Climate Dynamics (2019) 52:2017–2028
https://doi.org/10.1007/s00382-018-4238-8

Projections of West African summer monsoon rainfall extremes from two CORDEX models

A. A. Akinsanola[1] · Wen Zhou[1]

Received: 23 November 2017 / Accepted: 3 May 2018 / Published online: 8 May 2018

Abstract

Global warming has a profound impact on the vulnerable environment of West Africa; hence, robust climate projection, especially of rainfall extremes, is quite important. Based on two representative concentration pathway (RCP) scenarios, projected changes in extreme summer rainfall events over West Africa were investigated using data from the Coordinated Regional Climate Downscaling Experiment models. Eight (8) extreme rainfall indices (CDD, CWD, r10mm, r20mm, PRCPTOT, R95pTOT, rx5day, and sdii) defined by the Expert Team on Climate Change Detection and Indices were used in the study. The performance of the regional climate model (RCM) simulations was validated by comparing with GPCP and TRMM observation data sets. Results show that the RCMs reasonably reproduced the observed pattern of extreme rainfall over the region and further added significant value to the driven GCMs over some grids. Compared to the baseline period 1976–2005, future changes (2070–2099) in summer rainfall extremes under the RCP4.5 and RCP8.5 scenarios show statistically significant decreasing total rainfall (PRCPTOT), while consecutive dry days and extreme rainfall events (R95pTOT) are projected to increase significantly. There are obvious indications that simple rainfall intensity (sdii) will increase in the future. This does not amount to an increase in total rainfall but suggests a likelihood of greater intensity of rainfall events. Overall, our results project that West Africa may suffer more natural disasters such as droughts and floods in the future.

Keywords Regional climate model · Extreme precipitation · Climate change · Evaluation and future projection · Ensemble

1 Introduction

Extreme weather and climate events (e.g., heavy rainfall, heat waves, droughts, hurricanes) have always posed risks to human society. Most importantly, rainfall extremes, upon which this study focuses, have important implications for rain-fed agriculture, urban and rural development, hydroelectric power generation, human health, public infrastructure, and watershed management (Odoulami and Akinsanola 2017). Countries in West Africa are particularly vulnerable to extreme rainfall events because of low adaptive capacity due to limited access to information, finances, technology, and capital assets (Sylla et al. 2016). Historical records indicate that West Africa has experienced tremendous variability in rainfall, ranging from the devastating drought of the 1970s and 1980s, to recent increases in flooding (Nicholson 2013). As a matter of fact, IPCC (2013) reported a drying trend over West Africa in a longer time series ranging from 1951 to 2012, with a large-scale background connected to phase changes of the Pacific decadal oscillation and to internal variability (Zhou et al. 2008b; Zhang and Zhou 2011). This mechanism has also been demonstrated by numerical modelling experiments driven by historical SST data (Zhou et al. 2008a). In addition, external forcing such as that from aerosols has also contributed (Li et al. 2010). Recent and more extensive study by Ibrahim et al. (2014) revealed that in the last two decades, not only have annual rainfall totals increased, but rainy days have also become more frequent, leading to the partial recovery of rainfall amount (Lin et al. 2014; Sanogo et al. 2015). This recent recovery of Sahel rainfall has been attributed to the direct influence of higher levels of anthropogenic greenhouse gases in the atmosphere, along with changes in anthropogenic aerosol precursor

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00382-018-4238-8) contains supplementary material, which is available to authorized users.

✉ Wen Zhou
wenzhou@cityu.edu.hk

[1] Guy Carpenter Asia-Pacific Climate Impact Centre, School of Energy and Environment, City University of Hong Kong, Hong Kong, China

emissions (Ackerley et al. 2011; Biasutti 2013; Dong and Sutton 2015), although Mohino et al. (2011) indicated that natural variability might have played an important role.

Therefore, a matter of growing interest is the degree to which these extremes are changing through anthropogenic activities. For instance, the present-day warming and enhanced variability of rainfall are likely to be exacerbated in the future climate, with large regional variation and different degrees of confidence (Lobell et al. 2011; Anyamba et al. 2014), and thus the frequency and magnitude of extreme rainfall over the region are expected to increase throughout the twenty-first century (Kitoh et al. 2013; IPCC 2014). Thus, understanding the changes in extreme rainfall that may occur under the future climate is an important input for adaptation planning and policy making. Robust information on changes in the characteristics of future extreme rainfall to be used at local scales remains uncertain because the spatial distribution of rain gauges is not adequate to allow the description of local and regional characteristics of daily rainfall (Akinsanola et al. 2017b). Also, model grid resolutions are often too coarse to resolve extreme rainfall, primarily due to dynamics and parameterizations related to their coarse spatial resolution (Hudson and Jones 2002). Therefore, there is need for a regionalization process to resolve small-scale weather events and thus improve the ability to model extreme rainfall. This is usually achieved through either dynamical or statistical downscaling (Hewitson and Crane 1996). Dynamical downscaling, which often involves a regional climate model (RCM) nested in a global circulation model (GCM), is generally considered more reliable than statistical downscaling due to the dynamical frames and physics processes included in RCMs, although the former is more computationally intensive and time consuming than the latter (Ji and Kang 2013).

The World Climate Research Program (WCRP) Coordinated Regional Climate Experiment (CORDEX) (Giorgi et al. 2009) was established to provide global coordination of regional climate downscaling to explore the historical and future climates of the defined regions, and to contribute to the information needs of climate change adaptation, impact assessment, and policy making. In the first phase of CORDEX, an ensemble of RCMs for Africa, forced by ERA-Interim reanalysis, has been completed at grid resolutions of 0.44° (about 50 km) and analysed extensively in detail by Nikulin et al. (2012). Follow-up studies over the region have focused mostly on rainfall climatology (Kalognomou et al. 2013; Kim et al. 2013; Gbobaniyi et al. 2014; Akinsanola et al. 2015; Akinsanola and Ogunjobi 2017), and they reported separately that RCMs reasonably reproduce general rainfall characteristics, although biases remain and are found to be specific to individual models, regions, and seasons. Conversely, their results show that the multi-model ensemble mean generally outperforms any individual simulation and that the RCMs significantly improve simulations of rainfall climate. Similar results were also found in a daily rainfall assessment (Klutse et al. 2015), where the multi-model ensemble mean outperformed most of the individual RCM members in terms of mean rainfall climatology, frequency, and intensity of wet days, and to a lesser extent the 95th percentile. Generally, the finer resolution resulting from dynamical downscaling has led to the improved representation of West African rainfall variability at a climatological timescale (Akinsanola et al. 2017a), and the extreme events that are sometimes absent in GCM simulations are generally better reproduced. In fact, the overall evidence presented in previous studies shows that the accuracy of RCMs in reproducing the spatial and temporal features of precipitation grows with increasing model resolution (Maraun et al. 2010); it is therefore also expected that they would provide meaningful future projections.

Studies focusing on climate change impacts, especially rainfall extremes, over all of West Africa are rare, and agriculture, hydroelectric power generation, and water resources in this region are the most vulnerable to these projected changes. Therefore, projected changes in extreme rainfall using multiple dynamical downscaling simulations are especially meaningful over West Africa considering its peculiarities and vulnerability. The ability of the CORDEX RCMs to simulate rainfall extremes and present projections for the end of the twenty-first century over West Africa is evaluated in this study. The paper is organized as follows. Section 2 will describe data and methodology. Evaluation of a historical model simulation in terms of extreme rainfall will be given in Sect. 3. Future projections under the two RCPs will be presented in Sect. 4. The final section will provide a summary and conclusions.

