Evaluation of the Tropical Rainfall Measuring Mission (TRMM) 3B42 and 3B43 products relative to Synoptic Weather Station Observations over Cameroon

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Abstract

The Tropical Rainfall Measuring Mission (TRMM) daily (3B42) and monthly (3B43) rainfall products are evaluated relative to synoptic weather station observations in Cameroon and according to the main agro-climatic regions. In order to achieve this goal, deterministic and categorical metrics were used, as well as inter annual variability and seasonnal distributions. Outcomes of the comparison showed that synoptic weather station data are strongly correlated with the TRMM 3B43 data and that rainfall distribution is characteristic for each agro-climatic region. The highest skill scores were observed in the Sudano-sahelian, High Savannah, and Western Highlands zones, while the Uni-modal Equatorial zone displayed the lowest correspondence scores between TRMM rainfall estimates and station-based observations. Daily TRMM 3B42 showed good performance in detecting rainy events, especially for light and moderate intensity rainfall events. TRMM 3B42 overestimates rainfall intensities except in the uni-modal region where rainfall intensities are underestimated. Rainfall seasonnality, as well convective zone are well reproduced by the TRMM datasets. Overall, the skill of TRMM 3B42 decreases for increasing precipitation intensities.

Key words: TRMM 3B42, TRMM 3B43, rain gauge, synoptic weather station, satellite based rainfall

1 Introduction

Climatic excess and deficit rainfall associated with floods and droughts respectively, greatly impact socio-economic activities such as agriculture and water resource management, as well as on human livelihoods, particularly in developing countries with agriculture-based economies and vulnerable populations. Therefore, rainfall plays many important roles in

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the Earth system, including being the primary source of freshwater, defining conditions for diverse ecosystems, and enabling economic activities. As such, rainfall information from any given hydrological system is of crucial importance (Munzimi et al 2015), characterizing Congo Basin rainfall and climate using Tropical Rainfall Measuring Mission (TRMM) satellite data and limited rain gauge ground observations. With shifting seasons, increasing water scarcity, and potentially more frequent and intense extreme events (Change 2007; Field et al 2012), climate change is bringing a series of disasters and livelihood impacts to the poorest and most vulnerable countries and communities, and is placing development assistance at risk. Over the past decades, progressively more attention has been given to converging Disaster Risk Reduction (DRR) and Climate Change Adaptation (CCA) agendas conceptually and in practice at sub-national, national, and international levels (Tom et al 2010). A good knowledge of climatic information is crucial to achieve such programs, particularly weather forecasts and climate change model-based projections. Such information are necessary for policy makers for efficient planning at national and regional scale.

The West and Central Africa regions have been identified by the United Nations as one of the nine "hot spots" of the world for environmental changes (Koster et al 2004). These regions have also experienced the largest decrease in rainfall over the past 60 years, despite a partial return to normal since 1990 (Aich et al 2013; Roudier et al 2014; Vrieling et al 2013; Yepdo et al 2009; Mohino et al 2010). In Central Africa particularly, numerous studies (e.g. Raghavendra et al 2020; Zhou et al 2014; Hua et al 2016, 2018; Jiang et al 2019) pointed out the long-term drying and rainfall decline in this region. For example, Raghavendra et al (2020) found a significant increase in the number of dry Madden-Julian Oscillation (MJO) days (3.47 days/decade) tending to intensify the large-scale drying trend over the Congo during October–March which enhances the net drying trend by 13.6% over the Congo. Zhou et al (2014) presented observational evidence for a widespread decline in forest greenness over the past decade based on analyses of satellite data and argued that the decline in vegetation greenness, particularly in the northern Congolese forest is generally consistent with decreases in rainfall, terrestrial water storage and water content. Similarly, Jiang et al (2019) showed that the dry season length in the Congo basin increased by 6.4–10.4 days per decade in the period 1988–2013 attributed to an earlier dry season onset caused by long-term droughts due to decreased rainfall in the pre-dry season (April–June).

Until the 1970s, studies have focused on the annual cycle of rainfall and variability without really understanding its inter-annual variability (Pohl 2007; Samba and Nganga 2012; Nicholson et al 2019; Vondou et al 2010a, 2010b; Sandjon et al 2012, 2014; Zebaze et al 2017; Kamsu-Tamo et al 2014). These studies have clearly demonstrated the importance of the equatorial Walker-type circulation over the Congo basin. Hua et al (2016) investigated the possible causes of the Central Equatorial African long-term drought and found that the drought results primarily from Sea Surface Temperature (SST) variations over Indo-Pacific associated with the enhanced and westward extended tropical Walker circulation associated with reduced low-level moisture transport and weaker West African monsoon. What does clearly emerge from the various studies is that factors in rainfall variability vary tremendously within equatorial Africa and that the regionalization of the factors and the factors themselves vary by season (Nicholson et al 2019). Climate and environmental monitoring in this region, by taking into account the various factors and to potentially predict future changes, require detailed knowledge of the rainfall distribution at different timescales. This was once available, as thousands of stations were operative in equatorial Africa in the mid-twentieth century. However, in most countries of equatorial Africa, the networks have continually declined since the 1970s or 1980s (Nicholson 2018; Nicholson et al 2019; Guenang and Mkankam-Kamga 2012; Sultan and Janicot 2004; Washington et al 2013). Munzimi et al (2015) stated that with station data being sparse, not covering concurrent time periods, and having incomplete time series, achieving consistency is a challenge, while Dinku et al (2007) reported that the number of rain gauges throughout Africa is small and unevenly distributed, and the gauge network is deteriorating. Satellite rainfall estimates are being used widely in place of gauge observations or to supplement gauge observations. Thus, climate model outputs and water ressource management, particularly in regions with sparse ground based observations are inherently prone to uncertainties. In such cases, validations with reanalysis data have shown promise, particularly when knowledge of the state of the atmosphere on a uniform grid is required (Mooney et al 2011). In addition to re-analysis datasets, useful rainfall estimates have been derived from space missions devoted to measuring precipitation such as the Tropical Rainfall Mission Measurement (TRMM) (Huffman et al 2001; Huffman et al 2007). Numerous studies compared these datasets with in situ observations (Roads et al 1992; Poccard et al 2000; Nicholson et al 2003, 2019; Camberlin et al 2019; Munzimi et al 2015) and evaluated Regional Climate Models (RCM)(Lowrey and Yang 2008; Flaounas et al 2010; Tchotchou and Mkankam-Kamga 2010; Igri et al 2015, 2018; Tanessong et al 2014, 2017; Komkoua Mbienda et al 2017a, 2017b; Tamoffo et al 2019a, 2019b; Fotso-Nguemo et al 2017a, 2017b), including temperature (using ERA-Interim reanalysis data) and precipitation (using TRMM data). They found that satellite rainfall products can be used as reference data for model validation without having a good knowledge on their associated errors. Poccard et al (2000) compared rainfall structures in the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) dataset and in situ observations across tropical Africa, showing that the reanalysis rainfall is closer to the observation in regions with a single rainy season per year. More recently, Munzimi et al (2015) tested and reported the use of limited rainfall gauge data within the Democratic Republic of Congo (DRC) to recalibrate a TRMM science product (TRMM 3B42, version 6) in characterizing precipitation and climate in the Congo basin. They compared and adjusted Rainfall estimates from TRMM using ground precipitation data from 12 DRC meteorological stations from 1998 to 2007. They found that version-6 TRMM 3B42 data are appropriate for quantifying Congo basin rainfall regimes and for deriving climate maps when calibrated by ground gauge datasets from within the region and that the version-7 TRMM 3B43 product accurately depicted Congo basin precipitation without bias. Nicholson et al (2019) evaluated a set of satellite rainfall products and the Global Precipitation Centre Climatology (GPCC) gauge dataset over the Congo basin for the 1983–94, and 1998–2010 periods. They found a good linkage between several products in respect with in situ data. Furthermore, they stated that the performance of the products evaluated is notably poorer in recent years (1998–2010), when the station network is sparse, than during the period 1983–94, when the dense station network provides reliable estimates of rainfall. In their study, Camberlin et al (2019) made an intercomparison of seven gridded rainfall products incorporating satellite data over Central Africa. They reported that there is an overall good reproduction of the mean rainfall regimes and the spatial patterns of mean annual rainfall, though some discrepancies exist in the longitudinal distribution of rainfall along the Equator from Gabon to the eastern DRC.

