Projected trends of extreme rainfall events from CMIP5 models over Central Africa

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In this study, the projections of daily rainfall from an ensemble mean of 20 global climate models (GCMs) are used to examine projected trends in heavy rainfall distribution over Central Africa (CA), under the representative concentration pathway 8.5. For this purpose, two analyses periods of 40-years have been selected (2006–2045 and 2056–2095) to compute trends in the 90th and 99th percentiles of the daily rainfall distributions. We found that large increase trend is mostly found in the 99th percentile of rainfall events, over southern Chad, northern Cameroon, northern Zambia, and in the Great Lakes Area. This can be attributed to the increase of moisture convergence intensified by the presence of the Congo Basin rainforest. It is also shown that the largest number of GCMs with a trend of the same sign as the average trend is observed over the above regions. It is thus clear that the projected increase trends in heavy rainfall events may further worsen floods which are real problems in the CA countries. Therefore, strong subregional policies are needed to help design effective adaptation and mitigation measures for the region’s countries.

KEYWORDS
Central Africa, CMIP5, extreme rainfall, future change, trends

1 INTRODUCTION

Central Africa (CA) is one of the world’s regions where economy greatly depends on agriculture and hydro-power. This region is also highly susceptible to experience catastrophic flooding or severe droughts, as it is crossed in its northern part by savannah. For example, the most recent events are the floods that occurred in three successive years (June 20, 2015, June 23, 2016, and July 3, 2017) in Douala (Cameroon), causing enormous economic losses, coupled with human life losses (Tanessong, Vondou, Djomou, & Igri, 2017). Because of these large economic and societal impacts, it is important to assess potential changes in heavy rainfall distribution for adaptation planning and policy making over this area.

Several authors have been interested in the study of extreme events over Africa, using either in situ data (Aguilar et al., 2009; Djomou, Monkam, & Lenouo, 2009; Fauchereau, Trzaska, Rouault, & Richard, 2003; Hua et al., 2016; Kruger, 2006; New et al., 2006), or climate models (Abiodun et al., 2017; Diallo et al., 2016; Klutse et al., 2016; Pinto et al., 2016; Shongwe et al., 2009; Shongwe, van Oldenborgh, van den Hurk, & van Aalst, 2011; Sylla et al., 2015). However, only few of these works focuses on the Central African region (e.g., Aguilar et al., 2009; Hua et al., 2016). It is evident that extreme rainfall events over the African continent are becoming more frequent and more severe. For example in their works, Fauchereau et al. (2003) identified regions of South Africa which experienced more extreme rainfall events in the later decades of the 20th
century. They found a statistically significant increase in the frequency of very heavy rainfall. Kruger (2006) found an increase trends in the number of extreme rainfall days over southern Africa. In their investigations over South and West Africa, New et al. (2006) found an increase in trend of extreme rainfall days. Aguilar et al. (2009) conclude that while the majority of the analyzed world has shown an increase in heavy rainfall frequency over the last half 20th century, CA on contrary showed a decrease. Recently, the results of Hua et al. (2016) indicate that the last three decades long-term drought over CA can be explained by the large-scale response of the atmosphere to tropical sea surface temperature (SST) variations.

Results from climate models suggest that these trends will continue worldwide under enhanced greenhouse gas (GHG) conditions (e.g., Abiodun et al., 2017; Pinto et al., 2016; Shongwe et al., 2009, 2011; Sillmann, Kharin, Zhang, & Bronaugh, 2013). Shongwe et al. (2009) and Shongwe et al. (2011) found projected increases in the intensity of heavy rainfall over East Africa, with more severe rainfall deficits in southern Africa by using an ensemble of 12 global climate models (GCMs).

In this study we present the projected trends of the 90th and 99th percentile of rainfall events over CA, from 20 GCMs produced under the fifth phase of the Coupled Model Inter-comparison Project (CMIP5; Taylor, Stouffer, & Meehl, 2012; see, Table 1), under the representative concentration pathway (RCP) reflecting an 8.5 W m⁻² radiative forcing change at the end of the twenty-first century (RCP 8.5) due to high GHG concentration level. This study is based on data from CMIP5, which may be useful for climate change impact studies and adaptation policies is the first one to focus on the projections of heavy rainfall in this region.

