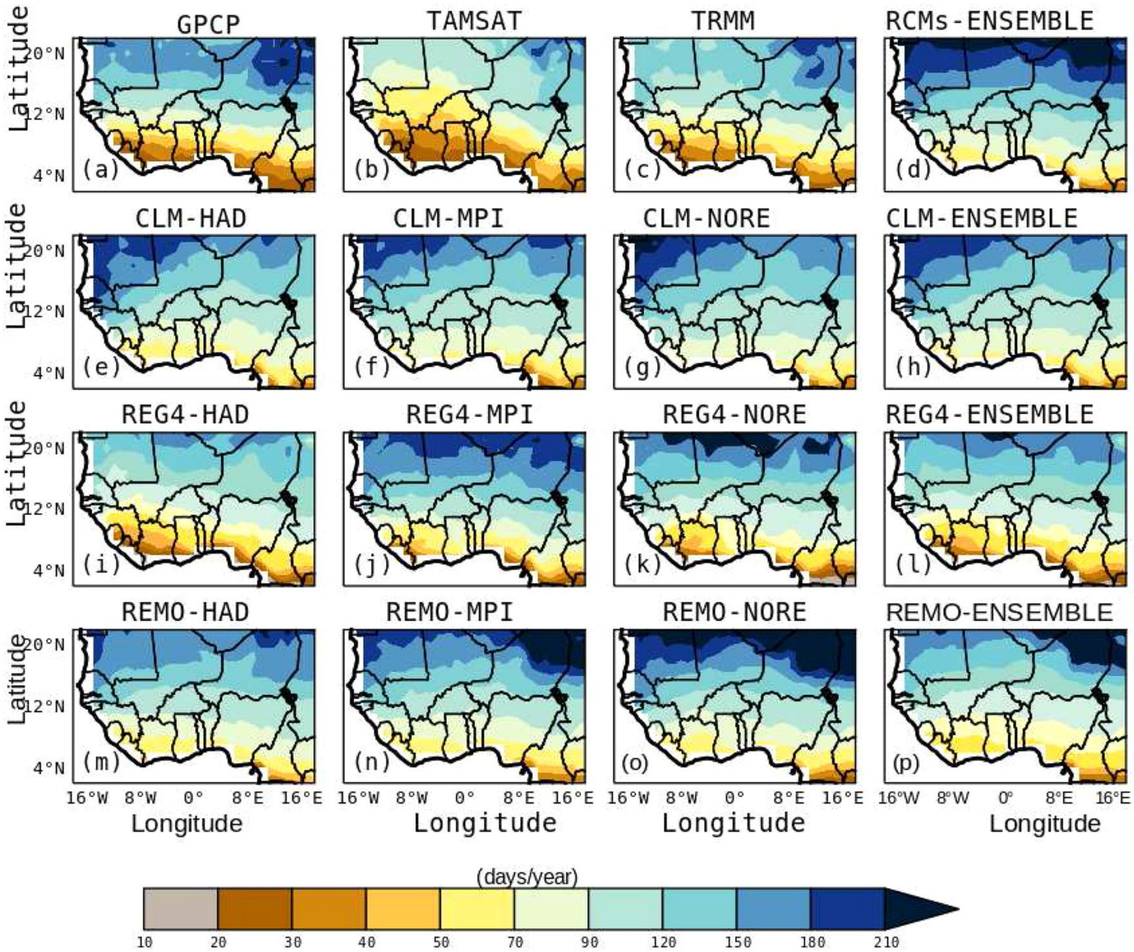


**Fig. 3** The same as Fig. 2 but for Maximum consecutive dry days

The maximum consecutive dry days for the reference observation/satellite data and RCMs were also considered and the results presented in Fig. 3. The three observations/satellite data report identical strata over the region. They showed strong agreement in identifying the maximum consecutive dry days in the range 20–30 days per year along the coast. The lowest maximum consecutive dry days in the range 20–30 days per year was more pronounced along the coast in GPCP and TAMSAT than TRMM. Northward of this band is the 30–40 maximum consecutive dry days per year which has more spatial extent in TAMSAT but least extent in TRMM. Beyond this strata is the 40–50 days per year of maximum consecutive dry days with a strip of 50–60 days running through the middle. GPCP and TRMM presents identical spatial extent for this region while TAMSAT has an extended region especially around the northwestern part. A thin stratum representing 80–100 days per year of maximum consecutive dry days was also observed in the three reference observation data. Beyond this region, the three reference observation data presents different results. GPCP shows two layers (100–120 days/year and 120–140 days/year) before most of the Sahara desert with maximum consecutive dry days above 140 days/year. However, TAMSAT showed 100–140 days/year beyond the same region and a little patch of dry days above 140 days/year. Most of the Sahara desert, according to TRMM, have between 100–140 days/year of maximum consecutive dry days with a little patch of extreme dry days in the northeast region. In the CLM based RCMs, the 20–40 days/year band observed along the coasts in the reference observation data were not pronounced. The CLM-HAD model has maximum consecutive dry days between 60–80 days per year along the coast with strips of 50–60 days per year occurring in some regions. Identical spatial extent was covered by the CLM-MPI model but without the 50–60 strip. However, the spatial extent of the 60–80 days per year maximum consecutive days in the CLM-NORE model is limited and restricted to the coastal lines of West Africa. Generally, CLM-based RCMs grossly overestimate maximum consecutive dry days along the coast by an average of 40 days/year. REG4-based RCMs were found to capture the low values of maximum consecutive dry days along the coast but underrepresented the spatial