2 Data and methodology

2.1 Study area

West Africa (0°–20°N, 20°W–20°E), as shown in Fig. 1, is subdivided into three latitudinal subregions following Akinsanola et al. (2015, 2017b), which include the Guinea coast (latitude 4°°–8°N; longitude 20°W–20°E), which borders the tropical Atlantic Ocean in the south; the Savannah (latitude 8°–11°N; longitude 20°W–20°E), an intermediate subregion; and the Sahel (latitude 11°–16°N; longitude 20°W–20°E) to the north. The Guinea coast experiences a bimodal rainfall regime that is centered in the summer monsoon period of June–September, with August being the period of a short dry season. The Savannah and Sahel subregions experience a unimodal rainfall regime, with maximum rainfall occurring in August. The ranges of annual rainfall amount are 400–600 mm in the Sahel; 900–1200 mm in the

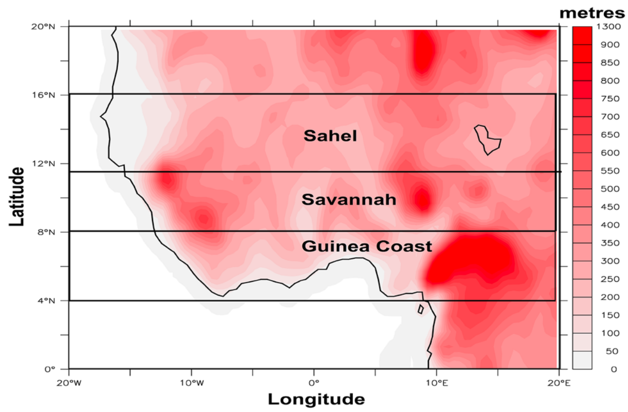

Fig. 1 Study domain showing West African topography and the regions designated as Guinea coast, Savannah, and Sahel in the study

Savannah; and 1500–2000 mm in the Guinea coast (Akinsanola et al. 2017b). Furthermore, West African rainfall regimes follow the seasonal migration of the intertropical discontinuity zone (ITD) and the northward penetration of the southwesterly monsoon flow. The West African climate is also greatly influenced by complex topography; some of the most important plateaus are Fouta Djallon, Jos Plateau, and the Cameroon Highlands.

2.2 Model

In this study, dynamically downscaled daily rainfall from two RCM simulations that were available at the time of analysis in the CORDEX project is analysed. The Rossby Center (SMHI) regional climate model (RCA4; Dieterich et al. 2013) and the Consortium for Small-scale Modelling (COSMO) Regional Climate Model (COSMO-CLM; Panitz et al. 2014) are used to downscale four Coupled Model Intercomparison Project Phase 5 (CMIP5) GCMs (CNRM-CM5, EC-EARTH, HadGEM2-ES, and MPI-ESM-LR). All simulations are performed at a grid resolution of 0.44° × 0.44° over the same African domain. Details of the models can be found in Dieterich et al. (2013) and Panitz et al. (2014). The CMIP5 GCM projections are forced by the Representative Concentration Pathways (RCPs) as described in Moss et al. (2010) and van Vuuren et al. (2011). The RCPs are prescribed greenhouse-gas concentration pathways throughout the twenty-first century, which correspond to different radiative forcing stabilization levels by the year 2100. RCP4.5 and RCP8.5, which respectively represent mid- and high-level emission scenarios, are used in this study.

2.3 Observations

In this study, two observation products are used to evaluate the models' skill in simulating extreme rainfall indices, namely the Global Precipitation Climatology Project One-Degree Daily (GPCP 1DD Version 1.2; Huffman et al. 2001), available for the period 1997–2005, and the 0.25° resolution Tropical Rainfall Measuring Mission (TRMM 3B43 version 7; Huffman et al. 2007), available for the period 1998–2005. It is worth noting that gridded observation products may have potential uncertainties due to uncertainties in the data sources and processing algorithms (Xu and Powell 2012). However, these two gridded rainfall datasets, which are based on gauge-satellite products, have shown remarkable performance over the years, especially over Africa, where daily rainfall gauge datasets are evidently scarce. In fact, they have been described as an alternative for evaluating climate models (e.g., Nikulin et al. 2012; Sylla et al. 2013; Akinsanola et al. 2017b). Nevertheless, Sylla et al. (2013) and Odoulami and Akinsanola (2017) found that these two satellite-derived rainfall datasets exhibit substantial systematic differences in mean rainfall, especially in the frequency of wet days, intensity, and extremes, as well as in the maximum length of wet and dry spells. Also, the GPCP is more consistent with other observations.

2.4 Methodology

Eight (8) precipitation indices (see Table 1) used in this study are based on the definitions recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI). These indices are based on daily rainfall and have been widely used in the detection, attribution, and projection of changes in climate extremes (Donat et al. 2013; Sillmann et al. 2013). Detailed description of the indices can be found on the ETCCDI website, http://etccdi.pacificclimate.org/list_27_indices.shtml. Since over 75% of the annual rainfall in the region is received during the summer monsoon months (Sylla et al. 2013; Akinsanola et al. 2017a; Odoulami and Akinsanola 2017), all indices are calculated for the summer monsoon period of June–September for both historical and future scenario simulations. The model evaluation analysis is carried out by considering a common period across the observations and simulations (1998–2005). In order to facilitate convenient comparisons, all the datasets used in this study were regridded to a spatial resolution of 0.44° using the bilinear interpolation technique presented in Nikulin et al. (2012), except for TRMM observations in which the distance-weighted interpolation method (Jones 1999) was used to keep its high-resolution details, and were all integrated over the West African domain of 0°–20°N, 20°W–20°E. The root mean square error (RMSE) and pattern correlation coefficient (PCC) were used to assess the models' performance. Similarly, to evaluate the ability of CORDEX RCMs to improve (or not) the driven GCM simulations in the present time period, we used the added

Table 1 List of climate extreme indices of ETCCDI used in this study

S/N	Extreme indices	Name	Definition	Units
1	CDD	Consecutive dry days	Maximum number of consecutive days with RR < 1.0 mm	Days
2	CWD	Consecutive wet days	Maximum number of consecutive days with RR ≥ 1 mm	Days
3	PRCPTOT	Total wet-day rainfall	Total rainfall in wet days (RR ≥ 1 mm)	mm
4	r10mm	Heavy rainfall days	Number of days when RR ≥ 10 mm	Days
5	r20mm	Very heavy rainfall days	Number of days when RR ≥ 20 mm	Days
6	R95pTOT	Extremely wet days	Total rainfall when RR > 95th percentile	mm
7	rx5day	Maximum consecutive 5-day rainfall	Maximum consecutive 5-day rainfall	mm
8	sdii	Simple rainfall intensity index	Total rainfall divided by the number of wet days in the year	mm/day

value approach proposed by Di Luca et al. (2012) and later adopted by Dosio et al. (2015):

$$AV = \frac{(X_{GCM} - X_{OBS})^2 - (X_{RCM} - X_{OBS})^2}{Max((X_{GCM} - X_{OBS})^2, (X_{RCM} - X_{OBS})^2)}$$

where X_{GCM}, X_{OBS}, and X_{RCM} represents the index calculated from large-scale forcing (CMIP5 GCMs), observation (GPCP), and RCMs, respectively. Defined in this way, added value is positive where the RCM models' squared error is smaller than that of the corresponding GCM, that is, where the RCM models improve the GCMs' results. Normalization is introduced so that $-1 \leq AV \leq 1$ (Dosio et al. 2015).

For analysis of the climate projections, we focus on the end of the twenty-first century (2070–2099) relative to a 30-year historical time period (1976–2005). The future time slice (2070–2099) is compared with the historical time (1976–2005) to assess the projected changes, and the statistical significance is evaluated using a *t*-test.