In the next section, a brief description of the study area, data and methodology used are presented. In Section 3, results for current climate obtained from the ensemble mean GCMs which are compared to the observational datasets and the projected trends are presented. Summary of the findings and conclusions are presented in Section 4.

2 STUDY AREA, DATA AND METHODOLOGY

This study is done over the Central African region, defined between 15°S and 15°N latitude, and 5°E and 35°E longitude (see Figure 1), which has a complex and heterogeneous topography with extensive mountain, coast, lakes and rivers.

For the analyses, we used daily rainfall data from 20 available GCMs of the CMIP5 project (from 1850 to 2100; Table 1). Other daily rainfall from the Global Precipitation Climatology Project 1DD (GPCP version 1.2; 1.0° × 1.0° resolution; from 1997 to 2014) and from the Tropical Rainfall Measurement Mission 3B42 (TRMM version 7; 0.25° × 0.25° resolution; from 1998 to 2013), are used as observation in order to consider uncertainties in observed data. In addition, the large-scale atmospheric winds fields (meridional and zonal) simulated by the 20 GCMs are compared with the reanalysis data from the European Center for Medium-Range Weather Forecast ERA-Interim (ERA; 1.50° × 1.50° resolution; from 1979 to present) and from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP; 2.50° × 2.50° resolution; from 1948 to present). To ease comparison between all datasets, GCMs and TRMM are interpolated onto the GPCP grid point (1.0° × 1.0° resolution) according to the bilinear interpolation.
Rainfall from each of 20 GCMs over CA is evaluated for the current climate (1998–2005) in order to select the best models by using the Taylor diagram (Taylor, 2001). The Taylor diagram provides a concise statistical summary of the degree of correlation, root mean square error, and standard deviation ratio. Only best models selected through this analysis will be used to compute ensemble mean GCMs. In this study, we focus on the 90th and 99th percentiles of rainfall distribution to examine projected trends in heavy rainfall for the middle (2006–2045) and late twenty-first century (2056–2095). As done in Villarini, Scoccimarro, and Gualdi (2013), we focus on the ensemble mean trend for the 90th and 99th percentiles of rainfall distribution by computing the values of these two percentiles at each grid point and for each year. After that, we have computed the slope of the trend line for each of these times series and for each of the 20 models. Finally, we considered the average of the best model’s slopes (according to the Taylor diagram analysis) as the representative slope values.

3 | RESULTS

In this section, we first focused on the results of the GCMs simulations under current climate (1998–2005) by comparing the 90th and 99th percentiles of the ensemble mean GCMs with respect to the observational datasets (TRMM and GPCP), and then turn our attention to the projected trends of the two percentiles over the study domain.

It has been recognized that in an ensemble mean model approach, poorly selected models can degrade the overall signal of the ensemble mean. To distinguish good and poor models from the 20 GCMs listed in Table 1, the Taylor diagram is used on the basis of the composites of climatological mean field for monthly rainfall over the study region (Figure 2). The following two criteria are applied to select highly performing models: (a) the pattern correlation (i.e., the cosine of the azimuthal angle in a polar coordinate in the figure) should be greater than 0.6; (b) the spatial standardized deviation ratio (the spatial standard deviation normalized by the observed spatial standard deviation) should be within the range of 1.00 ± 0.25. Based on the above criteria, 11 highly performing models are selected. The good models include: ACCESS1–0, BCC-CSM1–1-M, BNU-ESM, CMCC-CESM, CanESM2, EC-EARTH, GFDL-CM3, HadGEM2-ES, MPI-ESM-LR, MPI-ESM-MR, and MRI-CGCM3 (see Figure 2). In the rest of the paper, the ensemble mean of GCMs will be done considering only the above good models.

