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Research Article

Regional Climate Model Sensitivity to Domain Size for the Simulation of the West African Summer Monsoon Rainfall

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We use the International Centre for Theoretical Physics (ICTP) Regional Climate Model (RegCM3) to study the impact of different domain sizes on the simulation of the West African summer monsoon rainfall and circulation features. RegCM3 simulates drier conditions over the default domain (RegCM-D1) and its westward extension (RegCM-D2), much less dryness over the eastward extended domain (RegCM-D3) and excessive wetness in the domain extended northward into the extratropical regions (RegCM-D4). This overestimation is related to the existence of larger source of humidity due to the inclusion of a more significant portion of the Atlantic Ocean and to a weakening of the African Easterly Jet (AEJ), which both favor stronger westerlies advecting moisture towards the land. The best performance is, however, captured in the RegCM-D3 experiment, and this originates from a simulation of moderate westerly moisture fluxes along with a stronger AEJ and occurrences of more frequent African Easterly Waves (AEWs). Therefore, the choice of the domain for regional climate model simulation of the West African summer monsoon rainfall is of critical importance, and caution needs to be taken to account for the main regional forcings including mostly the necessary humidity sources of the tropical Atlantic Ocean and the AEWs genesis region upstream of Sudanese Highlands.

1. Introduction

The West African Monsoon (WAM) system consists of many atmospheric features including the low-level monsoon flow, the midtropospheric African Easterly Jet (AEJ), and the synoptic disturbances along the jet axis so-called African Easterly Waves (AEWs) and the upper level Tropical Easterly Jet (TEJ). The low-level monsoon flow originates from meridional surface pressure gradient established between the land and the ocean during the summer season [1]. The AEJ appears over West Africa during the boreal summer as a result of the strong meridional surface moisture and temperature gradients between the Sahara and equatorial Africa tied to the deep convective heating [2–4]. The AEWs are generated upstream of Sudanese highlands and propagate across West Africa around the midtropospheric AEJ through combined baroclinic and barotropic conversion [4, 5]. The TEJ, which is associated with the upper-level outflow from the Asian monsoon [6], also circulates across West Africa during the boreal summer season. These features interact in a complex way and are responsible for the summer monsoon precipitation over the region. For example, the low-level monsoon flow is the major component for the moisture transport into the West Africa continent from the Atlantic Ocean; the position and strength of the AEJ cause rainfall variability by transporting moisture away from the continent [7] and by interacting with mesoscale convective systems embedded in the AEWs [8] while the strength of the TEJ acts mainly in the lifetime of these systems [9] which are responsible for most of rain over West Africa [10].

Although it is complex, the WAM system is of major economic and social importance to the population of the region whose economy heavily relies on rain-fed agriculture. Therefore, accurate simulation of its features will help the understanding of its dynamics and variability to improve our skill in predicting its onset and evolution. Many studies have used regional climate models to understand the WAM system. For instance, Vizy and Cook [11] studied the

response of the WAM to tropical oceanic heating. Jenkins et al. [9] and Sylla et al. [12] investigated the main drivers of the present day and future Sahel droughts. Abiodun et al. [7] documented the impact of deforestation and desertification over West Africa while Moufouma-Okia and Rowell [13] examined the effect of soil moisture initialization on the WAM simulation.

All the studies mentioned above show a substantial progress in understanding the WAM dynamical and physical features using regional climate models. The potential of the RegCM3 as a tool to study WAM circulation have been highlighted in many studies including (but not limited to) Afiesimama et al. [14], Sylla et al. [15], and Sylla et al. [16]. The model has been shown to be capable of reproducing the mean climatology and the variability of the WAM climate. However, since the system consists of atmospheric features that are generated in different locations and sensitive to different topography and surface conditions of the region, selecting the domain size for the regional climate simulation is crucial to be able to get the important sources of forcing features from the boundaries.

Regional climate models are driven by time-dependent large-scale meteorological fields specified at the boundaries of the chosen domain. Anthes et al. [17] and Giorgi and Mearns [18] showed that the choice of domain size and location affects the balance between the boundary and internal model forcings in the simulation. The location of boundaries in relation to the regional sources of forcings in a particular climatic region can also affect the regional climate model solution [19]. As a matter of fact, Seth and Giorgi [20] showed that the lateral boundaries must be placed well outside the region of interest to avoid unrealistic response to internal forcings while Jones et al. [21] showed that the regional domain must be large enough to allow the full development of small-scale features over the area of interest.

These indicate that the domain size can have significant effects on the simulation of regional climate models and therefore a careful choice of the domain is needed for particular studies. In this paper, we investigate how the sizes/extensions of regional model domain affect the WAM circulation and consequently the simulation of rainfall during the peak (JJA) of the rainy season. The model and experiments are briefly described in Section 2 and the results are discussed in Section 3 while final considerations are given in Section 4.

2. Model Description and Experiments

The ICTP Regional Climate Model, RegCM3 [22–24] is used in this study. RegCM3 is a primitive equation, sigma vertical coordinate model based on the hydrostatic dynamical core of the NCAR/PSU's mesoscale meteorological model MM5 [25]. Radiation is represented by the CCM3 parameterization of Kiehl et al. [26] and the planetary boundary layer scheme is by Holtslag et al. [27]. Interactions between the land surface and the atmosphere are described using the Biosphere Atmosphere Transfer Scheme (BATS1E; [28]). The scheme of Zeng et al. [29] is used to represent fluxes from water surfaces. Convective precipitation is calculated with the scheme of Grell et al. [25] applying the Fritsch and Chappell [30] closure assumption. Resolvable precipitation processes are treated with the subgrid explicit moisture scheme (SUBEX) of Pal et al. [31], which is a physically based parameterization including subgrid scale cloud fraction, cloud water accretion, and evaporation of falling raindrops. This model configuration is the same used by Sylla et al. [16] and Sylla et al. [4]. This choice was based on an in-depth analysis of the model performance in multidecadal simulations of present day climate.

Four sets of experiments, covering each 5 years (2001–2005) as in Sylla et al. [4], have been conducted over different domain sizes (see Figure 1(a)) using 50 km of horizontal resolution and 18 verticals level with a top at 5 mb. The first (RegCM-D1) domain covers mostly West Africa and a little part of the Atlantic Ocean (D1: 25E–25W; 10S–25N). The second experiment (RegCM-D2) extends this domain further west with much larger Ocean area up to 45°W (D2: 45E–25W; 10S–25N). The third simulation (RegCM-D3) is carried out in a domain that covers D2 but extended eastward up to East Africa (35°E) including some of the highlands where AEWs are generated (D3: 45E–35W; 10S–25N). The last simulation (RegCM-D4) extends D3 northward up to 45°N to allow RegCM3 to simulate its own circulation around the Azores high (D4: 45E–35W; 10S–45N). Each of these domain comprises a buffer zone is just 12 grid-points (∼5°). The topography exhibits some localized highlands (e.g., Figure 1(a)): Guinea Highlands (GH), Jos Plateau (JP), and Cameroun Mountains (CM) while the eastward extended domain comprises also part of the East African complex terrains for instance the Sudanese Highlands (SH). The topography is derived from the United States Geological Survey's (USGS) GTOPO 30 seconds (∼1 km of resolution) global elevation data which is interpolated onto the model grid (50 km).

All the experiments are conducted using initial and lateral boundary conditions created from the ERA-Interim 1.5°× 1.5° gridded reanalysis [32], which is the third generation of European Centre of Medium-Range Weather Forecast (ECMWF) reanalysis product. Sea surface temperatures (SSTs) for all experiments is obtained from the National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation (OI) SST. The OISST used here is produced weekly on a one-degree grid [33]. The boundary conditions and SST are updated four times daily in RegCM3 using the relaxation procedure described by Giorgi et al. [23].

These sets of experiments will help addressing the effect of the western, eastern, and northern boundary on the simulation of the different West African summer monsoon features and rainfall. As a matter of fact, the analysis is carried out by considering the simulated mean rainfall but also the frequency and intensity of daily rainfall events. We should mention that only the core of the West African rainfall season June-August (JJA) is considered in the study because of its large contribution on the region's annual mean precipitation. We evaluate the effect of (1) the westward extension of the domain by comparing RegCM-D2 and RegCM-D1, (2) the eastward extension by comparing RegCM-D3 and

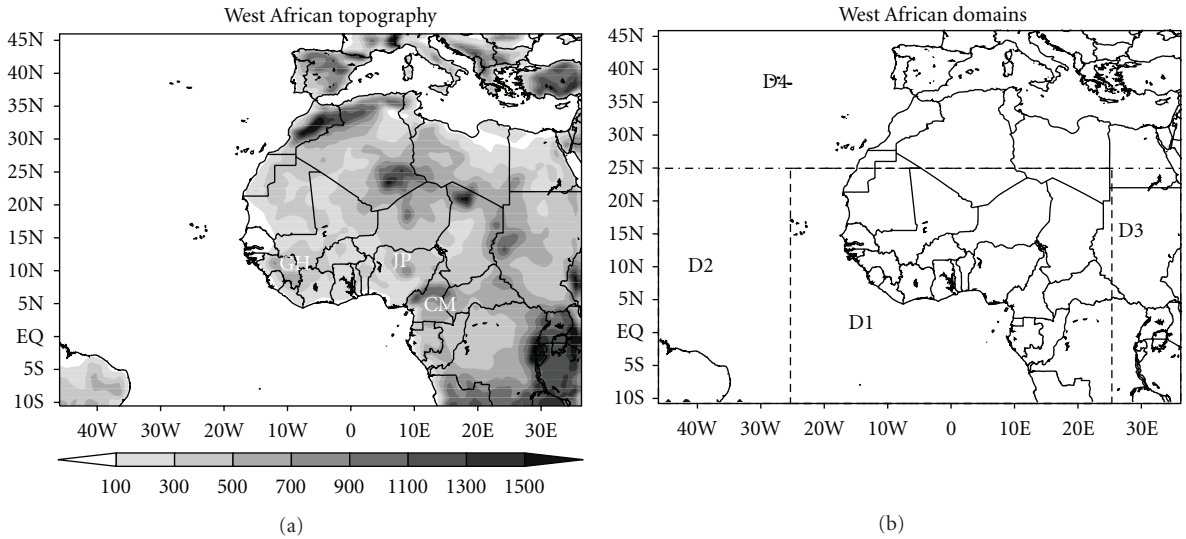

Figure 1: (a) The West African domain sizes and (b) topography (in meters). The analyzed domain for quantitative assessment extends from 20°W to 20°E and 0 to 20°N in red. The highlands are highlighted by their respective acronyms: Guinea Highlands (GH), Jos Plateau (JP), Cameroun Mountains (CM), and Sudanese Highlands (SH).

RegCM-D2, and (3) the northward extension by comparing RegCM-D4 and RegCM-D3.