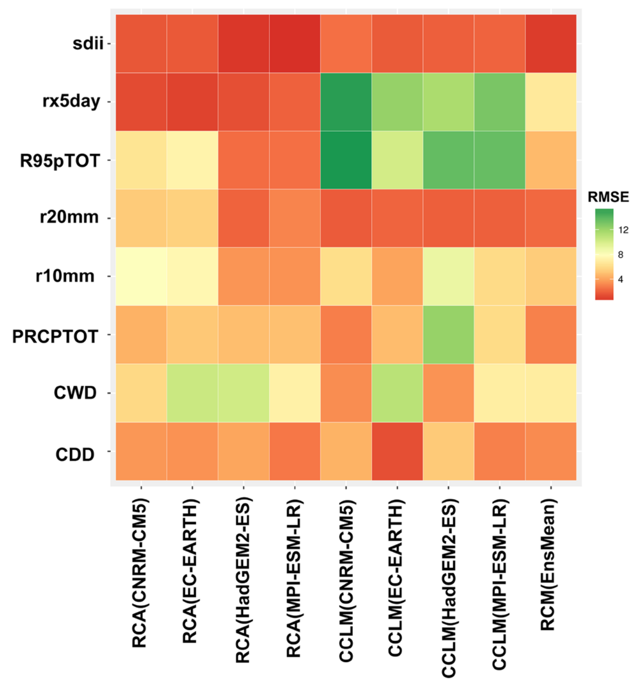

Fig. 2 Root-mean-square error (RMSE) for the rainfall extreme indices for the period 1998–2005. GPCP observations were used as the reference

3 Evaluation of simulated rainfall extreme

The performance of each index is first evaluated by assessing its RMSE relative to GPCP observations, as presented in Fig. 2. The RCMs have similar skill depending on the index, although CCLM simulations exhibit large errors for rx5day and PRCPTOT. The multi-model ensemble mean (EnsMean) shows a relatively low RMSE value, implying an obvious reduction in systematic errors noticeable among the individual RCM members. Figure 3 presents the spatial distribution of summer (JJAS) consecutive dry days (CDD) over West Africa for GPCP (Fig. 3a), TRMM (Fig. 3b), the EnsMean (Fig. 3c), and each of the ensemble members (Fig. 3d–k). The EnsMean defined herein is the average of RCA4 and CCLM driven by the CMIP5 GCMs. The stippling in Figs. 3, 4 and 5 represents grids where there is added value in the indices from the RCMs compared to the indices from the GCMs for the reference period. In the evaluation of CDD, a rainfall threshold of below 1 mm has been assumed in order to distinguish between wet and dry days. The maximum number of dry days is located over the Sahel subregion in the two observation datasets, while the Guinea coast exhibits the fewest. The RCM members and their EnsMean realistically reproduce the CDD, and the PCC exceeds 0.9 in all model members. Noticeable also is that the RCMs add remarkable value over several grids within the region.

The spatial distribution of total summer (JJAS) wet-day rainfall (PRCPTOT) is presented in Fig. 4. In the observation datasets of GPCP and TRMM, PRCPTOT maxima are located within the Guinea coast subregion of West Africa, especially over the complex terrain of the Fouta Djallon highlands, Cameroon Highlands, and Jos Plateau. Significant differences can be found across the observation datasets

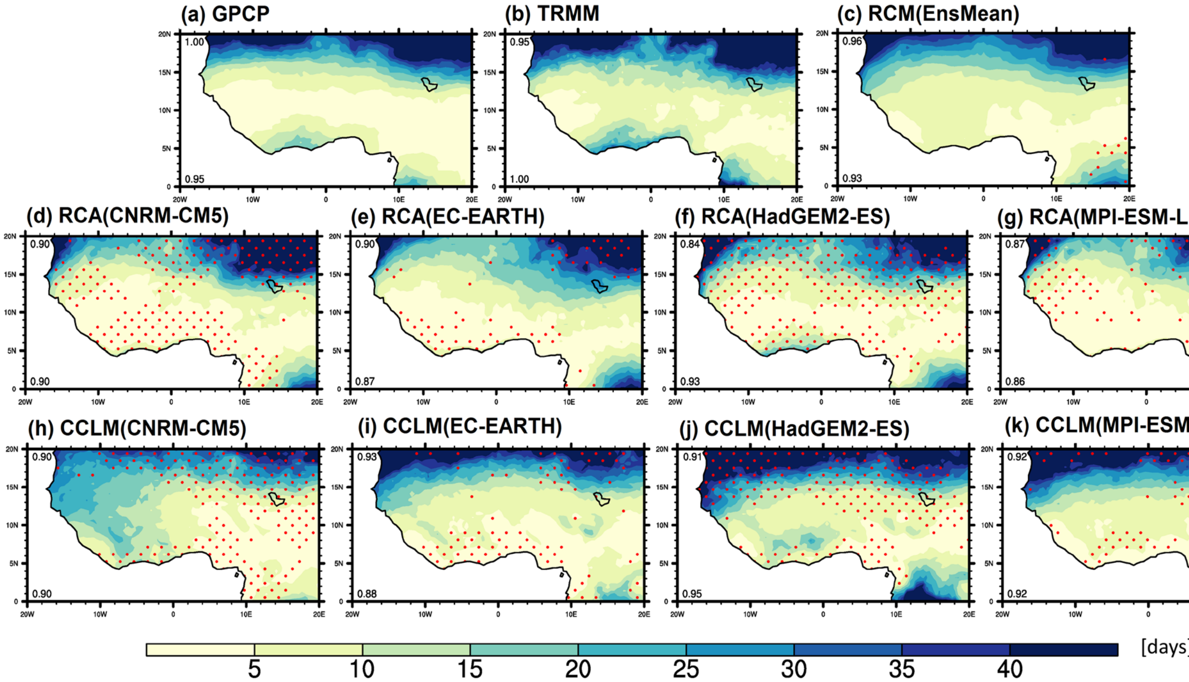

Fig. 3 Consecutive dry days (CDD) for the period 1998–2005 for **a** GPCP, **b** TRMM, **c** multi-model ensemble mean of CCLM and RCA4 forced by GCMs, **d**–**g** RCA forced by different GCMs, **h**–**k** CCLM forced by different GCMs. Stippling indicates grid points with value added by dynamical downscaling. The top left number is the PCC with GPCP and the bottom left with TRMM

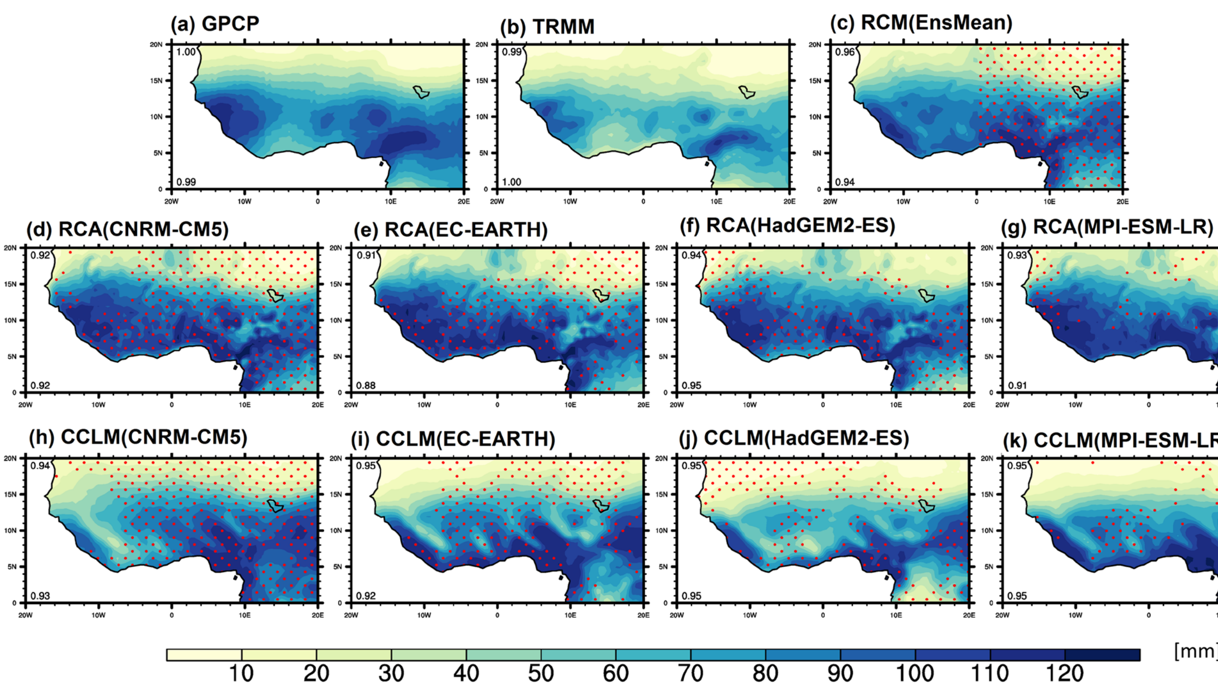

Fig. 4 Same as Fig. 3 but for total annual wet-day rainfall (PRCPTOT)

