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ORIGINAL PAPER

Assessing the capability of CORDEX models in simulating onset of rainfall in West Africa

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Abstract Reliable forecasts of rainfall-onset dates (RODs) are crucial for agricultural planning and food security in West Africa. This study evaluates the ability of nine CORDEX regional climate models (RCMs: ARPEGE, CRCM5, RACMO, RCA35, REMO, RegCM3, PRECIS, CCLM and WRF) in simulating RODs over the region. Four definitions are used to compute RODs, and two observation datasets (GPCP and TRMM) are used in the model evaluation. The evaluation considers how well the RCMs, driven by ERA-Interim reanalysis (ERAIN), simulate the observed mean, standard deviation and inter-annual variability of RODs over West Africa. It also investigates how well the models link RODs with the northward movement of the monsoon system over the region. The model performances are compared to that of the driving reanalysis—ERAIN. Observations show that the mean RODs in West Africa have a zonal distribution, and the dates increase from the Guinea coast northward. ERAIN fails to reproduce the spatial distribution of the RODs as observed. The performance of some RCMs in simulating the RODs depends on the ROD definition used. For instance, ARPEGE, RACMO, PRECIS and CCLM produce a better ROD distribution than that of ERAIN when three of the ROD definitions are used, but give a worse ROD distribution than that of ERAIN when the fourth definition is used. However, regardless of the definition used, CCRM5, RCA35, REMO, RegCM3 and WRF show a remarkable improvement over ERAIN. The study shows that the ability of the RCMs in simulating RODs over West Africa strongly depends on how well the models reproduce the northward movement of the monsoon system and the associated features. The results show that there are some differences in the RODs obtained between the two observation datasets and RCMs, and the differences are magnified by differences in the ROD definitions. However, the study shows that most CORDEX RCMs have remarkable skills in predicting the RODs in West Africa.

1 Introduction

West African countries depend on rain-fed agriculture as the main source of income. As a result, the socio-economy and gross domestic products (GDPs) of these countries are strongly influenced by climate variability and change. For instance, the decrease in Sahelian rainfall in the 1970s and 1980s led to severe droughts, famines and many socio-economic problems in West Africa (Nicholson et al. 2000; Abiodun et al. 2008; Djiotang et al. 2010). Water management and agricultural practices depend not only on the amount of the annual rainfall but also on the onset and temporal distribution of the rainfall. The timing of the rainfall onset is crucial for agricultural planning. For instance, an early or late onset of rainfall may drastically reduce crop yields if the agricultural practices are not adapted to accommodate it. However, predicting the rainfall-onset date (ROD) in West Africa, particularly in the Sahel, remains a big challenge because of its great variability. Omotosho (1992) showed that the ROD variability can be as large as the length of the rainy season. The consequences of unreliable predictions of RODs include crop failure, famine and health problems. Hence, there is a keen interest in improving knowledge on predicting RODs in West Africa, as its reliable prediction will help combat famine and enhance food security.

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Various studies have suggested different factors that may control the ROD. The factors include sea surface temperatures, vegetation and soil moisture, wind shear, the mid- and upper tropospheric jets (African easterly jet (AEJ) and tropical easterly jet (TEJ), respectively), moist static energy or equivalent potential temperature gradient and the strength and position of the Saharan heat low, which controls the southerly inflow of moist air into the West African subcontinent. Many empirical models have used these factors in predicting the ROD. Notable among these are models based on upper atmospheric winds (Omotosho 1990, 1992) and on sea surface temperature (Lamb and Peppler 1992; Eltahir and Gong 1996; Janicot et al. 1998), rainfall–evapotranspiration relations (Cocheme and Fraquin1967) and equivalent potential temperature (Oduru 1989; Omotosho et al. 2000). Other methods are based on precipitation or surface data only (Sarria-Dodd and Jolliffe 2001; Ati et al. 2002 and Omotosho et al. 2000). The main problem with the empirical models is their low skill in simulating the ROD. This may be owing to a lack of sufficient data in developing countries or training for implementation of the models. The other problem is that empirical models are not dynamically competent since they cannot account for all the factors that control RODs.

To overcome the shortcomings of empirical approaches, some studies have employed dynamic methods (i.e. atmosphere–ocean general circulation models, AOGCMs) in predicting RODs (e.g. Cook and Vizy 2006; Djiotang et al. 2010), but AOGCMs usually have coarse horizontal grid resolution (typically 2°×2° long×lat); therefore, they cannot represent well the influence of mesoscale features (such as isolated reliefs, lakes, coastlines and sharp variation in vegetation, temperature and soil moisture) on RODs (e.g. Druyan et al. 2010; Xue et al. 2010). As a result, AOGCM simulations are usually downscaled using regional climate models (RCMs) with a higher resolution (typically 10–50 km) than AOGCMs. Many studies have demonstrated the capability of RCMs in simulating the intra-seasonal, inter-annual and decadal variability of rainfall, as well as the characteristics of the West African monsoon system (WAMS; e.g. Omotosho and Abiodun 2007; Afiesimama et al. 2006; Sylla et al. 2009, 2010; Vigaud et al. 2009; Pu and Cook 2010; Abiodun et al. 2012). However, some studies have examined the ability of RCMs to simulate the ROD over West Africa (e.g. Ramel et al. 2006; Vanvyve et al. 2007; Sijikumar et al. 2006), but these studies focused on individual models designed for some specific purpose, making it difficult to know the general performance of RCMs in simulating RODs over West Africa. Hence, there is a need for multi-RCM inter-comparisons on ROD simulation over West Africa. The present study is in that direction.

There have been some multi-RCM experiments with encouraging results over West Africa. These include the West African Monsoon Modeling and Evaluation (WAMME; e.g. Druyan et al. 2010; Xue et al. 2010), the Monsoon Multidisciplinary Analyses (AMMA, van der Linden and Mitchell 2009, e.g. Ruti et al. 2011; Hourdin et al. 2010) and the ENSEMBLE-AMMA project (e.g. Paeth et al. 2011; Diallo et al. 2012a; Sylla et al. 2013). These multi-RCM studies show different results over West Africa. For instance, Druyan et al. (2010) evaluate the ability of five RCMs in simulating the WAM systems and found that the RCMs skillfully represent the monsoon onset. Hourdin et al. (2010) used AMMA model inter-comparison to study the seasonal and intra-seasonal variations in climate over the Sahel and found many discrepancies among the RCMs in simulating rainfall and the latitudinal position of AEJ over the Sahel. They show that none of the RCMs captures all the aspects of the monsoon system. In the inter-comparison of the multi-model RCM from the ENSEMBLES and AMMA projects, Paeth et al. (2011) also found that RCMs exhibit systematic errors in simulating the amplitude and pattern of the West African rainfall; the RCMs have a dry bias in sub-Saharan Africa. Meanwhile, Diallo et al. (2012b) and Sylla et al. (2013) reported RCMs that give a remarkable simulation of the inter-annual variability of rainfall, with a correlation coefficient greater than 0.5. However, most of the above studies indicated that the RCMs' ensemble mean always outperforms individual RCMs in simulating precipitation, but this is not always true for temperature.

The most recent multi-RCM experiment is the Coordinated Regional Downscaling Experiment of Africa (CORDEX-Africa; Nikulin et al. 2012, Gbobaniyi et al. 2013). One of the aims of CORDEX-Africa is to evaluate the quality of RCMs in simulating precipitation and to close the gap of data accessibility of the regions, thereby enabling the scientific community to give suitable information to decision-makers (Nikulin et al. 2012). Nikulin et al. (2012) and Gbobaniyi et al. (2013) found that most RCMs realistically capture the WAM and its related features over West Africa. However, no study has investigated how CORDEX-Africa RCMs perform in simulating the RODs over West Africa. The main goal of the present study is to extend the analyses of Nikulin et al. (2012) and to focus on RODs over West Africa. Hence, the study evaluates the performance of CORDEX-Africa RCMs in simulating the ROD over West Africa. The paper is structured as follows: Section 2 describes the data and methods used in the study, Section 3 presents the results and discussions and Section 4 gives the conclusions of the study.

2 Data and methods

2.1 Data

The study used observation, reanalysis and RCMs' simulation datasets. The observation datasets, which were obtained from the Tropical Rainfall Measuring Mission (TRMM, 3B42 version 6; 0.25° spatial and 3-h resolutions; 1998–2010; Huffman

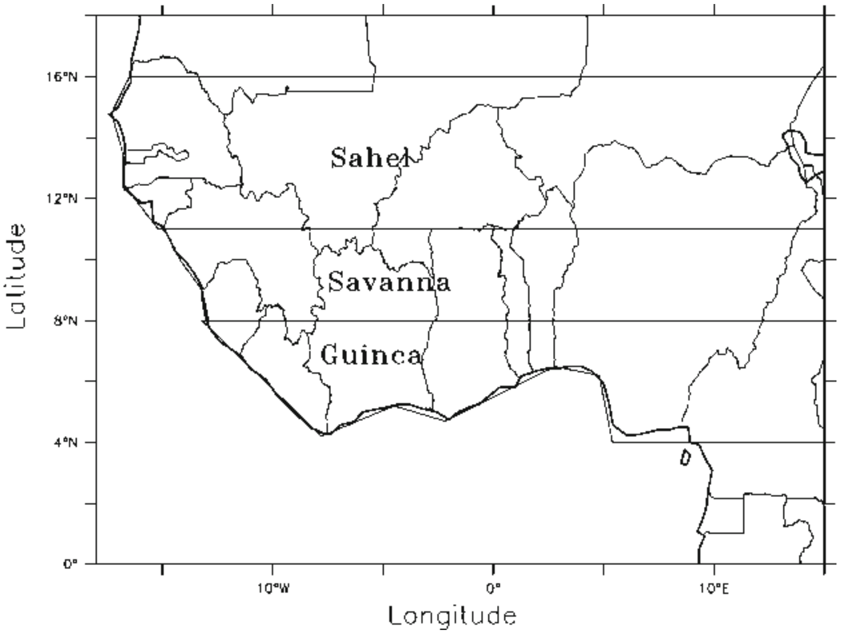

Fig. 1 West African domain divided into three climatic zones: Guinea (4°N–8°N), Savanna (8°N–11°N) and Sahel (11°N–16°N)

et al. 2007) and the Global Precipitation Climatology Project (GPCP, version 1.1; 1° spatial and daily temporal resolution; 1998–2010; Huffman et al. 2001), were used to evaluate the RCM simulations. The use of two observations datasets (GPCP and TRMM) was to account for differences in and uncertainty around observed RODs (Huffman et al. 2009; Huffman and Bolvin 2011). The reanalysis datasets are the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERAIN; 1989–2008; Dee et al. 2011). The simulation datasets are from nine of the RCMs that participated in the CORDEX-Africa experiment. The RCMs used are ARPEGE, RCA35, PRECIS, CRCM5, REMO, CCLM, RACMO, RegCM3 and WRF. The CORDEX simulation domain (about 25°W–60°E and 44°S–42°N; Nikulin et al. 2012) is much wider than our study domain (West Africa; 18°W–25°E and 0°N–18°N). All the simulations were initialized and driven at the lateral boundaries driven by the ERAIN datasets. All the RCMs used the same sea surface temperature (SST) from ERAIN as ocean boundary condition, except that RegCM3 used the National Oceanic Atmospheric Administration (NOAA) weekly optimum-interpolated SST (Reynolds et al. 2007), and the Canadian Regional Climate Model (CRCM) used the Atmospheric Model Inter-comparison Project, phase 2 (AMIP2) SST (Nikulin et al. 2012). The dynamics and physical parameterizations used in the RCMs for the simulations are given in Nikulin et al. (2012). The CORDEX-Africa simulations were obtained at the Climate Systems Analysis Group (CSAG) at the University of Cape Town. Following Omotosho and Abiodun (2007) and Abiodun et al. (2012), this study divides West African domain into three climatic zones: Guinea (4°N–8°N), Savanna (8°N–11°N) and Sahel (11°N–16°N) as shown in Fig. 1.