The performance of each experiment is assessed by comparing with the high-resolution (0.25°× 0.25°) product of Tropical Rainfall Measuring Mission (TRMM; [34, 35]). TRMM is satellite-derived daily and monthly rainfall providing data for the entire tropics since November 1997. The GPCP (Global Precipitation Climatology Project, 2.5°× 2.5° resolution; [36], product is also used as additional reference for the baseline validation to account for uncertainties in rainfall observations [37]. Although both of them are mainly based on satellite observations, they have also been compared and merged with ground station rain gauges to create the final products.

For quantitative assessment, we evaluate the spatial patterns of the experiments' bias but also some quantitative measures being mean bias (MB), root mean square difference (RMSD), and pattern correlation coefficient (PCC) with respect to the TRMM rainfall. Although we plot the common region across the simulations, the statistic measures are computed over the analyzed domain (Figure 1(b)), thus excluding the buffer zone of D1. The MB, RMSD, and PCC can be considered as measures of model systematic errors and performance as they provide information at both the regional and the grid point levels. The origins of the different performance of the regional climate model to simulate the seasonal rainfall will therefore be examined through the WAM features for instance the monsoon flow, the subsequent vertically integrated moisture flux, the AEJ, the TEJ, the upward motion between the jets axis, and the AEWs.

3. Results

3.1. The Simulated Rainfall Patterns. The effect of various domain sizes (e.g., Figure 1(b)) is investigated for rainfall and the relevant monsoon circulation features. For instance, we intercompare D1 and D2, D2 and D3, and D3 and D4 as mentioned above. Figures 2(a)–2(f) shows the summer (JJA) mean rainfall from GPCP and TRMM observations along with the RegCM3 simulations over the different domains. Observations (both GPCP and TRMM) display the ITCZ in a zonal and tilted band between 8°N and 13°N, with rainfall decreasing south and north of it. Precipitation maxima are, however, located in orographic regions such as the Guinea highlands, Jos plateau, and Cameroun Mountains (e.g., Figure 1(a)). TRMM shows some fine-scale localized intense rainfall amount, not captured in GPCP, which are related to local topography and are mostly artifact of the higher resolution.

RegCM3 reproduces quite well this spatial distribution, in particular the ITCZ position, the northern and southern gradients of rainfall and the location of maxima over orographic regions in all domains with PCCs of around 0.80. Note that some cores of large rainfall amount are present at the margins of the eastern boundary of both D1 and D2. We should mention that these are just due to the presence of boundary effects in regional climate model simulation [20] because of the proximity of this area to the eastern boundary. Therefore, they are not considered here.

The different domains exhibit different bias patterns as displayed in Figures 3(a)–3(d). In addition, Table 1 summarizes the quantitative measures MB, RMSD, and PCC calculated for each of the simulations with respect to TRMM. RegCM-D1 and RegCM-D2 are drier than TRMM over most of land and oceanic areas resulting, respectively, in an MB of −7.5% and −4.5% and an RMSD of 1.97 mm/day and 1.88 mm/day. This dryness is reduced in both magnitude and spatial extent in RegCM-D3 experiment where the model also simulates some few wet bias along the Gulf of Guinea and the ITCZ regions. The larger and more extended wet

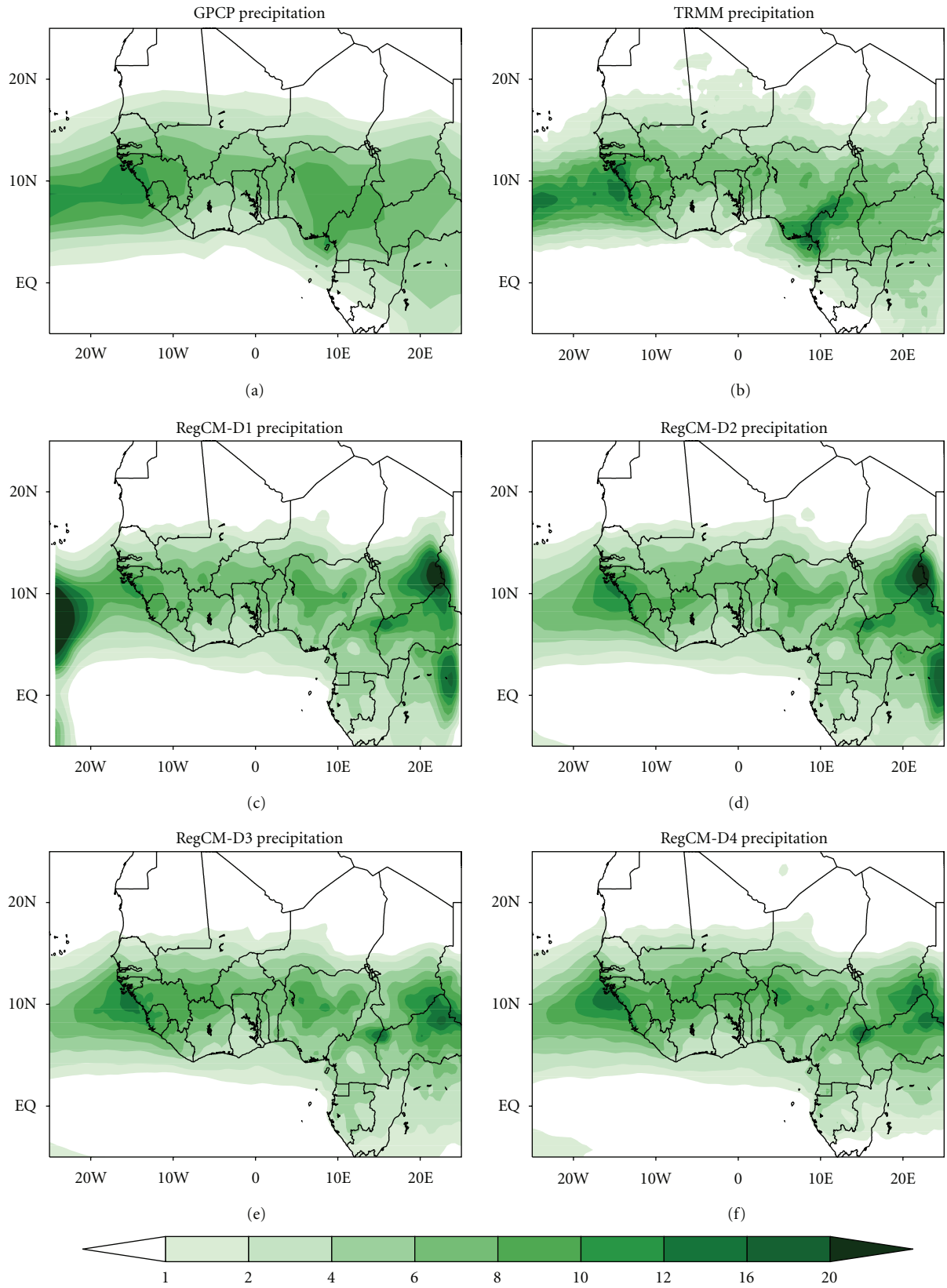

Figure 2: Mean JJA rainfall averaged for the period 2001–2005 from (a) GPCP, (b) TRMM, (c) RegCM-D1, (d) RegCM-D2, (e) RegCM-D3, and (f) RegCM-D4. Units are expressed in mm/day.

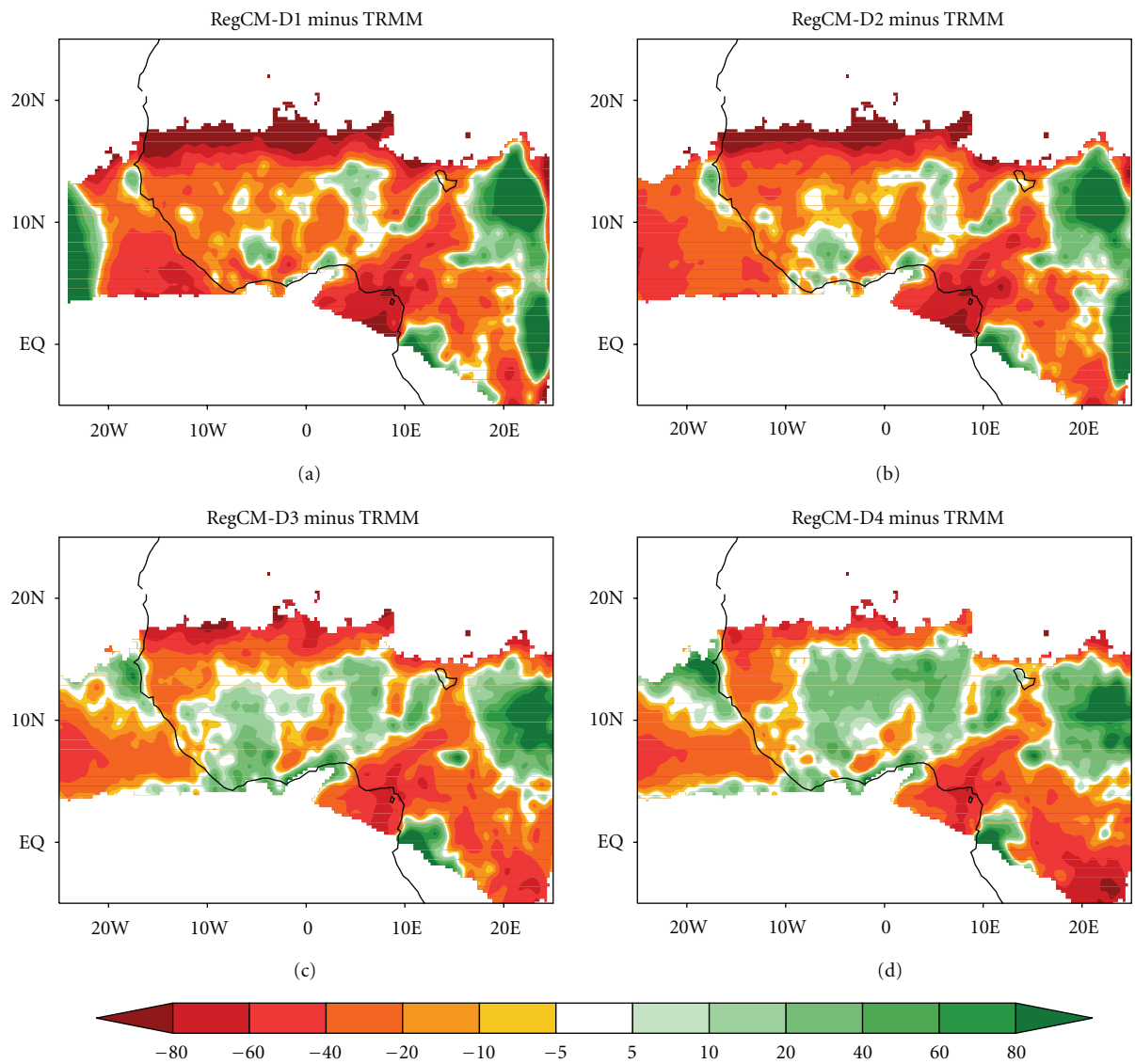

Figure 3: Differences in mean JJA rainfall between (a) RegCM-D1 and TRMM, (b) RegCM-D2 and TRMM, (c) RegCM-D3 and TRMM and (d) RegCM-D4, and TRMM. Units are expressed as percentage of TRMM values.

biases are, however, found in RegCM-D4. This is consistent with the lower MB (−2.95%) and RMSD (1.80 mm/day) simulated in RegCM-D3 compared to those of RegCM-D4 (4.07% and 1.93 mm/day, resp.). It is worth noting that RegCM-D3 exhibits also the larger PCC.