regarding the magnitude and spatial extent of PRCPTOT. For instance, the GPCP shows higher PRCPTOT over the maximum rainfall centres within the Guinea coast. The pattern correlation coefficient (PCC) between the GPCP and TRMM exceeds 0.9, indicating a good level of agreement. However, the RCMs reasonably capture the main features of

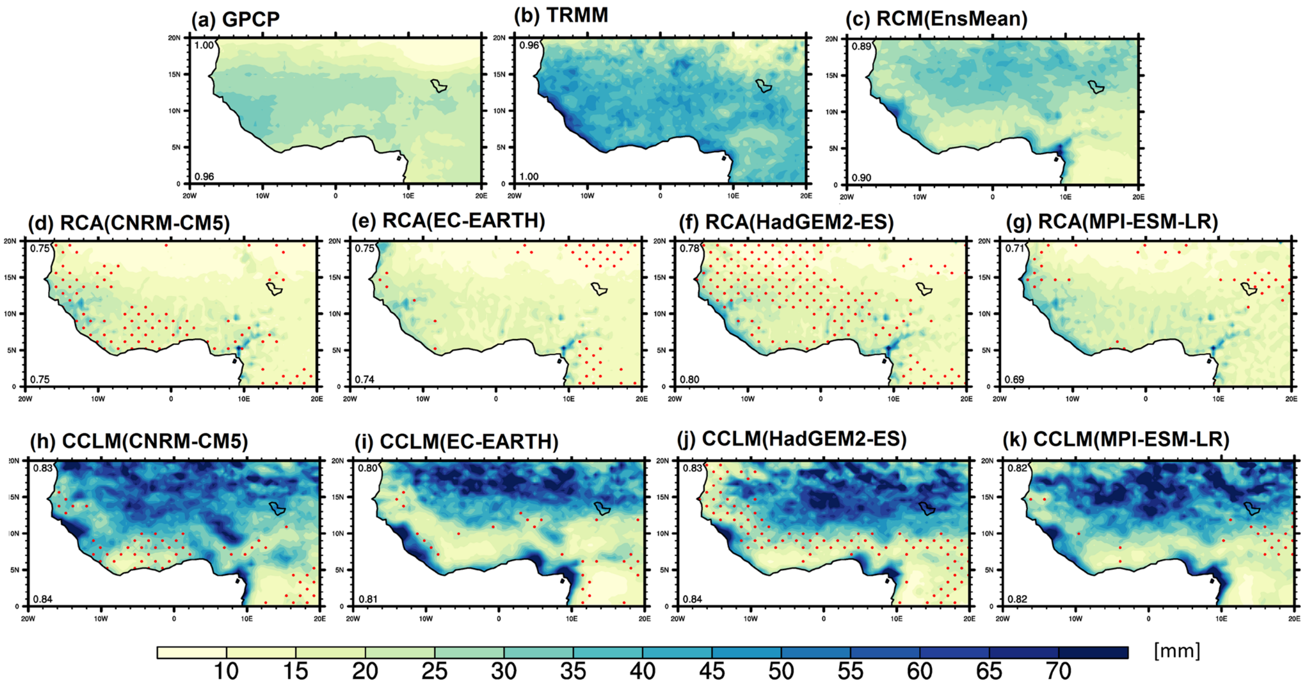

Fig. 5 Same as Fig. 3 but for annual total rainfall greater than or equal to the daily 95th percentile (R95pTOT)

the climatological pattern of PRCPTOT when compared to the two observation datasets. In particular, the north–south gradient in rainfall totals over West Africa and the band of relatively low rainfall that stretches across the Sahel belt are well replicated by the RCMs. It is worth mentioning that RCA4 (CCLM) slightly overestimates (underestimates) the magnitude of PRCPTOT in all the individual RCM forced runs, especially over the maximum rainfall centres (i.e., the effect of topography is more evident). These noticeable biases may be due to the inability of the RCMs to resolve the complex topography, or the large-scale atmospheric circulation pattern could lead to increased moisture input from the Atlantic Ocean into the study area (Pinto et al. 2016). In fact, Kotlarski et al. (2014) have argued that the models' overestimation might be related to the effects of non-smoothed model topography, leading to sharp gradients between neighbouring grid boxes and generation of small-scale waves. This can lead to premature water vapour condensation with early rainfall occurrence when humid air is lifted over a mountainous area (Bucchignani et al. 2016). Based on the PCC of PRCPTOT, the EnsMean slightly outperforms individual model simulations as a result of the cancellation of spatial errors. Similar results are also found in the spatial distribution of rainfall on extreme wet days (R95pTOT), as presented in Fig. 5. The RCA4 (CCLM) simulated extreme is closer to GPCP (TRMM) observations. Although the RCM downscaled simulations improve the GCM results in some grids, the EnsMean generally outperforms the RCM members and is closer to the TRMM observations (PCC = 0.90) than GPCP (PCC = 0.89). As is evident from the limited samples, the use of the multi-model ensembles using different RCMs driven by different GCMs might provide an optimal approach to the simulation of climate change scenarios over West Africa. Based on the added value analysis, it is observed that RCA4 significantly improves the GCM performance for more areas of the West African domain than CCLM. These results further buttress the idea presented in the works of Giorgi (1990) and Di Luca et al. (2012), who reported separately that RCMs can adequately resolve processes and feedbacks that operate at a subgrid-scale GCM resolution.

In the evaluation of consecutive wet days (CWD) presented in supplementary Figure S1, the assumed 1 mm rainfall threshold helps to partially remove the problem associated with the RCMs of simulating too many low-intensity rainfall events (Gutowski et al. 2003). The overall pattern of these indices is reasonably well represented in the simulations, although the magnitude varies considerably among the models. Nevertheless, there is still significant noticeable added value in the dynamically downscaled GCM data. The individual RCM members and their EnsMean are more closely related to the GPCP observations than the TRMM data, based on PCC and visual assessments. The spatial distributions of heavy rainfall days (r10mm) and very heavy rainfall days (r20mm) (see supplementary Figures S2 and S3) are similar to the spatial distribution observed in PRCPTOT. Both GPCP and TRMM indicate a good level of agreement, with PCC exceeding 0.9. The r10mm and r20mm events are slightly underestimated/overestimated as described for PRCPTOT, and the RCMs also show remarkable added value to the GCM forcing data. The spatial distribution of the maximum 5-day rainfall (rx5day) (see supplementary Figure S4) and rainfall intensity (sdii) (see supplementary Figure S5) are generally better represented in RCA4 than in CCLM, with noticeable biases over some grids.