2.2 Definition of ROD

There are different definitions for determining RODs in West Africa (i.e. Omotosho 1990; Odekunle 2006; Laux et al. 2008). However, these definitions do sometimes produce different RODs even when applied to the same observation dataset (e.g. Laux et al. 2008). For this study, we selected and

Table 1 Definitions of ROD over West Africa

Methods	Definition ROD	Reference
DEF1	The first decade (10 days) with at least 25 mm of rains, followed by two decades of at least 20 mm of rains	AGRHYMET (1996)
DEF2	The total of at least 25 mm of rainfall within 5 days. The starting day and at least two other days in this 5-day period must be wet (at least 0.1-mm rainfall recorded), followed by a no dry period of seven or more consecutive days occurring in the following 30 days	Stern et al. (1981)
DEF3	Any date after 1 January (instead of 1 May) totalling at least 20 mm of rainfall observed within three consecutive days without a dry period in the next 30 days that exceeds 7 days	Sivakumar (1988)
DEF4	The first two rains totalling 20 mm or more within 7 days, followed by 2 to 3 weeks each with at least 50 % of the weekly crop–water requirement and without a dry spell within 2 to 3 weeks	Omotosho et al. (2000)

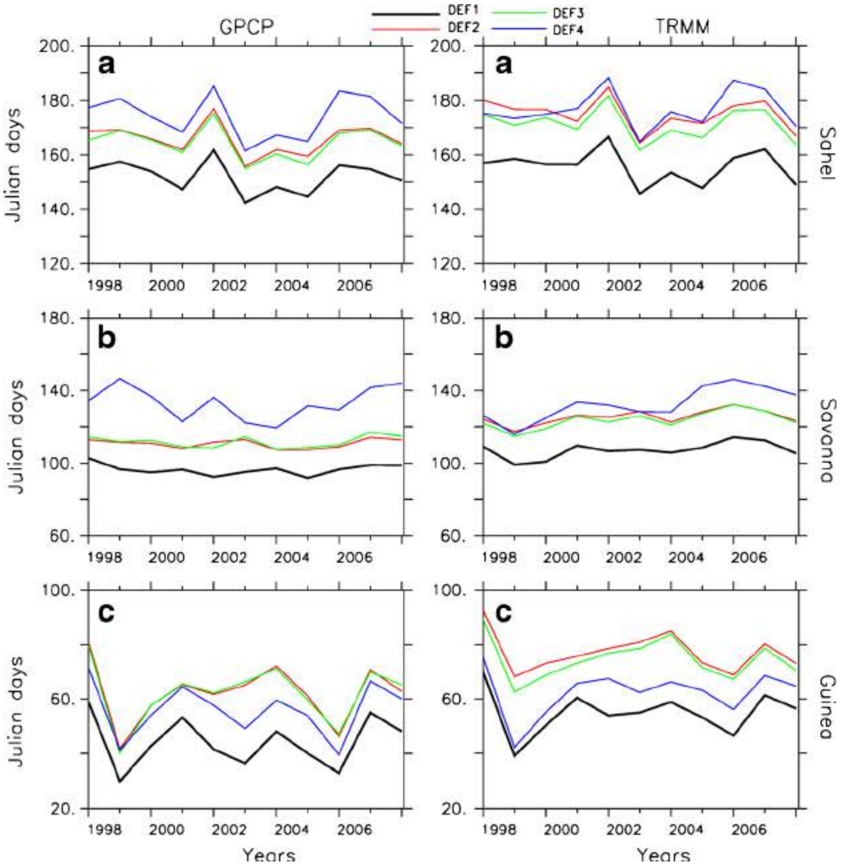

Fig. 2 The inter-annual variation of rainfall onset dates calculated with the four methods using observed datasets (GPCP, *left panels*; TRMM, *right panels*) for 1998–2008 over Guinea (*bottom panels*), Savanna (*middle panels*) and Sahel (*top panels*)

compared four prominent ROD definitions over West Africa. The definitions (hereafter DEF1, DEF2, DEF3 and DEF4) are given in Table 1. DEF1 is based on AGRHYMET (1996), DEF2 on Stern et al. (1981), DEF3 on Sivakumar (1988) and DEF4 on Omotosho et al. (2000). We applied the four definitions to compute ROD over each zone in West Africa using two observation datasets and compared the results.

3 Results and discussion

The results of the study are discussed in two parts. The first part examines the differences and similarities between the definitions and compares their sensitivity to changes in observed rainfall datasets (GPCP and TRMM). The second part evaluates the capability of the RCMs in simulating the ROD.

3.1 Comparison of rainfall onset definitions

The four definitions (DEF1, DEF2, DEF3 and DEF4) produce different rainfall-onset dates (RODs) over each zone in West Africa (Fig. 2, Table 2). Over the Sahel, the definitions present different RODs for each year but show similar patterns for the inter-annual variability of ROD (Fig. 2a, b). For instance, the difference between the RODs is up to 30 days in 2002, but all the definitions agree that the Sahel experienced the latest

Table 2 The mean rainfall onset dates (RODs) over West Africa for the period 1998–2008, as obtained with four onsets methods (DEF1, DEF2, DEF3 and DEF4) using GPCP and TRIMM datasets. The difference between RODs from the two dataset (Δ in days) is indicated for each definition

Methods	Guinea			Savanna			Sahel		
	GPCP	TRMM	Δ	GPCP	TRMM	Δ	GPCP	TRMM	Δ
DEF1	13 Feb	24 Feb	11	05 Apr	16 Apr	11	31 May	03 Jun	4
DEF2	02 Mar	17 Mar	15	19 Apr	04 May	15	13 Jun	22 Jun	9
DEF3	02 Mar	14 Mar	12	20 Apr	02 May	12	12 Jun	19 Jun	7
DEF4	25 Feb	02 Mar	6	12 May	11 May	1	22 Jun	24 Jun	2

Table 3 The standard deviation of rainfall onset dates (RODs) over West Africa for the period 1998–2008, as obtained with four onsets methods (DEF1, DEF2, DEF3 and DEF4) using GPCP and TRIMM datasets. The difference between the ROD standard deviation from the two datasets (*Δ* in days) is indicated for each method

Methods	Guinea			Savanna			Sahel		
	GPCP	TRMM	Δ	GPCP	TRMM	Δ	GPCP	TRMM	*Δ*
DEF1	9	8	1	3	4	1	6	6	0
DEF2	11	7	4	2	4	2	6	6	0
DEF3	11	7	4	3	5	0	6	6	0
DEF4	10	8	2	9	9	0	8	7	1

RODs in the year. Similarly, the spread in the RODs in 2003 is more than 30 days, but the definitions agree that the earliest RODs occur in the 2003. Among the definitions, DEF1 consistently produces the earliest ROD (i.e. earliest date), while DEF4 gives the latest date. In most years, DEF2 and DEF3 produce the RODs that fall within those of DEF1 and DEF2; the maximum difference between DEF2 and DEF3 is less than 5 days. The strong agreement between DEF2 and DEF3 may

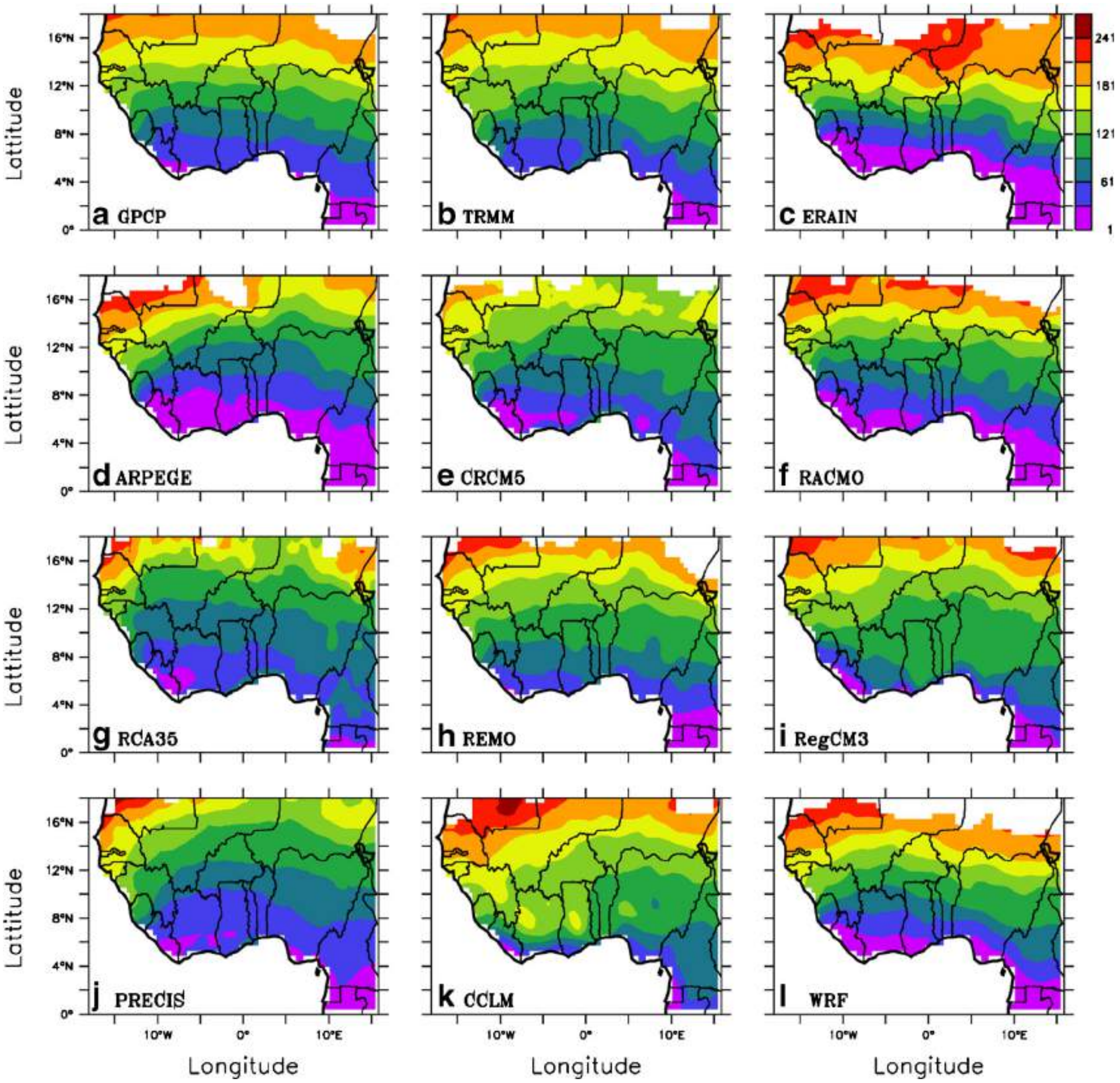

Fig. 3 Mean onset dates as observed (GPCP/TRMM) and simulated (CORDEX RCMS) in DEF1 over West Africa for the period of 1998–2008

