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Investigating the diurnal cycle of precipitation over Central Africa

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Abstract

The present study investigated the reliability of downscaling tool RegCM4.4 to simulate 2002–2006 June–September diurnal cycle precipitation characteristics. Besides their diurnal cycles, the spatial and temporal patterns in precipitation intensity, amount and frequency over Central Africa (CA) are investigated. Diurnal variance, phase and amplitude based on 3-hourly model simulations are obtained by diurnal harmonics from each 24-h period. Two statistical measures are used to evaluate model performance: the root mean square error and the index of agreement. The result shows that the RegCM outputs are well simulated compared with reference data in revealing the temporal and spatial patterns of precipitation amount and frequency over the continental area with some systematic wet biases over Cameroon highlands area. Diurnal variability of precipitation frequency and amount are properly well reproduced by the model with an afternoon peak around 1800 LST over entire domain except Atlantic Ocean sub-region. The model does not properly describe the observed diurnal variation of precipitation intensity over the study area. One of the prominent results is that the pattern of precipitation frequency is quite similar to that of precipitation amount. This strong relationship between these two precipitation characteristics over the entire region of interest suggests that the diurnal precipitation variability is generally determined by how often it rains.

KEYWORDS

Central Africa, diurnal cycle, Fourier analysis, precipitation, RegCM4.4

1 | INTRODUCTION

Regional climate models (RCMs) are dynamical downscaling tools, which give information from global climate models. Their better representation of fine-scale physical processes (IPCC, 2007) makes them widely used for regional climate study in various part of the world. Central Africa (CA) is one of such regions having a complex climate with many factors influencing its variability (S. E. Nicholson & Dezfuli, 2013). Furthermore, rainfall modelling is one of the most arduous tasks in an RCM. So far, precipitation analyses over this region have usually targeted on time-averaged mean rates or accumulated amounts (e.g., Komkoua Mbienda, Tchawoua, et al., 2017a, 2017b; Komkoua Mbienda, Guenang, Tanessong, Ashu Ngono, et al., 2021; Sonkoue et al., 2018; Vondou & Haensler, 2017), while other precipitation characteristics such as diurnal cycle have recently been studied. Vondou et al. (2017) evaluate the performance of the Regional Climate Model (RegCM4) in capturing the diurnal cycle of precipitation over CA. They found that the propagating diurnal cycle of precipitation is well captured by the model. Komkoua Mbienda, Guenang, Tanessong, and Tchakoutio Sandjon (2019) investigate the potential effects of atmospheric aerosols on the diurnal cycle of precipitation over CA by RegCM4.4. In their study, they found that the amplitude of precipitation is systematically affected by either a reduction or an increase and that the scattering and absorption of solar radiation by aerosols can explain the reduction in diurnal amplitude of precipitation. None of these previous studies has focused on the characteristics of rainfall diurnal cycle, which encompasses precipitation intensity, frequency and amount. Nevertheless, such studies have been carried out outside CA. In America, Qian et al. (2006) have found that the rainfall diurnal cycle significantly contributes to modulate run-off, soil moisture, sensible heat flux and evaporation over land. In addition, the study of diurnal cycle can provide useful information for validating some parameterizations like cumulus convective schemes in climate model (Betts & Jacob, 2002; Dai, 2006; Dai & Trenberth, 2004; Demott et al., 2007; Lee et al., 2007; Liang et al., 2004).

Current RCMs can succeed to simulate not only the observed diurnal variation of precipitation, but also their regional characteristics. The simulated characteristics (amount, intensity and frequency) of 24-h cycle of precipitation from previous studies by controlled models generally agree with the observed 24-h cycle. Koo and Hong (2010) analysed the variations in this cycle in terms of simulated rainfall over eastern part of Asia in two RCMs. They found that simulations are comparable to observations. Dai et al. (1999) investigated the characteristics of 24-h variations of summer precipitation over some region in America from observed and simulated dataset. These two studies pointed out a close relation between the observed and simulated dataset, although an important challenge for climate models remains: (i) they tend to overestimate precipitation frequency and underestimate precipitation intensity due to too weak criteria used to initiate convection and too much cloudiness, hereby generating convective activity to occur too early (Dai et al., 1999), and (ii) the simulated frequency and amount of precipitation peaked too early (Jeon et al., 2011; Koo & Hong, 2010).

In their studies, Dahlström (2006) and Wern and German (2009) have investigated the intensity and duration of precipitation events at regional scale and highlighted its possible connection to the 24-h cycle of rainfall. Over United Kingdom, Xiao et al. (2018) investigated the 24-h cycle of the rainfall frequency, amount and intensity by using the hourly precipitation dataset for 90 stations for 7 years. According to the authors, the average precipitation amount over the whole region of interest depicted two comparable peaks in the early morning and late afternoon, which were contributed by the frequency and intensity, respectively. In addition, Zhou et al. (2008) using rain gauge records over China found that the precipitation frequency is slightly larger than the precipitation intensity. However, the above-mentioned studies are conducted in regions where there is no paucity of gauge data. Therefore, in other regions such as CA where there is a lack of observational data, the characterization of diurnal cycle can only be done by using modelling tools.

Since modelling studies can improve forecasting skills (e.g., Lee et al., 2007), provide reliability of some physical parameterizations (e.g., Wang et al., 2007) and enhance our comprehension of some important apparatus, which drives the 24-h cycle of precipitation (e.g., Kataoka & Satomura, 2005), the main objective of the present study is to investigate the ability of the Abdus Salam International Centre for Theoretical Physics Regional Climate Model version 4.4 (RegCM4.4) over CA focusing on the characteristics of 24-h variation of rainfall. In fact, compared to annual cycle, which is accurately simulated by most models at regional scales (Fernandez-Diaz et al., 2013), some RCMs encountered difficulties in simulating the 24-h cycle of precipitation, which are generally imputable to the parameterizations of convection (Nikulin et al., 2012). Moreover, RCMs are useful tools to investigate mechanisms that explain rainfall diurnal cycles (Hernandez-diaz et al., 2012; Wu et al., 2020) and their capability to represent precipitation amount, intensity and frequency over CA has not been verified. Because precipitation over several parts of CA takes place generally from June to September (Komkoua Mbienda, Tchawoua, et al., 2017a), we will turn our attention to the June–July–August–September period. The present study seeks to answer the following questions: (1) Are RegCM4.4 simulations useful for Investigating diurnal cycle of precipitation in terms of precipitation intensity, frequency and amount over CA? (2) What are the spatial and temporal structures of these characteristics over CA? Diurnal variations of simulated precipitation will be compared with satellite products (used here as reference rainfall dataset).

The rest of the paper is organized as follows: methodology including the model and experimental designs as well as data and general process is described in Section 2; the results and discussions are described in Section 3;

and summary and conclusion of the study are given in Section 4.

2 | METHODOLOGY

Apart from the description of dataset used in the present study, we describe in this section the RCM used and experimental designs as well as model domain.

2.1 | Model and general process

As mentioned earlier, RCM used for this study is RegCM4.4 (Giorgi, Coppola, et al., 2012; Giorgi, Elguindi, et al., 2015). This dynamical downscaling tool is a mended version of RgCM version 3 (Pal et al., 2007). This version is an evolution of its previous version RegCM2 (Giorgi, Marinucci, & Bates, 1993a; Giorgi, Marinucci, Bates, & De Canio, 1993b). These RegCM versions have the same model dynamics. In fact, RegCM4 is a hydrostatic sigma vertical coordinate model, whose horizontal resolution can vary from 10 to 100 km and simulation period can vary from days to several decades. The model uses a prescribed sea surface temperature (SST) as initial conditions as described in the subsection below. Various studies conducted worldwide demonstrate the ability of RegCM to study regional climate (e.g., Giorgi and Shields (1999) over America, Steiner et al. (2005) over Asia, Komkoua Mbienda, Tchawoua, et al. (2017a) over Africa, and Torma et al. (2010) over Europe). A recent study conducted by Komkoua Mbienda, Tchawoua, et al. (2017a) shows that this model can be used to downscale precipitation over CA (Figure 1). RegCM4.4 set-up is summarized in Table 1. The aforementioned studies provide not only full model description, but also pertinent references.