It is thus evident that substantial discrepancies exist across the different simulations. This is highlighted in Figures 4(a)–4(c). Differences between RegCM-D2 and RegCM-D1 (e.g., Figure 4(a)), which represents the extension of the western boundary effect, show mostly a noisy pattern in the land where rainfall increases and decreases for about 20% and −20%. The most significant change (up to 40%) is shown at the Guinea coast between 15°W and 5°W and off the west coast. These changes have lead to a larger maximum over the orographic regions and the ocean ITCZ in RegCM-D2 compared to RegCM-D1. The effect of the extension of the eastern boundary, illustrated by the difference between RegCM-D3 and RegCM-D2 (Figure 4(b)) impacts mostly the zonal rainfall band around 12°N with an increase of the intensity of about 20–30%, contributing

Table 1: Mean Bias (MB), Root Mean Square Difference (RMSD) and Pattern Correlation Coefficient (PCC) for each of the simulation with respect to TRMM over the analyzed domain (e.g., Figure 1(b)). MB is expressed as percentage of TRMM values while RMSD as mm/day.

	Domain 1	Domain 2	Domain 3	Domain 4
MB	−7.53	−5.42	−2.95	4.07
RMSD	1.97	1.88	1.80	1.93
PCC	0.79	0.80	0.82	0.80

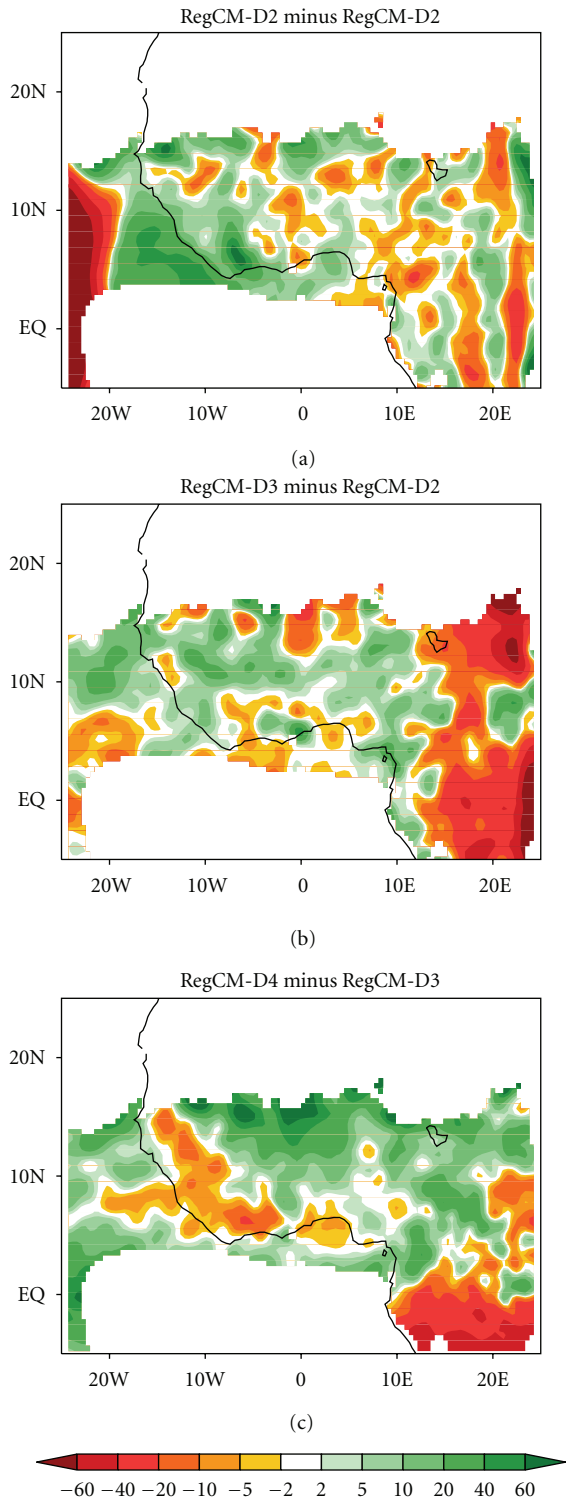

Figure 4: Differences among the simulations of mean JJA rainfall between (a) RegCM-D2 and RegCM-D1, (b) RegCM-D3 and RegCM-D2, and (c) RegCM-D4 and RegCM-D3. Units are expressed as percentage of, respectively, RegCM-D1, RegCM-D2, and RegCM-D3 values.

to the inland extension and stronger but more realistic orographic maximum over the Guinea Highlands and ITCZ. The most significant changes are obtained when the northern boundary of D3 is extended further north up to 45°N. In fact, RegCM-D4 shows a sharper and stronger ITCZ, causing an overestimation of rainfall in these convective regions and also over the Sahel of about more than 30–50%. Note that some slight decrease is shown in the western coastal areas.

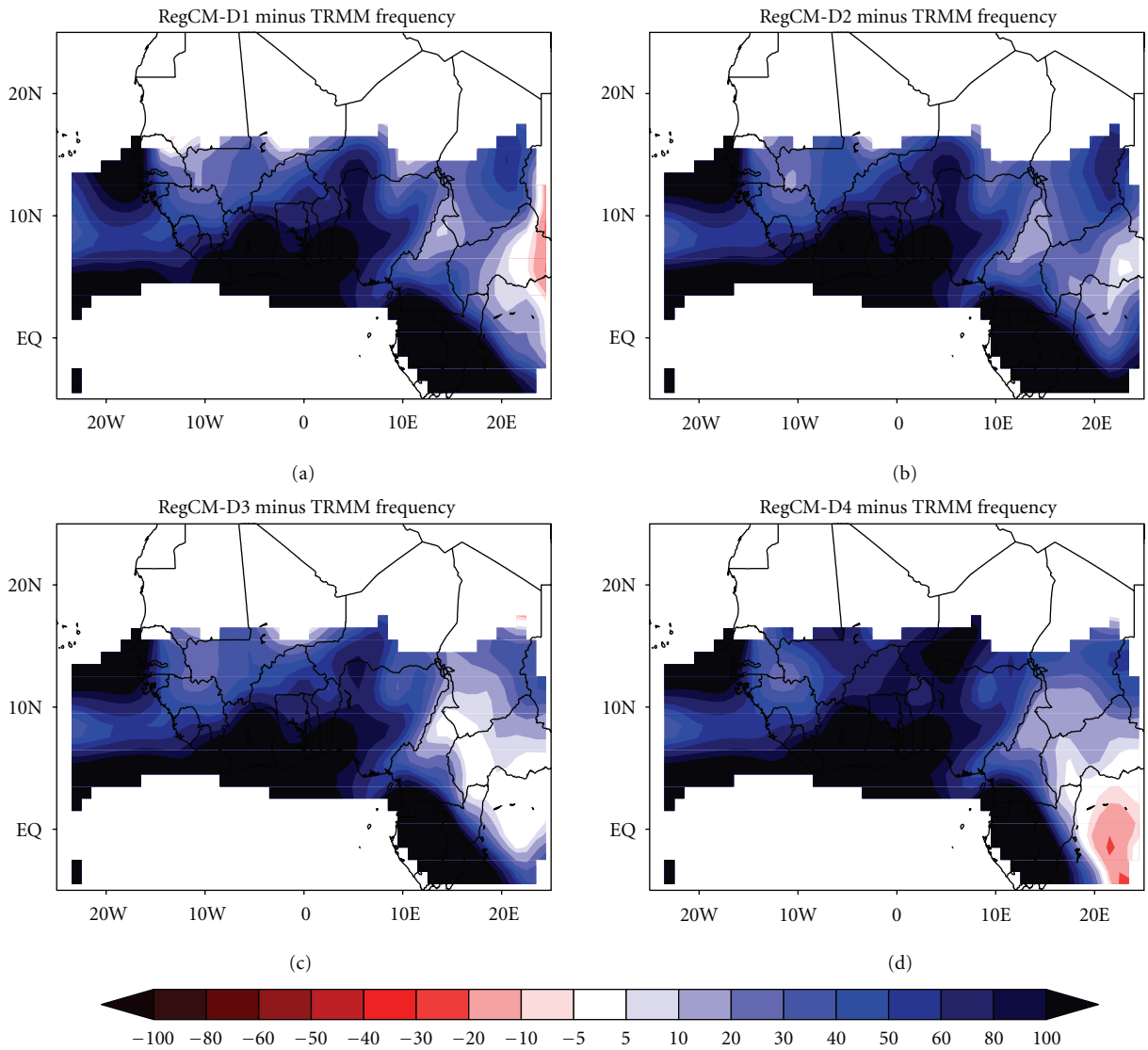

Figure 5: Differences in mean number of rainfall events between (a) RegCM-D1 and TRMM, (b) RegCM-D2 and TRMM, (c) RegCM-D3 and TRMM, and (d) RegCM-D4 and TRMM. Units are expressed as percentage of TRMM values.

Overall, based on the spatial distribution, the mean and the pattern of bias, the RMSD and the PCC analysis, we conclude that the RegCM-D3 is performing better than the other model configurations in simulating the West African summer monsoon rainfall in both magnitude and spatial distribution.