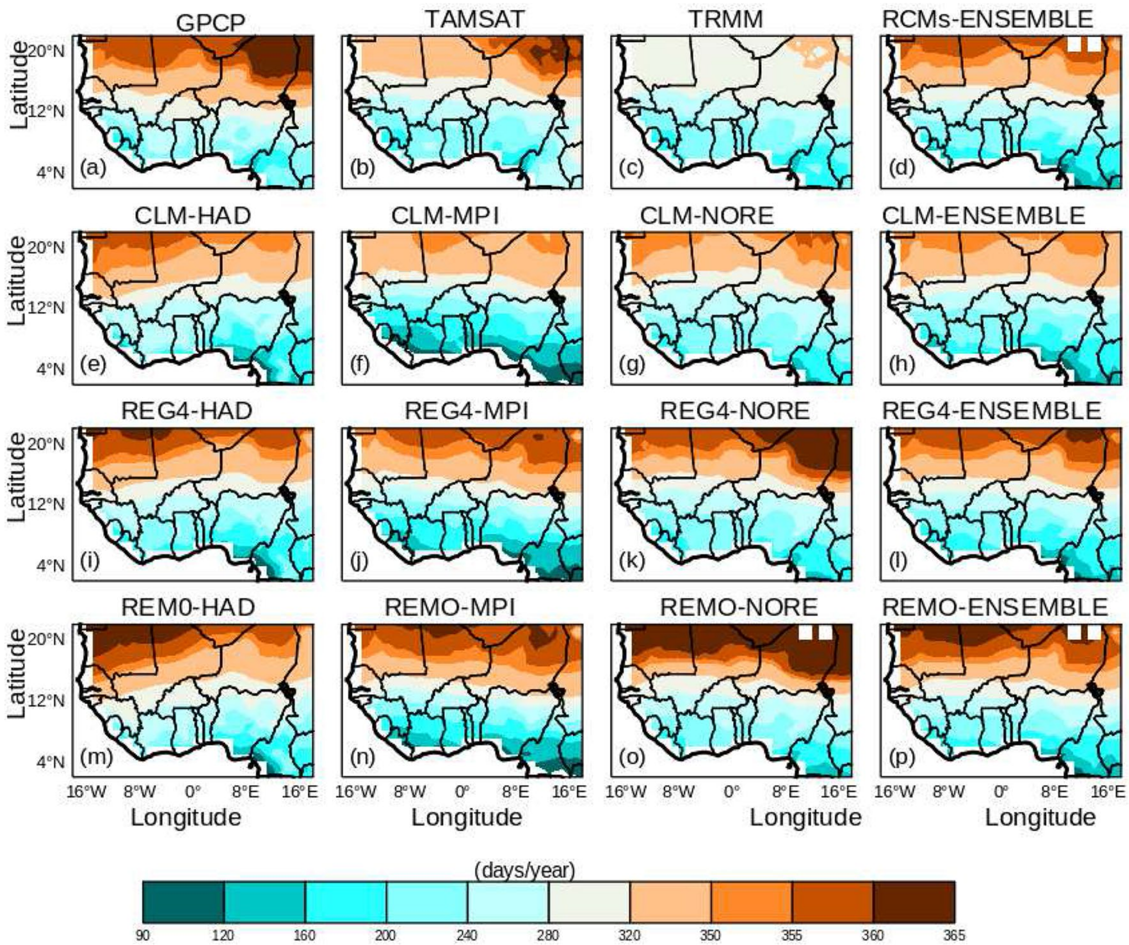


**Fig. 4** The same as Fig. 2 but for Number of dry days (days/year)

extent. This spatial distribution is not improved upon also in their ensemble mean plots but shows that REG4 RCMS simulations are influenced also by the configurations of their driving GCMs. From 12°$N$ equatorwards, REMO-based models showed identical patterns with CLM-based models. Overall, the models overestimated the stratification reported in the reference observation data. In agreement with both GPCP and TRMM, all the models reproduced maximum consecutive dry days between 80–100 days/year around the 12° latitude. Generally, different RCMs with the same GCM simulated similar spatial distribution of maximum consecutive dry days over the region. This shows the driving GCMs appears to influence the simulations of consecutive dry days more than the individual model configuration of the RCMs. Table 3 shows that the GCMs derived ensemble of MPI-ESM-LR and HADGEM2-ES exhibits an overall better performance in the simulation of consecutive dry days by having the lowest RMSE value of 26.58 and 26.52 respectively that is quite lower than other ensemble means considered. The REMO-HAD RCM-GCM combination gives the lowest RMSE for consecutive dry days simulation over the study area. All the models and their ensemble are unable to reproduce the strong agreement in the representation of the magnitude and spatial extent of maximum consecutive dry days along the coasts as indicated in the reference datasets. REG4 RCMs and its ensemble however reduced the magnitude of underestimation in the maximum consecutive dry days along the coasts.

Regional hydrology, with it's direct and indirect impact on different sectors of the economy, is affected by the frequency of dry days (Polade et al. 2014). In this study, the spatial variation of dry days as reported by both reference observation and RCMs (Fig. 4) are examined. The differences between the three reference observation data lies in the spatial extent of the different strata reported. TAMSAT and TRMM reported identical spatial extent for low number of dry days along the coast which is larger than that reported by GPCP. Beyond this region, both TAMSAT and TRMM reported lower values compared to GPCP. Generally, TRMM differs largely from GPCP and TAMSAT in the representation of number of dry days in a year over most parts of Niger, Mauritania, Mali and Chad. These has been associated to the