While, in principle, satellite data now provide the needed spatial detail, the available satellite products have generally been validated only over eastern equatorial Africa, a region very different climatically from the Congo basin. Two validations that did emphasize the Congo basin found large discrepancies between gauge and satellite data (McCollum et al 2000; Yin et al 2004). Negrón Juárez et al (2009) and Sun et al (2018) similarly found satellite estimates of rainfall to be poor over equatorial Africa, with wide discrepancies among the various satellite products. This was particularly the case for the Congo basin.

Despite the availability of these recent works to understand climate change and variability over the Congo rainforests, the physical mechanisms involved are only partially understood (e.g., Hua et al 2018; Jiang et al 2019). This knowledge gap is further aggravated over Africa (especially the Congo) due to the relative lack of fundamental research and absence of field measurements (e.g., Washington et al 2013; Lee and Biasutti 2014; Alsdorf et al 2016) when compared to other parts of the world including the Congo's counterpart the Amazon rainforest (Alsdorf et al 2016). In addition, the case of Cameroon is more specific and challenging due to the fact that the country has five different climate regimes (hereafter called ecological zones). Unfortunetely, limitated studies investigated the Cameroon's complexity climate which belong separetely to the Congo basin and to the saharan-sahelian climate regimes, with a huge sensitivity to orography, coastal circulation and easterly waves. This study aims at evaluating the performance of TRMM datasets over Cameroon through a comparison with synoptic weather station observations. We will investigate the inter-annual, seasonal and daily distributions, evaluate the dynamics associated to rainfall types and heavy rainfall occurrences. The time period for the evaluation covers the overlap between in situ observations and TRMM data, i.e. 1998-2008 and 1998-2000, respectively. The outcomes of the study will provide insights into how synoptic weather station data and satellite-based rainfall estimates can be used optimally to characterise rainfall patterns over Cameroon's main ecological zones.

The present study is organized as follows : Section 2 presents the study area with agro-climatic zones in Cameroon. Section 3 describes the data. Section 4 provides the methodology used. Section 5 describes the major results obtained from the study and Section 6 is devoted to the discussion.

2 Study area: Agro-climatic zones in Cameroon

The study region in Cameroon (2°N-14°N and 9°E-16°E) encompasses five distinct agro-ecological zones as shown in Fig. 1 (Bele et al 2013).

The Sudano-sahelian zone encompasses the northernmost regions of the country and is characterised by mean annual rainfall of 800 mm/year. This zone is the driest with the highest temperatures and the most sunshine hours. The Guinea Savannah zone includes the Adamaoua region (mean annual rainfall approximately 1500 mm/year), characterised by high elevation and cool temperatures throughout the year. The Bi-modal Equatorial zone is the largest (average rainfall approximately 2000 mm/year, mean annual temperature approximately 25°C) and is characterised by two distinct dry seasons: a short dry season and a long dry season. The Mono-modal Equatorial zone, situated along the coast, is the rainiest with 2500 mm/year annual rainfall due to humidity from the Atlantic Ocean and sea breeze modulating temperatures. The Western Highlands zone is characterised by climatic features similar to the Guinea Savannah zone.

3 Data

3.1 *In situ Rainfall Observations: National Meteorological and Hydrological Services (NMHS) data*

Hourly rain gauge rainfall records (mm/hour) from 21 stations across Cameroon were obtained from NMHS as shown in Fig. 2 and coverage of the dataset is summarised in Table 1. Homogeneity tests were carried out to analyse the homogeneity of the stations data. The results of these tests (not shown here) show that several stations are homogeneous.

3.2 *Satellite Based Rainfall Estimates: TRMM datasets*

The Tropical Rainfall Measuring Mission (TRMM), a joint mission of the US National Aeronautics and Space Administration (NASA) and the Japanese National Space Development Agency (NASDA), provided data on precipitation in the tropics and subtropics (Huffman et al 2007). TRMM 3B42 V7 (daily rainfall estimates) and TRMM 3B43 V6 (mean monthly rainfall estimates), both on a $0.25° \times 0.25°$ grid were obtained from the NASA web site (http://trmm.gsfc.nasa.gov/) for the evaluation undertaken here.

3.3 *Climate Hazards InfraRed Precipitation with Stations (CHIRPS)*

The CHIRPS dataset (Funk et al, 2015) were developed by the U.S. Geological Survey (USGS) and the Climate Hazards Group at the University of California. Quasi-global gridded products are available from 1981 to near-present at 0.05° spatial resolution (5.3 km) and at pentadal, dekadal, and monthly temporal resolution. CHIRPS data were used in this study to represent the spatial distribution of the climatology (1983-2013) of the annual accumulated rainfall.

4 Methodology for TRMM Evaluation

The evaluation of TRMM rainfall products relative to in situ observations at rain gauges is carried out according to the weather station in the five agro-ecological zones in Cameroon because rainfall distribution is correlated with vegetation productivity and thus will allow water ressources management according to each region. TRMM data at $0.25° \times 0.25°$ grid scales containing rain gauges are compared with the in situ observations at the daily and monthly time steps. TRMM grids selected in this study are those in which the stations are located. Commonly used deterministic metrics such as mean error (ME), correlation coefficient (CC), mean absolute error (MAE), and root mean square error (RMSE) were used to quantify differences between TRMM and gauge data (Igri et al 2015). ME is simply the difference between the average satellite-based estimates and average observed rainfall, and therefore expresses the bias of the satellite-based estimates rainfall. The CC (perfect value 1) indicates the degree of correspondence between the satellite-based estimates and observed rainfall. MAE (perfect value 0) is the arithmetic average of the absolute values of the differences between the TRMM and observations. Similarly, the RMSE (perfect value 0) measures the error magnitude, but gives more weight to the larger errors.