4 Projections of extreme rainfall

In this section, the EnsMean of the dynamically downscaled projected changes in rainfall-based indices for the end of the twenty-first century (2070–2099) is discussed. Changes that are statistically significant at the 5% significance level are indicated by stippling. The significance of the changes was tested with a *t*-test. The spatial distributions of the projected future changes in extreme rainfall indices over West Africa under RCP4.5 and RCP8.5 are shown in Figs. 6 and 7, respectively. The EnsMean projects a significant decrease in summer PRCPTOT over the entire West African domain under the RCP4.5 scenario, except for the southern tip of the Fouta Djallon highlands, where a significant increase is observed (Fig. 6b). The analysis reveals that the sign of the projected changes remains the same for both scenarios, but the magnitude and area extent is greater for RCP8.5. In contrast, the maximum number of consecutive dry days (CDD) is projected to increase over the majority of the domain, with longer dry spells projected over the Sahelian belt (Figs. 6a, 7a). The projected reduction in PRCPTOT accompanied by increases in CDD would evidently have significant impacts on rain-fed agriculture, hydroelectric power generation, and water resources. The R95pTOT, rx5day, and sdii indices generally increase over all of West Africa in both scenarios, with the spatial extent and magnitude greater under RCP8.5, implying high frequency of flooding over the region, while the r10mm is projected to significantly decrease over the Sahel and increase over the Guinea coast. Projected changes in CWD (see supplementary Figures S6a and S7a) and r20mm (see supplementary Figures S6b and S7b) show a significant decrease (increase) in CWD (r20mm) over the majority of the West African domain. Our result is consistent with that of Kitoh et al. (2013), who reported that the African monsoon region would experience a rather modest mean precipitation in the future, but large precipitation extremes.

Overall, the projections are consistent with the main findings in the literature. Sun et al. (2016) analysed extreme event indicators considering 14 CMIP5 climate models, showing that the magnitudes of the index changes were generally larger for higher emission scenarios, confirming that changes in the indices were highly dependent on radiative forcing (Li et al. 2013).

A detailed assessment of the projected changes in rainfall extremes by the end of the twenty-first century (2070–2099) for the three homogeneous subregions (Guinea coast, Savannah, and Sahel) is presented in Fig. 8. As a measure of the model agreement and thus the reduction of uncertainty in the projected changes, we have superimposed the projected changes in each of the RCM members on its EnsMean. The projected changes over the Savannah and Sahel are mostly closely related, and the model spread is generally similar. Decreases in PRCPTOT (Fig. 8) and CWD (see supplementary Figure S8) are projected in all three subregions, with more than 60% of the models agreeing with the projected reduction. The projected increases in R95pTOT, r10mm, r20mm, rx5day, and sdii in all subregions are evident. These projected increases may be connected with the expected increase in surface temperature, since a warmer atmosphere has a larger moisture-holding capacity (Lenderink and van Meijgaard 2010). The CDD is expected to decrease over the Guinea coast and increase over the Savannah and Sahel (Fig. 8). Interestingly, a significant increase in the CDD coupled with increasing R95pTOT, especially over the Savannah and Sahel, indicates that these subregions are projected to have a high incidence of drought and flood disasters. The higher probability of these combined natural disasters may threaten the available water resources of these subregions and thus affect the regional availability of food and possibly alter social stability.

5 Summary and conclusions

In this study, the capabilities of RCM simulations from the CORDEX-Africa project and their multi-model ensemble were investigated and used to assess the potential impact of climate change on future extreme rainfall across West Africa during the summer monsoon period of June–September. The multi-model ensemble consists of two RCMs, namely RCA4 and CCLM4.8, driven by four different GCMs (CNRM-CM5, EC-EARTH, HadGEM2-ES, and MPI-ESM-LR) for two radiative forcing scenarios, RCP4.5 and RCP8.5. Eight ETCCCDI rainfall indices computed for the dynamical downscaling were evaluated at the historical timescale (1998–2005) by comparing with GPCP and TRMM gridded rainfall observation datasets. These results were further compared with their GCM forcing for the historical climate conditions over West Africa to demonstrate the added value of the dynamical downscaling. Finally, future changes in the eight rainfall indices were assessed by comparing the future climate conditions (2070–2099) with the historical time period of 1976–2005 under RCP4.5 and RCP8.5. Results reveal that the two observational datasets GPCP and TRMM

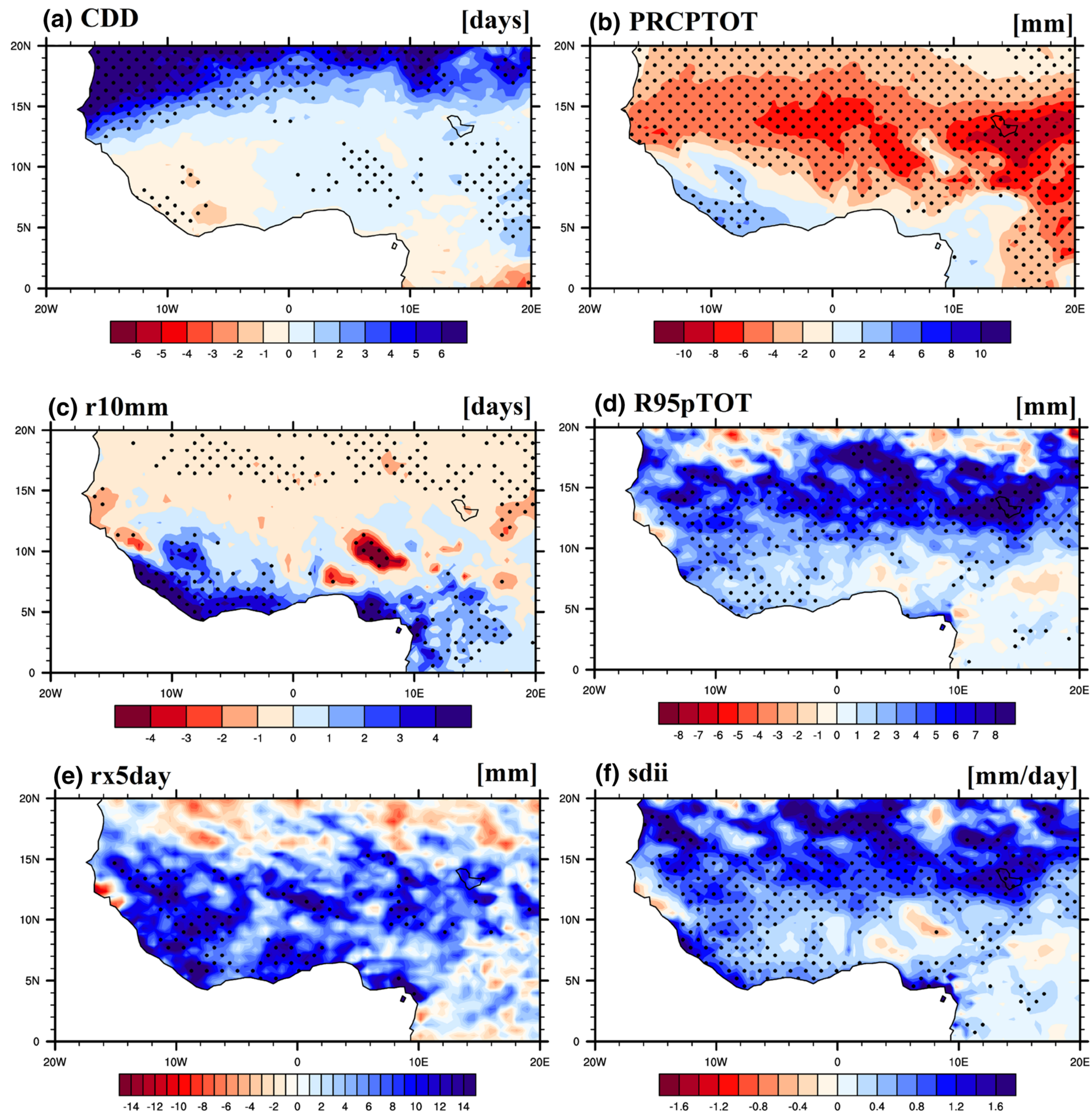

Fig. 6 Projected multi-model mean changes in extreme events for the period 2070–2099 under the RCP4.5 emission scenario, relative to the reference period 1976–2005. Stippling indicates grid points with changes that are statistically significant (5% significance level using *t*-test)

exhibit substantial differences, with reasonable (low) agreement for moderate (rare) extremes. This result adds noticeable uncertainty to RCM validation. Further results show that the RCMs can reproduce the climatology of extreme rainfall over West Africa very well, although the ensemble of both RCMs driven by all the GCMs exhibited better performance than individual RCM members. Generally, the dynamical downscaling of the GCMs by RCMs adds value to the regional rainfall simulation over certain grids, especially in regions of strong orographic forcing, owing to the improved resolution and better representation of finer-scale physical processes. We observed that extreme rainfall simulated by the RCMs may have been determined by the model physics and parameterizations rather than the driving GCMs.