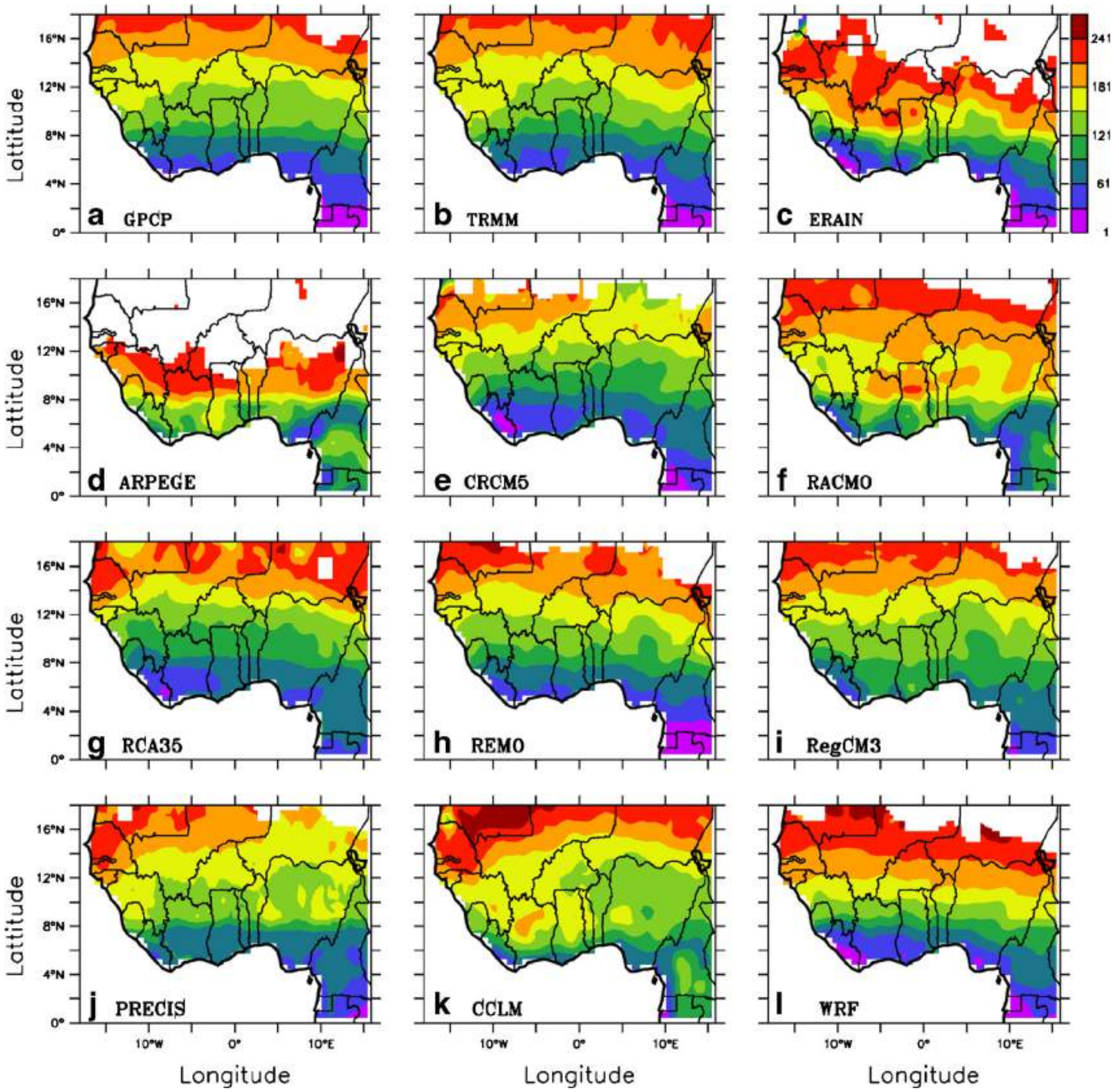

Fig. 4 Mean onset dates as observed (GPCP/TRMM) and simulated (CORDEX RCMS) in DEF4 over West Africa for the period of 1998–2008

be because the two definitions use the same criteria for identifying false ROD (Stern et al. 1981). With each definition, there are substantial differences between ROD in GPCP and TRMM datasets. For example, DEF2 and DEF3 produce later RODs in TRMM than in GPCP. The differences between the RODs with DEF2 (or DEF3) and DEF4 are smaller in the TRMM dataset than in GPCP. However, with both datasets, the characteristics of the RODs over the Savanna are similar to that over the Sahel (Fig. 2b), except that the ROD is earlier over the Savanna than over the Sahel. The characteristics of RODs over Guinea differ from that of the Sahel or the Savanna. Nevertheless, among the three zones (Guinea, Savanna and Sahel), Guinea experiences the earliest ROD and has the most pronounced difference between ROD of GPCP and TRIMM (Fig. 2c), suggesting that the zone has the highest uncertainty in the observed ROD owing to different datasets and definitions for obtaining the ROD.

Tables 2 and 3 present the mean and standard deviation of the RODs for each definition. In general, the mean RODs fall within February–March in Guinea, April–May in the Savanna and May–June in the Sahel. However, DEF1 is an outlier. It consistently produces the earliest RODs in each zone and shows large differences in RODs from the two datasets (11, 11 and 4 days over Guinea, Savanna and Sahel, respectively). The other three definitions (DEF2, DEF3 and DEF4) give comparable RODs, but DEF2 and DEF3 also produce large differences in the RODs from GPCP and TRMM. DEF4 gives the lowest difference in the RODs from the datasets and produces the least differences in the RODs' standard deviation from the datasets (Tables 2 and 3). However, it is difficult to conclude that DEF4 gives the best RODs among the four definitions.

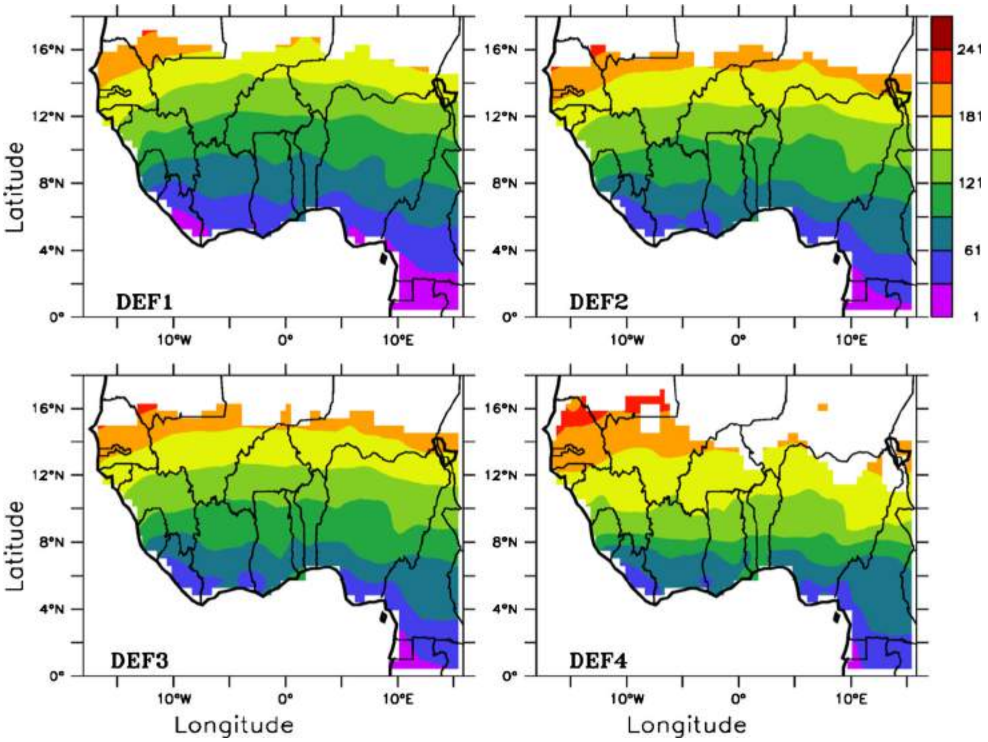

Fig. 5 CORDEX-RCMs ensemble ROD mean over West Africa (Guinea, Savanna and Sahel, respectively) for the period of 1998–2008

3.2 Evaluation of simulated rainfall-onset dates by CORDEX models

To evaluate the capability of the CORDEX models in simulating the characteristics of RODs over West Africa, we compare the simulated RODs with the observed (GPCP and TRMM) using the four onset definitions. The evaluation focuses on how well the models simulate the mean, interannual variability of RODs for the period 1998–2008 using each definition.

3.2.1 Spatial distribution of RODs over West Africa

Figures 3 and 4 compare the spatial distribution of the stimulated RODs over West Africa with observations (GPCP and TRMM) for DEF1 and DEF4, respectively. Corresponding figures for DEF2 and DEF3 are similar to those of DEF1; therefore, they are not shown. With all the definitions, the observed RODs (Figs. 3a, b and 4a, b) are generally zonal; the values increase gradually from the coast to inland. However, the distribution is more zonal in DEF1 than in DEF4, and the ROD is earlier north of 8°N in DEF1 than in DEF4. With all the definitions, ERAIN does not capture the spatial distribution of the RODs as observed in GPCP and TRMM. With DEF1, it produces earlier RODs (than observed) south of 8°N, and with DEF4, it gives much earlier RODs over most areas in West Africa, especially north of 8°N and fails to meet the criteria for RODs north of 12°N. The reason for the shortcomings of ERAIN may be related to formulations and physical parameterization (i.e. rainfall parameterization schemes) used to produce ERAIN and the rainfall parameterization schemes in the GCM used for its forecast.

Some RCMs show remarkable improvements over the ERAIN in simulating the RODs, while other RCMs perform worse than the reanalysis (Figs. 3 and 4); however, the performance of some RCMs in simulating the RODs depends on the ROD definition used. Regardless of the definition, the RODs produced by CRCM5, RCA35, REMO, RegCM3 and WRF show remarkable improvement over that of ERAIN when compared with observations, except that RegCM3 produces earlier RODs over Guinea. ARPEGE, RACMO, PRECIS and CCLM also show some improvement over ERAIN when DEF1, DEF2 or DEF3 are used, but not when DEF4 is used. With DEF4, ARPEGE simulates similar ROD patterns as in ERAIN, overestimates the RODs north of 8°N and fails to meet DEF4 ROD criteria north of 10°N; CRCM5 underestimates the RODs north of 10°N; and RACMO fails to reproduce the zonal pattern of RODs in 8°N–12°N, producing a local maximum ROD in the northern part of Ghana. Regardless of the definition used, CCLM fails to reproduce the observed zonal distribution south of 12°N; instead, it produces a local maximum over Cote d'Ivoire in DEF4.

Figure 5 shows the spatial distribution of the RCMs' ensemble mean ROD for each definition. The results are similar