Although changes in the boundary locations trigger internal variability in the regional climate model, that latter does affect only the day-to-day model solution and not the mean climatology [38–40]. This suggests rationales to further analyze how the distribution of daily rainfall, specifically the frequency and intensity of wet days, is affected by the choice of the domain size. The difference in the frequency of wet days between each of the model configurations and the TRMM observation are displayed in Figures 5(a)–5(d). All the RegCM3 simulations consistently and substantially overestimate the number of wet days over the entire analyzed domain, mostly along the Gulf of Guinea, off the Senegal coast, and over central West Africa. In the first three domains (D1, D2, and D3), the difference maps exhibit similar characteristics among the simulations and this indicates that the smaller domain and its westward and eastward extension do not significantly impact the occurrence of wet days. The number of these events is only affected by the northern boundary location (RegCM-D4) which yields to the largest overestimation in the central regions of West Africa. The corresponding differences between the simulations and TRMM observation for the intensity of the rainfall events are presented in Figures 6(a)–6(d). As opposite to the frequency spatial distribution, the regional model generally simulates less intensity of rainfall events with respect to TRMM. Key difference among

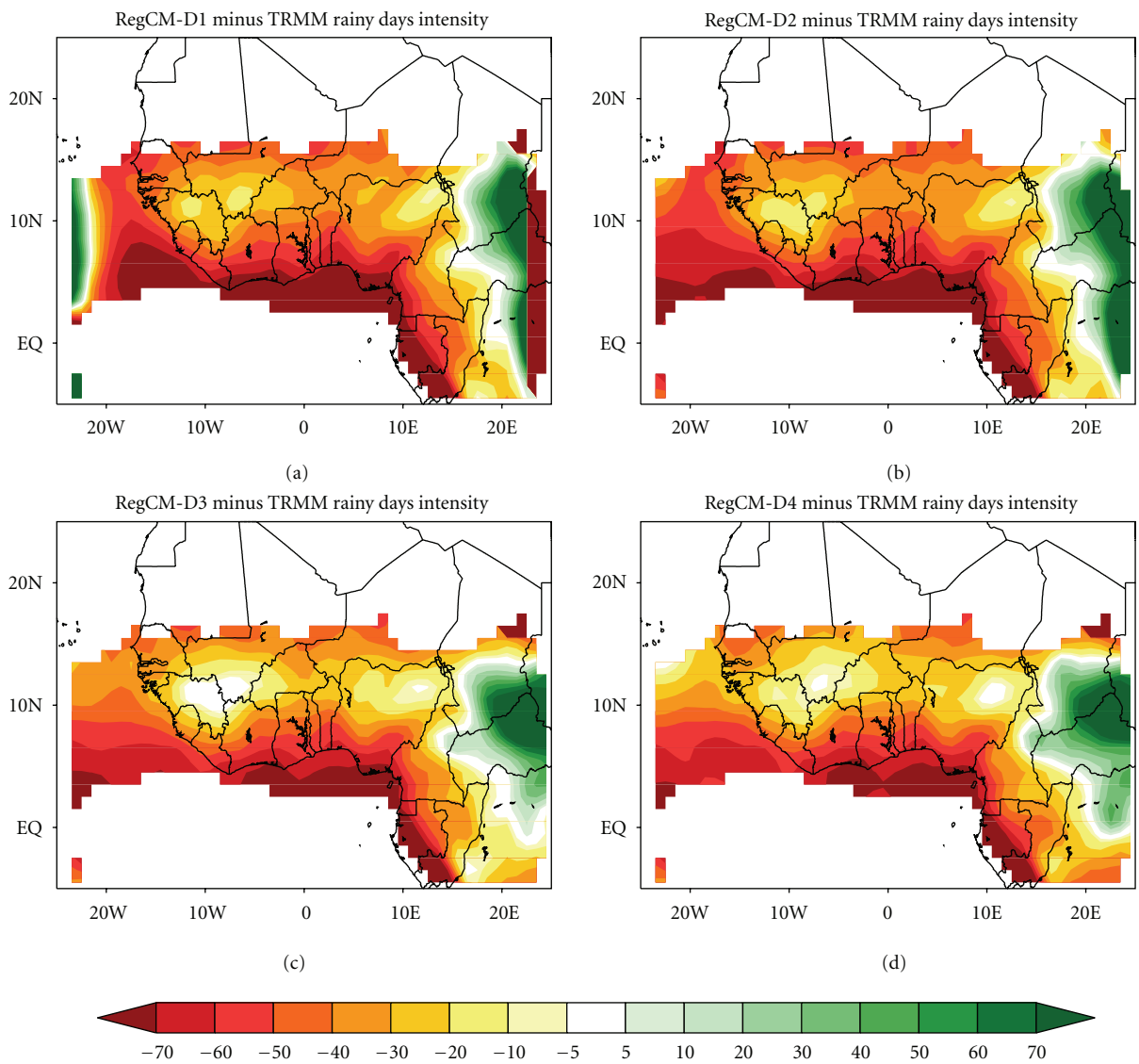

Figure 6: Differences in mean intensity of rainfall events between (a) RegCM-D1 and TRMM, (b) RegCM-D2 and TRMM, (c) RegCM-D3 and TRMM, and (d) RegCM-D4 and TRMM. Units are expressed as percentage of TRMM values.

the different model configurations is that RegCM-D1 and RegCM-D2 show larger underestimation along the ITCZ compared to RegCM-D3 and RegCM-D4.

Overall, an intercomparison of the different simulations indicates that both the default domain (RegCM-D1) and its westward extension (RegCM-D2) produce lesser intensity of rainfall events which explain the larger dry bias and that the northward extension (RegCM-D4) favors more frequent and more intensity of rainfall events (compared to other domains' simulation) consistent to the larger wet bias over the ITCZ. We should note that RegCM-D3 is mostly similar to RegCM-D2 for the frequency and to RegCM-D4 for the intensity. Therefore, RegCM-D3 has an intermediate behavior which supports its best performance in capturing the mean summer monsoon rainfall.

From the above analysis, it is clear that the locations of the western, eastern, and northern boundaries have strong effects on the regional climate model simulation of the monsoon precipitation pattern over West Africa. These effects are, respectively, (1) increases of rainfall over the orographic regions adjacent to the west coast and along the ocean ITCZ, (2) inland extension of the Guinea highlands maxima and strengthening of the ITCZ, and (3) sharpening of the ITCZ and large increase of rainfall in the Sudano-Sahel and the Sahel regions. The best performance is, however, shown in RegCM-D3. As the rainfall pattern over West Africa is associated with the migration of the low-pressure system ITCZ to the north [41–43] and the mesoscale convective systems, which are related to the dynamics of the WAM [9, 10, 16, 44], these differences in the simulations due to the

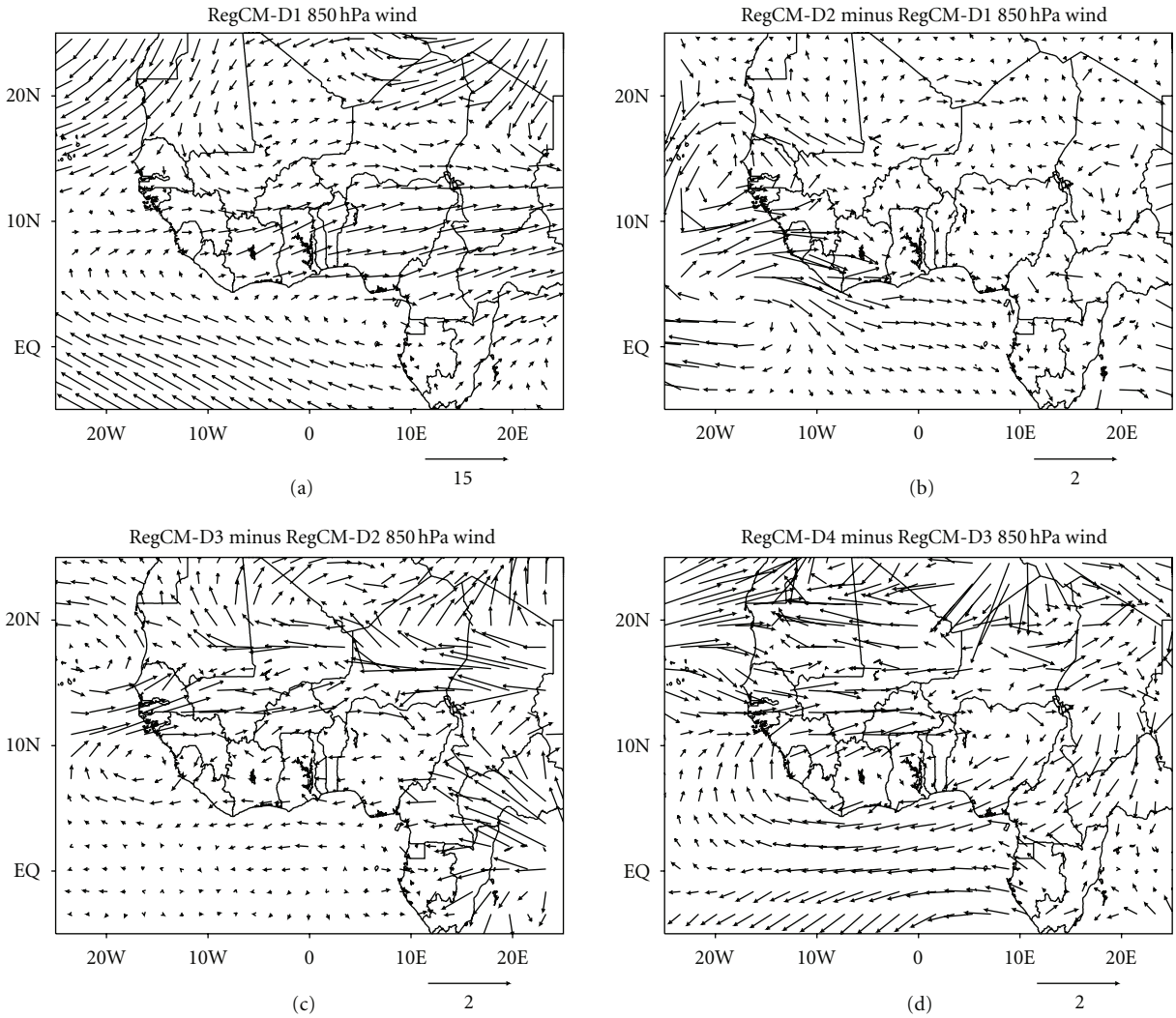

Figure 7: Mean JJA low-level (850 hPa) monsoon flow averaged for the period 2001–2005 for (a) RegCM-D1, (b) the differences between RegCM-D2 and RegCM-D1, (c) the differences between RegCM-D3 and RegCM-D2, and (d) the differences between RegCM-D4 and RegCM-D3. Units are expressed in m/s.

selection of different domain sizes must be originated from the simulated monsoon circulation features.