Future changes in rainfall indices based on multi-model ensemble mean projections indicate statistically significant

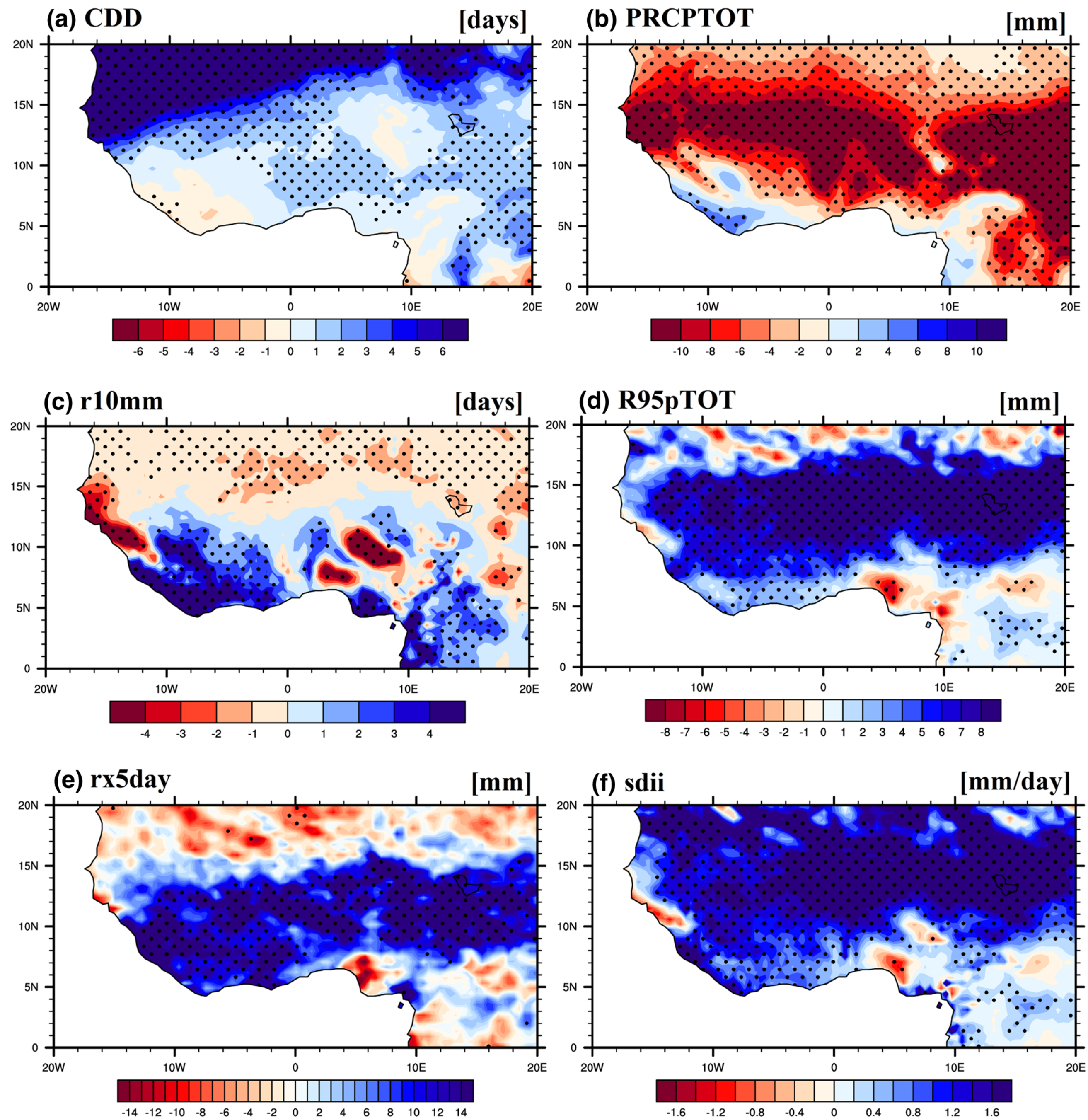

Fig. 7 Same as Fig. 6, but for the RCP8.5 emission scenario

decreases in total summer rainfall (PRCPTOT) of about 1–39% but an increase in the magnitude of extreme rainfall events (R95pTOT) of about 1–38% in most regions of West Africa. A profound increase in consecutive dry days (CDD) and a decrease in consecutive wet days (CWD) are generally observed. Among the regions considered, the Savannah and Sahel particularly stand out, not only with an intensification of dry conditions represented by a projected increase in CDD of about 2–60%, but also, rainfall would likely be much more extreme if it occurred as described by rx5day and R95pTOT. In fact, rx5day and R95pTOT are projected to increase over the Savannah and Sahel by about 2–35 and 1–38%, respectively. The consistent and high inter-model agreement on the sign of the change further affirms the reliability of the projected changes, although noticeable uncertainty still exists. Furthermore, the magnitudes of the projected increases and decreases are greater under RCP8.5 compared to RCP4.5, which may be a result of their different