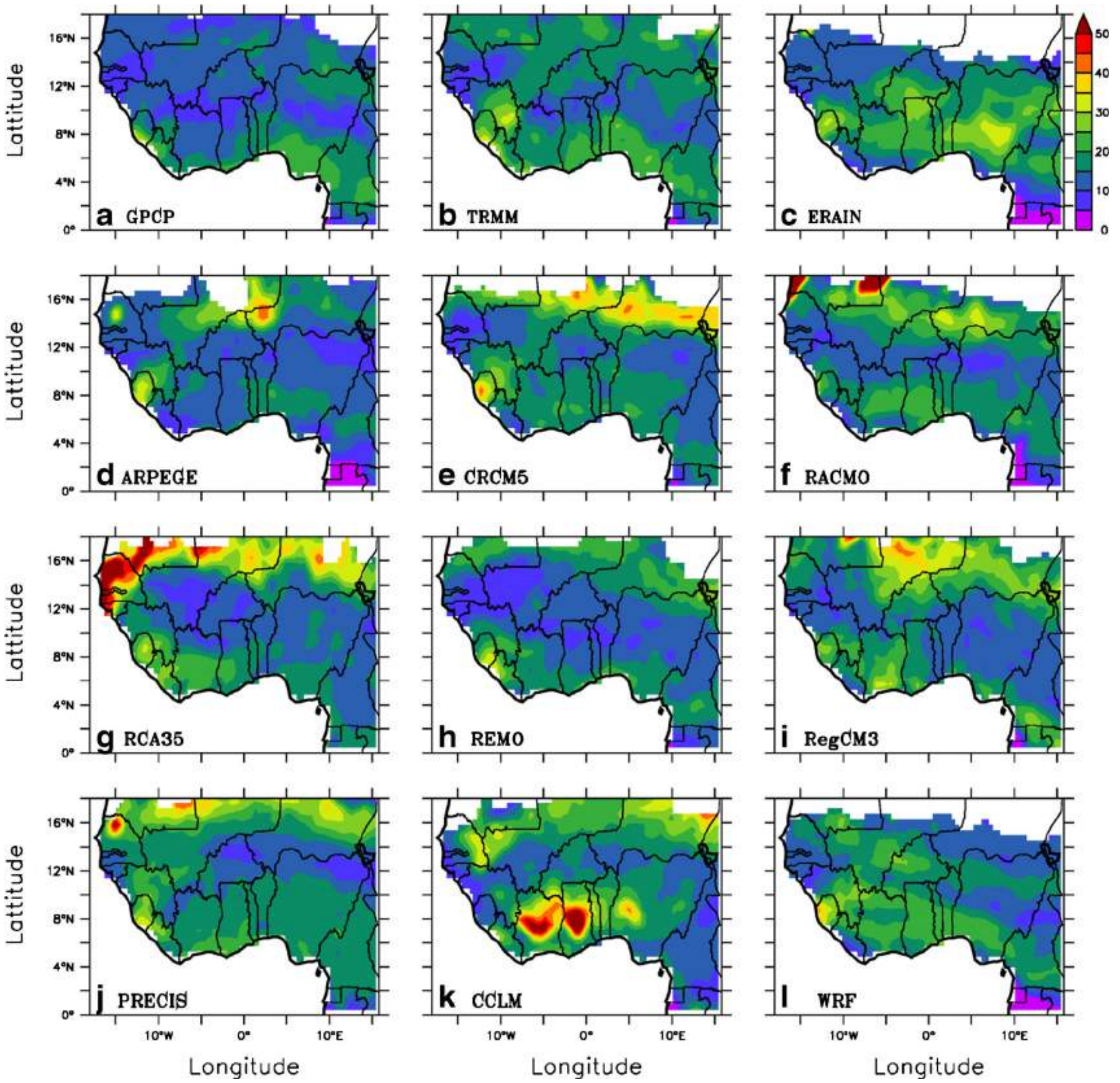

Fig. 6 Standard deviation of onset dates as observed (GPCP/TRMM) and simulated (CORDEX RCM) in DEF1 over West Africa for the period of 1998–2008

to the observed (GPCP and TRMM). The ROD of the RCMs' ensemble mean varies from February to April in DEF2, DEF3 and DEF4 over Guinea and varies from February to March in DEF1. Over the Savanna, the multi-RCMs' mean in DEF1 gives the earliest ROD and the latest RODs in DEF4 (from April to May). As a result, the multi-RCMs' mean improves the simulated ROD over Guinea, the Savanna and the southern part of the Sahel for all the definitions. However, the results are different over the northern part of the Sahel for all the definitions. For instance, in DEF4, the RCMs' mean fails to simulate RODs over the central and eastern part of the Sahel (over northern Mali, Burkina Faso and Niger). The improvement of the multi-RCMs' mean over individual RCM results found in this study is consistent with previous studies (e.g. Paeth et al. 2011, Diallo et al. 2012a, b, Sylla et al. 2013) that attribute the improvement to the cancelling of individual RCM errors in the multi-RCMs' mean; this is true for the multi-RCMs' ROD mean.

Figures 6 and 7 compare the simulated ROD standard deviation (σ) with the observed (GPCP and TRMM) for DEF1 and DEF4, respectively. The results for DEF2 and DEF4 are similar to those of DEF1 and therefore are not shown. The σ is the spread of RODs around the temporal mean; hence, it is a measure of the inter-annual variability of the RODs: high σ indicates high inter-annual variability, while low σ indicates low inter-annual variability. However, it should be noted that the 1998–2008 period is too short, and estimations of the standard deviation can be noisy, one outlier can strongly affects the results obtained. With DEF1, both observations show similar patterns of σ over Guinea and the Savanna, except that TRMM shows a local maximum in the western part of the Savanna (i.e. over Republic of Guinea).

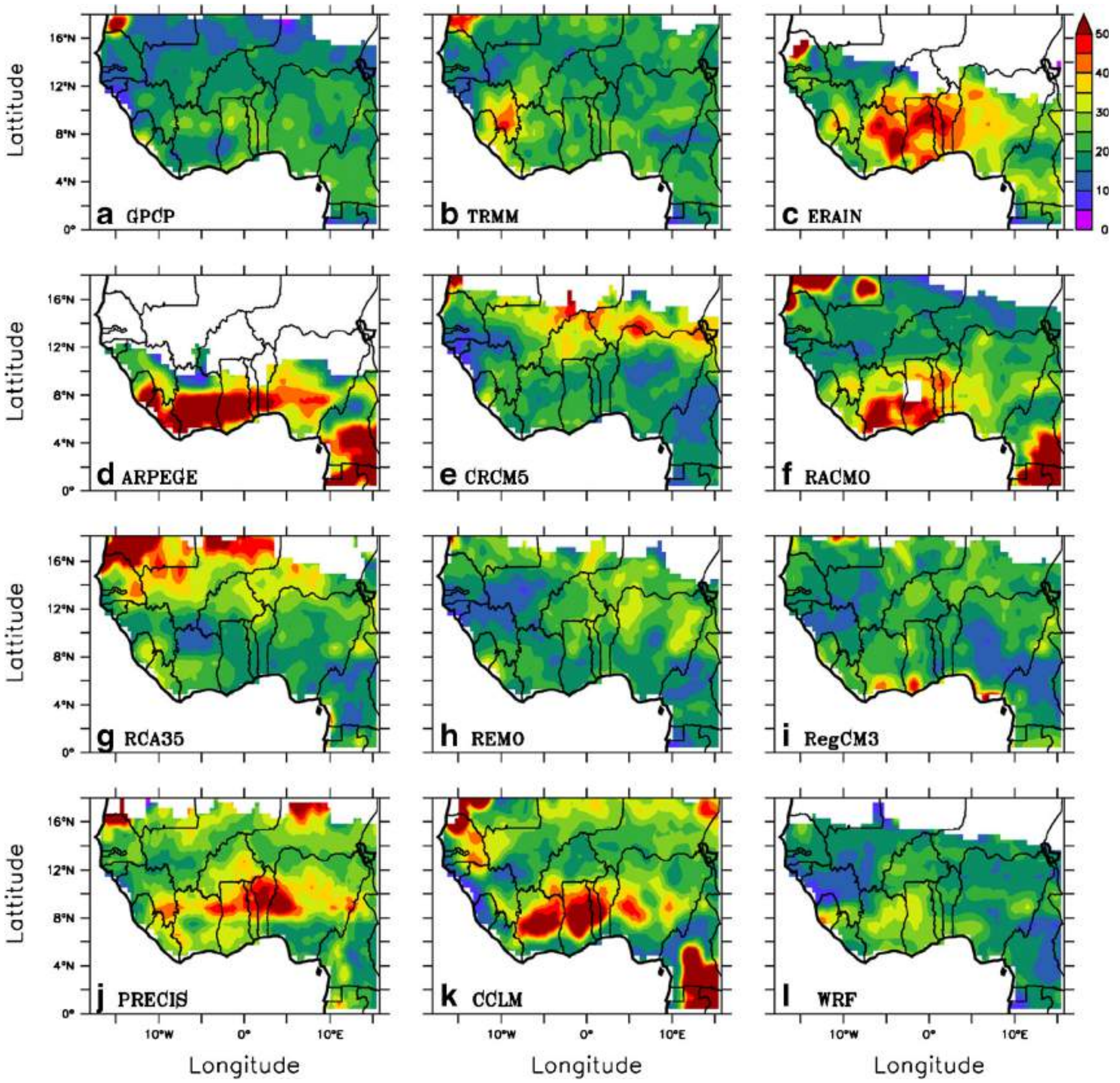

Fig. 7 Standard deviation of onset dates as observed (GPCP/TRMM) and simulated (CORDEX RCM) in DEF4 over West Africa for the period of 1998–2008

However, with DEF4, the magnitude of σ is the same over the three zones, but the local maximum of σ (over Republic of Guinea) produced by TRMM is higher with DEF4 than with DEF1. Nevertheless, ERAIN does not capture the distribution of σ in the observation (GPCP or TRMM) regardless of the definitions used. With DEF1, the reanalysis overestimates the ROD standard deviation (i.e. the inter-annual variability) by about 10 days over the Savanna, especially over the eastern Cote d'Ivoire, northern Ghana, Benin, Togo and southern Nigeria (Fig. 6). The overestimation is worst over the zone with DEF4 (Fig. 7). In addition, ERAIN fails to reproduce σ north of 14°N using any of the definitions because the reanalysis does not meet the criteria for obtaining RODs with DEF4 north of 14°N.

Most of the RCMs do not capture the distribution of σ (i.e. the inter-annual variability). They overestimate it, particularly over the northern part of the Sahel (RCA35, PRECIS, CRCM5 and CCLM), central Savanna (CCLM, RACMO and PRECIS) and along the coast (ARPEGE, CCLM and RACMO) depending on the definitions used. Some RCMs (ARPEGE, CCLM, PRECIS, RACMO and RCA35) simulate worse ROD standard deviation distribution than ERAIN regardless of the definitions used. For instance, ARPEGE fails to satisfy DEF4 criteria north of 10°N, while CCLM largely overestimates σ south of 10°N for each DEF. Nevertheless, some RCMs perform better than ERAIN depending on the definitions used and the geographical location considered (i.e. ARGEGE with DEF1 over Guinea and CRCM5 with DEF3 and 4 over Guinea and the Savanna), showing a lower bias in the simulated standard deviation (i.e. weaker the inter-annual variability). However, three RCMs (REMO, RegCM3 and WRF) produce better results than ERAIN, regardless of the

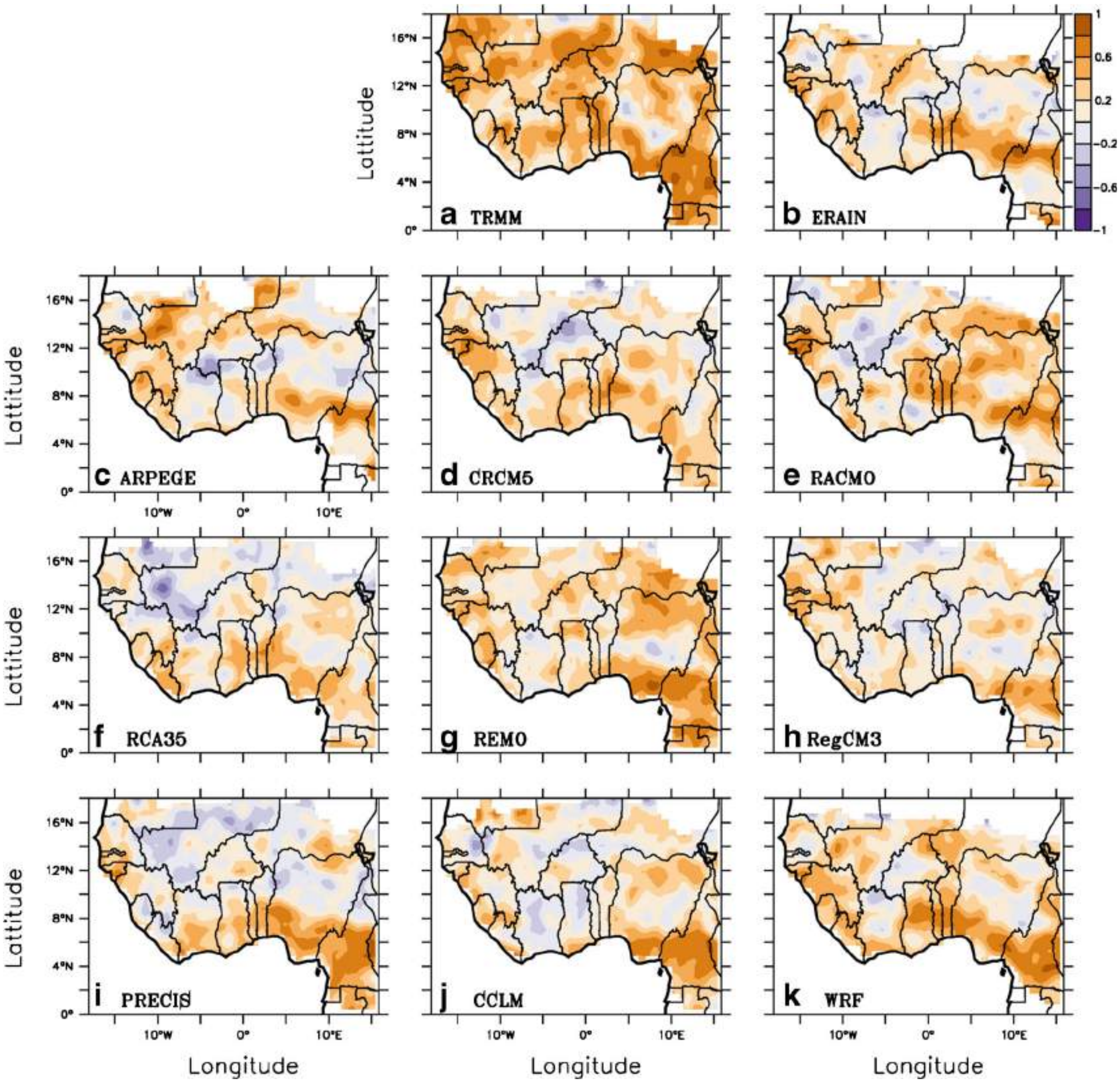

Fig. 8 Correlation of onset dates with respect to observed (GPCP) and simulated (CORDEX RCMs) in DEF1 over West Africa for the period of 1998–2008

definition used. Overall, REMO reproduces the σ pattern better than any other RCM does, regardless of the definition used.