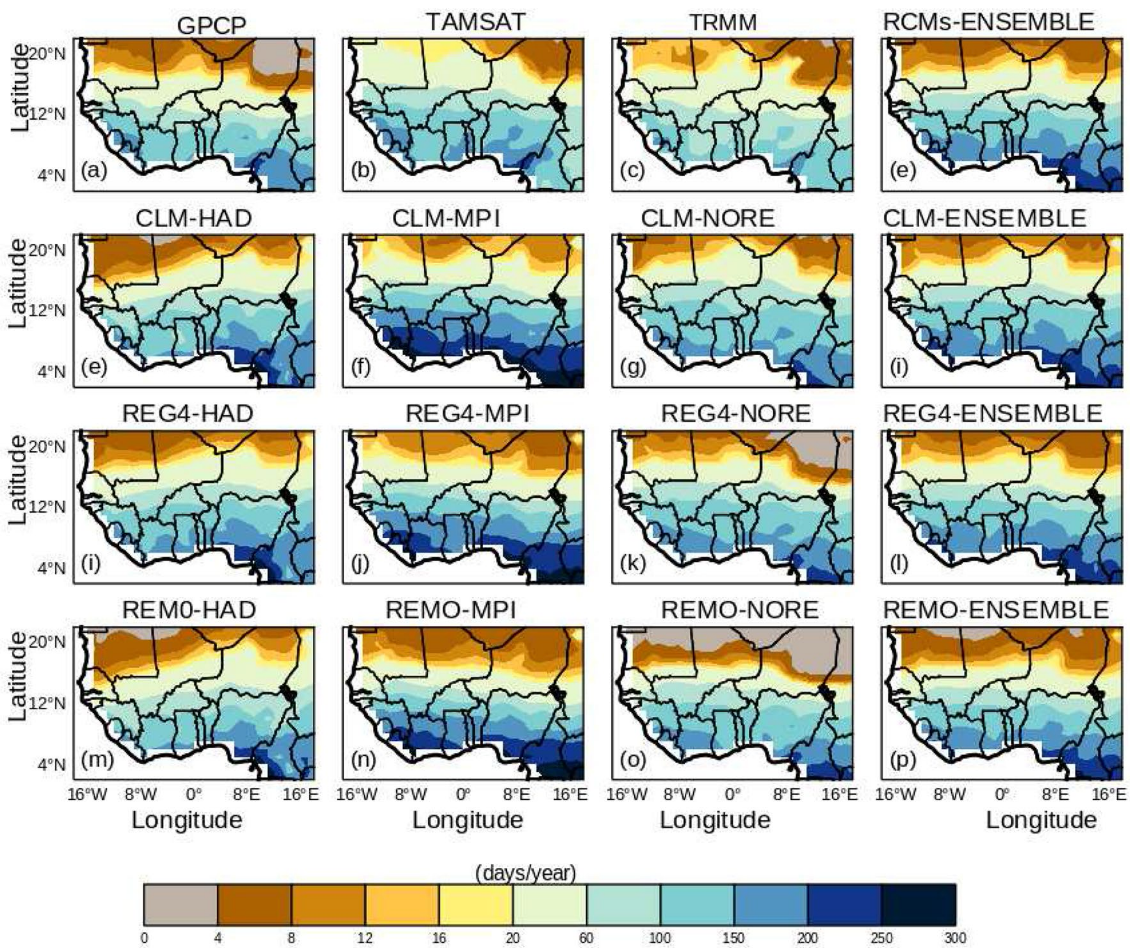


**Fig. 5** The same as Fig. 2 but for Number of wet days (days/year)

retrieval, merging and interpolation techniques adopted as well as the different guage analysis products used (Nikulin et al. 2012). The pattern of dry day numbers reproduced by CLM-based models were identical. However, the values reported by CLM-HAD were significantly lower than the CLM-MPI and CLM-NORE values especially in the northern region. CLM-HAD was observed to reproduced comparable patterns with TRMM while CLM-MPI and CLM-NORE has identical pattern with both GPCP and TAMSAT. REG4-based models showed extremely low values along the coastline of West Africa. Except for the high values in northeastern region and along the coastline, REG4-NORE reproduced remarkably well the pattern observed in GPCP. REMO-based models reproduced different patterns, especially in the northern region of West Africa. The "bulge" observed around the north-central region in REMO-HAD model was not observed in both REMO-MPI and REMO-NORE. While REMO-MPI reproduced a reduced spatial extent of number of dry days as observed in GPCP, REMO-NORE largely overestimated for the region. In many of the models, transition due to vegetation changes were reported along the 12° N latitude. REMO-MPI was found to have the best performance over the region with an RMSE value of 20.51. Generally, the MPI-GCMs ensemble has the best performance with an RMSE of 25.01.

The number of wet days in a year has implication for agriculture and disaster management (Klutse et al. 2021a). It is pertinent to understand the performance of different models in capturing the number of wet days per year for policy formulation and planning. Figure 5 shows the number of wet days per year from the reference observation and RCM models over West Africa. Two areas were found to be prominent based on high number of wet days per year—Guinea highlands and coast of Nigeria. GPCP and TAMSAT reported similar values for the two regions, however, GPCP showed a larger spatial extent extending into Cameroon. TRMM showed a lower value, compared to GPCP and TAMSAT for the two regions. The highest number of wet days per year was observed around the Cameroon mountains along the Nigeria-Cameroon border. GPCP and TAMSAT also showed a region with 110–150 days per year between and north of the two areas. For this region, TRMM reported