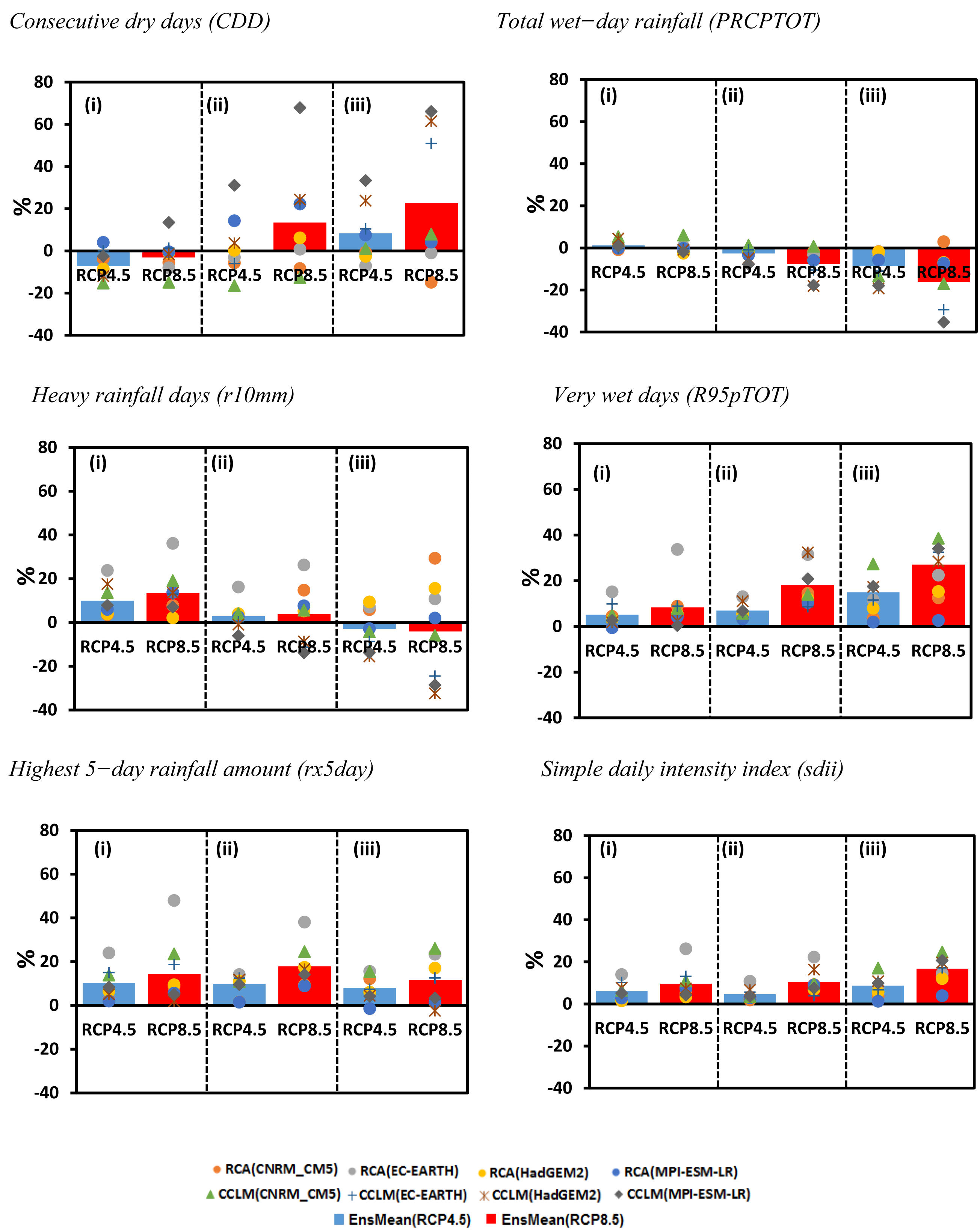

Fig. 8 Projected changes in rainfall extreme indices over the time period 2070–2099 as differences relative to the reference period (1976–2005) for RCP4.5 EnsMean (blue) and RCP8.5 EnsMean (red) over (i) Guinea Coast, (ii) Savannah, (iii) Sahel

climate sensitivities and feedback mechanisms. The higher probability of combined natural disasters may threaten the available water resources of the region and thus affect the regional availability of the food supply and possibly alter social stability. Therefore, it is crucial for West African countries, especially those within the Savannah and Sahel subregions, to seriously consider implementing adaptation strategies and mitigation measures to combat the potential impact of climate change on future summer monsoon rainfall and associated extremes. The remarkable performance of the CORDEX RCMs indicates the necessity of the dynamical downscaling technique and the robustness of regional climate simulation in future regional climate projection over West Africa. Possible mechanisms for the projected future changes will require further investigation.

Acknowledgements This work is supported by National Nature Science Foundation of China Grant (41675062), and the Research Grants Council of the Hong Kong Special Administrative Region, China (CityU 11305715 and 11335316). The first author is a recipient of a research studentship provided by the City University of Hong Kong (CityU). The authors appreciate WCRP and START for setting up and funding the CORDEX-Africa analysis initiative and the University of Cape Town for leading the training and analysis program. We are very grateful to the regional downscaling group who kindly shared the downscaled data used in this study. We are grateful to the services that have operated the GPCP and TRMM datasets. We thank the anonymous reviewers for their constructive comments and suggestions.

References

Ackerley D, Booth BBB, Knight SHE, Highwood EJ, Frame DJ, Allen MR, Rowell DP (2011) Sensitivity of twentieth-century Sahel rainfall to sulfate aerosol and CO2 forcing. J Clim 24:4999–5014. https://doi.org/10.1175/JCLI-D-11-00019.1

Akinsanola AA, Ogunjobi (2017) Evaluation of present-day rainfall simulations over West Africa in CORDEX regional climate models. KO Environ Earth Sci 76:366. https://doi.org/10.1007/s12665-017-6691-9

Akinsanola AA, Ogunjobi KO, Gbode IE, Ajayi VO (2015) Assessing the capabilities of three regional climate models over CORDEX Africa in simulating west African summer monsoon precipitation. Adv Meteorol 2015:935431. https://doi.org/10.1155/2015/935431

Akinsanola AA, Ajayi VO, Adejare AT, Adeyeri OE, Gbode IE, Ogunjobi KO, Nikulin G, Abolude AT (2017a) Evaluation of rainfall simulations over West Africa in dynamically downscaled CMIP5 global circulation models. Theor Appl Climatol. https://doi.org/10.1007/s00704-017-2087-8

Akinsanola AA, Ogunjobi KO, Ajayi VO et al (2017b) Comparison of five gridded precipitation products at climatological scales over West Africa. Meteorol Atmos Phys 129:669. https://doi.org/10.1007/s00703-016-0493-6

Anyamba A, Small JL, Britch SC, Tucker CJ, Pak EW, Reynolds CA et al (2014) Recent weather extremes and impacts on agricultural production and vector-borne disease outbreak patterns. PLoS One 9(3):e92538. https://doi.org/10.1371/journal.pone.00925

Biasutti M (2013) Forced Sahel rainfall trends in the CMIP5 archive. J Geophys Res Atmos 118:1613–1623. https://doi.org/10.1002/jgrd.50206

Bucchignani E, Zollo AL, Cattaneo L, Montesarchio M, Mercogliano P (2016) Extreme weather events over China: assessment of COSMO-CLM simulations and future scenarios. Int J Climatol 37:1578–1594. https://doi.org/10.1002/joc.4798

Di Luca A, de Elía R, Laprise R (2012) Potential for added value in precipitation simulated by high-resolution nested regional climate models and observations. Clim Dyn 38:1229–1247

Dieterich C, Schimanke S, Wang S, Väli G, Liu Y et al (2013) Evaluation of the SMHI coupled atmosphere-ice ocean model RCA4 NEMO. Rep Oceanogr 47:80

Donat MG, Alexander LV, Yang H, Durre I, Vose R, Caesar J (2013) Global land-based datasets for monitoring climatic extremes. Bull Am Meteorol Soc 94:997–1006. https://doi.org/10.1175/BAMS-D-12-00109.1

Dong BW, Sutton R (2015) Dominant role of greenhouse gas forcing in the recovery of Sahel rainfall. Nat Clim Chang 5:757–760. https://doi.org/10.1038/nclimate2664

Dosio A, Panitz HJ, Schubert-Frisius M, Lüthi D (2015) Dynamical downscaling of CMIP5 global circulation models over CORDEX-Africa with COSMO-CLM: evaluation over the present climate and analysis of the added value. Clim Dyn 44:2637–2661

Gbobaniyi E, Sarr A, Sylla MB, Diallo I, Lennard C, Dosio A et al (2014) Climatology, annual cycle and interannual variability of precipitation and temperature in CORDEX simulations over West Africa. Int J Climatol 34:2241–2257

Giorgi F (1990) Simulation of regional climate using a limited area model nested in a general circulation model. J Clim 3:941–963

Giorgi F, Jones C, Asrar G (2009) Addressing climate information needs at the regional level: the CORDEX framework. WMO Bull 58:175

Gutowski WJ Jr, Decker SG, Donavon RA, Pan Z, Arritt RW, Takle ES (2003) Temporal–spatial scales of observed and simulated precipitation in central U.S. climate. J Clim 16:3841–3847, https://doi.org/10.1175/1520-0442(2003)016,3841:TSOOAS.2.0.CO;2

Hewitson BC, Crane RG (1996) Climate downscaling: techniques and application. Clim Res 7:85–95