Figure 1 shows the model terrain, the study area as well as four homogeneous sub-regions: Sahel (Sa) (9° N–14° N, 7° E–21° E), Cameroon highlands (CH) (5° N–8° N, 8.2° E–16° E), Congo basin (CB) (5° S–4° N, 15° E–26° E) and Atlantic Ocean (AO) (7° S–4° N, 1° E–9° E). A 6-year simulation, from January 2001 to December 2006, was conducted. The first year (2001) is not used in the analysis, which considered as spin-up. In fact, as found by Komkoua Mbienda, Tchawoua, et al. (2017a), 2002 registered an excess of +8% of the precipitation mean, 2003 is a normal year, 2005 is the driest year since 1998 and 2004 and 2006 did not register extreme precipitation anomalies. Therefore, they claim that 2002–2006 represent a wide range of precipitation variability over CA. To obtain the 24-h amplitude variance and phase based on 3-hourly model outputs, precipitation from each 24-h period is fitted to diurnal harmonics (Angelis & McGregor, 2004; Sen Roy & Balling, 2007; Wilks, 2006). Fourier analysis is used to determine the variance, phase and amplitude of diurnal cycle.

At each grid point and for each hour, June–July–August–September mean precipitation (that is the average of June–July–August–September precipitation computed at each grid point) frequency (that is percentage of all hours during June–July–August–September getting measurable precipitation, greater than 0.1 mm/h for the gridded precipitation from model and reference data), amount (the accumulated precipitation amount during June–July–August–September) and intensity (precipitation rates averaged over the precipitating hours) were calculated for each year. It is worth to notice that

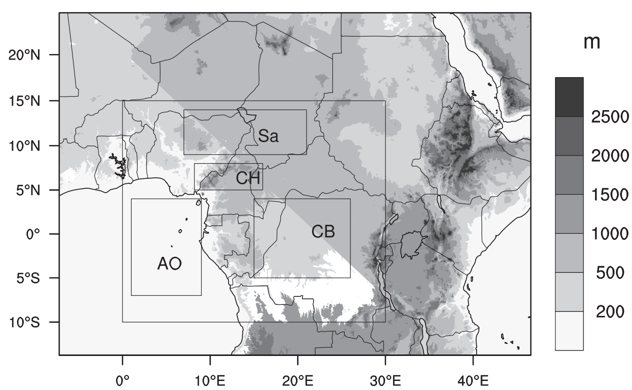

FIGURE 1 Surface elevation (m) of the simulation domain encompassing the study area indicated by the big box. The four small boxes indicate the four sub-regions, Sahel (Sa), Atlantic Ocean (AO), Congo basin (CB), Cameroon highlands (CH), for which the emphasis of the model results has been done

TABLE 1 Summary of model's parameterizations and set-up

Model aspects	Parameterizations/values
Dynamics	Hydrostatic, σ-vertical coordinate (Giorgi, Marinucci, & Bates, 1993a)
Radiative transfer	Modified CCM3 (Kiehl et al., 1996)
PBL	Modified Holtslag (Holtslag et al., 1990)
Cumulus convection	Grell (Grell, 1993) with Arakawa and Schulbert closure (Arakawa & Schubert, 1974)
Land surface	BATS (Dickinson et al., 1993)
Ocean fluxes	BATS (Dickinson et al., 1993)
Central longitude	7.5° E
Central latitude	6.5° N
Horizontal resolution	40 × 40 km
Top level	5 hPa

the June–July–August–September rainfall amount is the product of the number of days, intensity and frequency. The precipitation amount P_a and precipitation frequency P_f are computed as follows:

$$P_a(h) = \frac{1}{n}\sum_{d=1}^{n} P(h,d), \tag{1}$$

$$P_f(h) = \frac{1}{n}\sum_{d=1}^{n} O(h,d), \tag{2}$$

with

$$O(h,d) = \begin{cases} 1 \text{ if } \mathrm{P(h,d)} \geq 0.1\,\mathrm{mm/h} \\ 0 \text{ if } \mathrm{P(h,d)} < 0.1\,\mathrm{mm/h}, \end{cases} \tag{3}$$

where $P(h,d)$ is the rainfall at a given hour (h) and day (d), whereas n is the total number of days.

Two statistical measures are used to evaluate the model's performance: the root mean square error (RMSE) and index of agreement (IA) (Willmott et al., 2012). IA can be written as follows:

$$\mathrm{IA} = \begin{cases} 1 - \dfrac{\sum_{i=1}^{n} |S_i - O_i|}{2\sum_{i=1}^{n} |O_i - \mu|}, & \text{when } \sum_{i=1}^{n} |S_i - O_i| \leq 2\sum_{i=1}^{n} |O_i - \mu| \\ \dfrac{2\sum_{i=1}^{n} |O_i - \mu|}{\sum_{i=1}^{n} |S_i - O_i} - 1, & \text{when } \sum_{i=1}^{n} |S_i - O_i| > 2\sum_{i=1}^{n} |O_i - \mu|, \end{cases} \tag{4}$$

where $S_i; i = 1, 2, ..., n$ are simulation data and $O_i; i = 1, 2, ..., n$ are their pair-wise-matched observations. μ is the mean of the observed variables (O_i).

2.2 | Data

Two categories of dataset are used in this study.

Initial boundary conditions are taken from the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis called ERA-Interim (Dee, 2011). These 6-hourly data have a horizontal resolution of 1.5° × 1.5°. ERA-Interim combines ground-based meteorological networks and observations from satellites. GTOPO topography dataset and Global Land Cover Characteristics (GLCC) at 2 min resolution (New et al., 2000) are also used for terrain and land use, respectively.

Some of the difficulties that arise when studying recent climate over Africa are the irregular and sparse station network (Dezfuli, 2011). Indeed, most stations were available throughout the period 1948–1988. Therefore, the use of reference datasets instead of observed data is crucial. The present study used the 3-hourly 3B42 Tropical Rainfall Measuring Mission (TRMM) and Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) data as reference datasets. Several studies have already shown the ability of these datasets to reproduce observed climate over the study region (e.g., S. Nicholson et al., 2019; Tanessong et al., 2019). This last study has shown a good correlation coefficient over various parts of their study area between TRMM and observed datasets, which reaches 0.8 on average with a significant level of 95% of confidence using *t*-test, whereas the first one obtained correlations in the order of 0.65 for both TRMM and PERSIANN products.

Simulated rainfall is compared with TRMM-3B42 dataset, which has 0.25° × 0.25° latitude by longitude as horizontal resolution. The study of Munzimi et al. (2015) shows that the 3-hourly estimation of rainfall may be well depicted by TRMM over region including Congo basin without bias. Besides the TRMM 3B42, PERSIANN satellite products are also used. Nguyen et al. (2019) revealed that the PERSIANN dataset is adequate for near real-time precipitation analyses, high-resolution, especially in remote regions over the world where extensive gauges or radar network for precipitation dataset is not available. Moreover, TRMM and PERSIANN satellite products have been previously used to evaluate RCMs (e.g., Adler et al., 2000; Bowman, 2005; Dai, 2006). Therefore, they can be used as training data for climate models. PERSIANN and TRMM 3B42 data have the same horizontal resolution.

According to the previous study conducted in Africa (e.g., Camberlin et al., 2019; Moudi et al., 2021) and above studies (e.g., Almazroui, 2011; Zhou et al., 2008), TRMM product shows good performance and is more reliable than PERSIANN product. Therefore, this last product is used mainly to verify the general pattern obtained with TRMM. To perform statistical parameters (RMSE and IA), observational data are interpolated to RegCM4.4 grid using conservative remapping.

3 | RESULTS AND DISCUSSION

Spatial features of rainfall intensity, amount and frequency as well as their diurnal cycles are investigated. Besides analysing spatial features, the diurnal cycles of these precipitation characteristics are also computed and analysed.