3.2. The Simulated Monsoon Circulation Features. The low-level (850 hPa) wind field is shown in Figures 7(a)–7(d) for respectively RegCM-D1, RegCM-D2 minus RegCM-D1, RegCM-D3 minus RegCM-D2 and RegCM-D4 minus RegCM-D3. RegCM-D1 shows the monsoon flow, primarily southeasterlies in the Southern Hemisphere becoming southwesterlies and westerlies as they cross the equator. Compared to RegCM-D1, RegCM-D2 simulates stronger monsoon flow off the west coast, in the Guinea highlands, and the Gulf of Guinea. Similarly, differences between RegCM-D3 and RegCM-D2, and on the other hand between RegCM-D4 and RegCM-D3, indicate significant increase of the inflow from the Atlantic Ocean to the land around the 12°N zonal band which lies along the ITCZ. Since the monsoon flow is the major source of humidity for West Africa, the above suggests more humidity transport as the domain extends. To test this hypothesis, we display, respectively, the vertically integrated meridional and zonal moisture fluxes in Figures 8(a)–8(d) and Figures 9(a)–9(d) for each simulation. The simulated meridional moisture flux is mostly southerly over land and off the west coast. It reveals very few differences among the different model configurations mostly located around and north of Guinea highlands. The zonal moisture flux, however, exhibits marked differences mostly in the westerly component. In fact, RegCM-D2 simulates stronger zonal moisture flux (with respect to RegCM-D1) off the west coast, the Gulf of Guinea and along the Sahel band. These fluxes are mainly westerlies and they originate from the availability of larger source of moisture due to the larger portion of the Atlantic Ocean included in the domain. This contributes to enhance the moisture advection inland. Moreover compared to RegCM-D2, the simulation over the Domain D3 shows a widening of the

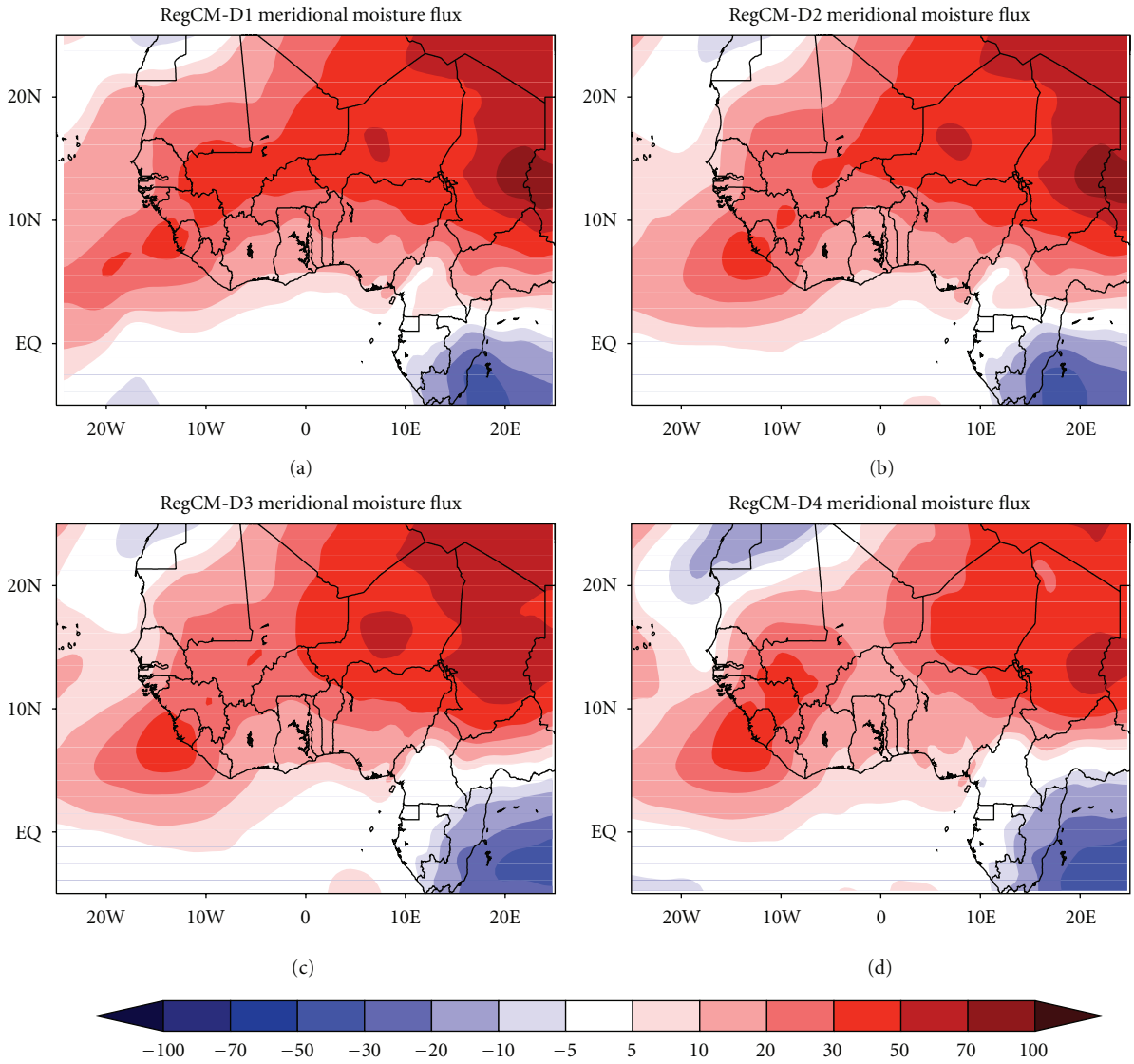

Figure 8: Mean JJA vertically integrated meridional moisture flux averaged for the period 2001–2005 for (a) RegCM-D1, (b) RegCM-D2, (c) RegCM-D3, and (d) RegCM-D4. Positive values denote southerly flow. Units are expressed in kg m^{-1} s^{-1}.

maxima off the west coast and also a northward shift and an intensification of the core in the Sahel as a consequence of the weakening of the easterly flow. In RegCM-D4, both the increase of the moisture sources and disappearance of the easterly flow act to further enhance the westerly component of the zonal moisture inflow. Therefore, the zonal moisture flux tends to amplify as the domain extends. The results appear to be consistent to the larger, intermediate, and lower amount of rainfall captured, respectively, in RegCM-D4, RegCM-D3, and RegCM-D2 and RegCM-D1 simulations.

Having examined the low-level monsoon flow and the corresponding integrated moisture fluxes, we now turn our attention to the AEJ. The 650 hPa mean zonal wind depicting the AEJ from the different simulations shows, from Figures 10(a)–10(d), that RegCM-D1 and RegCM-D2 capture similar jet core with speed reaching 14 m/s, getting a bit narrower in RegCM-D3 and much weaker (for about 4 m/s) in RegCM-D4. This suggests that the western and eastern boundaries do not significantly affect the simulation. The reason is that in these domains, the surface conditions (mostly temperature gradient) are not substantially different. In turn, the location of the northern boundary strongly impacts the AEJ strength and spatial pattern. This is originated from the weakening of the lower-level baroclinicity due to decrease in temperature related to the increase in precipitation between 10°N and 15°N [4, 45]. The weaker AEJ is consistent to the disappearance of the easterly component of the integrated zonal moisture flux which led to an increase of the westerly flow and large overestimation of the monsoon rainfall. The simulations of Tropical Easterly Jet (TEJ) across the domains do not show any substantial differences and therefore they are not shown for brevity.

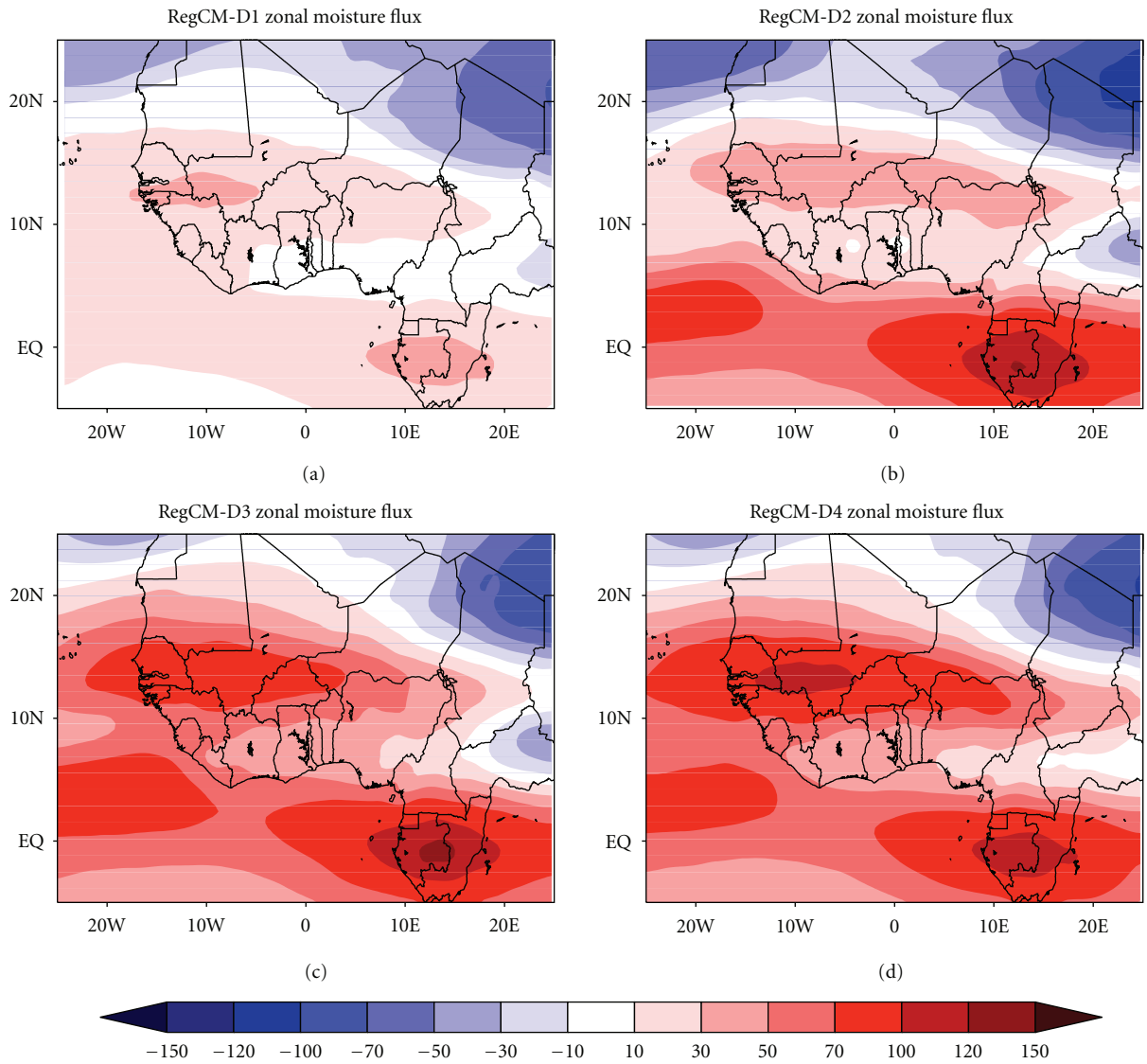

Figure 9: Mean JJA vertically integrated zonal moisture flux averaged for the period 2001–2005 for (a) RegCM-D1, (b) RegCM-D2, (c) RegCM-D3, and (d) RegCM-D4. Positive values denote westerly flow. Units are expressed in kg m^{-1} s^{-1}.