Hudson DA, Jones RG (2002) Regional climate model simulations of present-day and future climates of Southern Africa. Tech. rep. Hadley Centre Technical Note 39. Hadley Centre for Climate Prediction and Research, Met Office, Bracknell

Huffman GJ, Adler RF, Morrissey MM, Bolvin DT, Curtis S, Joyce R, McGavock B, Susskind J (2001) Global precipitation at one-degree daily resolution from multisatellite observations. J Hydrometeorol 2:36–50

Huffman G, Adler R, Bolvin D, Gu G, Nelkin E et al (2007) The TRMM multisatellite precipitation analysis (TMPA): quasiglobal, multiyear, combined-sensor precipitation estimates at fine scales. J Hydrometeorology 8:38–55

Ibrahim B, Karambiri H, Polcher J, Yacouba H, Ribstein P (2014) Changes in rainfall regime over Burkina Faso under the climate change conditions simulated by 5 regional climate models. Clim Dyn 42:1363–1381. https://doi.org/10.1007/s00382-013-1837-2

IPCC (2013). Climate change 2013: the physical science basis. In Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, p 1535. https://doi.org/10.1017/CBO9781107415324

IPCC (2014) Climate Change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Ji ZM, Kang SC (2013) Double-nested dynamical downscaling experiments over the Tibetan Plateau and their projection of climate change under two RCP scenarios. J Atmos Sci 70(4):1278–1290

Jones PW (1999) First- and second-order conservative remapping schemes for grids in spherical coordinates. Mon Weather Rev 127:2204–2210

Kalognomou EA, Lennard C, Shongwe M, Pinto I, Favre A,, et al (2013) A diagnostic evaluation of precipitation in CORDEX models over Southern Africa. J Clim 26:9477–9506

Kim J, Waliser DE, Mattmann CA, Goodale CE, Hart AF, Zimdars PA et al (2013) Evaluation of the CORDEX Africa multi-RCM hindcast: systematic model errors. Clim Dyn 42:1189–1202

Kitoh A et al. (2013) Monsoons in a changing world: a regional perspective in a global context. J Geophys Res Atmos 118. https://doi.org/10.1002/jgrd.502580

Klutse NAB, Sylla MB, Diallo I, Sarr A, Dosio A, Diedhiou A et al (2015) Daily characteristics of west African summer monsoon precipitation in CORDEX simulations. Theor Appl Climatol 123:369. doi.https://doi.org/10.1007/s00704-014-1352-3

Kotlarski S, Keuler K, Christensen OB, Colette A, Déqué M, Gobiet A, Goergen K, Jacob D, Lüthi D, van Meijgaard E, Nikulin G, Schär C, Teichmann C, Vautard R, Warrach-Sagi K, Wulfmeyer V (2014) Regional climate modeling on European scales: a joint standard evaluation of the EURO-CORDEX RCM ensemble. Geosci Model Dev 7:1297–1333. https://doi.org/10.5194/gmd-7-1297-2014

Lenderink G, van Meijgaard E (2010) Linking increases in hourly precipitation extremes to atmospheric temperature and moisture changes. Environ Res Lett 5:025208. https://doi.org/10.1088/1748-9326/5/2/025208

Li H, Zhou T, Li C (2010) Decreasing trend in global land monsoon precipitation over the past 50 years simulated by a coupled climate model. Adv Atmos Sci 27(2):285–292. https://doi.org/10.1007/s00376-009-8173-9

Li L et al (2013) The flexible global ocean-atmosphere-land system model, grid-point version 2: FGOALS-g2. Adv Atmos Sci 30(3):543–560. https://doi.org/10.1007/s00376-012-2140-6

Lin R, Zhou T, Qian Y (2014) Evaluation of global monsoon precipitation changes based on five reanalysis datasets. J Clim 27(3):1271–1289. https://doi.org/10.1175/JCLI-D-13-00215.1

Lobell DB, Schlenker WS, Costa-Roberts J (2011) Climate trends and global crop production since 1980. Science 333:616–620

Maraun D et al (2010) Precipitation downscaling under climate change: recent developments to bridge the gap between dynamical models and the end user. Rev Geophys 48:RG3003. https://doi.org/10.1029/2009RG000314

Mohino E, Janicot S, Bader J (2011) Sahel rainfall and decadal to multi-decadal sea surface temperature variability. Clim Dyn 37:419–440. https://doi.org/10.1007/s00382-010-0867-2

Moss R, Edmonds J, Hibbard K, Manning M, Rose S, van Vuuren D et al (2010) The next generation of scenarios for climate change research and assessment. Nature 463:747–756

Nicholson SE (2013) The West African Sahel: a review of recent studies on the rainfall regime and its interannual variability. ISRN Meteorol 2013:32. https://doi.org/10.1155/2013/453521 **(Article ID 453521)**

Nikulin G, Jones C, Giorgi F, Asrar G, Büchner M, Cerezo-Mota R et al (2012) Precipitation climatology in an ensemble of CORDEX-Africa regional climate simulations. J Clim 25:6057–6078

Odoulami RC, Akinsanola AA (2017) Recent assessment of West African summer monsoon daily rainfall trends. Weather. https://doi.org/10.1002/wea.2965

Panitz HJ, Dosio A, Büchner M, Lïthi D, Keuler K (2014) COSMO-CLM (CCLM) climate simulations over CORDEX-Africa domain: analysis of the ERA-Interim driven simulations at 0.44 and 0.22 resolution. Clim Dyn 42:3015. doi.https://doi.org/10.1007/s00382-013-1834-5

Pinto I, Lennard C, Tadross M et al (2016) Evaluation and projections of extreme precipitation over southern Africa from two CORDEX models. Clim Chang 135:655. https://doi.org/10.1007/s10584-015-1573-1

Sanogo S, Fink AH, Omotosho JA, Ba A, Redl R, Ermert V (2015) Spatio-temporal characteristics of the recent rainfall recovery in West Africa. Int J Climatol 35:4589–4605. https://doi.org/10.1002/joc.4309

Sillmann J, Kharin V, Zwiers F, Zhang X, Bronaugh D (2013) Climate extremes indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections. J Geophy Res Atmos 118:2473–2493

Sun QH, Miao CY, Duan QY (2016) Extreme climate events and agricultural climate indices in China: CMIP5 model evaluation and projections. Int J Climatol 36:43–61

Sylla M, Giorgi F, Coppola E, Mariotti L (2013) Uncertainties in daily rainfall over Africa: assessment of gridded observation products and evaluation of a regional climate model simulation. Int J Climatol 33:1805–1817

Sylla MB, Pal JS, Wang GL, Lawrence PJ (2016) Impact of land cover characterization on regional climate modelling over West Africa. Clim Dyn 46:637–650. https://doi.org/10.1007/s00382-015-2603-4

van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt GC, Kram T, Krey V, Lamarque JF, Masui T, Meinshausen M, Nakicenovic N, Smith SJ, Rose SK (2011) The representative concentration pathways: an overview. Clim Chang 109(1–2):5–31. https://doi.org/10.1007/s10584-011-0148-z

Xu J, Powell A (2012) Uncertainty estimation of the global temperature trends for multiple radiosondes, reanalyses, and CMIP3/IPCC climate model simulations. Theor Appl Climatol 108:505–518. https://doi.org/10.1007/s00704-011-0548-z

Zhang L, Zhou T (2011) An assessment of monsoon precipitation changes during 1901–2001. Clim Dyn 37:279–296. https://doi.org/10.1007/s00382-011-0993-5

Zhou T, Yu R, Li H, Wang B (2008a) Ocean forcing to changes in global monsoon precipitation over the recent half-century. J Clim 21(15):3833–3852

Zhou T, Zhang L, Li H (2008b) Changes in global land monsoon area and total rainfall accumulation over the last half century. Geophys Res Lett. https://doi.org/10.1029/2008GL034881