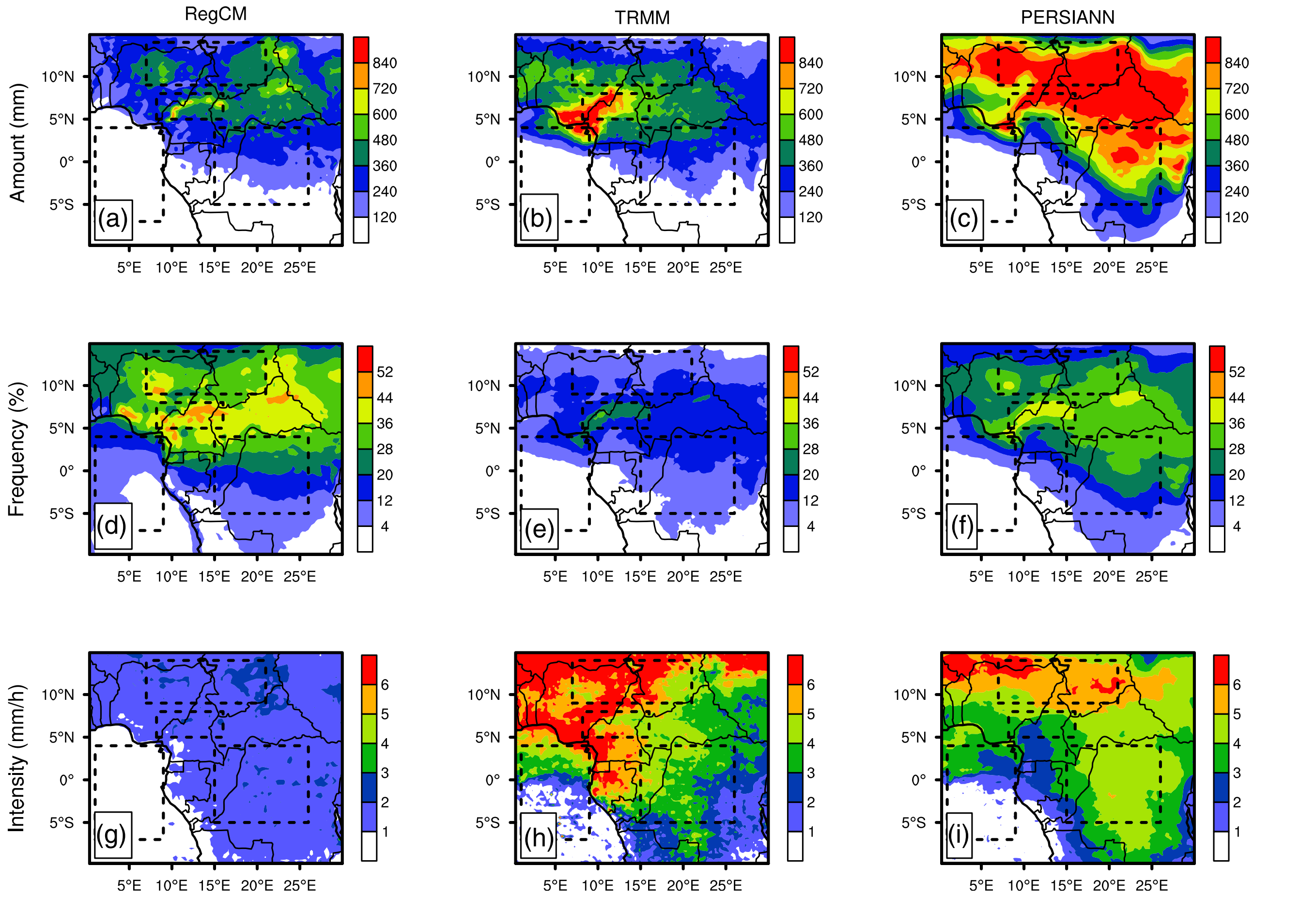

FIGURE 2 Spatial distributions of June–July–August–September mean (a)–(c) precipitation amount (mm), (d)–(f) frequency (%), and (g)–(i) intensity (mm/h) from (a), (d), (g) RegCM; (b), (e), (h) TRMM; and (c), (f), (i) PERSIANN

TABLE 2 Index of agreement (IA) between the simulated and satellite-derived precipitation amount, frequency and intensity for the entire domain and for the four sub-regions identified in Figure 1

	Amount		Frequency		Intensity	
Region	TRMM	PERSIANN	TRMM	PERSIANN	TRMM	PERSIANN
CA	0.66	0.61	−0.03	0.63	0.71	0.73
Sa	0.44	0.27	−0.62	0.25	−0.32	−0.30
CH	0.42	0.40	−0.36	0.29	−0.37	−0.17
CB	0.66	0.33	−0.08	0.58	0.03	−0.34
AO	0.69	0.68	0.55	0.52	0.74	0.65

Abbreviations: AO, Atlantic Ocean; CA, Central Africa; CB, Congo basin; CH, Cameroon highlands; PERSIANN, Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks; Sa, Sahel; TRMM, Tropical Rainfall Measuring Mission.

TABLE 3 RMSE (units: mm/h for amount, % for frequency and mm/h for intensity) between the simulated and satellite-derived precipitation amount, frequency and intensity for the entire domain and for the four sub-regions identified in Figure 1

	Amount		Frequency		Intensity	
Region	TRMM	PERSIANN	TRMM	PERSIANN	TRMM	PERSIANN
CA	0.26	0.60	15	7	297.16	219.47
Sa	0.16	0.95	21	7	4.34	3.80
CH	0.59	0.72	21	9	3.99	2.07
CB	0.08	0.67	10	4	2.00	2.48
AO	0.31	0.23	4	4	562.34	448.13

Abbreviations: AO, Atlantic Ocean; CA, Central Africa; CB, Congo basin; CH, Cameroon highlands; PERSIANN, Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks; Sa, Sahel; TRMM, Tropical Rainfall Measuring Mission.

3.1 | Spatial features of precipitation amount, frequency and intensity

Figure 2 compares the spatial distributions of multi-year (2002–2006) June–July–August–September precipitation intensity, amount and frequency from RegCM as well as TRMM-3B42 and PERSIANN products. Precipitation amount, precipitation intensity and precipitation frequency are plotted with values in mm, mm/h and percentage, respectively. Corresponding IA and RMSE among model and reference data are reported in Tables 2 and 3. On the whole, the distribution of simulated CA precipitation frequency is outstandingly well reproduced, whatever the sub-regions considered, albeit some important overestimation in latitudes above 0 compared with the TRMM products. Over land, these products are generally lower than PERSIANN in terms of precipitation amount, which could partially result from different ways of conducting the analysis techniques. In PERSIANN, a neural network is used to perform rainfall from infrared images of global geosynchronous satellites, whereas in TRMM-3B42, rainfall estimates are used to adjust