Another important feature for the WAM circulation is the strong ascent in the vertical wind bounded by the jet axes and responsible for the location and strength of the ITCZ [46]. This is characterized in a latitude-height cross-section of the vertical wind averaged between 10°E and 10°W and displayed in Figures 11(a)–11(d) for each simulation respectively. As documented in Sylla et al. [16], all the RegCM3 simulations exhibit an upward motion at around 5°N, 10°N and 15–25°N, respectively, connected to friction occurring at the interface between the ocean and land surface in the lower-level [41], to the midtropospheric ITCZ strong ascent and to the Saharan Thermal Low uplift. This deep midtropospheric ascent core is not substantially different in RegCM-D1, RegCM-D2, and RegCM-D3 simulations in both shape and magnitude whereas in RegCM-D4, it is more extended towards the northern latitudes suggesting a wider area of strong convective activity and upward transport of moisture from the monsoon flow level to the upper levels. Furthermore RegCM-D1, RegCM-D2, and RegCM-D3 show some subsidence just below the midtropospheric ascent, which is missing in the RegCM-D4. The wider area of convective activity and the absence of subsidence just below to counterbalance it have led to the excessive rainfall along the ITCZ and the Sahel regions in the RegCM-D4. These larger rainfall amounts and the wider convective activity's region can be assimilated to a poleward extent of the monsoon. This poleward extent of the monsoon rainfall along with the weaker AEJ both found with a northern boundary placed further north around the Azores High region (RegCM-D4) suggest the existence of some

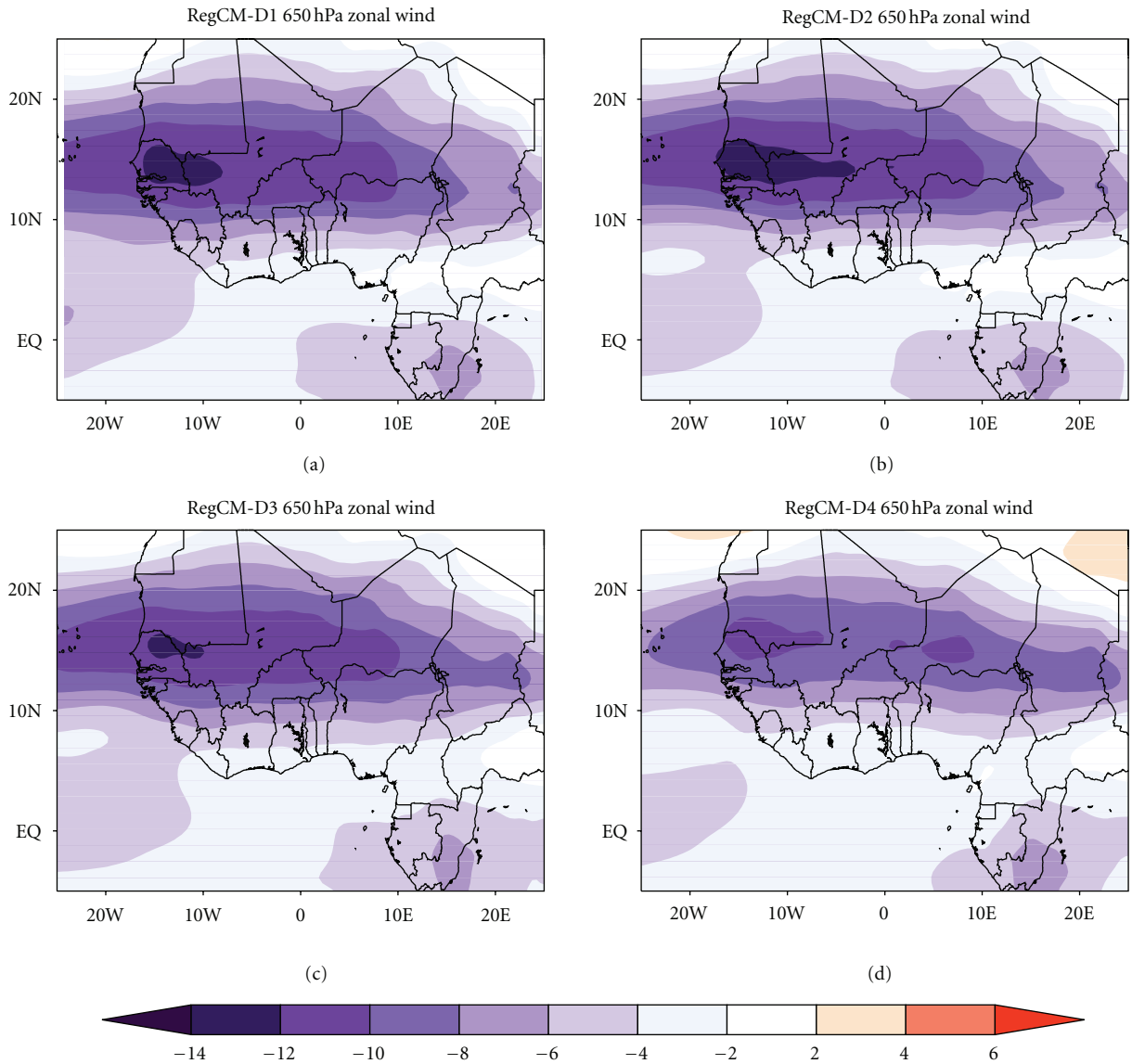

Figure 10: Mean JJA zonal wind at 650 hPa averaged for the period 2001–2005 for (a) RegCM-D1, (b) RegCM-D2, (c) RegCM-D3, and (d) RegCM-D4. Units are expressed in m/s.

interactions between the extratropics and the WAM [47, 48]. However, this is out of the scope of the paper and is not analyzed here.

The last WAM feature examined is the AEWs that connect weather and climate and therefore are key drivers of climate variability in the region. Figures 12(a)–12(d) displays the 3–5 days bandpass filtered JJA 650 hPa meridional wind variance averaged over the whole simulation period depicting the AEW activity [4, 49, 50] for each of the model configuration. Their simulations by RegCM3 and how they are related to the atmospheric deep convection are analyzed in details by Sylla et al. [4]. In the smallest (default: D1) domain, the main AEW activity is confined over West Africa while the extension of the western boundary extends it over the Atlantic Ocean causing its weakening in most of the land. The highest changes occur with the extension of the eastern boundary, when the domain (D3) includes regions where AEWs are generated. Substantial increases of the activity are simulated compared to RegCM-D1 and RegCM-D2. This is related to a general overestimation of the frequency of the waves simulated by RegCM3 over the genesis region and to the tendency of this model to produce more instability along the ITZC [4]. Comparison between the RegCM-D4 and RegCM-D3 simulations suggests that the northern boundary location has only a little impact on the waves' activity. The larger wave activity in RegCM-D3 and RegCM-D4 compared to other domains simulation is an indication of more mesoscale convective systems embedded in the AEWs and responsible for most of the rain over West Africa (e.g., [8, 10]). This is thus consistent to the more rainfall amount simulated along the ITCZ in RegCM-D3 and RegCM-D4 compared to RegCM-D1 and RegCM-D2.

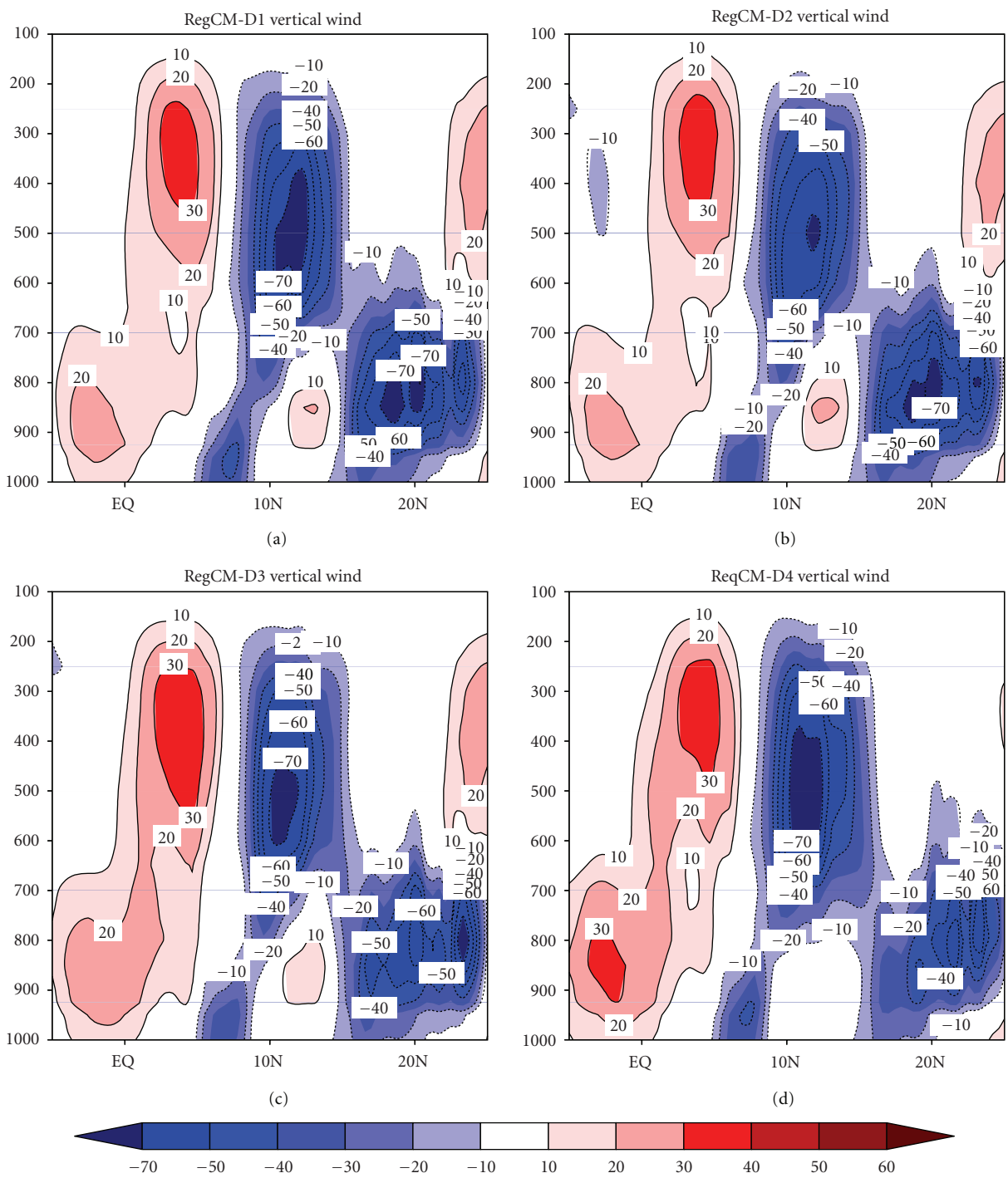

Figure 11: Mean JJA latitude-height cross section of vertical velocity averaged between 10°E–10°W for (a) RegCM-D1, (b) RegCM-D2, (c) RegCM-D3, and (d) RegCM-D4. Units are expressed in mm/s.