Additionally, categorical statistics were computed (Wilks et al 2006) on the basis of 2×2 contingency table of rainfall occurrence (Table 2) where h is the number of hits (rainfall correctly detected in TRMM and observed at the gauge), f is the number of false alarms (rainfall detected in TRMM, but not observed at the gauge), m is the number of misses (rainfall observed at the gauge, but not detected in TRMM), and c is the number of correct negatives (no rainfall observed at the gauge and no rainfall detected in TRMM), with $N = h + f + m + c$, representing the total number of gauge-grid cell pairs (Ebert et al 2007) .

Categorical statistics ratio bias (BIAS), probability of detection (POD), probability of false detection (POFD), and the equitable threat score (ETS) are computed as follow:

$$BIAS = \frac{h+f}{h+m}, \quad POD = \frac{h}{h+m}, \quad POFD = \frac{f}{f+c}, \quad ETC = \frac{h-k}{h+f+m-k} \tag{1}$$

where k is given by

$$k = \frac{(h+m)(h+f)}{h+f+m+c} \tag{2}$$

The ratio bias (BIAS) is the ratio of satellite-based rainfall estimates to observed rainfall events; a BIAS score above 1.0 indicates overestimation of the number of rain events in satellite data, and a score below 1.0 underestimation (Scheel et al 2011; Cai et al 2016). POD evaluates the ability of TRMM 3B42 to detect rainfall events. POFD is the percentage of the observed no rain events, which were incorrectly estimated as rain events in the satellite data. ETS evaluates how skilful satellite-based rainfall estimates are relative to rain gauge observations, and the scores can be compared equally across different regimes.

The statistical measures above are calculated for the daily, monthly, and annual time series of TRMM-gauge pair time series data, and the results are presented and discussed according to agro-ecological zones.

5 Results

5.1 Monthly to annual timescale rainfall variability

Fig. 3 shows the mean monthly accumulated rainfall according the to five agro-ecological zones. As displayed in Fig.3, the Sudano-Sahelian is the driest zone in Cameroon. It receives approximately on average 3 months of rainfall during the African monsoonal period (Vondou et al 2010b; Tchotchou and Mkankam-Kamga 2010). The rainy season effectively starts in June and ends in September. Maximun rainfall occurs in august with over 200 mm in Garoua and Kaele. Rainfall occurrences are generally highly convective. The remaining period, ie from october to may is the dry period. This zone, which encompasses the Maroua, Garoua main cities, is the most vulnerable zone of the country to extreme events such as droughts and floods. In addition, population living in this area are the most exposed to famine (Guenang and Mkankam-Kamga, 2012; Penlap et al, 2004).

For the Highs Savannahs zone of Cameroon also called the Adamawa region, both TRMM algorithm and Ground Data (GD) in these stations (Ngaoundere, Banyo and Touboro) have similar seasonal distributions during the monsoon period, especially in august when rainfall occurrence reaches its peak. Discrepancy between these datasets is particularly more highlighted in Banyo where TRMM retrieved data overestimate the GD. The correspondence between the two datasets is more readily compared by displaying statistic scores.

Furthermore, in the Highlands zone (Bamenda, Dschang and Kundja), the global tendency is overestimation by GD. Maximum rainfall occurs in august and the dry season is identified to be in December-January-February (DJF). Ones more in this zone, there is a good agreement between TRMM algorithms and GD.

The difference between TRMM 3B43 data and GD is remarkable in the forest zones. The main feature is overestimation by 3B43. Monthly mean zonal analysis for the study period in this zone reveals that such features are persistent during the whole year. This tendency is generally less in DJF and is strongest in June-July-August-September (JJAS) when rainfall is highest as this period corresponds to the monsoon period. But, an exception behavior has been shown in the Douala station where TRMM data are underestimated all over the study period.

In addition, mean monthly comparisons between rain gauge precipitation and TRMM 3B43 for the different zones averaged from 1998 to 2008 revealed that, in general, GD showed closer agreement with 3B43 algorithms, although GD in stations in the Northernmost parts of Cameroon (Kaele, Garoua, Ngaoundere, Banyo, Touboro) have the closest agreement with 3B43 data compared to the Southernmost parts ones, specially in the uni-modal (Newsonne, Mukunje, Mpundu, Nkongsamba) and bi-modal Equatorial zones(Abong-Mbang, Akonolinga, Bertoua, Ambam, Bertoua, Ebolowa).

Fig.4 and Fig.5 represent the annual correlation and the annual bias of rainfall distribution respectively in the different stations.

As stated earlier, the global tendency is overestimation by TRMM algorithm. Both datasets statistically agree by displaying high annual correlation. For example, annual correlation in Ngaoundere station (Fig.4) is at least 0.85 during the eight years of available data (from 1998 to 2005). In Fig.5, the mean annual biases are plotted over the available data for the five zones. The biases appear to be random with either overestimation or underestimation and ranging from -18 mm to 14 mm. This analysis tends to confirm the trend seen in Fig.3. Moreover, the annual correlation (Fig.4) is generally higher than 70% in the whole study period. It can be partially concluded that TRMM has a good performance over the soudano-sahelian zone. Comparison made with other zones exhibits in general cases that the rainfall peak in this agroecological zone is the lowest one all over the four zones.

Comparatively, TRMM data more agree with the GD in sahelian zone. Fig.4 shows a good correlation coefficient between GD and TRMM datasets which reaches 0.8 on average in this zone. During the studied years, statistic parameters are significant at the level of 95% of confidence using t-test. In general, negative biases are found in Kaele and Garoua, that lead to a strong tendency to overestimation by GD, although there is a remarkably good agreement between the TRMM and GD in March-April-May (MAM) and August-September-October-November (ASON). All over this period, in the sahelian zone, TRMM shows the rainfall peak (240 mm/month) in Kaele and Garoua in August which is roughly like those provide by the GD and this month is therefore the rainiest one.

Moreover, the underestimation at Douala station is blamed to a large-fraction of warm rain (hard to detect from algorithms based on cold IR temperatures and 85 GHZ ice scattering) and changes in the TRMM rainfall estimations over land and sea (over ocean, the 37 GHZ channel allows for direct rainfall estimates). Such changes create "boundary effects" at the coast. Exception behavior shown in the Douala station in the annual distribution can also be partially attributed to sea-breeze (Vondou et al 2010b).