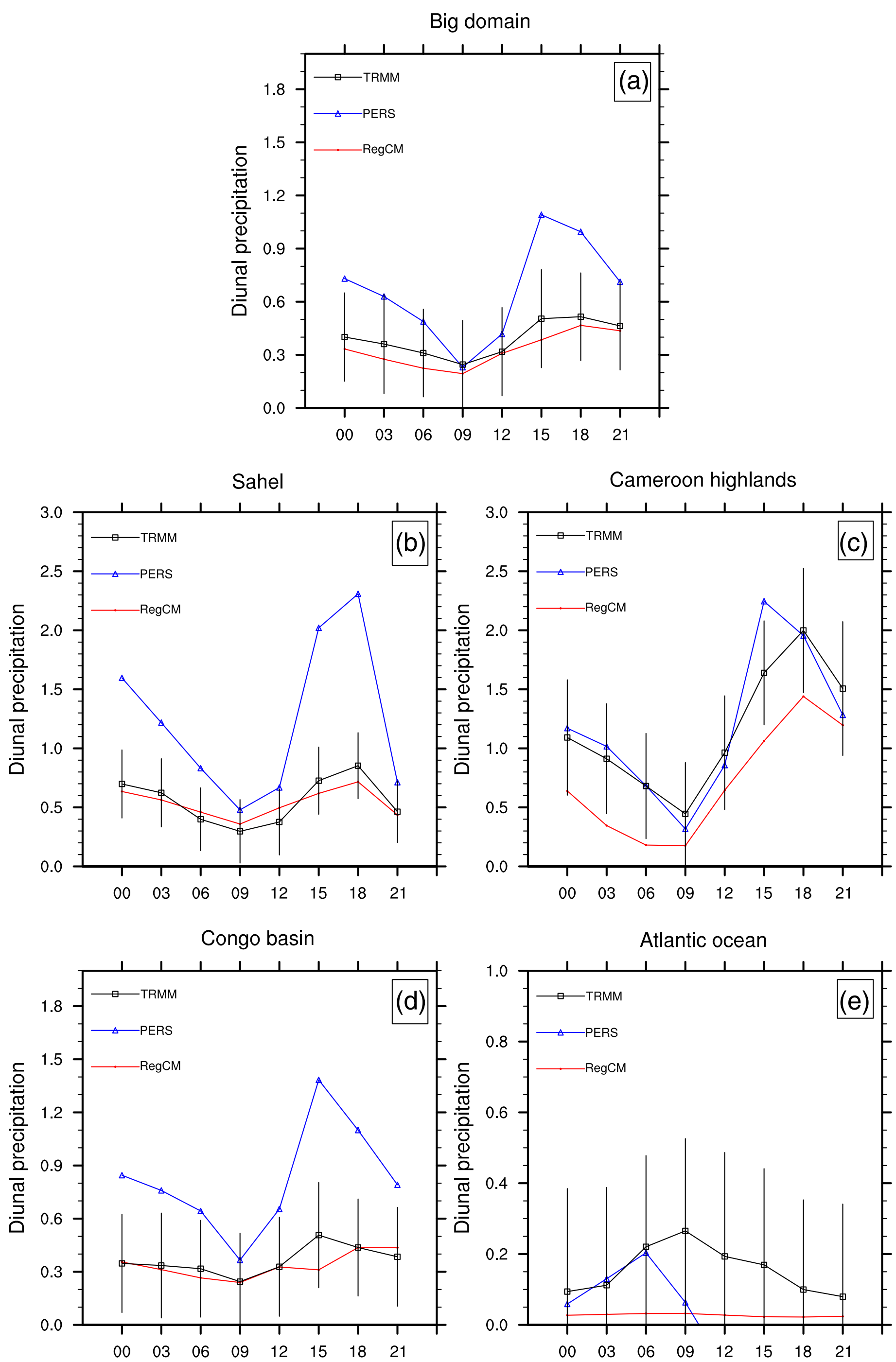

FIGURE 3 Average diurnal cycle of rainfall (mm/h) in the four regions defined in Figure 1 for June–July–August–September season

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infrared estimates from geostationary infrared observations. RegCM precipitation amount (Figure 2a) with highest values around 720 mm over CA are common in TRMM satellite products (Figure 2b), but PERSIANN products (Figure 2c) reveal substantial discrepancies among these datasets. Except for AO sub-region, these discrepancies are characterized by heavy precipitation amount over the continental sub-regions. This tendency of the model precipitation amount to be close to TRMM and underestimated compared with PERSIANN is quite different when observing precipitation intensity (Figure 2d–f). Meanwhile, RegCM precipitation intensity (Figure 2g) is always underestimated over both Atlantic and continental sub-regions. These findings are illustrated in Tables 2 and 3, which show the difference between simulated and satellite-derived precipitation amount, frequency and intensity for the entire domain and the four sub-regions in terms of IA and RMSE, respectively. IA (RMSE) is generally higher (lower) with TRMM than PERSIANN for precipitation amount and conversely, IA (RMSE) is generally lower (higher) with TRMM than PERSIANN for precipitation frequency. More precisely, IA recorded for the entire study area are 0.66 (0.61) for precipitation amount and 0.71 (0.73) for

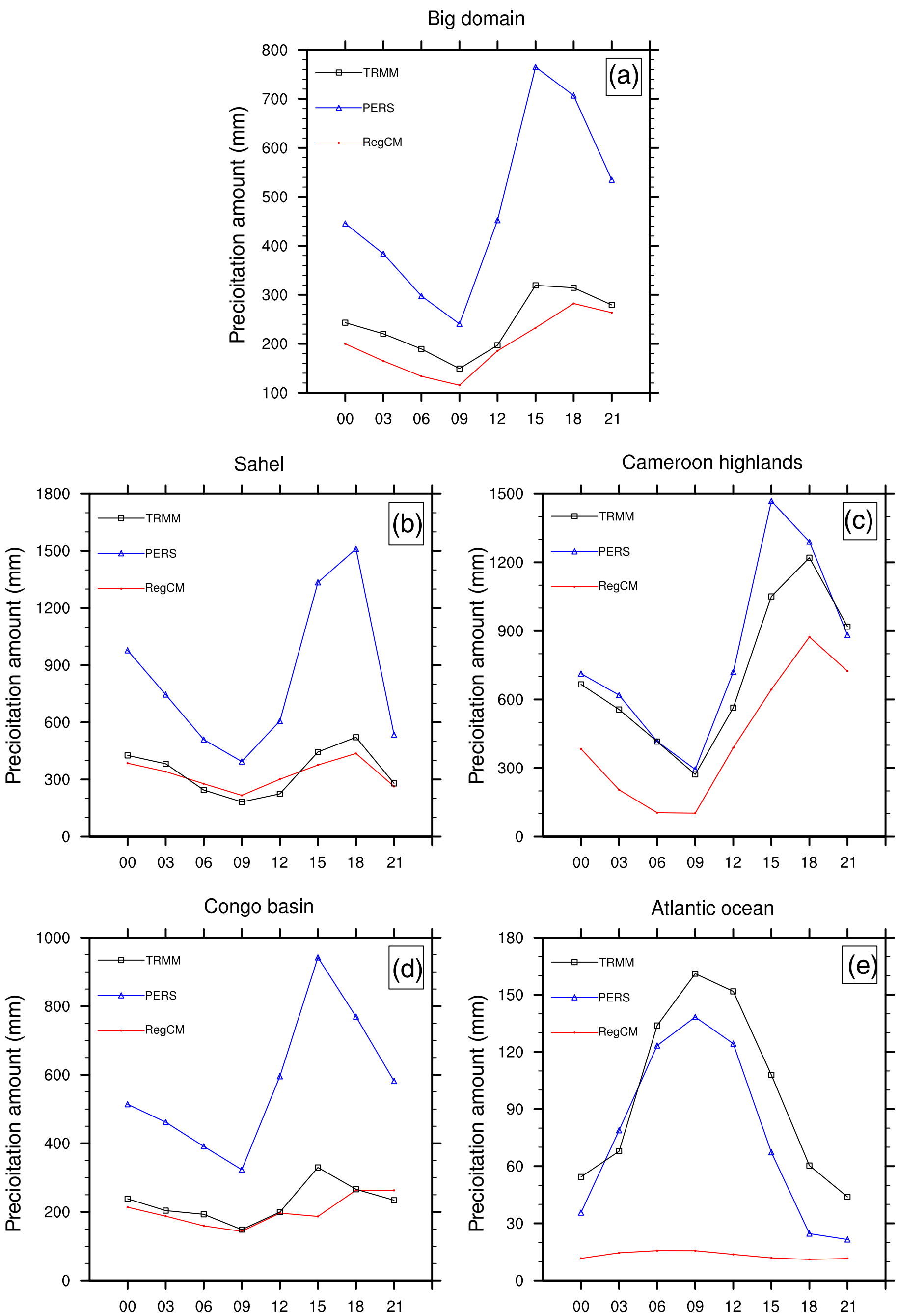

FIGURE 4 Mean diurnal cycle of June–July–August–September precipitation amount averaged over the four selected regions outlined in Figure 1 from RegCM (red line) and two satellite products (blue: TRMM; black: CHRS). The unit of x-axis is LST in hours