Figure 3 exhibit various features of the CA climatology: (a) the total rainfall (shade; in mm/day) averaged during the 1998–2005 period, superimposed on the 925 hPa low-level wind (arrows; in m/s) from the ensemble mean GCMs as well as the observational datasets (Figure 3a–c); (b) the bias in term of total rainfall (shade; in mm/day) and the 925 hPa low-level wind (arrows; in m/s) between GPCP and TRMM/ERA and NCEP, GCMs and TRMM/GCMs and ERAIN as well as GCMs and GPCP/GCMs and NCEP (Figure 3d–f); (c) the values of the 90th and 99th percentiles (in mm/day) averaged over the 1998–2005 period, normalized by the maximum value over the spatial domain from the ensemble mean GCMs as well as TRMM and GPCP (Figure 3g–i). Concerning the 90th and 99th percentiles of rainfall, the spatial patterns of TRMM and GPCP exhibit larger rainfall values over the northern part of CA and some coastal regions (Nigeria, Cameroon, Equatorial
Guinea, and Gabon). Smallest values are located over southern Angola and in the Atlantic Ocean (Figure 3g,h,j,k). Although the two observational datasets (GPCP and TRMM) show a similar spatial pattern of mean rainfall (Figure 3a,b,d), TRMM generally produced higher values of extreme rainfall than GPCP over the Central African domain. Here, the largest value for the 90th percentile is 53.38 mm/day for TRMM and 29.15 mm/day for GPCP. Similarly, results for the 99th percentile are 147.86 mm/day for TRMM and 49.74 mm/day for GPCP. This behavior is linked to the large difference in their native spatial resolutions (0.25° × 0.25° for TRMM and 1.0° × 1.0° for GPCP) which confers a strong variability to TRMM compared to GPCP over CA (Fotso-Nguemo et al., 2017).

The ensemble mean GCMs succeed to reproduce the spatial patterns exhibited by GPCP more than those of TRMM, with maximum values which are generally smaller (19.24 mm/day for the 90th percentile and 40.44 mm/day for the 99th percentile). Some of the possible explanations for this behavior are associated with the resolution of the models which may be too coarse than TRMM and GPCP (see Table 1), and with the known difficulties of these models in reproducing rainfall statistics, in particular for the upper tail of the distribution (Villarini et al., 2013). Moreover, it is worth mentioning that the ensemble mean GCMs show similar spatial patterns of mean rainfall with values that are much similar to TRMM and GPCP (see Figure 3c). Both the 90th and 99th percentile are overestimated over the Great Lakes Area and in the Atlantic Ocean (Figure 3i, l). The bias observed is probably linked to the overestimation of the total rainfall (Figure 3e,f) and suggest that the ensemble mean GCMs simulate too strong moisture transport as shown by wind fields in Figure 3e,f. However, Sillmann et al. (2013) found that the CMIP5 models generally agree with observational records better than the CMIP3 models when dealing with rainfall extremes. With these limitations in mind, we examine the projected trend of the 90th and 99th percentiles of rainfall distribution over the study domain.

Figure 4 highlights some interesting features when comparing between the two percentiles as well as the two different periods. Generally, significant trends in the 99th percentile (Figure 4b,d) are much stronger than those for the 90th percentile (Figure 4a,c). The average trend for the 90th and 99th percentile indicates a tendency towards increasing trends over most part of CA. The increase trends observed in the extreme rainfall events may be related to the increase of moisture convergence intensified by the presence of the Congo Basin rainforest, which has the highest value of the recycling ratio in the region compared to the Indian and Atlantic Ocean (Dyer et al., 2017). Recently, a similar result was reported by Sylla et al. (2015) over West Africa. In their study, they have associated this behavior with the increase of moisture convergence in the boundary layer, favored by larger amounts of moist static energy and instability.