In the above mentioned zones, 3B43 closely matches the rain GD, except in the Bi-modal Equatorial zone (Fig.7) where 3B43 has the worst agreement. The highest negative biases are recorded in the Douala station with values reaching -110 mm/year and the highest positive biases are recorded in the Mpundu station with the values higher than 200 mm/year (see Fig.5). In general, the best agreements are obtained in the Sahel, Savannah and Highlands zones. Also, in comparison with other regions, forest zone has the poorest agreement for all the years considered. This can be caused by orographic effects or other synoptic perturbations. In uni-modal Equatorial zone, the poorest agreements with rain GD are recorded during the monsoon period, corresponding to the peak of the wet season June-July-August (JJA). This zone has the worst correlation, while for the Sahel, Savannah and Highlands regions the correlations are generally higher than those obtained in the forest zones. Overall, monthly to annual rainfall distribution in Cameroon is strongly linked to the tropical rain belt position as shown in Fig.6.

When the tropical rain belt reaches its maximum position (around 20°) in August-September, the driest region of the country (the soudano-sahel zone) receives its maximum precipitation. This feature is also noticed for the others zones of the country, especially for uni-modal distribution regions. Thus, uni-modal rainfall distribution is typically modulated by the seasonal tropical rain belt variability. Retreat and onset of the rainfall can also be explained by the tropical rain belt southernmost (minimun value) and northernmost (maximum value) positions as displayed in Fig.6. For instance, when the tropical rain belt reaches its southernmost position, especially between november and march, the whole country is in the dry season characterized meteorological phenomena such as haze and sand with visibility less than 4000 meter in average. This feature matches the TRMM data as shown in Fig.3.

5.2 Daily station rainfall

Daily time series of accumulated rainfall are presented for six (6) stations for the years 1998, 1999 and 2000 in Fig.7 and Fig.8.

Difference between daily in situ observation and TRMM precipitation over these regions can be clearly seen in the amplitude of the peak. 3B42 overestimates in situ observations by showing higher precipitation amount in all the stations for the whole period. In addition, overestimation is more pronounced during monsoon period when stations receive their maximum rainfall amount. In the meantime, daily rainfall reproduces the same features as depicted by monthly and annual time scales rainfall series for different regions. Year to year rainfall variability follow the same daily time series over all stations. The overestimation that occurs in 3B42 is largely attributed to the cold top clouds, to the retrieval algorithm that fail to consider the altitude of an object (Scheel et al 2011) .

Fig.9 shows the categorical indices for mean daily rainfall and linear regression fitting for years 1998 to 2000 for Bertoua, Garoua, Maroua, Douala, Ebolowa, Ngaoundere and Yaounde stations.

The figure has been shown in order to estimate the accuracy of 3B42 and to assess its performance in detecting precipitations amount. Numerical difference in rain amounts shows overestimation of daily rainfall as shown by a negative ME over different stations. The average error magnitude measured by RMSE and MAE depicts significant difference between 3B42 and rain gauges data. Whereas, correlations are moderate (0.5) between 3B42 and rain gauges data for all stations. The correspondence indicates the performance of 3B42 in estimating precipitations in certain extent (Cai et al 2016).

In Fig.10, we display the sensitivity of categorical indices (BIAS, POD, POFD and ETS) to the rainfall thresholds extending from 0.1 mm/day to 35 mm/day that we consider as light to heavy rainfall.

In terms of occurrences, rainy events are overforecasted by 3B42 with a BIAS (frequency bias) greater than 1 (Fig.10(a)), except for Douala station where rain events are underforecasted for rainfall threshold less than 2 mm/day. In general, the global trend is increasing in BIAS score with rainfall threshold. A sudden shift and rapid increasing is observed in BIAS trend for rainfall thresholds greater than 10 mm/day, suggesting that 3B42 capability worsens in detecting heavy rainfall. The tendency is similar for all the stations, no matter the agroecological zones. The strange behavior in Douala station could be attributed to boundary effects as mentioned above leading to cold bias. For the three remaining indices (Fig.10 (a), (b) and (c)), the global trend is a significant decreasing with an increasing threshold.

The POD is very significant (more than 60%) for light rainfall. When daily precipitation intensity increases from moderate to heavy, only less than 40% of rainfall is detected by 3B42. A close look at the POD distribution shows that 3B42 in Ngaoundere and Bertoua stations performs well in detecting heavy rainfall, with at least half of rain events detected. In general, POD indicates that 3B42 can only correctly estimate light to moderate rain events with sufficient credibility. This finding is similar to the results found by Cai et al (2016). However, POFD consistently decreases with daily precipitation intensity as shown by Fig.10 (d). Special tendency is shown by Maroua and Garoua stations, where we have a better score of POFD. No rain events incorrectly forescasted in these stations are the best even for heavy rainfall. This trend is in accordance with the good performance of 3B43 in these regions as shown in the previous sections. Moreover, satellites estimates in these regions are generally the best because they only receive rainfall during the monsoon period with is more calibrated by satellites sensors and where no boundary effects are present (no forests and no sea vicinity).

As POFD can characterize the fraction of the case that the observed no rain day is mistakenly identified as rain day by 3B42, so it is evident that 3B42 is more likely to regard no rain day as rain day incorrectly for light rain intensity. Though it shows a poorer score of POFD for light rain intensity than that for heavy rain intensity, much better scores of POD, BIAS, even the comprehensive index ETS are obtained for light rain intensity. Thus, 3B42 has a higher probability to correctly identify numerous light rain events with an improved accuracy compared to heavy rain event, as stated by Cai et al (2016). In general all stations located in forest zones (uni modal and bi modal) and in the Highland zones show scores that are lower, likely due to the mountainous terrain and related high spatial rainfall variability where stations show low spatial representativeness, introducing large uncertainties as found by (Monsieurs et al 2018; Camberlin et al 2019).