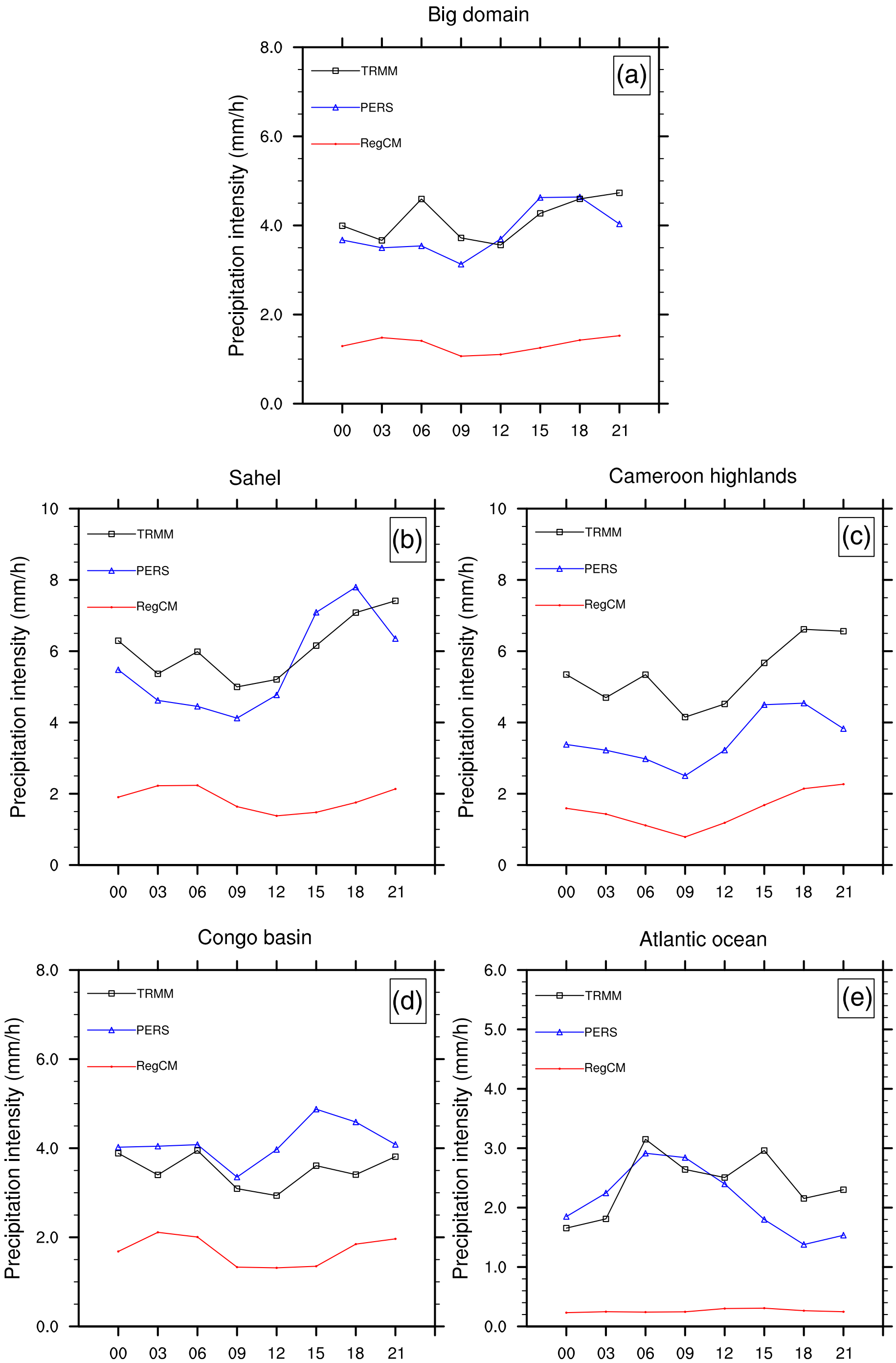

FIGURE 5 Same as Figure 4, but for precipitation intensity

precipitation intensity with TRMM (PERSIANN) as baseline data. These values have to be taken with caution because the topography of the entire region is quite different when moving from one sub-region to another. Indeed, these metrics are 0.44 (0.27), 0.42 (0.40) and 0.66 (0.33) for Sa, CH and CB sub-regions for precipitation amount, respectively. For precipitation intensity, these values are decreased with both reference data and much more with PERSIANN (Table 2). These results suggest that in RegCM, precipitation amount more systematically depends on the topography than precipitation intensity, which is not well simulated. As also pointed out by Dai et al. (2007), these two satellite products show that the use of reference data mentioned above to improve sampling do not change the mean intensity and frequency significantly, and that spatial variations in mean rainfall amount come generally from rainfall frequency rather than intensity. This result suggests that the simulated precipitation intensity can be linked to large-scale precipitation, which in turn is not well accounted for by RegCM4 as highlighted by Komkoua Mbienda, Tchawoua, et al. (2017a). Moreover, looking at the

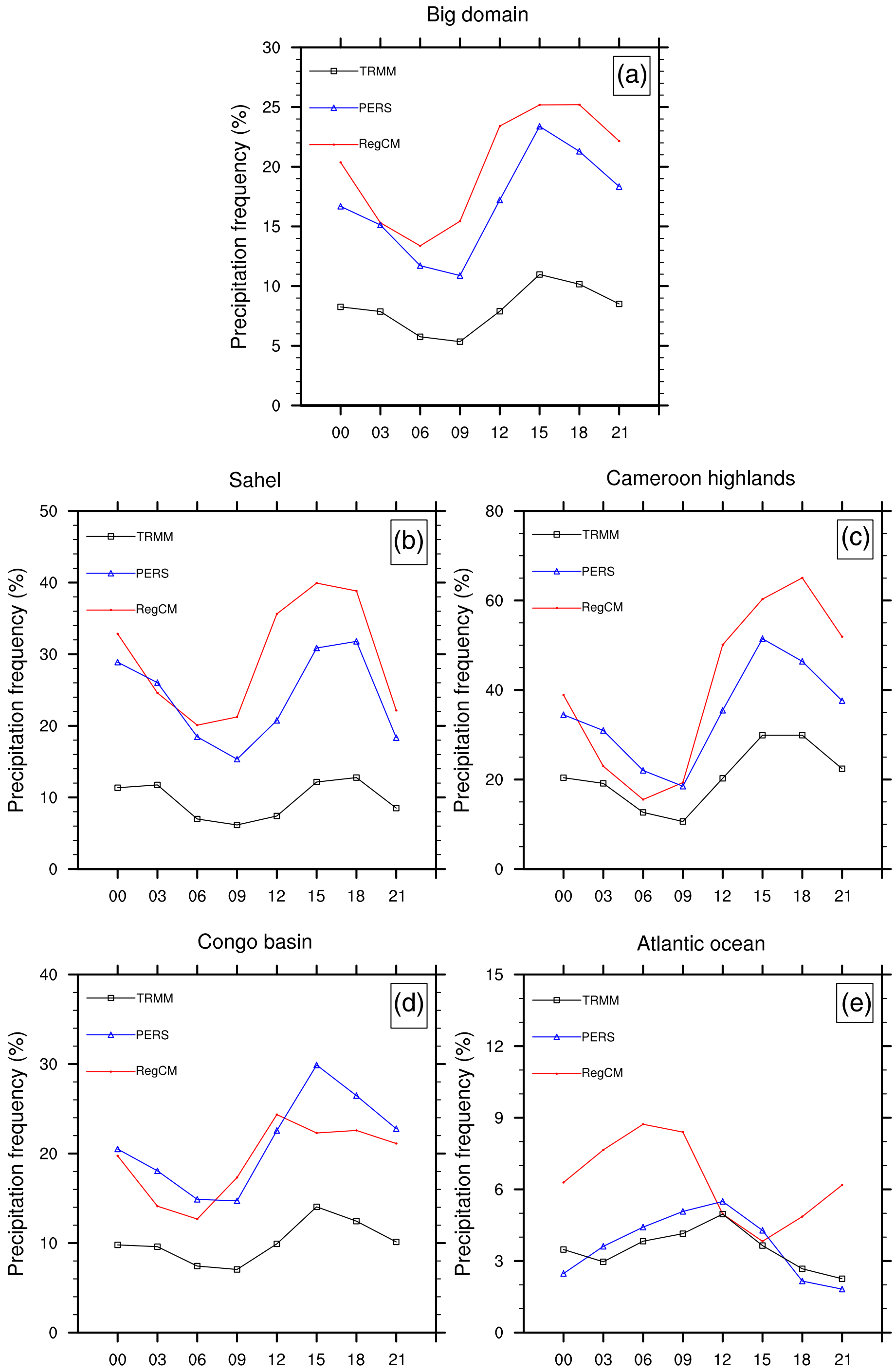

FIGURE 6 Same as Figure 4, but for precipitation frequency

topographical map of the study area (Figure 1) as well as Figure 2g, it can be inferred that an improvement of surface scheme in the model can induce a better representation of simulated precipitation.