From this analysis, it is evident that the location of the regional climate model domain boundaries significantly impacts the simulation of the different components of the WAM system along with the summer monsoon rainfall. The monsoon flow and the vertically integrated moisture fluxes are sensitive to any extension of the domain size, the impact on AEJ occurs mostly with the northern boundary while the AEWs activity, exhibiting the largest effects, is more pronounced by an eastward extension of the domain. Given that the simulation of rainfall is more realistic in D3, this overall intercomparison suggests that domain choice for studying the West African summer monsoon climate should be located along the tropical belt and include a large portion of the Atlantic Ocean and regions over the East African

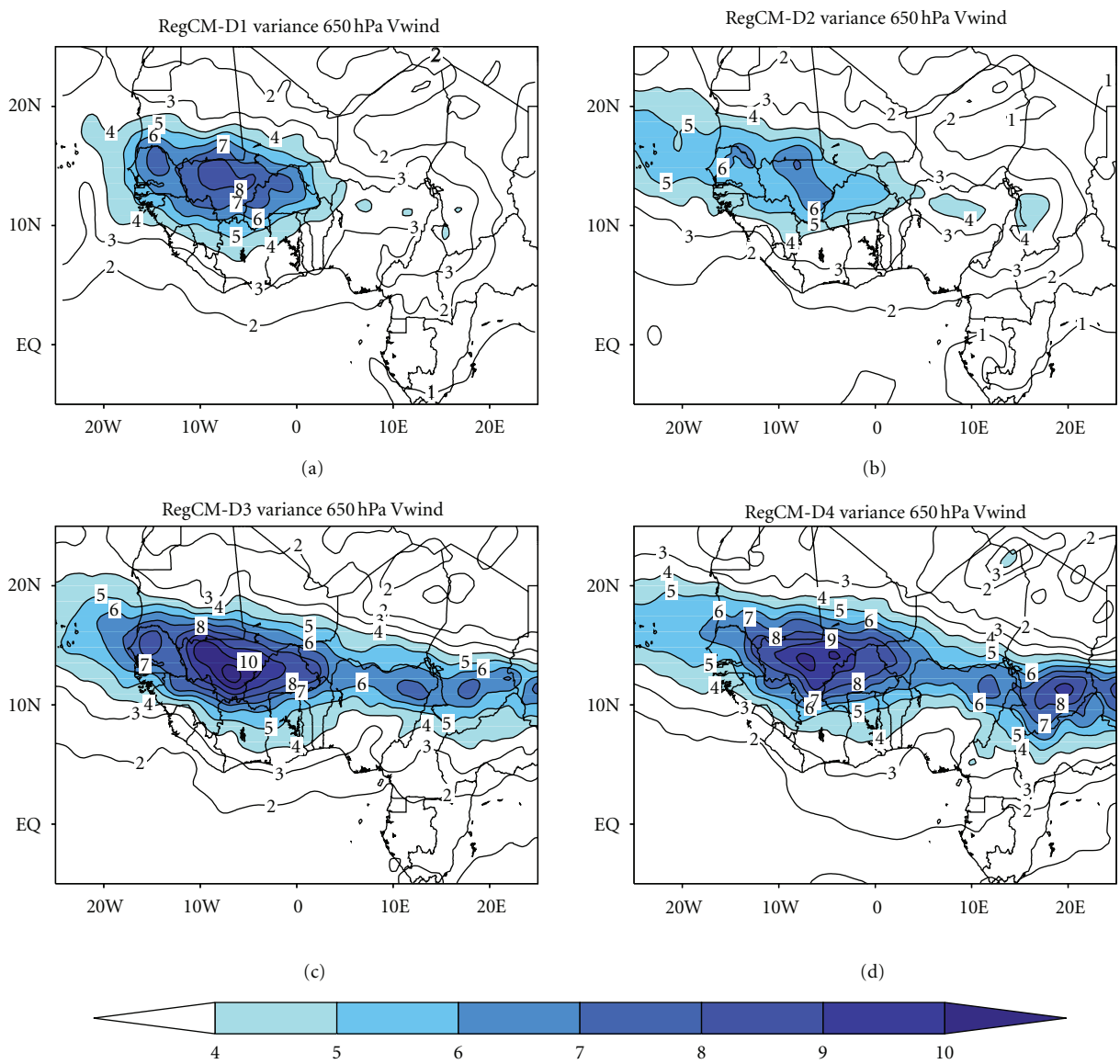

Figure 12: Mean variance of the 3–5 days bandpass filtered of the 650 hPa JJA meridional wind for (a) RegCM-D1, (b) RegCM-D2, (c) RegCM-D3, and (d) RegCM-D4. Units are expressed in m/s.

complex terrains (upstream of Sudanese Highlands) to allow the regional climate model to develop a strong monsoon flow, produce large vertically integrated zonal moisture flux, and generate its own AEW features.

4. Summary and Conclusion

In this paper the impact of different domain sizes in the simulation of the West African summer monsoon rainfall is examined using the ICTP-RegCM3. The four different domains in which the simulations are conducted comprise a default one covering mostly West Africa and some part of the Atlantic Ocean; an extended domain toward the west with much larger oceanic region; an eastward extension of that latter up to the East Africa Highlands and finally a last domain covering the regions around the Azores High and extended up to 45°N.

All of the RegCM3 simulations capture well the observed precipitation pattern, particularly the ITCZ position, the northern and southern gradients of rainfall, and the location of maxima over orographic regions. However substantial discrepancies regarding the amount of mean summer monsoon rainfall and the frequency and intensity of rainfall events occur across the different domains. In fact, when the domain is extended westward, the regional climate model simulates higher rainfall amount off the west coast along with an overestimation of rainfall events and much less rainfall intensity. Increases in mean seasonal rainfall over the Guinea Highlands and along the ITCZ arise with an eastward extension of that latter domain. Finally, when the

northern boundary is displaced further north up to 45°N, the simulation produces a more intense ITCZ in both land and the Atlantic Ocean, thus overestimating rainfall over much part of central West Africa. It should be noted that the more realistic simulation of the rainfall pattern and intensity is achieved with both a westward and eastward extension of the default domain (e.g., in RegCM-D3). This originates from a more moderate overestimation of the frequency of the rainfall events along with lesser underestimation of their intensity. We thus investigate whether the reasons for these discrepancies in the simulations of the summer monsoon rainfall over West Africa can be found in the behavior of the simulated monsoon circulations features.

Firstly, the monsoon flow and the subsequent vertically integrated zonal moisture flux (mostly westerly) become stronger as the domain extends in both the Atlantic Ocean and towards the East African highlands. In fact, the westward (RegCM-D2) and northward (RegCM-D4) extension of the domain has provided larger source of humidity which favors more moisture advection inland while the eastward (RegCM-D3 and RegCM-D4) extension decreases the easterly flux thereby increases the westerlies. This explains the larger westerly moisture inflow in RegCM-D4, the moderate one in RegCM-D3, and the lower amount in both RegCM-D1 and RegCM-D2 over land.

Secondly, the AEJ and the ascent along the ITCZ are not substantially different in RegCM-D1, RegCM-D2, and RegCM-D3 and in fact, are quasiequally strong, indicating that the eastward and westward locations of the boundary forcings are of minor importance for the simulation of these features because they are mainly driven by surface conditions surface conditions which are similar across these simulations. However, when the northern boundary is placed further north to include the region of Azores High, the AEJ becomes weaker and the width of the deep core of ascent wider due to decreased meridional surface air temperature gradient and suggesting some influence of the extratropics on the WAM climate. This weaker AEJ is also consistent with the larger integrated westerly moisture flux found in this simulation.

Finally, the AEWs activity is lower with a westward extension of the default domain but largest when the domain covers parts of the East African Highlands (in both RegCM-D3 and RegCM-D4). This indicates that the eastward extension tends to increase instability in the simulations and that regional climate model produces excessive numbers of AEWs in the genesis region that would favor more rainfall.

It is thus evident that each of the different domain extensions gives rise to different behavior of the circulation features and that the more accurate simulation of rainfall occurring in Domain D3 is mostly connected to a strong monsoon flow, an intermediate integrated zonal moisture flux, and larger magnitude of the AEWs activity. Therefore domain choice for studying the West African summer monsoon climate must be situated mostly in the tropics and should include a large portion of the Atlantic Ocean and regions upstream of Sudanese Highlands to allow the regional climate model to, respectively, develop enough zonal moisture advection and to generate its own AEW features.

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References

[1] C. D. Thorncroft, H. Nguyen, and C. Zhang, "Annual cycle of the West African monsoon: regional circulations and associated water vapour transport," *Quarterly Journal of the Royal Meteorological Society*, vol. 137, no. 654, pp. 129–147, 2011.

[2] K. H. Cook, "Generation of the African easterly jet and its role in determining West African precipitation," *Journal of Climate*, vol. 12, no. 5 I, pp. 1165–1184, 1999.

[3] C. D. Thorncroft and M. Blackburn, "Maintenance of the African easterly jet," *Quarterly Journal of the Royal Meteorological Society*, vol. 125, no. 555, pp. 763–786, 1999.

[4] M. B. Sylla, F. Giorgi, P. M. Ruti, S. Calmanti, and A. Dell'Aquila, "The impact of deep convection on the West African summer monsoon climate: a regional climate model sensitivity study," *Quarterly Journal of the Royal Meteorological Society*, vol. 137, no. 659, pp. 1417–1430, 2011.

[5] J. S. Hsieh and K. H. Cook, "A study of the energetics of African easterly waves using regional climate model," *Journal of the Atmospheric Sciences*, vol. 64, no. 2, pp. 421–440, 2007.

[6] V. Sathiyamoorthy, P. K. Pal, and P. C. Joshi, "Intraseasonal variability of the Tropical Easterly Jet," *Meteorology and Atmospheric Physics*, vol. 96, no. 3-4, pp. 305–316, 2007.

[7] B. J. Abiodun, J. S. Pal, E. A. Afiesimama, W. J. Gutowski, and A. Adedoyin, "Simulation of West African monsoon using RegCM3 Part II: impacts of deforestation and desertification," *Theoretical and Applied Climatology*, vol. 93, no. 3-4, pp. 245–261, 2008.