6 Discussion

Figure 11 displays the interannual Hovmöller diagrams of the monthly accumulated convective rainfall and climatology for the period 1998–2008. Two main convective precipitation cores are found around 6°N-8°N centrered on May and October and around 10°N-12°N centered on July. The core found in May is the most intensive when compared to others and the one in July is less intense than the one in October. This dynamic is consistent with the uni-modal and bi-modal rainfall distribution in the forest zones. The more important finding is that althought the convective core found in April–May is the most intensive, the rainy-season peaks in this period is drier than the rainy-season peaks in October, highlighting a seasonnality variation with respect to the stations distance to the equator where rainfall peak in the bi-modal region occurs during transitional seasons, corresponding to the northward passage of the rain belt in April and southward passages of the rain belt in October as found by Jiang et al (2019). When the tropical rain belt (TRB) is at its southernmost position, convection occurs around the 6°N with the core during the transition months (April, May) and October, consistent with the results obtained by Raghavendra et al (2018) and Munzimi et al (2015) who found that the passage of the intertropical convergence zone (ITCZ) results in two local rainy and dry seasons of varying length and intensity. The high intensity of thunderstorm in april results in less cumulative rainfall compared to the october's rainfall peak. This feature could be caused by moisture being transported deeper into the upper troposphere during April transition month (thunderstorms are more powerfull in April than in Octobrer), resulting in lesser moisture available to rain down to the surface (Raghavendra et al, 2018), an increase in virga (Sassen and Krueger, 1993) and high recycling ratio of water over the Congo Basin (e.g., Pokam et al 2012; Dyer et al 2017). Raghavendra et al (2018) also reviewed that the width (wide or norrow) and the strenght (intensity, number and area) of the TRB coupled with the expanding of the Hadley cell (Byrne and Schneider, 2016) can partly explain the occurrence of stronger updrafts and higher heights of convective cloud. Our results are also consistent with the results found by Camberlin et al (2019) where April and October are found to be the rainfall peak months for both hemispheres. In the bi-modal zone, the two rainy-season peaks are not "mirrored" or proportional (Munzimi et al, 2015). The october peak found is wetter than the april because the origin of the water vapor fluxes feeding the TRB varied by season. Suzuki (2011) stated that in April, the water vapor flux is mostly derived from the Indian Ocean via Tanzania in the congo Basin, whereas in October, the water vapor flux is supplied from within the Congo basin to whom belongs the bi-modal zone of Cameroon and some stations west of the congo basin boundaries.

Figures 12 and 13 show the spatiotemporal distribution of the 90th percentile of the monthly accumulated convective rainfall climatology (3A12) and the monthly accumulated non-convective rainfall climatology (difference between 3B42 and 3A12). It comes out that most contribution comes from convective precipitation for all months, except July, August and some extend September where the most contribution comes from stratiform precipitation, especially in the uni-modal and the Highland zone due to the vicinity of the coast (monsoon period). Even if a significant portion of tropical rainfall is stratiform, however, Schumacher and Houze Jr (2003) cited Central Africa as one of the areas where convective rain amounts are high and stratiform rain fractions are low (20%–30%). We also found most convective areas localized in the Highland and in the south of the Highs savannahs zones from March to May and in October. During the monsoon period, convective precipitatons are shifted north up to the Sudano-Sahelian zone and are attributed to the onset of the West African monsoon, which dominates the circulation between May–August (Sultan and Janicot, 2003). The uni-modal and bi-modal zones are strongly linked to the moonsson strengh, whereas the soudano-sahelian zone is most linked to Mesoscale Convective System (MCS) associated to African easterly waves activities (Nicholson et al 2003, 2019).

Furthermore, difference between total and convective precipitation (Figures 12 and 13) also shows a non negligeable contribution of stratiform rainfall in the Soudano-Sahelian (SS) zone. In fact, some cities in Cameroon have experienced flooding events, mostly in the Far north and the Littoral regions of Cameroon (located in the SS zone and the uni-modal-zone respectively) during the monsoon period (Igri et al 2015, Tanessong et al 2017). We can therefore conclude that heaviest rainfall are not always derived from tallest storms (in april and october), as found by Hamada et al (2015). Althought there is a strong correlation between convective and total precipitation, we can raise the fact that associated errors are still significant as shown in Figure 14. The Soudano-Sahelian zone shows lesser error than the others zones, while the uni-modal zone shows the highest error. The good correlation between convective precipitation abd total precipitation in SS zone explains why most rainfall in this region is of convective origin. This convective activity is consistent with the south and north tropical rain belt (TRB) displacement. Using 3A12, we compared the distribution of 3B42 and 3B43 in order to highlight the contribution of convective precipitation in Cameroon. Precipitation distribution is modulated by the tropical rainbell and the Madden-Julian Oscillation (MJO), not at the same frequency in the whole country, but with different intensity according to each ecological zone. With relation to MJO, Raghavendra et al (2020) found a significant distinction between rainfall amounts observed during the wet and dry RMM phases across different months of the year, while the migration of the tropical rainbelt strongly dictates seasonal rainfall amounts and thunderstorm activity (Nicholson 2018; Taylor et al 2018). Rainfall is typically enhanced during the wet Real-time Multivariate MJO Index (RMM) phase (phase 2) and reduced during the dry RMM phases (phases 5 and 6). The dry annual bias shown by TRMM, especiallly over the uni-modal zone could be explained by omitted rainfall events, specifically a lack of sensitivity to different types of rain by TRMM sensors. TRMM 3B42 data are also insensitive to light-rain events; such light-rain events, which are characteristic of stratiform rain in the region, are more frequent during the Congo basin dry season (Munzimi et al, 2015).

7 Conclusion

The objective of this study was to assess the correspondence between TRMM (3B42 et 3B43) and 21 weather stations unevenly distributed over Cameroon and representing different agro-climatic regions in terms of annual cycles, number and intensities of wet events, trying to point out those regions where the agreement is the best/the worst. In order to achieve this goal, deterministic and categorical metrics were used. Annual rainfall cycles showed that TRMM 3B43 slightly underestimates rainfall in the Sahel, Savannah and Highlands zones whereas it overestimates in the uni-modal and bi-modal Equatorial zones. The discrepancies are generally most pronounced in the bi-modal Equatorial zone. In general, the study showed that 3B43 closely matches rain gauge data, suggesting that the goal of the TRMM algorithm was largely achieved as stated by Debo and Kenji (2003). Therefore TRMM 3B43 can be used as reference data for validating numerical weather forecast models as a replacement of gauge data. For instance, the best agreements with rain gauge data are obtained in the Cameroon northern zone (Soudano-saharian and High Savannah) rather than for its southern counterpart leading to two majors climatic regions in Cameroon: the North region of Cameroon with the rainy season in JJA and the South region with the rainy season ranging from March to November. Meanwhile, daily 3B42 depicts a good performance in detecting rainy events with a reasonable extent, especially for light and moderate rainfall. TRMM 3B42 overestimates rain events except in Douala where rain events are underestimated and its performance decreases with precipitations intensities.

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Table 1

Summary of available in situ rainfall observations in Cameroon from 1998 to present. N.A stands for Not Available.