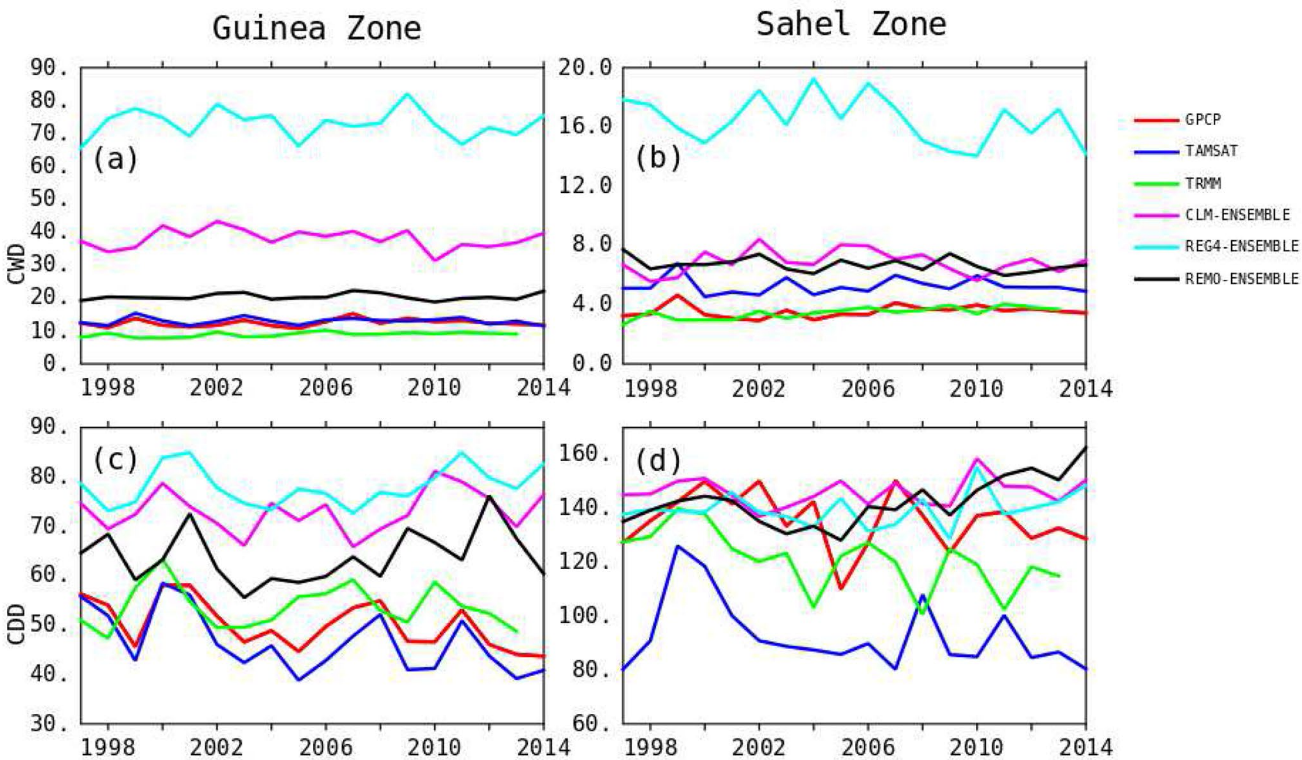


**Fig. 6** Inter-annual variability of consecutive wet days (**a**–**b**) and consecutive dry days (**c**–**d**) averaged along the Guinea (2° N – 12° N; 16° W – 16° E) and Sahel (12° N – 20° N; 16° W – 16° E) zones of West Africa

values largely between 50 and 70 days per year. Around latitude 12° N lies a narrow band with three delineated strips (90–100 days/year, 70–90 days/year, and 50–70 days/year) according to GPCP and TAMSAT. This three delineated strips were reproduced remarkably well by the REG4-based models. The pattern observed around the Guinea highlands and coastal region of Nigeria were overestimated in the REG4-based models. REG4-based models large captured the pattern seen in reference observation data north of 12° but overestimated the values south of this latitude. CLM-based models did not capture the spatial pattern observed in both GPCP and TAMSAT. CLM-HAD and CLM-NORE seems to reproduced patterns observed in TRMM between 10° – 12° N. REMO-based models seem to capture the reference observation patterns (GPCP and TAMSAT) except the coastal regions of Nigeria.

The inter-annual variability from CORDEX-CORE RCMs show a relatively good skill in the evolution pattern for consecutive wet and dry days along the Guinea and Sahel zones of West Africa 6. The models shows similar trend and magnitude for all the four indices considered along the two zones. The magnitude of observed CWD and CDD along the Guinea zone ranges between 10–12 days/year and 40–65 days/year respectively. REMO ensemble consistently capture the trend and magnitude of both CWD and CDD with the least positive bias of 10–20 days/year along the Guinea in contrast to REG4 which has the largest positive bias of up to more than 30 days/year. Along the Sahel, CLM and REMO ensemble shows a better performance of CWD with minimal positive bias of 2–4 days/year. All the models fall within the observation range of in the representation of CDD along the Sahel.