[8] K. I. Mohr and C. D. Thorncroft, "Intense convective systems in West Africa and their relationship to the African easterly jet," *Quarterly Journal of the Royal Meteorological Society*, vol. 132, no. 614, pp. 163–176, 2006.

[9] G. S. Jenkins, A. T. Gaye, and B. Sylla, "Late 20th century attribution of drying trends in the Sahel from the Regional Climate Model (RegCM3)," *Geophysical Research Letters*, vol. 32, no. 22, Article ID L22705, pp. 1–4, 2005.

[10] A. Gaye, A. Viltard, and P. de Félice, "Squall lines and rainfall over Western Africa during summer 1986 and 87," *Meteorology and Atmospheric Physics*, vol. 90, no. 3-4, pp. 215–224, 2005.

[11] E. K. Vizy and K. H. Cook, "Development and application of a mesoscale climate model for the tropics: influence of sea surface temperature anomalies on the West African monsoon," *Journal of Geophysical Research D*, vol. 107, no. 3, Article ID 4023, 2002.

[12] M. B. Sylla, A. T. Gaye, G. S. Jenkins, J. S. Pal, and F. Giorgi, "Consistency of projected drought over the Sahel with changes in the monsoon circulation and extremes in a regional climate model projections," *Journal of Geophysical Research D*, vol. 115, no. 16, Article ID D16108, 2010.

[13] W. Moufouma-Okia and D. P. Rowell, "Impact of soil moisture initialisation and lateral boundary conditions on regional climate model simulations of the West African Monsoon," *Climate Dynamics*, vol. 35, no. 1, pp. 213–229, 2010.

[14] E. A. Afiesimama, J. S. Pal, B. J. Abiodun, W. J. Gutowski, and A. Adedoyin, "Simulation of West African monsoon using the RegCM3. Part I: model validation and interannual variability," *Theoretical and Applied Climatology*, vol. 86, no. 1–4, pp. 23–37, 2006.

[15] M. B. Sylla, A. T. Gaye, J. S. Pal, G. S. Jenkins, and X. Q. Bi, "High-resolution simulations of West African climate using regional climate model (RegCM3) with different lateral boundary conditions," *Theoretical and Applied Climatology*, vol. 98, no. 3-4, pp. 293–314, 2009.

[16] M. B. Sylla, A. Dell'Aquila, P. M. Ruti, and F. Giorgi, "Simulation of the intraseasonal and the interannual variability of rainfall over West Africa with RegCM3 during the monsoon period," *International Journal of Climatology*, vol. 30, no. 12, pp. 1865–1883, 2010.

[17] R. A. Anthes, Ying-Hwa Kuo, Eirh-Yu Hsie, S. Low-Nam, and T. W. Bettge, "Estimation of skill and uncertainty in regional numerical models," *Quarterly Journal of the Royal Meteorological Society*, vol. 115, no. 488, pp. 763–806, 1989.

[18] F. Giorgi and L. O. Mearns, "Introduction to special section: regional climate modeling revisited," *Journal of Geophysical Research*, vol. 104, pp. 6335–6352, 1999.

[19] S. A. Rauscher, A. Seth, J. H. Qian, and S. J. Camargo, "Domain choice in an experimental nested modeling prediction system for South America," *Theoretical and Applied Climatology*, vol. 86, no. 1–4, pp. 229–246, 2006.

[20] A. Seth and F. Giorgi, "The effects of domain choice on summer precipitation simulation and sensitivity in a regional climate model," *Journal of Climate*, vol. 11, no. 10, pp. 2698–2712, 1998.

[21] R. G. Jones, J. M. Murphy, and M. Noguer, "Simulation of climate change over Europe using a nested regional-climate model. I: assessment of control climate, including sensitivity to location of lateral boundaries," *Quarterly Journal of the Royal Meteorological Society*, vol. 121, no. 526 B, pp. 1413–1449, 1995.

[22] F. Giorgi, M. R. Marinucci, and G. T. Bates, "Development of a second-generation regional climate model (RegCM2). Part I: boundary-layer and radiative transfer processes," *Monthly Weather Review*, vol. 121, no. 10, pp. 2794–2813, 1993.

[23] F. Giorgi, M. R. Marinucci, G. T. Bates, and G. De Canio, "Development of a second-generation regional climate model (RegCM2). Part II: convective processes and assimilation of lateral boundary conditions," *Monthly Weather Review*, vol. 121, no. 10, pp. 2814–2832, 1993.

[24] J. S. Pal, F. Giorgi, X. Bi et al., "The ICTP RegCM3 and RegCNET: regional climate modeling for the developing world," *Bulletin of American Meteorological Society*, vol. 88, pp. 1395–1409, 2007.

[25] G. A. Grell, J. Dudhia, and D. R. Stauffer, "Description of the fifth generation Penn State/NCAR mesoscale model (MM5)," Technical Note NCAR/TN-398+STR, 1994.

[26] J. T. Kiehl, J. J. Hack, G. B. Bonan et al., "Description of the NCAR Community Climate Model (CCM3)," Tech. Rep. TN-420+STR, NCAR, Boulder, Colo, USA, 1996.

[27] A. A. M. Holtslag, E. I. F. De Bruijn, and H. L. Pan, "A high resolution air mass transformation model for short-range weather forecasting," *Monthly Weather Review*, vol. 118, no. 8, pp. 1561–1575, 1990.

[28] R. E. Dickinson, A. Henderson-Sellers, and P. J. Kennedy, "Biosphere–atmosphere transfer scheme (BATS) version 1E as coupled to the NCAR Community Climate Model," Technical Note NCAR/TN-387+STR, 1993.

[29] X. Zeng, M. Zhao, and R. E. Dickinson, "Intercomparison of bulk aerodynamic algorithms for the computation of sea surface fluxes using TOGA COARE and TAO data," *Journal of Climate*, vol. 11, no. 10, pp. 2628–2644, 1998.

[30] J. M. Fritsch and C. F. Chappell, "Numerical prediction of convectively driven mesoscale pressure systems. Part I: convective parameterization," *Journal of the Atmospheric Sciences*, vol. 37, no. 8, pp. 1722–1733, 1980.

[31] J. S. Pal, E. E. Small, and E. A. B. Eltahir, "Simulation of regional-scale water and energy budgets: representation of subgrid cloud and precipitation processes within RegCM," *Journal of Geophysical Research D*, vol. 105, no. 24, pp. 29579–29594, 2000.

[32] S. Uppala, D. Dee, S. Kobayashi, P. Berrisford, and A. Simmons, "Towards a climate data assimilation system: status update of ERA-Interim," *ECMWF Newsletter*, vol. 115, pp. 12–18, 2008.

[33] R. W. Reynolds, N. A. Rayner, T. M. Smith, D. C. Stokes, and W. Wang, "An improved in situ and satellite SST analysis for climate," *Journal of Climate*, vol. 15, no. 13, pp. 1609–1625, 2002.

[34] C. Kummerow, Y. Hong, W. S. Olson et al., "The evolution of the Goddard profiling algorithm (GPROF) for rainfall estimation from passive microwave sensors," *Journal of Applied Meteorology*, vol. 40, no. 11, pp. 1801–1820, 2001.

[35] G. J. Huffman, R. F. Adler, D. T. Bolvin et al., "The TRMM multisatellite precipitation analysis (TMPA): quasi-global, multiyear, combined-sensor precipitation estimates at fine scales," *Journal of Hydrometeorology*, vol. 8, no. 1, pp. 38–55, 2007.

[36] R. F. Adler, G. J. Huffman, A. Chang et al., "The version-2 global precipitation climatology project (GPCP) monthly precipitation analysis (1979-present)," *Journal of Hydrometeorology*, vol. 4, no. 6, pp. 1147–1167, 2003.

[37] M. B. Sylla, F. Giorgi, E. Coppola, and L. Mariotti, "Uncertainties in daily rainfall over Africa: assessment of observation products and evaluation of a regional climate model simulation," submitted to *International Journal of Climatology*.

[38] F. Giorgi and X. Bi, "A study of internal variability of a regional climate model," *Journal of Geophysical Research D*, vol. 105, no. 24, pp. 29503–29521, 2000.

[39] M. M. Kgatuke, W. A. Landman, A. Beraki, and M. P. Mbedzi, "The internal variability of the RegCM3 over South Africa," *International Journal of Climatology*, vol. 28, no. 4, pp. 505–520, 2008.

[40] E. Vanvyve, N. Hall, C. Messager, S. Leroux, and J. P. van Ypersele, "Internal variability in a regional climate model over West Africa," *Climate Dynamics*, vol. 30, no. 2-3, pp. 191–202, 2008.

[41] S. E. Nicholson, B. Some, and B. Kone, "An analysis of recent rainfall conditions in West Africa, including the rainy seasons of the 1997 El Nino and the 1998 La Nina years," *Journal of Climate*, vol. 13, no. 14, pp. 2628–2640, 2000.

[42] V. Mathon and H. Laurent, "Life cycle of Sahelian mesoscale convective cloud systems," *Quarterly Journal of the Royal Meteorological Society*, vol. 127, no. 572, pp. 377–406, 2001.

[43] M. B. Sylla, E. Coppola, L. Mariotti et al., "Multiyear simulation of the African climate using a regional climate model (RegCM3) with the high resolution ERA-interim reanalysis," *Climate Dynamics*, vol. 35, no. 1, pp. 231–247, 2010.

[44] B. Sultan, S. Janicot, and A. Diedhiou, "The West African monsoon dynamics. Part I: documentation of intraseasonal variability," *Journal of Climate*, vol. 16, no. 21, pp. 3389–3406, 2003.

[45] M. B. Sylla, F. Giorgi, and F. Stordal, "The large-scale origins of rainfall and temperature bias in high resolution simulations over southern Africa," *Climate Research*. In press.
[46] S. E. Nicholson, "The intensity, location and structure of the tropical rainbelt over west Africa as factors in interannual variability," *International Journal of Climatology*, vol. 28, no. 13, pp. 1775–1785, 2008.
[47] M. J. Rodwell and B. J. Hoskins, "Subtropical anticyclones and summer monsoons," *Journal of Climate*, vol. 14, no. 15, pp. 3192–3211, 2001.
[48] C. Chou and J. D. Neelin, "Mechanisms limiting the northward extent of the northern summer monsoons over North America, Asia, and Africa," *Journal of Climate*, vol. 16, no. 3, pp. 406–425, 2003.
[49] A. Diedhiou, S. Janicot, A. Viltard, and P. De Felice, "Evidence of two regimes of easterly waves over West Africa and the tropical Atlantic," *Geophysical Research Letters*, vol. 25, no. 15, pp. 2805–2808, 1998.
[50] A. Mekonnen, C. D. Thorncroft, and A. R. Aiyyer, "Analysis of convection and its association with African easterly waves," *Journal of Climate*, vol. 19, no. 20, pp. 5405–5421, 2006.