The broad patterns of rainfall frequency maps are similar to satellite products as well as RegCM outputs and they are comparable to those of mean rainfall amount mostly over the three sub-regions in the continental area, although PERSIANN shows higher amount than the other two products. The highest precipitation frequency (greater than 50%) and amount (greater than 600 mm) are seen over high altitude area (especially over CH sub-region), suggesting that topography plays a major role in the frequency and amount than in intensity. Moreover, the RegCM precipitation intensity patterns are less comparable to those in rainfall amount and frequency. This implies that spatial pattern of rainfall amount is set by how often it rains at various regions over the study area. This finding is quite different to that of Zhou et al. (2008) conducted over Eastern China.

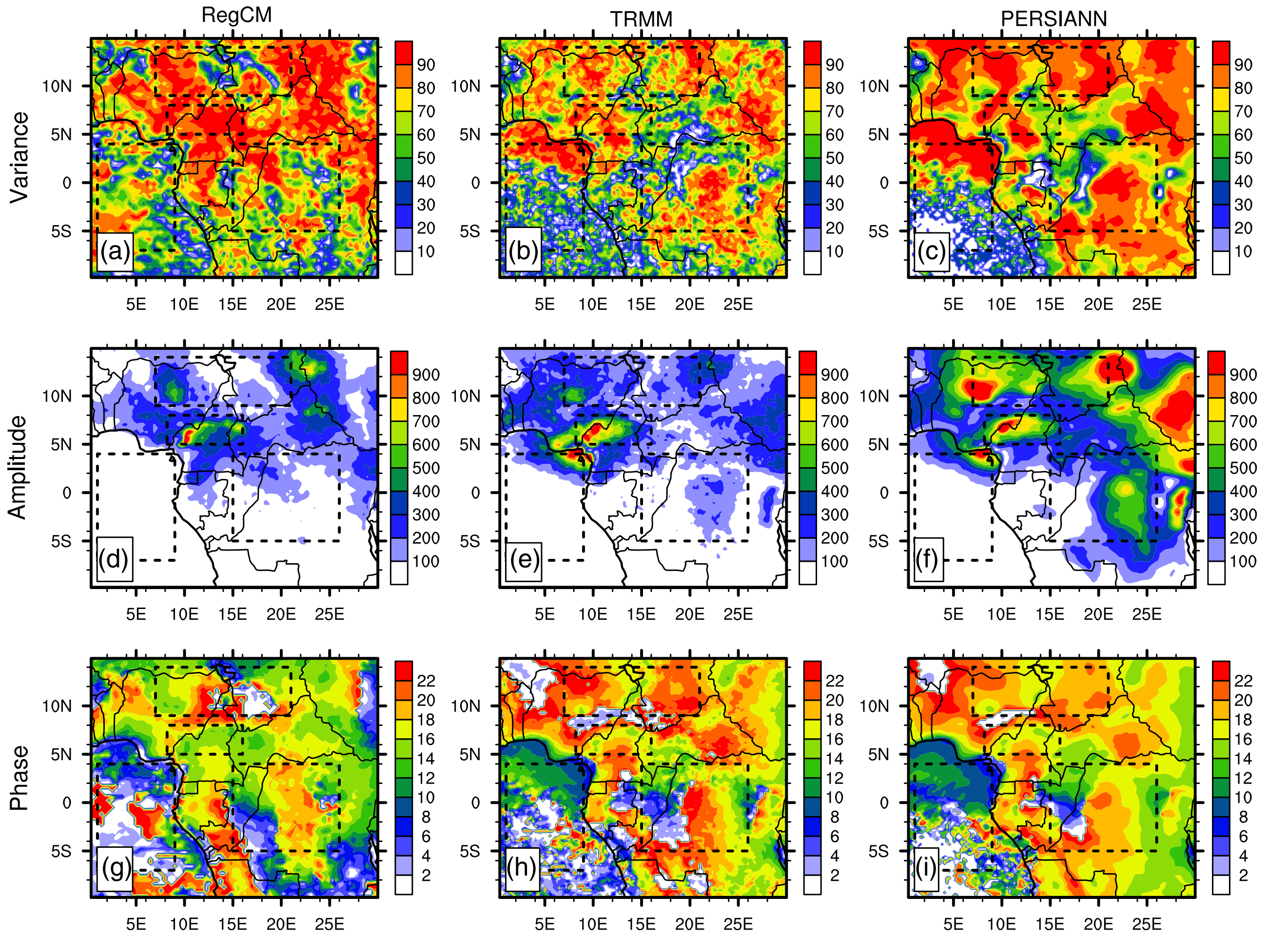

FIGURE 7 (Top) Percentage variance, (middle) amplitude and (bottom) phase explained by diurnal cycle of precipitation amount from (a), (d), (g) RegCM; (b), (e), (h) TRMM; and (c), (f), (i) PERSIANN

Indeed, they found that both frequency and intensity contribute to the diurnal variation of precipitation amount.

3.2 | Diurnal cycles of rainfall intensity, amount and frequency

The above analyses show that the precipitation spatial diurnal patterns are regularly determined by how frequently it rains rather than how heavy it rains in various regions over CA. Before analysing spatial patterns in peak timing and amplitude, diurnal cycle of multi-year (2002–2006) mean rainfall intensity, amount and frequency among the model and satellite datasets are investigated. Figure 3 compares 2002–2006 mean June–July–August–September precipitation diurnal cycle (mm/h) from RegCM and the two satellite products. Except AO sub-region, RegCM simulations show patterns that resemble satellite products, although they generally underestimate the June–July–August–September precipitation at each 3-hourly time period compared with PERSIANN product. This disability of the model to reproduce diurnal precipitation over ocean is certainly due not only to the convective activity, which is not well described by the chosen convective scheme, but also to the 24-h fluctuation of sea surface temperature (SST), since the 24-h fluctuation of oceanic precipitation is highly linked to the SST variability. In this last case, to enhance the 24-h variability of oceanic rainfall, ocean mixed layer model incorporating the 24-h variability of SST (Noh et al., 2002; Stephens et al., 2005) could be used in RegCM.