We evaluate the spatial distribution of the correlation (r) between observation (GPCP) and RCMs. A high correlation (typically $r>0.5$) implies a good agreement between the simulated and observed RODs, while a low correlation implies a weak agreement ($r<0.5$) or no agreement ($r<0.0$) between the simulated and observed RODs. The spatial correlation between TRMM and GPCP over West Africa is high and uniform over most of the region, though the value is higher and more uniform in DEF1 than DEF4 (Figs. 8a and 9a), especially over the eastern part of the Savanna. The maximum values ($r\approx0.9$) are over the northern Sahel and along the coast. The correlation coefficient between TRMM and ERAIN changes between positive and negative values over the domain, with the negative values dominating over more areas with DEF4 than with DEF1. The best agreement between TRMM and ERAIN results occurs along the coast south of 5°N over southern Nigeria. For the RCMs, the distribution of r is higher in DEF1 than in DEF4. Regardless of the definitions used, most of the RCMs simulate positive r (Figs. 8 and 9) along the coast of Guinea (ARPEGE, REMO, WRF, PRECIS, RCA35, CRCM5 and CCLM), western Sahel (RCA35, REMO, CRCM5, WRF, PRECIS and RACMO) and northern Sahel (ARPEGE, REMO, RACMO and WRF). Consequently, the RCMs (ARPEGE, REMO, WRF, CRCM5 and PRECIS) perform remarkably well and better than ERAIN as observed in TRMM in all the definitions, except for ARPEGE in DEF4. However, the models have negative r with GPCP over the central and eastern part of the Savanna and give similar or lower results than that of ERAIN in DEF1 and DEF4. Most RCMs show high (positive) correlations with observation

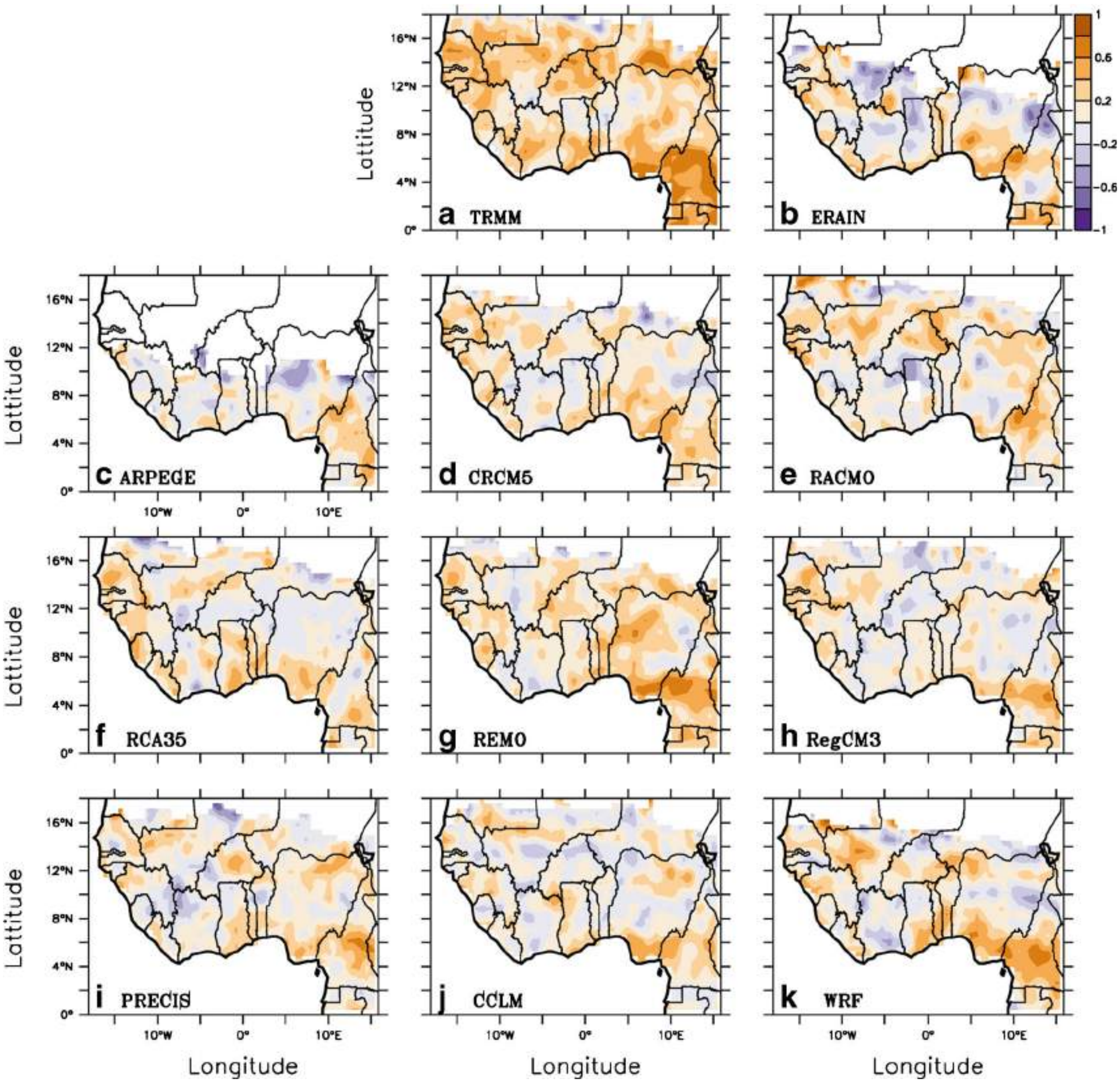

Fig. 9 Correlation of onset dates with respect to observed (GPCP) and simulated (CORDEX RCMs) in DEF4 over West Africa for the period of 1998–2008

over Guinea and the Sahel, but weak (positive and negative) correlations with observation over the Savanna. However, the RCMs' correlation outperforms ERAIN regardless of the definitions used, except along the coast at 5°N over southern Nigeria where it produces a higher correlation.

In general, the RCMs give a realistic simulation of the RODs over West Africa, though the quality of the simulate RODs depends on the definition of ROD used. Using DEF1, DEF2 or DEF3 enhances the performance of the model more than when using DEF4. Regardless of definition used, some RCMs (i.e. CRCM5, RCA35, REMO, RegCM3 and WRF) perform better than ERAIN in simulating the RODs, but some RCMs perform worse. The good performance of the RCMs in simulating the ROD in the present study is consistent with results of Nikulin et al. (2012), who found that the RCMs skillfully simulate the bimodal rainfall pattern over Guinea, the northward monsoon jump from Guinea to the Sahel and the position of the maximum rain band over the Savanna.

3.2.2 The ROD and WAMS

Here, we link the ROD with the northward progression of the WAMS. The monsoon is associated with atmospheric features like the Saharan heat low (SHL), the dry north-easterly Harmattan flow, the inter-tropical discontinuity (ITD) and the African easterly waves (AEW), the AEJ, TEJ (e.g. Omotosho and Abiodun 2007; Abiodun et al. 2011, 2012). Since the complex interaction of the features dictates the onset, intensity and location the monsoon, it is of interest to see how the RCMs link the RODs with them. Unfortunately, the first evaluation output of CORDEX available for the present study did not archive data needed to analyze all these features, but using the available data, we discuss the

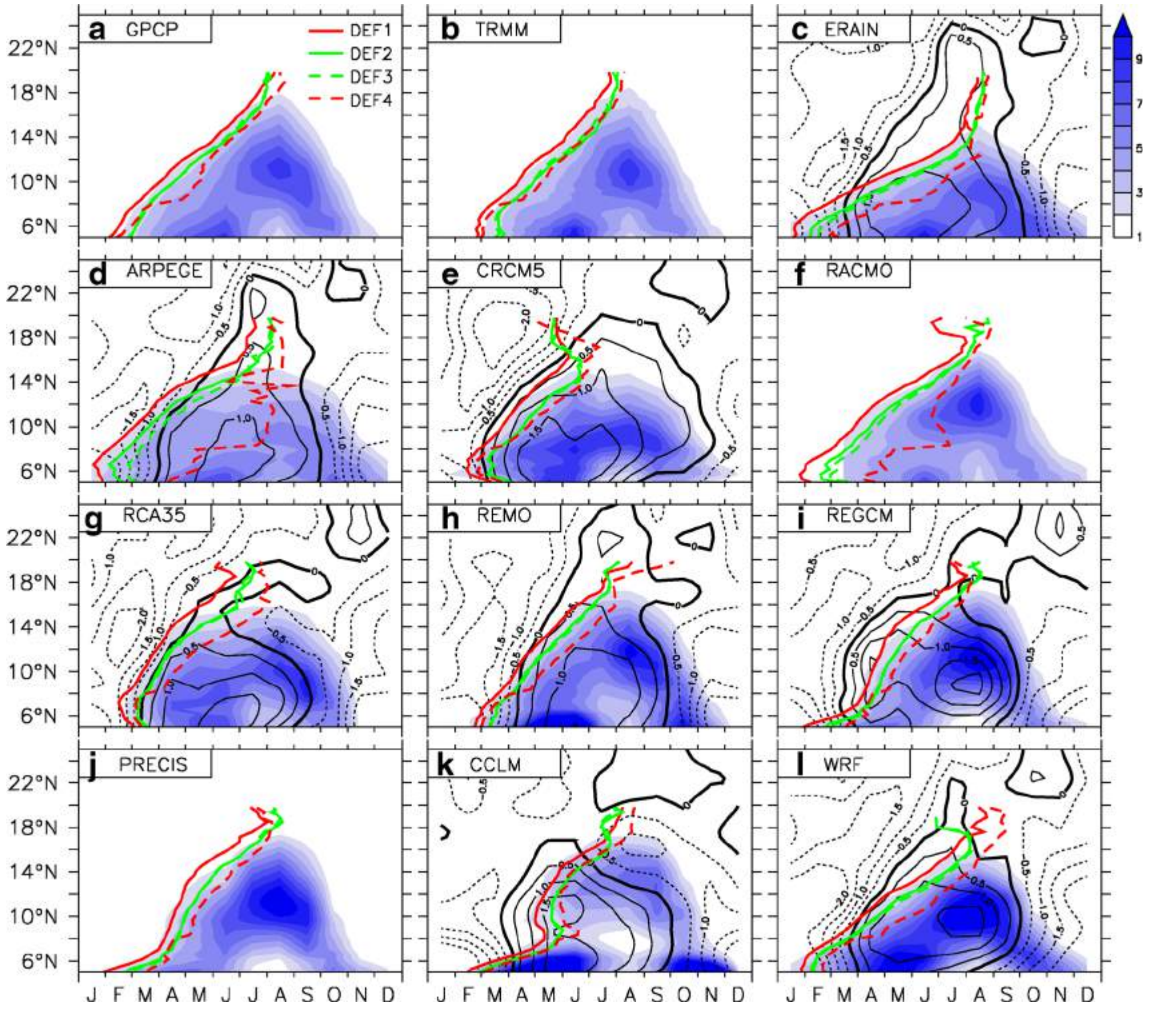

Fig. 10 Time–latitude cross-section of monthly rainfall (millimetres per day; *shaded*) and onset of monsoon rainfall (*green* and *red thick lines*) averaged over 10°W–10°E for observations (GPCP, TRMM) and CORDEX RCMs over West Africa for the period of 1998–2008. The corresponding zonal winds (*contours*) are shown in the background. Panels **a**, **b**, **e** and **i** have no wind data

relationship between RODs and the temperature maximum, moist south-westerly monsoon flow, ITD and the associated rainfall.