Station Name	Temporal Record	Lat [°N]	Lon [°E]	Station Elevation [m]
Abong-Mbang	1998-2008	3.96	13.18	693
Akonolinga	1998-2008	3.8	12.25	671
Ambam	1998-2008	2.38	11.26	602
Bafia	1998-2008	4.73	11.23	501
Bamenda	1998-2008	5.93	10.15	1668
Banyo	1998-2008	6.73	11.8	1110
Bertoua	1998-2008	4.58	13.68	668
Douala	1998-2008	4.01	9.73	5
Dschang	1998-2008	5.45	10.06	1339
Ebolowa	1998-2008	2.91	11.15	603
Garoua	1998-2008	9.33	13.38	242
Kaele	1998-2005	10.08	14.43	388
Koundja	1998-2005	5.63	10.73	1217
Kongsamba	1998-2008	4.95	9.93	816
Maroua-Salak	1998-2000	10.27	14.13	422
Newsonne	1998-2003/2005-07	4.06	9.36	N.A
Ngaoundere	1998-2005	7.35	13.25	1130
Mpundu	1998-2007	4.23	9.40	N.A
Mukunje	1998-2007	4.58	9.50	N.A
Touboro	1998-2005	7.76	15.36	500
Yaounde	1998-2000	3.51	11.28	760

Table 2

Contingency table

		Observed Rain	
		Yes	No
Estimated Rain	Yes	h	f
	No	m	c

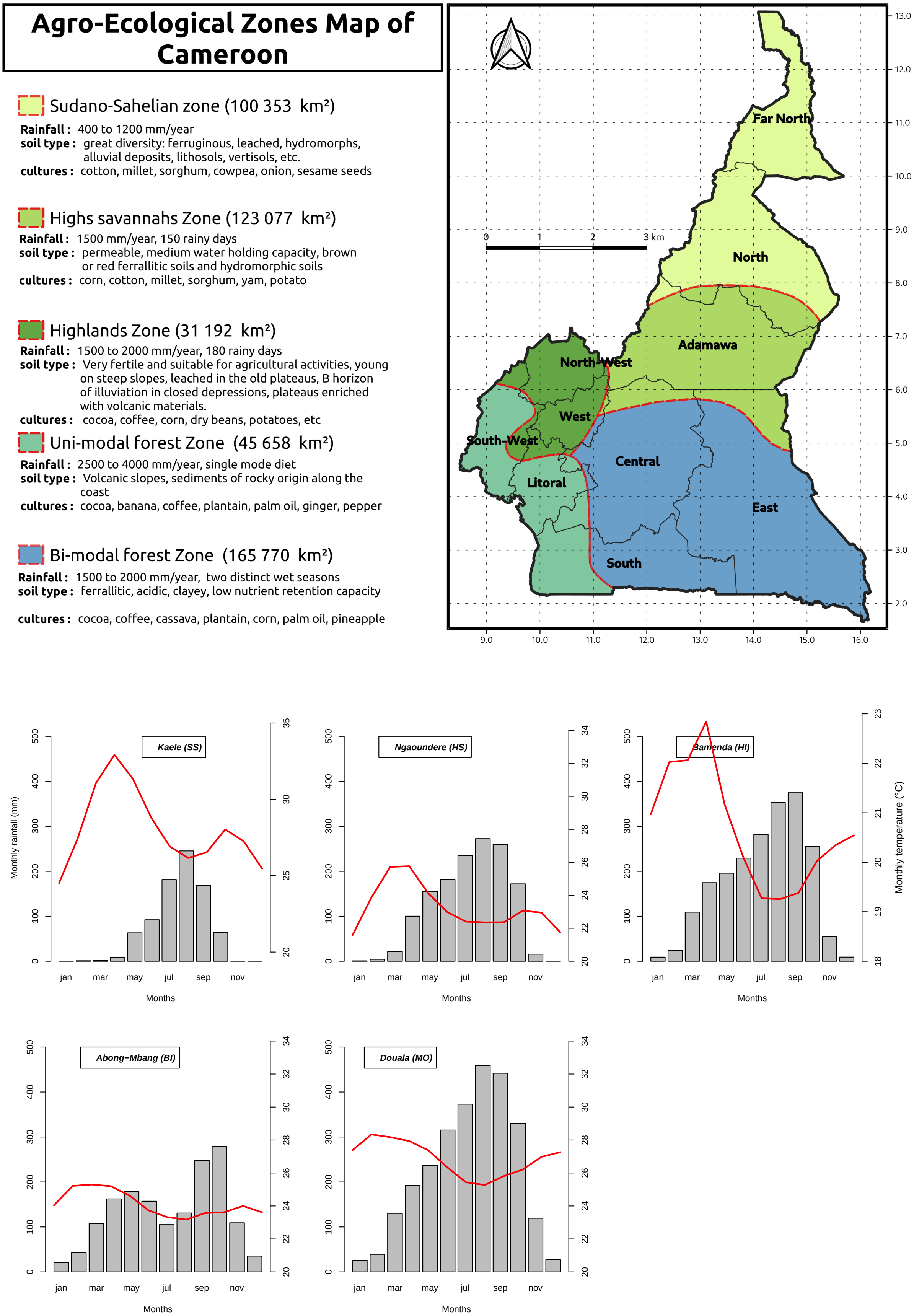

Fig. 1. Study domain with the five agro-ecological zones in Cameroon. The ombro thermic diagrams are also represented for five stations, each station representing an agroecological zone.