RegCM always peaks in the late afternoon around 1800 Local Solar Time (LST), while satellite products peak either around 1500 or 1800 LST. Figures 4–6 compare the 24-h cycles of 2002–2006 June–July–August–September rainfall frequency, amount and intensity from RegCM4 simulations, TRMM and PERSIANN averaged at each LST hour over entire domain and four sub-regions. The model-derived precipitation intensity (Figure 5) is generally lower than that from rain satellite

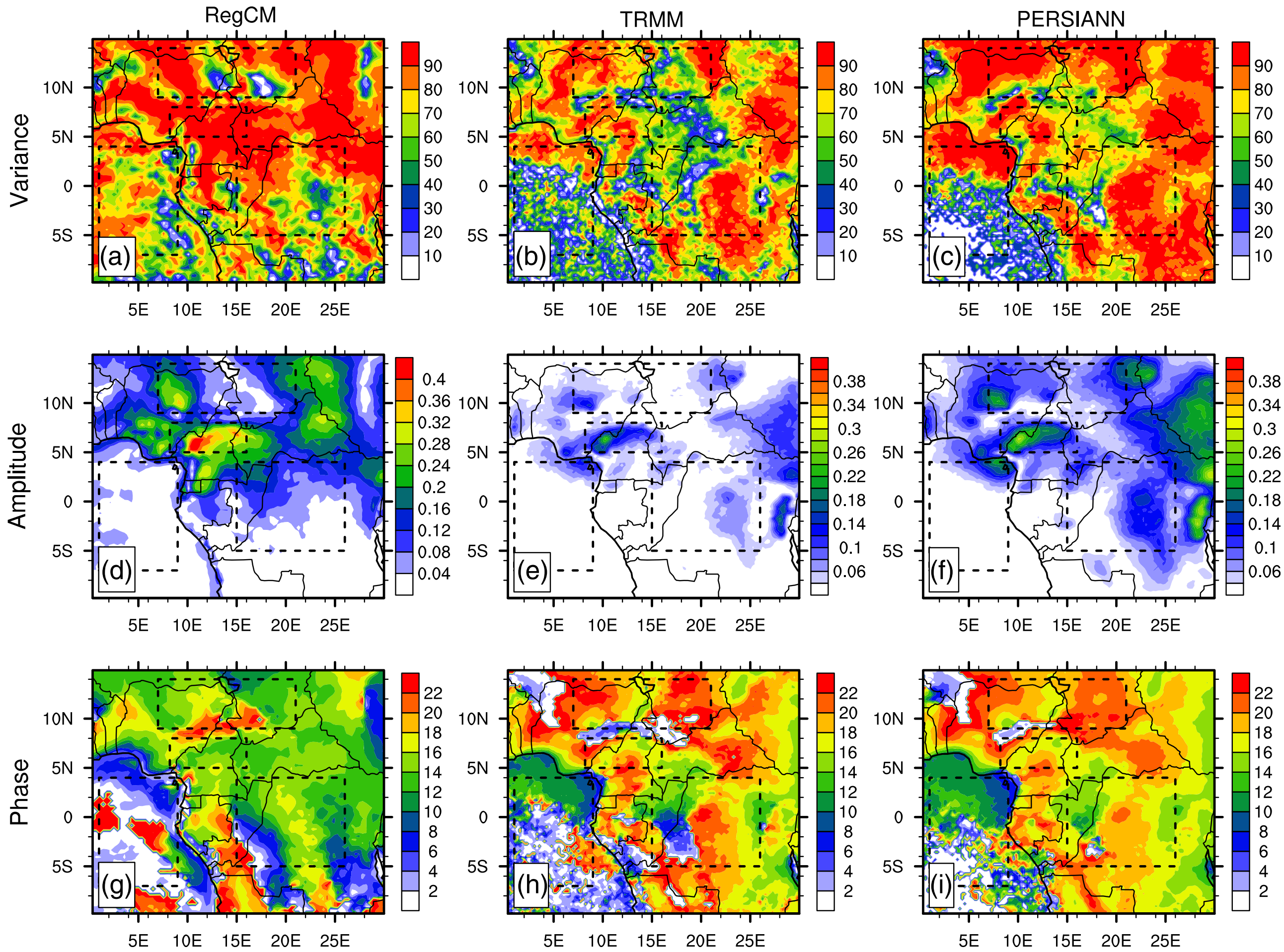

FIGURE 8 Same as Figure 7, but for precipitation frequency

measurements over CA with no realistic peak timing over different sub-regions, except Cameroon highlands (1800 LST). As shown in Figure 3, model and reference datasets depict great peaks around 1800 LST in Sahel sub-region and a more pronounced peak around 1500 LST in Cameroon highlands and Congo basin sub-regions. These characteristics are also reported in the amount and frequency of 24-h variability. In general, June–July–August–September rainfall over Sa and CH sub-regions has a couple of peaks in the frequency and amount: one around 0900 LST (in the morning) and another around 1800 LST (in the late afternoon). The diurnal precipitation amount accounts for most of the diurnal variation in satellite as well as in RegCM4 data. Since the quality of PERSIANN product is less superior to that of TRMM in measuring the rainfall amount (Zhou et al., 2008), results clearly show that the RegCM can be used to simulate precipitation amount in continental area over CA. As shown by the above figures, general patterns of rainfall frequency and amount are quite similar. Therefore, we can infer that the diurnal variation of rainfall amount is determined by how often it rains at each time over the study area.

Overall, RegCM has strong difficulties to represent the real patterns and times of maximum peaks of precipitation intensity over all sub-regions, although it is able to capture the patterns and peak times of the 24-h cycle of rainfall frequency and amount. These difficulties are strictly related to the RegCM's intrinsic inadequacy in representing a real pattern of rainfall intensity. This finding is close to that of Dai et al. (1999) who found that RegCM produces too much cloudiness, which reduces surface solar radiation and thus daytime peak warming at the surface.

3.3 | Spatial distribution of phase and amplitude in 24-h variations

Besides analysing diurnal cycles' precipitation characteristics described above, their spatial distribution of phase and amplitude are also computed and analysed. Indeed, to characterize these spatial patterns, amplitudes and phases of diurnal (24 h) harmonic of rainfall amount, frequency and intensity are estimated. Figures 7–9 show the