The observations (GPCP and TRMM; Fig. 10a, b) show that WAMS can be characterized into three different phases: the onset, the peak and the cessation of rainfall in agreement with previous studies (e.g. Le Barbe et al. 2002; Abiodun et al. 2011, 2012; Sylla et al. 2013). The onset of rainfall corresponds to the northward progression of the rain belt from the coast (about 6°N) to 16°N, and it is also associated with the position of ITD (Sultan and Janicot 2003, Omotosho and Abiodun 2007). Both observations (GPCP and TRMM) agree that the monsoon rainfall starts over the Guinea coast (5°N) in February–March and progresses inland (northward) to reach its northernmost position over the Sahel (about 18°N) in August. In ERAIN (Fig. 10c), the onset of rainfall starts earlier (i.e. January) than observed over the Guinea coast (5°N), and the northward progression is slower, reaching the northward position (about 14°N) over the Sahel. Hence, in ERAIN, the northernmost position of the monsoon rainfall is at least 3–4° latitude south of the observed position. That possibly explains why it fails to satisfy the ROD criteria north of 14°N in DEF4, while DEF1, DEF2 and DEF3 are not sensitive to that. Most RCMs (i.e. RACMO, REMO, RegCM3 and PRECIS) produce the start and inland penetration of the monsoon rainfall better than ERAIN does, although in some RCMs (i.e. CRCM5, RCA35 and WRF), the northernmost position is within 14°–15°N.

A notable feature in the northward progression of the monsoon rainfall is the so-called monsoon jump (e.g. Le Barbe et al. 2002; Abiodun et al. 2011, 2012), which signifies a break in the peak of monsoon rainfall during the northward progression. Both observations (GPCP and TRMM) show that the monsoon jump occurs over the Savanna (8°–10°N in June–July), with a local rainfall peak over Guinea (6°N in May–June) and another over the Sahel (11°N in August).

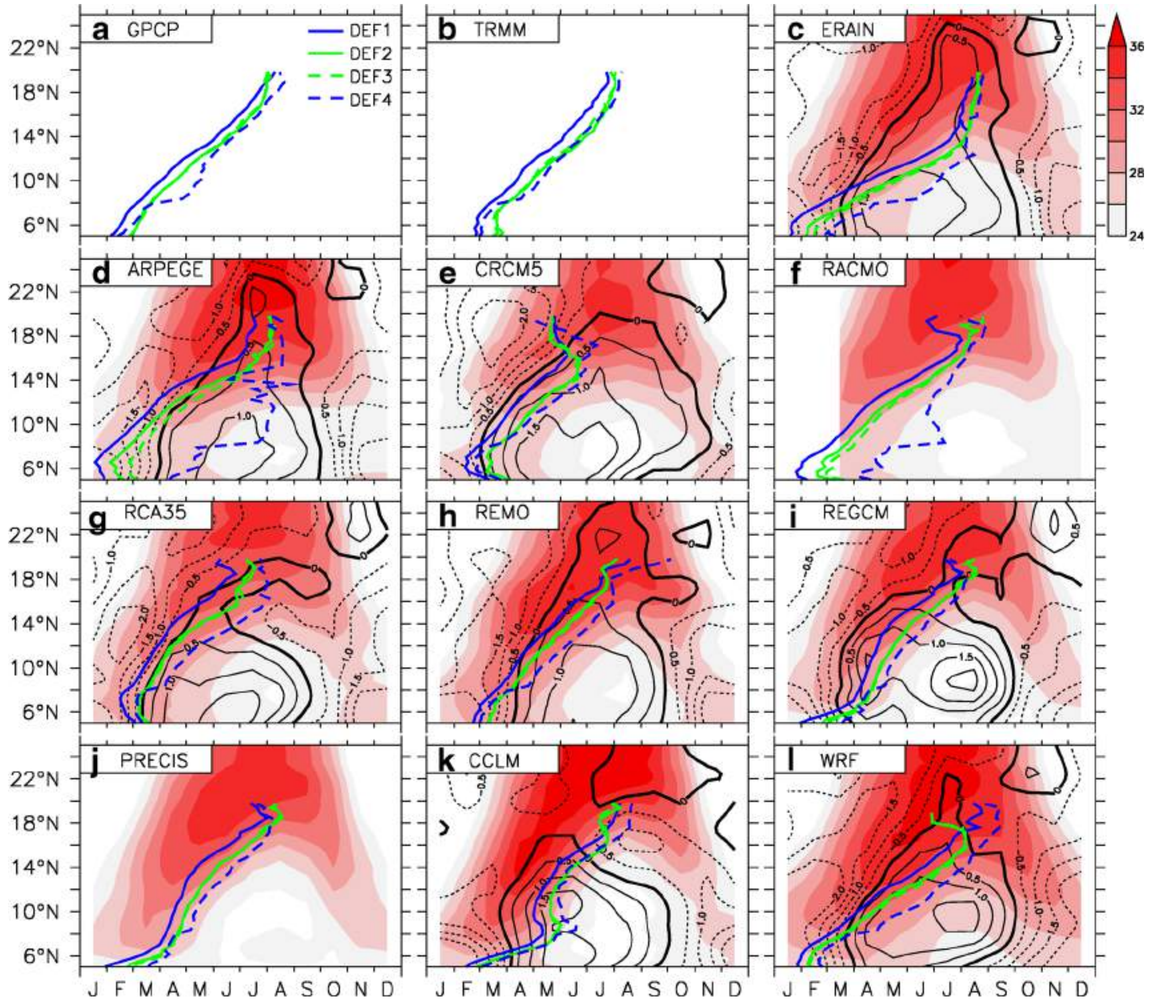

Fig. 11 Time–latitude cross-section of monthly temperature (degrees Celsius; *shaded*) and onset of monsoon rainfall (*green* and *blue thick lines*), averaged over 10 °W–10 °E for observations (GPCP, TRMM) and CORDEX RCMs over West Africa for the period of 1998–2008. The corresponding zonal winds (*contours*) are shown in the background. Panels **a**, **b**, **e** and **i** have no wind data

ERAIN poorly represents the monsoon jump. In ERAIN, the location is south of the observed and the values are higher than observed. In addition, the August rainfall peak is located over the Savanna (9°N) instead of over the Sahel (11°N) in the observation. While some RCMs (i.e. REMO, RegCM3) simulate the monsoon jump better than ERAIN does, ARPEGE simulates a worse monsoon jump than ERAIN does. However, Fig. 10 shows that the ROD definitions are sensitive to the rain jump (i.e. Fig. 10d, k) and, in this regard, DEF4 seems to be the most sensitive definition.

Despite the huge discrepancies in the monsoon rainfall produced by the RCMs (and ERAIN), there is a good agreement between their monsoon flows (Figs. 10 and 11). Figure 11 links the monsoon flows with the temperature fields that drive them. In all the RCMs (and ERAIN), the temperature maximum starts from Guinea in January–February and progresses northward (with higher values) to reach the northernmost position between 20° and 22°N (with a value of about 36 °C). The location of ITD, which indicates the northward boundary of the moist southwest monsoon flow, roughly lies over the temperature maximum, and the strength of the flow decreases northward but with a maximum value (about 1–2 ms^{-1}) over the Savanna in July–August. Note that the disagreement (or discrepancy) among the RCMs in simulating monsoon rainfall pattern (or RODs) is the highest between ARPEGE and REMO, yet these two models simulate similar monsoon flow pattern. This suggests that the main source of discrepancy among the RCMs in simulating the RODs is in their representation of the processes that convert the monsoon moisture to rainfall (i.e. rainfall or convection parameterization schemes), the soil moisture and the atmospheric feedback in the models, surface albedo, cloudiness, advection of temperature and energy fluxes (Sylla et al. 2012; Gbobaniyi et al. 2013). Various studies have indentified the convection scheme as a major bottleneck in simulating monsoon flow (e.g. Giorgi and Marinucci 1996; Fulakeza et al. 2002; Krishna et al.

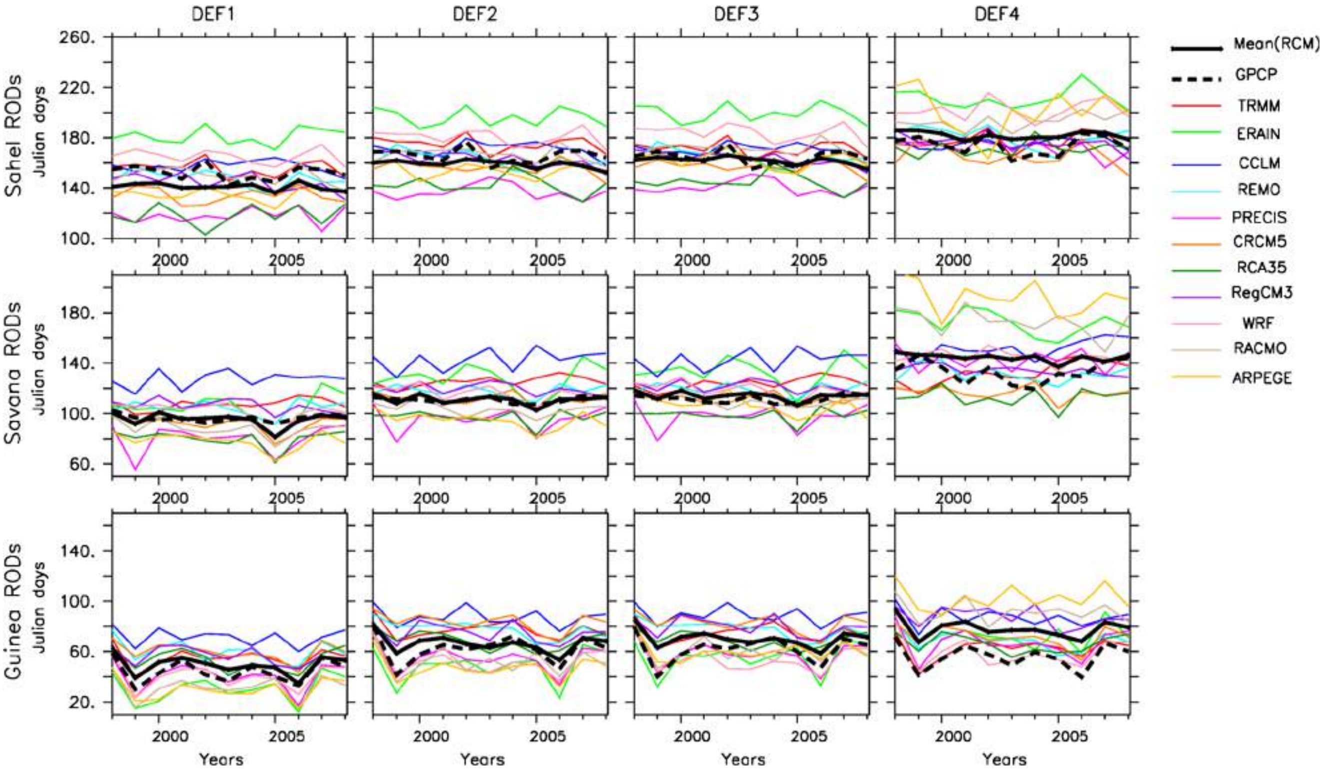

Fig. 12 Inter-annual variability of onset dates as observed (GPCP/TRMM; *dash lines*) and simulated (CORDEX RCM; *lines*) in DEF1 and 4 for the period 1998–2008 over West Africa (Guinea, Savanna and Sahel, respectively)

2011). Hence, applying empirical method/definition (e.g. Drobinski et al. 2005; Fontaine et al. 2008) to compute the ROD directly from RCMs' dynamic and thermo-dynamical fields (wind, temperature and moisture), instead of rainfall, may produce better and more consistent RODs from the RCMs. However, this is beyond the scope of the present study.