The mean monthly averages of the reference observation datasets and the RCMs ensemble for each indices along the Guinea and Sahel is presented in Fig. 7. The three reference observations show similar pattern and magnitude for all the indices considered. The biases from the extreme precipitation indices on an annual scale are reduced when the monthly averages are considered at the different climate zones. All the RCMs perform reasonably well with little biases in capturing the monthly variation of CDD along the Guinea and Sahel zones. RegCM4 models show the largest positive bias for CWD along the Guinea and Sahel zones. The bias ranges from 5–15 days/month during the rainy period of April to October along the Guinea zone and up to 4 days/month from June to September along the Sahel zone. Along the Sahel zone, the models perform fairly well in the representation of both the number of dry and wet days. However, in the Guinea

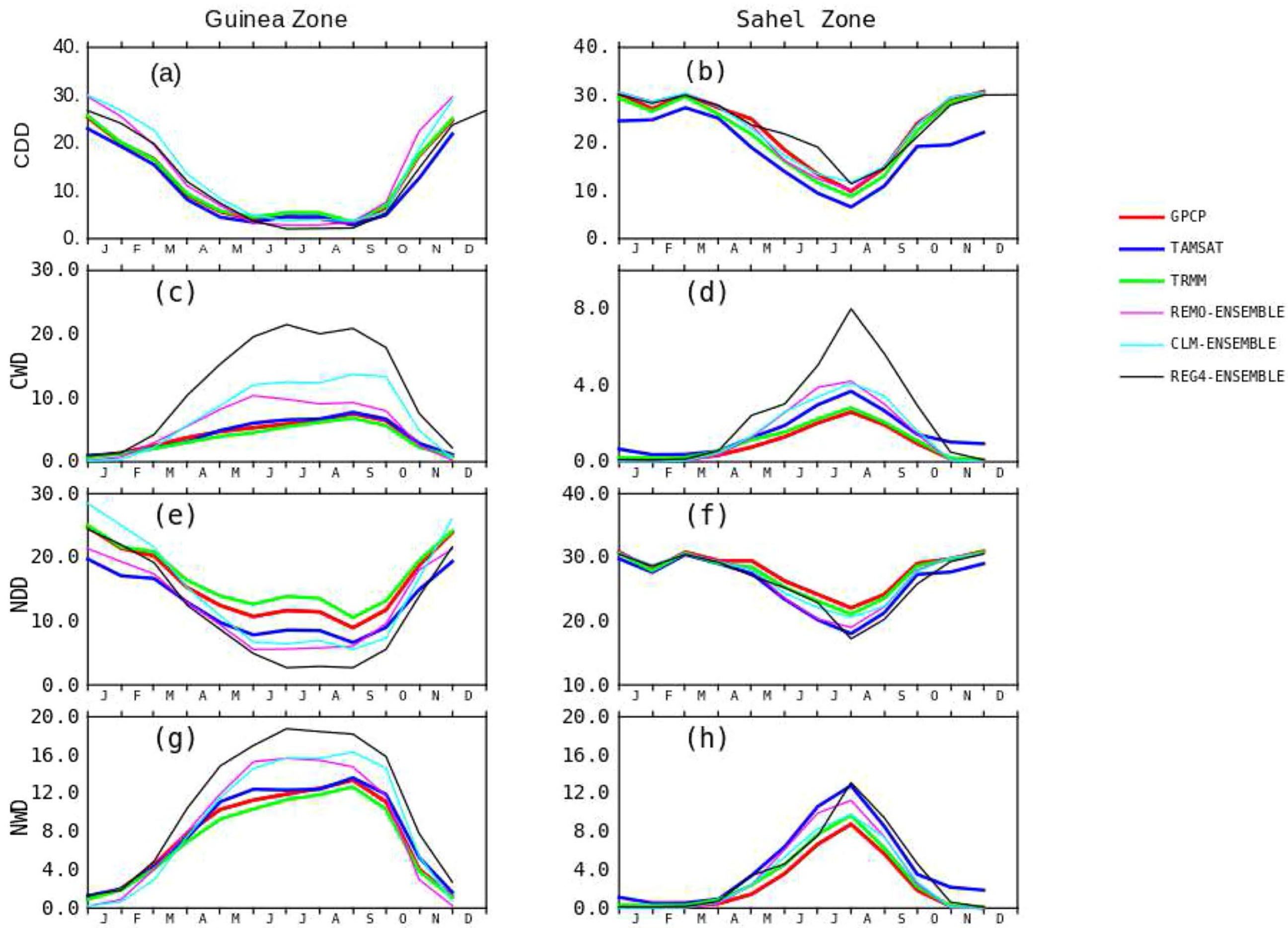


**Fig. 7** Annual cycle of monthly averaged consecutive dry days (**a–b**); consecutive wet days (**c–d**); number of dry days (**e–f**); number of wet days (**g–h**) averaged along the Guinea (2° N – 12° N; 16° W – 16° E) and Sahel (12° N – 20° N; 16° W – 16° E) zones of West Africa averaged for the period 1997–2014

zone, there is a slight overestimation of the magnitude of the number of dry and wet days by up to 10 days/month.

## Discussion

All the reference observation datasets show strong agreement in reproducing the magnitude and variability of consecutive dry days for the period 1997–2014 along the West Africa coasts. The ensemble mean of each of the RCMs and the different GCMs combinations generally show slightly improved results in contrast to the individual GCM-RCM combinations despite the obvious local differences arising in areas of complex topography (e.g. Jos Plateau in Nigeria, Cameroon highlands and Guinea highlands). The REMO-ensemble captured best the year-to-year variability compared to other models ensemble with a minimum positive bias within the range of 5–10 days. On the contrary, REG4 