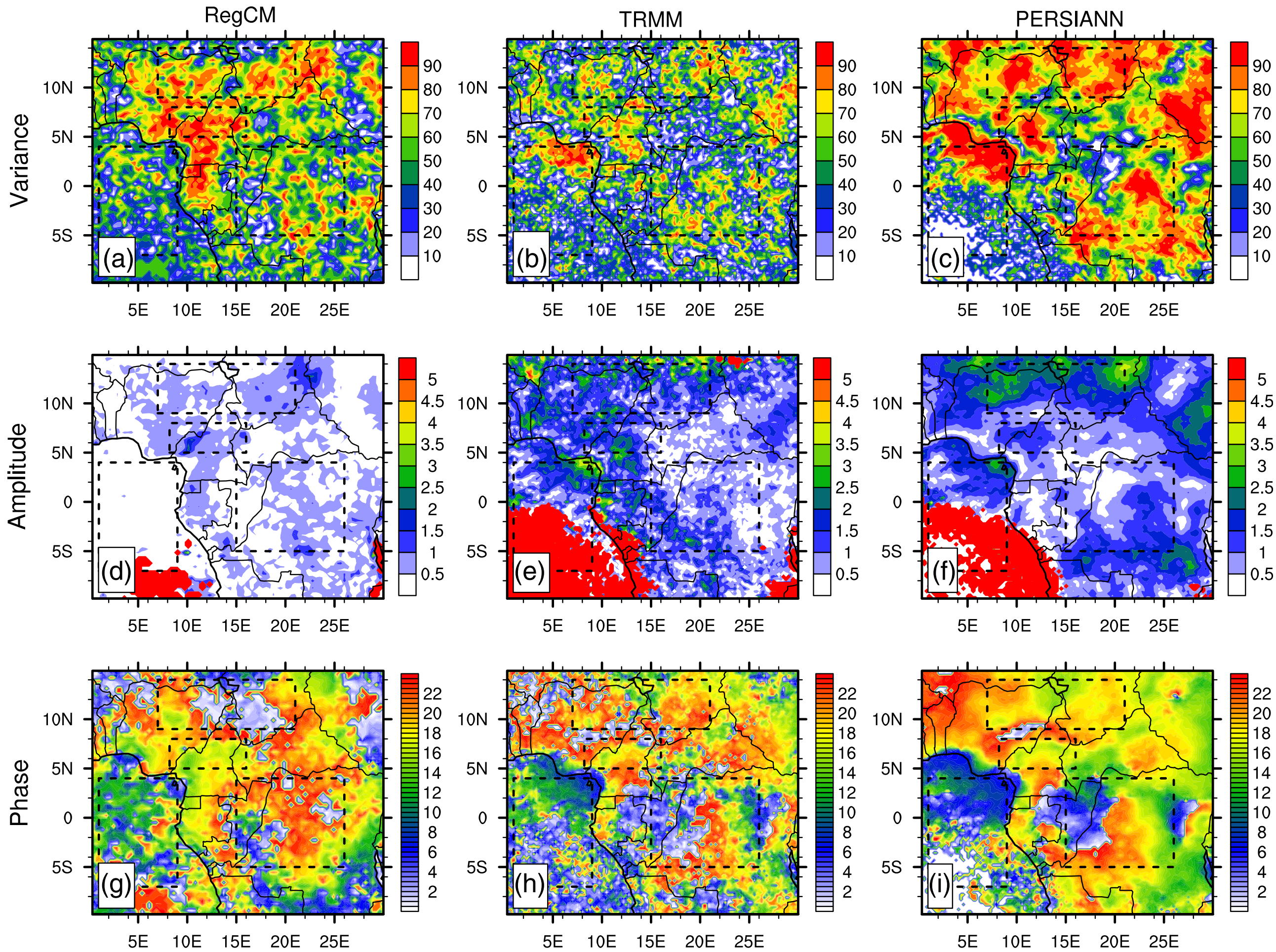

FIGURE 9 Same as Figure 7, but for precipitation intensity

percentage variance, amplitude and phase (peak time) of diurnal cycles of rainfall intensity, amount and frequency from RegCM, TRMM and PERSIANN data. Variances plotted in Figures 7a,b and 8a,b show that the first harmonic of Fourier transformation is adequate to represent the main characteristics of 24-h rainfall amount and frequency. Rainfall from this first harmonic accounts for at least 85% of quotidian variance in must locations over CA, including the four sub-regions. This finding is true for both model simulations and satellite products. As expected, the first harmonic cannot well represent diurnal variation of precipitation intensity mostly with RegCM and TRMM data (Figure 9a,b) than PERSIANN product (Figure 9c). As shown in the section presented below, this RegCM deficiency could be highly related to its intrinsic deficiency in simulating a real pattern of rainfall intensity.

RegCM does not capture the exact phase of precipitation amount and frequency although it looks like being able to capture the patterns of amplitude of precipitation amount compared with TRMM. Over Cameroon highlands, the peaks are practically pointing around 1200–1400 LST, which is nearly 4 h earlier than that of reference timing. Overall, compared with TRMM and PERSIANN, the model simulates too early the phase of precipitation amount and frequency. This discrepancy is most distinct in the Sa, CH, CB sub-regions. This is a well-known phenomenon found in many other existing RCMs. In fact, several studies have already suggested that too frequent convective rainfall leads to early peaks due to too sensitive initiation of convection (e.g., Shin et al., 2007; Rio et al., 2009), since convective precipitation controls almost all the rainfall activity over CA region (Komkoua Mbienda, Tchawoua, et al., 2017a).

The amplitude of diurnal cycle derived from RegCM must also be assessed in addition to the diurnal phase. As said earlier, RegCM data demonstrate similar 24-h amplitudes of precipitation amount to those of TRMM products over entire study area (Figure 7d,e), with the highest values of 900 mm recorded in CH sub-region. However, this result does not ensure good agreement of RegCM 24-h amplitude for precipitation intensity and frequency as shown in Figures 8 and 9. The most prominent features of Figure 9d are the underestimation of diurnal amplitude of precipitation intensity in the model compared with both satellite products. These products show comparable amplitude of precipitation intensity with values not exceeding 3 mm/h over continental region and similar patterns of amplitude of precipitation amount and frequency. The amplitudes obtained by PERSIANN are slightly higher than those of TRMM. Over regions with large amplitude of precipitation amount, such as Cameroon highlands (Figure 7d–f), the frequency also depicts great 24-h amplitudes (Figure 8d–f). Comparing the 24-h cycles between rainfall amount and frequency discloses a close similarity, pointing out that the 24-h variation of rainfall amount arises meanly from their frequency. The above analyses advocate that the RegCM 24-h cycle of precipitation amount is mostly related by frequency than intensity.

4 | CONCLUSION

Regional Climate Model version 4.4 (RegCM4.4) is analysed by comparing the temporal and spatial patterns of diurnal cycle of 5-year June–July–August–September precipitation with two satellite precipitation products (Tropical Rainfall Measuring Mission [TRMM] 3B42, Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks [PERSIANN]), with a focus on the precipitation amount, frequency and intensity. Results have been presented for four sub-regions (Sahel, Cameroon highlands (CH), Congo basin and AO) embedded in Central Africa (CA) using harmonic analysis.

Regarding the spatial features of precipitation characteristics, RegCM4.4 reproduces the observed spatial pattern of precipitation amount and precipitation frequency satisfactorily in CA compared with TRMM and PERSIANN products, respectively, although the index of agreement differs in the sub-regions. Patterns of precipitation frequency maps are similar to the satellite products as well as RegCM outputs and they are comparable to those of mean rainfall amount mostly over the three sub-regions in the continental area, although PERSIANN shows higher amount than the other two products. The highest precipitation frequency (greater than 50%) and amount (greater than 600 mm) are reported over high altitude area (especially over CH sub-region), suggesting that the topography acts as a key element in frequency and amount than in the intensity. Moreover, the RegCM precipitation intensity patterns resemble less of those in precipitation amount and frequency. This implies that spatial patterns of rainfall amount are determined by how often it rains in various regions over the study area.

It is also found that RegCM4 diurnal precipitation shows temporal pattern that are comparable to TRMM and PERSIANN, with some systematic wet biases over Cameroon highlands. For the entire region of study and other sub-regions, the difference between TRMM and PERSIANN is not small at all. Twenty-four-hour variations of rainfall amount and frequency are correctly represented by the model with an afternoon peak around 1800 LST in the entire domain except Atlantic Ocean sub-region. The model does not properly depict the observed characteristics in terms of 24-h variation of rainfall intensity over the study area. RegCM has a strong difficulty in representing the true patterns and times of maximum peaks of precipitation intensity in all sub-regions, although it well represents the patterns and peak times of the 24-h cycle of rainfall amount and frequency. This is strictly related to the RegCM's intrinsic deficiency to represent a realistic pattern of the rainfall intensity. Moreover, Llopart et al. (2020) have found that the atmospheric water budget and evapotranspiration are not well accounted for in RegCM.

One of the main results regarding spatial patterns of the whole precipitation characteristics is that the spatial distribution of precipitation frequency is quite similar to that in the rainfall amount more than the precipitation intensity does. RegCM does not well represent the real timing of maximum peaks of precipitation amount and frequency, although it looks like being able to capture the patterns of precipitation amount amplitude when compared with TRMM.

The analysis suggests that RegCM4.4 is able to capture the amount and frequency of precipitation, and the highest frequency and amount are recorded over high altitude area, suggesting that topography plays a major role in these rainfall characteristics. For the model to correctly simulate the diurnal cycle in June–July–August–September precipitation, it has to properly represent large-scale precipitation as well as land surface condition. Several indications of 24-h variation deficiency over oceans can be attributed to the convective scheme as well as to the 24-h cycle of sea surface temperature. The findings of this study should be helpful in evaluating the significance of 24-h cycle of rainfall over CA and its governing mechanisms. In a practical way, since the knowledge of intensity, amount and frequency of precipitations is crucial in planting and growing crops, we can infer that the present study can have a great importance in agricultural sector.

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AUTHOR CONTRIBUTIONS

P. C. Choumbou: Conceptualization (equal); methodology (equal); software (equal); writing – original draft (equal); writing – review and editing (equal). **A. J. Komkoua Mbienda:** Conceptualization (equal); data curation (equal); formal analysis (equal); investigation (equal); methodology (equal). **G. M. Guenang:** Data curation (equal); formal analysis (equal); investigation (equal). **D. Monkam:** Supervision (equal); writing – review and editing (equal). **F. Mkankam Kamga:** Project administration (equal); supervision (equal); writing – review and editing (equal).

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