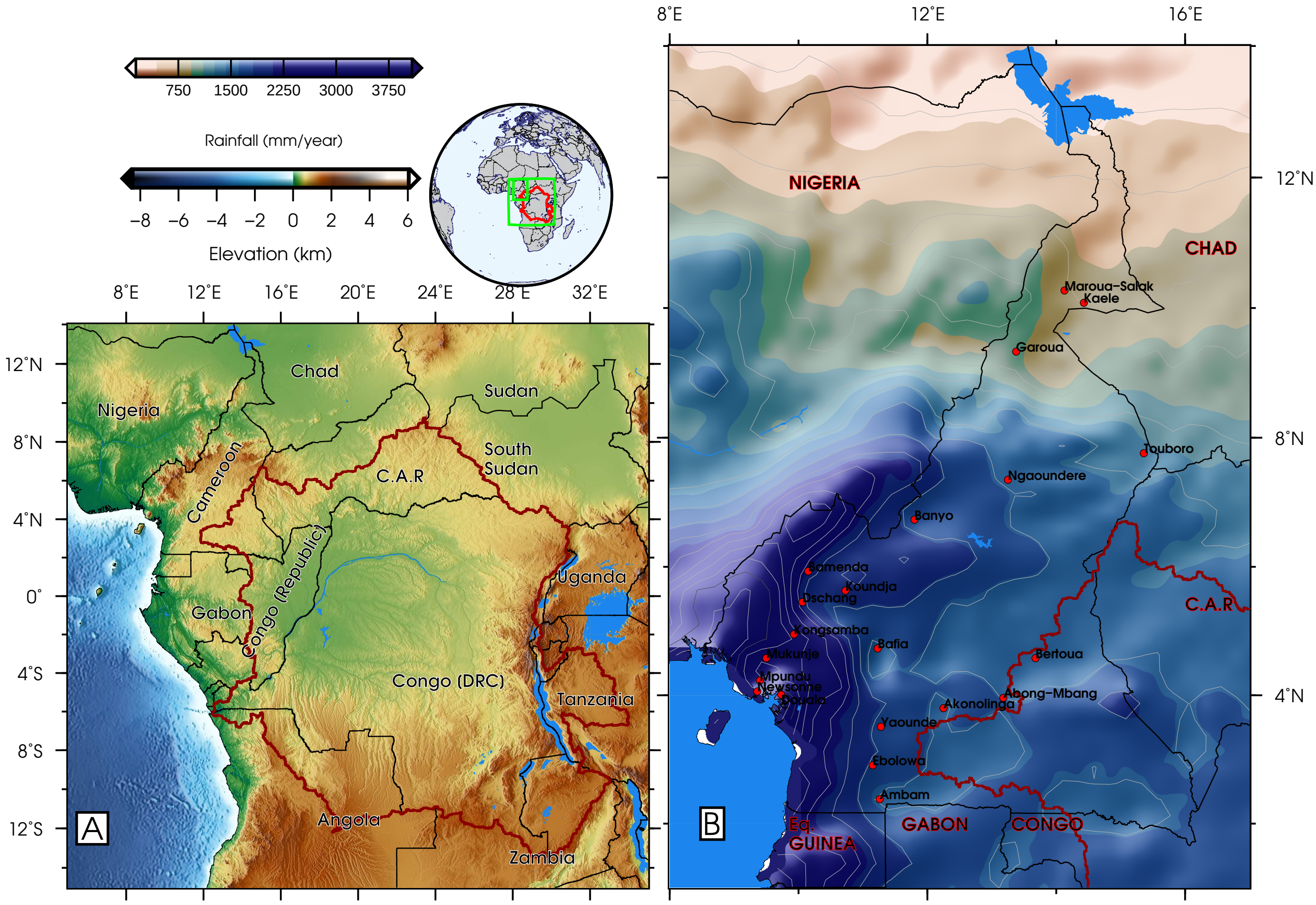

Fig. 2. (A) Study domain (Cameroon) with the Congo Basin (solid red line). (B) Geographical repartition of synoptic weather stations in Cameroon including the climatology of annual accumulated rainfall from CHIRPS data (1983-2013).

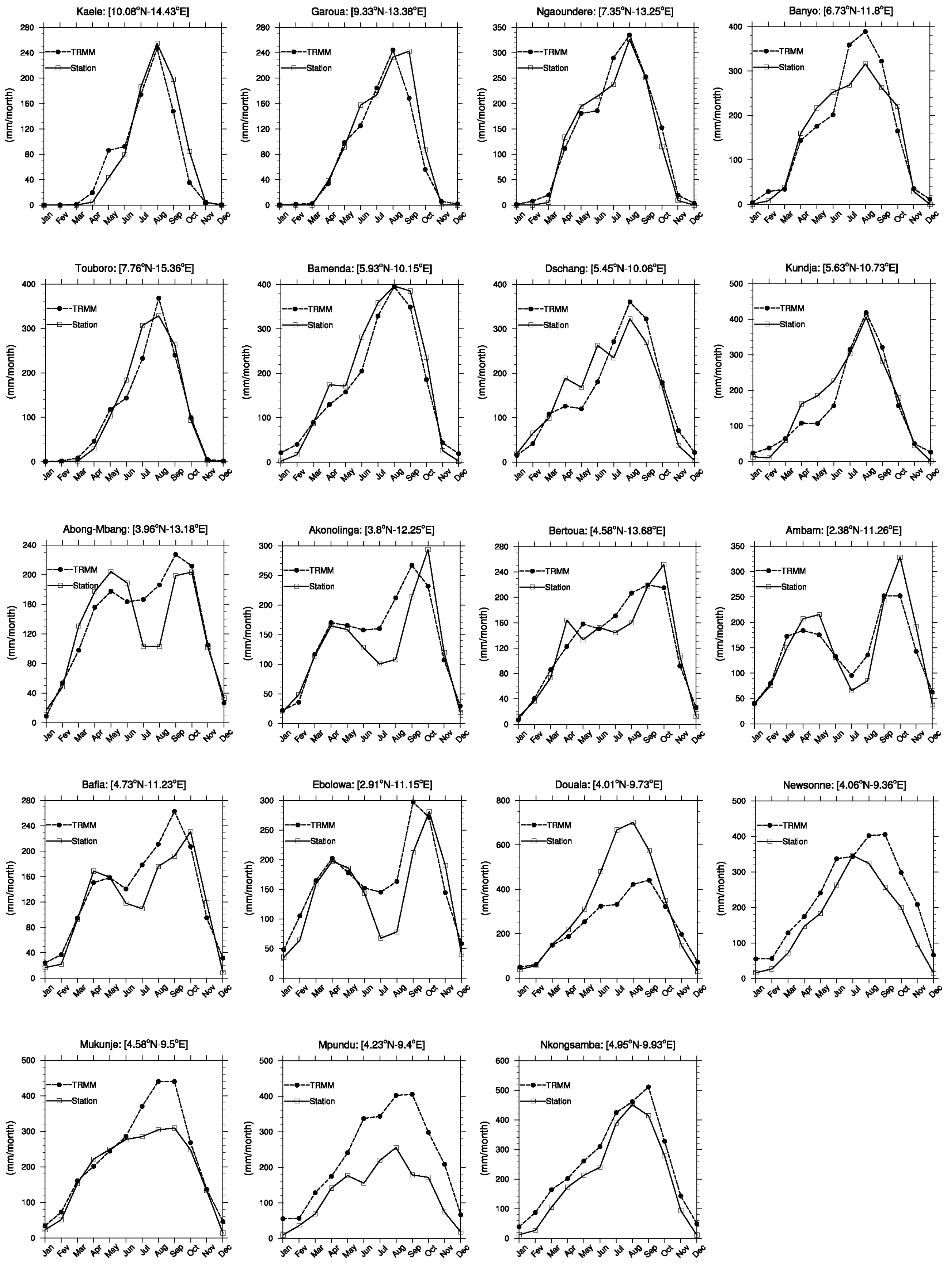

Fig. 3. Mean monthly accumulated (mm) rainfall for different stations. Stations are representative of the different agro-ecological zones as presented in Figure 2.