ensemble grossly overestimates the magnitude of consecutive wet days over the entire West Africa by more than 50 days. In the Sahel zone, both CCLM5 and REMO ensemble were able to capture the inter-annual variability and magnitude of consecutive wet days reasonably well relative to the reference observation. The modified Tiedtke cumulus convection scheme adopted by both CCLM5 and REMO based models shows that it is better suited for the West Africa region when compared to the cumulus convection combination adopted in REG4 models. Similarly, the choice of similar driving GCMs for REMO and CCLM5, which is the MPI-ESM-LR, also proves to be more suited in showing a fairly good representation of the precipitation indices on an annual scale with the lowest range of root mean square error in comparison to HADGEM2 or NORESM-M over the West Africa region. Generally, the CORDEX-CORE RCMs provide an improved performance over their driving GCMs in the representation of extreme precipitation events is consistent with other studies such as Coppola et al. (2021); Dosio et al. (2021).

**Table 4** Root mean square error of the models relative to GPCP based on annual scale (days/year)

| | Consecutive dry days | Consecutive wet days | Number of dry days | Number of wet days |
|---|---|---|---|---|
| GPCP | – | – | – | – |
| CLM-HAD | 35.24 | 19.10 | 29.05 | 26.86 |
| REG4-HAD | 27.08 | 39.46 | 50.43 | 47.09 |
| REMO-HAD | 25.74 | 7.40 | 21.74 | 18.91 |
| CLM-MPI | 29.21 | 19.11 | 27.21 | 27.21 |
| REG4-MPI | 25.96 | 30.16 | 37.84 | 37.84 |
| REMO-MPI | 33.77 | 5.38 | 20.51 | 19.81 |
| CLM-NORE | 36.75 | 21.92 | 24.96 | 24.92 |
| REG4-NORE | 39.06 | 35.19 | 37.49 | 37.39 |
| REMO-NORE | 58.82 | 6.11 | 20.57 | 19.88 |
| CLM-Ensemble | 33.18 | 19.85 | 26.01 | 25.32 |
| REG4-Ensemble | 29.45 | 34.47 | 40.53 | 39.52 |
| REMO-Ensemble | 37.36 | 6.02 | 17.23 | 16.43 |
| ALL-RCMs-Ensemble | 30.29 | 18.57 | 25.33 | 24.16 |
| HAD-GCMs-Ensemble | 26.52 | 20.34 | 30.78 | 27.56 |
| MPI-GCMs-Ensemble | 26.58 | 16.64 | 25.01 | 25.01 |
| NORESM-GCMs-Ensemble | 40.52 | 19.38 | 30.11 | 22.97 |