3.2.3 The inter-annual variation of RODs over the zones

Figure 12 shows the spread among the RCMs in simulating the inter-annual variation of RODs over the three climatic zones (Guinea, Savanna and Sahel) in West Africa. The spread, which can be roughly characterized by the range of the simulated RODs, indicates the uncertainty in the simulated ROD owing to physical parameterization errors in the RCMs. Over Guinea, most RCMs show that the earliest ROD occurs in 1999 and 2006, but the spread among the simulated RODs is more than 50 days using any of the definitions. ARPEGE consistently shows the earliest ROD with the first three definitions in agreement with Nikulin et al. (2012) that show that ARPEGE underestimates the rainfall over Guinea. Nevertheless, ARPEGE also shows the latest ROD with DEF4. CCLM consistently shows the latest ROD in DEF1, DEF2 and DEF3. Over the Savanna, the spread among the RCMs is widest with DEF4 (about 100 days). However, with the first three definitions, CCLM consistently shows the latest ROD while PRECIS shows the earliest ROD, and with DEF4, ARPEGE produces the latest ROD while RCA35 produces the earliest. Over the Sahel, the spread among the RCMs is narrowest with DEF4. PRECIS and RCA35 consistently show the earliest ROD in the first three definitions, while WRF shows the latest ROD in all the definitions. In most cases (except with DEF4 over Guinea), the observed RODs (GPCP) fall within the spread of the simulated RODs. Hence, the RCMs' ensemble ROD shows a lower bias than that of individual RCMs (Fig. 12). The ensemble ROD has the lowest bias (less than 5 days) with DEF2 and DEF3 over the Savanna and the highest bias (about 20 days) with DEF4 over Guinea.

The Taylor diagrams (Fig. 13), which plot the correlations (r) between the simulated and observed RODs against the normalised standard deviations (σ'), show different patterns over the three climatic zones. Over the Guinean zone, all RCMs and reanalysis cluster around a point ($r \approx 0.85$, $\sigma' \approx 0.90$) with all definitions. This implies that the RCMs and reanalysis show a very good and similar capability in simulating the inter-annual variability and standard deviation of RODs, though with different biases (Tables 4 and 5, Fig. 12). The correlation of the ensemble ROD is about 0.9 with DEF1 and DEF4, but about 0.8 with DEF2 and DEF3. Over the Savanna, the Taylor diagrams show a scatter pattern, except with DEF4, where most RCMs aligned on $r \approx 0.35$; REMO

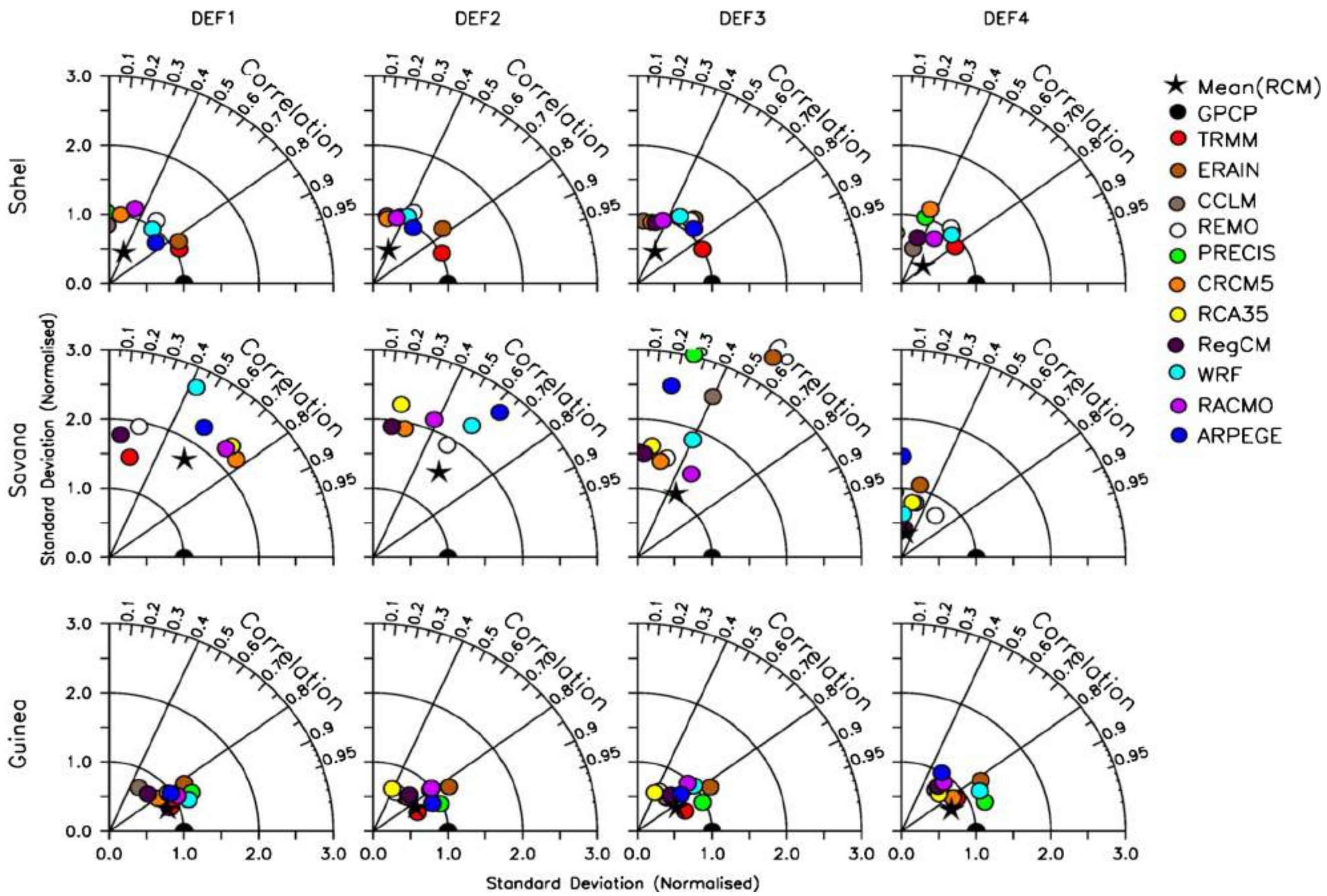

Fig. 13 Taylor diagram of ROD with respect to observed (GPCP) for simulated (CORDEX RCMs) in DEF1 and 4 over West Africa (Guinea, Savanna and Sahel, respectively) for the period of 1998–2008

produces the highest correlation (r=0.6) and the best standard deviation (σ'=1). This indicates that most RCMs perform poorly and differently in simulating the inter-annual variability and standard deviation of ROD over the Savanna. For the ensemble ROD, r=0.6 with the first three definitions, but r= 0.30 with DEF4; $\sigma'\approx$1.5, 1.5, 1.0 and 0.2 with DEF1, DEF2, DEF3 and DEF4, respectively. Over the Sahel, the results are similar to those over Guinea, except that the RCMs aligned on

Table 4 A comparison of simulated and observed RODs over Guinea, showing the mean, the bias in the mean (ΔM) and root mean square error (using GPCP as reference) in DEF1 for the period 1998–2008.

Models	Guinea			Savanna			Sahel		
	Mean	ΔM	RMSE	Mean	ΔM	RMSE	Mean	ΔM	RMSE
GPCP	13 Feb			5 Apr			31 May		
TRMM	30 Jan	14	5	18 Mar	18	6	15 May	16	4
ERAIN	22 Feb	9	5	20 Mar	16	5	28 Apr	33	11
ARPEGE	9 Feb	4	5	20 Mar	16	10	27 Apr	34	8
RCA35	24 Feb	11	3	16 Apr	11	5	3 Jun	3	3
PRECIS	28 Feb	16	5	1 Apr	5	5	13 May	18	7
CRCM5	29 Feb	17	5	13 Apr	8	6	24 May	7	6
REMO	11 Mar	28	8	6 May	31	8	6 Jun	6	8
CCLM	30 Jan	14	6	13 Apr	31	10	1 Jul	31	3
RACMO	31 Jan	12	5	28 Mar	8	5	29 May	2	7
RegCM3	25 Feb	12	6	15 Apr	10	6	24 May	7	9
WRF	9 Feb	4	4	10 Apr	5	7	12 Jun	12	5

Table 5 A comparison of simulated and observed RODs over Guinea, showing the mean, the bias in the mean (ΔM) and root mean square error (using GPCP as reference) in DEF4 for the period 1998–2008

Models	Guinea			Savanna			Sahel		
	Mean	ΔM	RMSE	Mean	ΔM	RMSE	Mean	ΔM	RMSE
GPCP	25 Feb			12 May			22 Jun		
TRMM	2 Mar	6	5	11 May	1	13	24 Jun	3	5
ERAIN	11 Mar	15	7	20 Jun	39	11	29 Jul	37	6
ARPEGE	11 Apr	46	9	11 Jul	60	15	21 Jul	29	20
RCA35	6 Mar	10	7	21 Apr	20	10	19 Jun	3	10
PRECIS	7 Mar	11	4	21 May	10	13	20 Jun	2	9
CRCM5	11 Mar	16	5	25 Apr	17	11	12 Jun	9	9
REMO	9 Mar	13	6	10 May	2	7	28 Jun	6	7
CCLM	27 Mar	31	8	30 May	19	10	23 Jun	1	8
RACMO	31 Mar	35	8	20 Jun	39	15	11 Jul	19	7
RegCM3	27 Mar	31	8	13 May	1	9	23 Jun	2	8
WRF	28 Feb	3	6	23 May	11	10	19 Jul	28	6

$\sigma' \approx 1.5$ with r varying from 0.0 to 0.7 and with DEF4 where models cluster around a point ($r \approx 0.6$, $\sigma' \approx 0.70$). The correlation for the ensemble ROD is about 0.4 with the first three definitions and 0.8 with DEF4; nevertheless, the standard deviation of the ensemble ROD is lower than that of any RCM. Hence, the best performance of the RCMs in simulating the inter-annual variability of ROD (i.e. correlation, standard deviation and root mean square errors) is over Guinea and their worst performance is over the Savanna.

4 Conclusion

In this study, we have compared and used four definitions (DEF1, DEF2, DEF3 and DEF4) of rainfall onset dates in evaluating the capability of CORDEX-Africa RCMs to simulate the characteristics of RODs over West Africa. The evaluation focuses on how well the CORDEX-Africa regional climate models (RCMs) simulate the mean, standard deviation and inter-annual variability of RODs as observed in GPCP and TRMM for the period 1998–2008. ERA-Interim (ERAIN) is also used for the RCMs' performance evaluation. Using the four definitions with observed datasets (GPCP and TRMM), DEF1 consistently produces the earliest ROD, while DEF4 gives the latest ROD.