There are also few areas in the western CA with negative or no trends, in particular over coastal countries and in the Atlantic Ocean. The negative trends observed in the extreme rainfall events is probably the consequence of the long term drought observed over CA during the last two decades and can be linked to changes in SST over the Indian Ocean associated with the enhanced and westward extended tropical Walker circulation (Hua et al., 2016). The trends in the 99th percentiles increase from the Atlantic Ocean to the continent. The average trend for the 99th
percentile (Figure 4b,d) shows a sharper difference between western and eastern parts of CA, with more increase trend in eastern part. This is probably due to the fact that the intra-seasonal variability of rainfall is much stronger in eastern than in western part of CA (Tchakoutio & Nzeukou, 2016). The differences in trends between the first and
second half of the twenty-first century are generally small, with a tendency towards increasing trends more pronounced over Nigeria, southern Chad, northern Cameroon, northern Zambia, and in the Great Lakes Area (Figure 4b,d). There are large areas of CA with increasing trends, with values exceeding 0.5 mm day$^{-1}$ decade$^{-1}$ (Figure 4b,d).

We have examined how robust these trend results are by counting the number of GCMs with a trend of the same sign as the average trend (Figure 5). The largest degree of agreement is over southern Chad, northern Cameroon, Equatorial Guinea, northern Gabon, northern Zambia, and in the Great Lakes Area with more than 80% of the models agreeing on the trend sign. These are also areas with the largest slope values (Figure 4). Overall, the results for the first and the second half of the twenty-first century of both 90th and 99th percentiles are almost similar.

4 | CONCLUSIONS AND DISCUSSION

In this paper we have investigated the projected trends in heavy rainfall distribution over CA, by using projections from 20 GCMs of CMIP5 produced under RCP8.5 scenario. We found that among the 20 GCMs used at the beginning of the study, only 11 could be considered as highly performing models over the Central African domain according to the Taylor diagram analysis. We also found that the ensemble mean GCMs is generally lower than TRMM and GPCP over the period 1998–2005. The overall spatial patterns of the ensemble mean GCMs, are similar to that of GPCP. Our results also indicate that the northern and eastern parts of the study domain are projected to experience increasing trends in the 90th and 99th percentiles of rainfall events. This increase can be linked to the increase of moisture convergence for which the Congo Basin rainforest plays a major role. The magnitude of these trends is rather large particularly in the 99th percentiles and for eastern CA. Over a 40-year period, there are areas in the eastern part of the domain in which the projected increase is about 30% with respect to average value of the 1966–2005 period.

Our results not necessarily contradict those of Aguilar et al. (2009) who found a decrease in extreme rainfall events over CA during the second half of the 20th century. In their work, indications about the reduction in extreme rainfall events are found especially over western CA. In this paper, we found that the heavy rainfall will increase significantly throughout the twenty-first century particularly for the 99th percentiles and over eastern CA. For instance, larger positive slope values for the 99th percentile indicate that there is a tendency towards more extreme rainfall events. The observed trends of heavy rainfall over the study region have a lot of implications: (a) the decrease trends could affect water resources availability, agriculture and hydro-power; (b) while the increase trend could aggravate floods which are major problems in many countries of the region. The tendency towards more intense rainfall events

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**FIGURE 4** Average trend (in mm day$^{-1}$ decade$^{-1}$) in the 90th (a, c) and 99th (b, d) percentiles. Results are for the trend estimates over the period 2006–2045 (a, b) and 2056–2095 (c, d). Stippling indicates statistically significant regions at 95% confidence level of the Mann-Kendall test.
found in this study is in agreement with the results obtained in other regions (Abiodun et al., 2017; Diallo et al., 2016; Groisman, Knight, & Karl, 2012; Klutse et al., 2016; Pinto et al., 2016; Shongwe et al., 2009, 2011; Sylla et al., 2015; Villarini et al., 2013).

With regard to these results, it is clear that possible climate change can substantially affect the climate of CA during the twenty-first century. The projected increase trends in heavy rainfall events may further worse floods which are real problems in the CA countries. Hence, increase in heavy rainfall events would affect the agricultural practices, crop production and food security. All these potential impacts need to be taken into consideration in preparing effective adaptation and mitigation measures for the region.

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Conflict of interest
No conflict of interest to declare.

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FIGURE 5 Number of GCMs (out of 11) with the sign of the trend which is the same as the mean trend for the 90th (a, c) and 99th (b, d) percentiles. Results are for the period 2006–2045 (a, b) and 2056–2095 (c, d)
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