Atmospheric parameters, especially precipitation, have been shown to have complex chaotic nature which makes long term prediction impossible (Fuwape et al. 2017, 2020; Ogunjo et al. 2019). Diatta et al. (2020) in a study to examine the role of extreme precipitation indices during summer to teleconnection remote indices such as Eastern Mediterranean Sea (EMS), Atlantic Meridional Mode, Maiden Julian Oscillation phase 8, El Niño 3.4 index, Trans-Atlantic-PacificOcean Dipole Index (TAPODI), Atlantic zone 3 SST anomaly (ATL3) and Northern Cold Tongue Index (NCTI) found that extreme precipitation of all Sahel is strongly teleconnected to the EMS while the Guinean coast is more linked to the ATL3, NCTI, TAPODI. Dynamical representation of atmospheric parameters within this region is expected to have some challenges. This could be observed in the biases reported in this study. Remedio et al. (2019); Gnitou et al. (2021) attributed these biases to uncertainties from observational data, boundary forcing conditions, and misrepresented processes. The misrepresentation of key processes such as monsoon processes and deep convection in the RCMs have been suggested to be responsible for some of the biases (Gnitou et al. 2021; Sylla et al. 2011; Nikulin et al. 2012) as well. Biases in the REG4 model might be caused by topography (Reboita et al. 2021). The inability of the RCMs to adequately simulate West African Monsoon has been attributed to their internal dynamics and physics (Gbobaniyi et al. 2014; Sylla et al. 2011). Based on these, we attribute the observed biases to the internal dynamics and physics of the models besides the input boundary forcing conditions.

## Conclusion

The dearth of meteorological data within the sub-Saharan region is well documented. The dynamics of the region makes it an important location in global climate study. Researchers investigating climate dynamics and variation in West Africa resort to alternative data including: remotely sensed data from satellite and reanalysis data combining model with in-situ data. These two sources are not without their limitations. There is the need to continue with investigating the performance of these two data sources over the region to ascertain their efficiency. In this study, the focus is to investigate the performance of three high resolution RCMs in the representation of warm and dry spells over West Africa for the period 1997–2014. The model simulations were compared with 3 reference observation datasets from GPCP, TAMSAT, and TRMM. All the three reference datasets show a strong agreement in the spatial distribution and magnitude of the maximum consecutive wet days. The REMO based models irrespective of its driving GCMs was able to reasonably reproduce the observed characteristics of consecutive wet days with a very low root mean square error of 6 days/year. On the other hand, other models (CLM and REG4) capture the pattern but grossly overestimate the magnitude along areas south of 12° N by more than 20 days/year. Generally, the performance of REMO models was remarkably outstanding with respect to the reference observation datasets for all the indices considered. Hence, REMO RCMs and its ensembles are the best performing in the region for their ability to reproduce the spatial distibution of extreme precipitation indices relative to other RCMs considered in this study. This is also in agreement with findings from Gnitou et al. (2021) in their assessment of CORDEX-CORE RCMs simulations over the Africa region. Results obtained in this study showed that the 3 RCMs considered generally captured the latitudinal decrease in wet spells (increase in dry spells) from the coasts to areas further inland in comparison to the reference observation datasets. Furthermore, most of the models were able to identify unique features within the region such as vegetation transition zones and topographical landmarks. However, the models (REG4, CLM and REMO) were found to either overestimate or underestimate extreme precipitation indices due to the influence of driving GCMs or the internal model physics of the RCMs. For instance, along the Guinea coasts, MPI-ESM driving GCM exhibits widespread higher magnitude of positive bias (100 days/year) in the pattern of number of wet days relative to the reference datasets irrespective of the downscaled RCMs used. On the contrary, the representation of the number of dry days, consecutive wet days and consecutive dry days depends more on the respective RCMs model physics and configurations, as it shows distinct spatial pattern and magnitude that is independent of the driving GCMs. This is manifested in the different magnitude of extreme precipitation indices (CWD, CDD and NDD) exhibited by the different RCMs though driven by the same GCMs. Therefore, bias corrections of the RCMs for impact studies is recommended.

**Author Contributions** CFO: data curation; formal analysis; visualization; investigation; methodology; writing-review and editing. OA: writing-review and editing. II: writing-review and editing. OA: writing-review and editing. SO: Conceptualization; investigation; methodology; writing-review and editing.

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**Data Availability Statement** All data used in this study are publicly available and listed in the methods section.

## Declarations

**Conflict of interest** The authors declare that they have no conflict of interest.

**Ethical approval** Not applicable.

**Consent to participate** Not applicable.

**Consent to publish** All authors agreed to the publication of the manuscript in its current form.

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