The spatial distribution of the observed mean ROD is generally zonal and the values increase inland from the coast, but the distribution is more zonal in DEF1 than in DEF4. The ROD is earlier north of 8°N than in DEF1 and in DEF4. ERAIN does not capture the spatial distribution of the ROD as observed in GPCP and TRMM, regardless of the ROD definition. Regardless of the definition used, some RCMs perform better than the ERAIN in simulating the spatial distribution of the ROD, while some RCMs perform worse than ERAIN. Other RCMs (ARPEGE, RACMO, PRECIS and CCLM) perform better than ERAIN when DEF1 (DEF2 or DEF3) is used, but perform worse than ERAIN when DEF4 is used. Observations show that monsoon rainfall starts over the Guinea coast (5°N) in February–March and progresses inland (northward) to reach its northernmost position over the Sahel (about 18°N) in August, but ERAIN produces a monsoon that starts earlier (i.e. January) and progresses slower than the observed, and the northernmost position of the monsoon rainfall in ERAIN is located south of the observed position. Some RCMs produce the start and inland penetration of the monsoon rainfall better than ERAIN does.

The good agreement among the RCMs and ERAIN in simulating temperature fields and monsoon flows over West Africa suggests that the main source of discrepancy among the RCMs in simulating the RODs is owing to the difference in the models representation of rainfall processes. In simulating the inter-annual variability of ROD, the RCMs perform best over Guinea and worst over the Savanna. The RCMs' ensemble mean outperforms individual RCMs and ERAIN in simulating the mean and inter-annual variability of RODs over West Africa, regardless the definition used. This study suggests that the performance of RCMs may be improved by using the ROD definition that uses the simulated dynamic and thermodynamic fields rather than rainfall fields.

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References

Abiodun BJ, Pal JS, Afiesimama EA, Gutowski WJ, Adedoyin A (2008) Simulation of West African monsoon using RegCM3 part II: impacts of deforestation and desertification. Theor Appl Climatol 93: 245–261. doi:10.1007/s00704-007-0333-1

Abiodun BJ, Gutowski W, Abatan AA, Prusa JM (2011) CAM-EULAG: a non hydrostatic atmospheric climate model with grid stretching. Acta Geophys 59(6):1158–1167

Abiodun BJ, Adeyewa ZD, Oguntunde PG, Salami AT, Ajayi VO (2012) Modelling the impacts of reforestation on future climate in West Africa. Theor Appl Climatol. doi:10.1007/s00704-012-0614-1

Afiesimama EA, Pal JS, Abiodun BJ, Gutowski WJ, Adedoyin A (2006) Simulation of West African monsoon using the RegCM3. Part I: model validation and interannual variability. Theor Appl Climatol 86:23–37

AGRHYMET (1996) Méthodologie de suivi des zones à risque. AGRH YMET FLASH, Bulletin de Suivi de la Campagne Agricole au Sahel 0/96, Vol. 2, 2 pp. [Available at Centre Regional AGRH YMET, B.P. 11011, Niamey, Niger.]

Ati FO, Stitger CJ, Oladipo EO (2002) A comparison of methods to determine the onset of the growing season in northern Nigeria. Int J Climatol 22:731–742

Cocheme J, Franquin P (1967) An agro-climatology survey of a semi-arid area in Africa, South of Sahara, FAO/WMO Technical Bulletin 86

Cook KH, Vizy EK (2006) Coupled model simulations of the West African monsoon system: twentieth- and twenty-first-century simulations. J Clim 19:3681–3703

Dee DP et al (2011) The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Q.J.R. Meteorol Soc 137:553–597. doi:10.1002/qj.828

Diallo I, Sylla MB, Giorgi F, Gaye AT, Camara M (2012a) Multi-model GCM-RCM ensemble-based projections of temperature and precipitation over West Africa for the early 21st century. Int J Geophys, Article ID 972896

Diallo I, Sylla MB, Camara M, Gaye AT (2012b) Interannual variability of rainfall and circulation features over the Sahel based on multiple regional climate models simulations. Theor Appl Climatol. doi:10.1007/s00704-012-0791-y

Djiotang et al (2010) Sensitivity of the simulated African monsoon of summers 1993 and 1999 to convective parameterization schemes in RegCM3. Theor Appl Climatol 100:207–220

Drobinski P, Sultan B, Janicot S (2005) Role of the Hoggar massif in the West African monsoon onset. Geophys Res Lett 32, L01705. doi:10.1029/2004GL020710

Druyan LM, Feng J, Cook KH, Xue Y, Fulakeza M, Hagos SM, Konare A, Moufouma-okia W, Rowell DP, Vizy EK, Ibrah SS (2010) The WAMME regional model intercomparison study. Clim Dyn 35:175–192

Eltahir E, Gong C (1996) Dynamics of wet and dry years in West Africa. J Clim 9:1030–1042

Fontaine B, Louvet S, Roucou P (2008) Definition and predictability of an OLR-based West African monsoon onset. Int J Climatol 28: 1787–1798

Fulakeza M, Druyan L, Krishnamurti T (2002) A simple soil moisture scheme for climate simulations in the tropics. Atmos Phys 79:105–126

Gbobaniyi E, Sarr A, Sylla MB, Diallo I, Lennard C, Dosio A, Dhiédiou A, Kamga A, Klutse NAB, Hewitson B, Nikulin G, Lamptey B (2013) Climatology, annual cycle and interannual variability of precipitation and temperature in CORDEX simulations over West Africa. Int J Climatol. doi:10.1002/joc.3834

Giorgi F, Marinucci M (1996) An investigation of the sensitivity of simulated precipitation to model resolution and its implication for climate studies. Mon Weather Rev 124:148–166

Hourdin, F, Mustat, I, Guichard, F, Ruti, PM, & Favot, F. Pham MMA, Grandpeix JY, Polcher J, Marquet P, Boone A, Lafore JP, Redelsperger JL, Dell'Aquilla A, Losada Doval T, Traore AK, Gallee H (2010) AMMA-Model intercomparison project. Bull Am Meteorol Soc

Huffman GJ, Bolvin DT (2011) TRMM and other data precipitation data set documentation. NASAGSFC Rep., 29 pp. ftp://precip.gsfc.nasa.gov/pub/trmmdocs/3B42_3B43_doc.pdf. Accessed 23 July 2013

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 multi-satellite observations. J Hydrometeorol 2:36–50

Huffman GJ et al (2007) The TRMM multisatellite precipitation analysis (TMPA): quasi-global, multiyear. combined-sensor precipitation estimates at fine scales. J Hydrometeorol 8:38–55

Huffman GJ, Adler RF, Bolvin DT, Gu G (2009) Improving the global precipitation record: GPCP version 2.1. Geophys Res Lett 36, L17808. doi:10.1029/2009GL040000

Janicot S, Harzallah A, Fontaine B, Moron V (1998) West African monsoon dynamics and eastern equatorial Atlantic and Pacific SST anomalies (1970–88). J Clim 11:1874–1882

Krishna et al (2011) Customization of WRF-ARW model with physical parameterization schemes for the simulation of tropical cyclones over North Indian Ocean. Nat Hazards. doi:10.1007/s11069-011-9862-0

Lamb PJ, Peppler RA (1992) Further case studies of tropical Atlantic surface atmospheric and oceanic patterns associated with sub-Saharan drought. J Clim 5:476–488

Laux P, Kunstmann H, árdossy AB (2008) Predicting the regional onset of the rainy season in West Africa. Int J Climatol 28:329–342

Le Barbe L, Lebel T, Tapsoba D (2002) Rainfall variability in West Africa during the years 1950–1990. J Clim 15(2):187–202

Nicholson SE, Some B, Kone B (2000) An analysis of recent rainfall conditions in West Africa, including the rainy seasons of the 1997 El Niño and the 1998 La Niña years. J Clim 13:2628–2640

Nikulin G et al (2012) Precipitation climatology in an ensemble of CORDEX-Africa regional climate simulations. J Clim 25:6057–6078

Odekunle TO (2006) Determining rainy season onset and retreat over Nigeria from precipitation amount and number of rainy days. Theor Appl Climatol 83:193–201

Oduru AK (1989) On the mean monthly equivalent potential temperature and rainfall in West Africa. Theor Appl Climatol 39:188–193

Omotosho JB (1990) Onset thunderstorms and precipitation over northern Nigeria. Int J Climatol 10:849–860

Omotosho JB (1992) Long-range prediction of the onset and end of the rainy season in the West African Sahel. Int J Climatol 12:369–382

Omotosho JB, Abiodun BJ (2007) A numerical study of moisture build-up and rainfall over West Africa. Meteorol Appl 14:209–225

Omotosho JB, Balogun AA, Ogunjobi K (2000) Predicting monthly and seasonal rainfall, onset and cessation of the rainy season in West Africa using only surface data. Int J Climatol 20:865–880

Paeth H, Hall NMJ, Gaertner MA, Alonso MD, Moumouni S, Polcher J, Ruti PM, Fink AH, Gosset M, Lebel T, Gaye AT, Rowell DP, Moufouma-Okia W, Jacob D, Rockel B, Giorgi F, Rummukainen M (2011) Progress in regional downscaling of West African precipitation. Atmos Sci Lett 12:75–82. doi:10.1002/asl.306

Pu B, Cook KH (2010) Dynamics of the West African westerly jet. J Clim 23:6263–6276

Ramel R, Gallée H, Messager C (2006) On the northward shift of the West African monsoon. Clim Dyn Res 26:429–440. doi:10.1007/s00382-005-0093-5

Reynolds RW, Smith TM, Liu C, Chelton DB, Casey KS, Schlax MG (2007) Daily high-resolution-blended analyses for sea surface temperature. J Clim 20:5473–5496

Ruti PM et al (2011) The West African climate system: a review of the AMMA model inter-comparison initiatives. Atmos Sci Lett 12:116–122. doi:10.1002/asl.305

Sarria-Dodd DE, Jolliffe IT (2001) Early detection of the wet season in semiarid tropical climates of western Africa. Int J Climatol 21:1251–1262

Sijikumar S, Roucou P, Fontaine B (2006) Monsoon onset over Sudan-Sahel: simulation by the regional scale model MM5. Geophys Res Lett 33: L03814. doi:10.1029/2005GL024819

Sivakumar MVK (1988) Predicting rainy season potential from the onset of rains in the Southern Sahelian and Sudanian climatic zones of West Africa. Agric For Meteorol 42:295–305

Stern RD, Dennett MD, Garbutt DJ (1981) The start of the rains in West Africa. J Clim 1:59–68

Sultan B, Janicot S (2003) The West African monsoon dynamics. Part II: the "preonset" and "onset" of the summer monsoon. J Clim 16: 3407–3427

Sylla MB et al (2009) High-resolution simulations of West African climate using regional climate model (RegCM3) with different lateral boundary conditions. Theor Appl Climatol 98:293–314

Sylla MB, Dell'Aquila A, Ruti PM, Giorgi F (2010) Simulation of the intraseasonal and the interannual variability of rainfall over West Africa with a RegCM3 during the monsoon period. Int J Climatol 30:1865–1883

Sylla MB, Giorgi F, Coppola E, Mariotti L (2012) Uncertainties in daily rainfall over Africa: assessment of gridded observation products and evaluation of a regional climate model simulation. Int J Climatol

Sylla MB, Diallo I, Pal JS (2013) West African monsoon in state-of-the-science regional climate models. doi. 10.5772/55140

Van der Linden, Mitchell (2009) ENSEMBLES: climate change and its impacts: summary of research and results from the ENSEMBLES project. Met Office Hadley Centre: Exter

Vanvyve E, Hall N, Messager C (2007) Internal variability in a regional climate model over West Africa. Clim Dyn. doi 10.1007/s00382-007-0281-6

Vigaud N et al (2009) WRF/ARPEGE-CLIMAT simulated climate trends over West Africa. Clim Dyn 36:925–944. doi:10.1007/s00382-009-0707-4

Xue Y et al (2010) Intercomparison and analyses of the climatology of the West African Monsoon in the West African monsoon modeling and evaluation project (WAMME) first model intercomparison experiment. Clim Dyn 35:3–27. doi:10.1007/s00382-010-0778-2