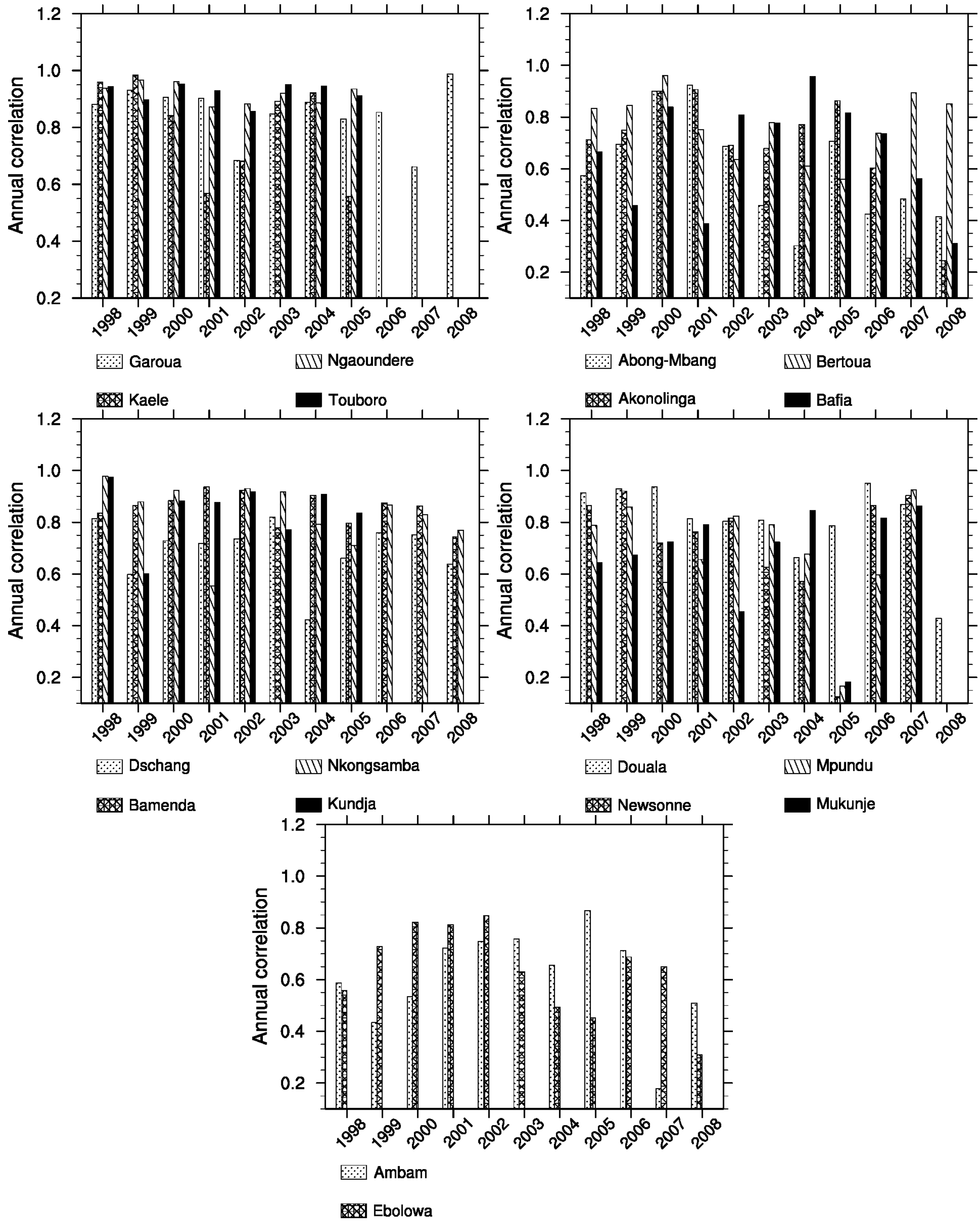

Fig. 4. Mean annual correlation for the mentioned stations.

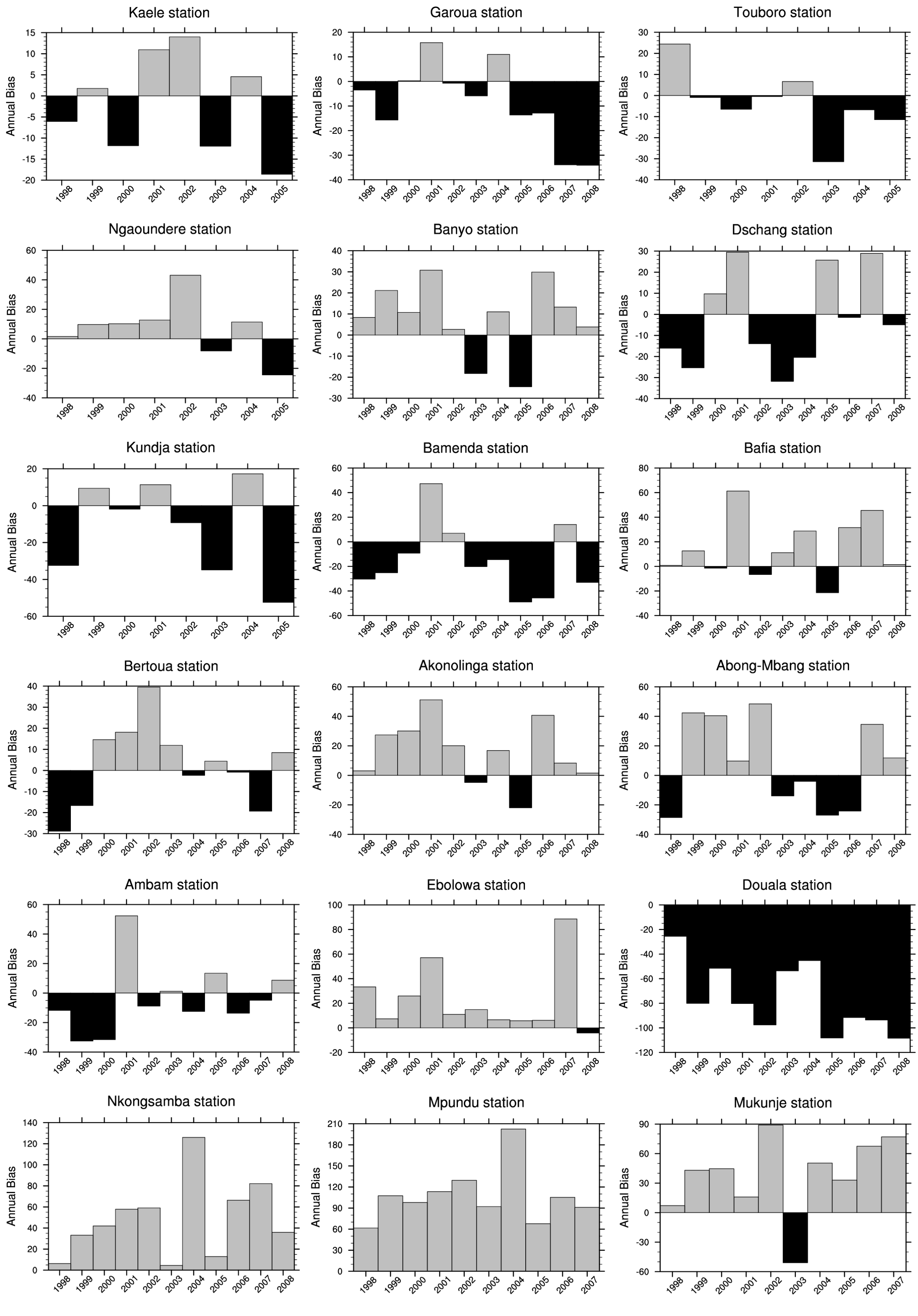

Fig. 5. Mean annual biases (mm/year) over the available data period for different stations

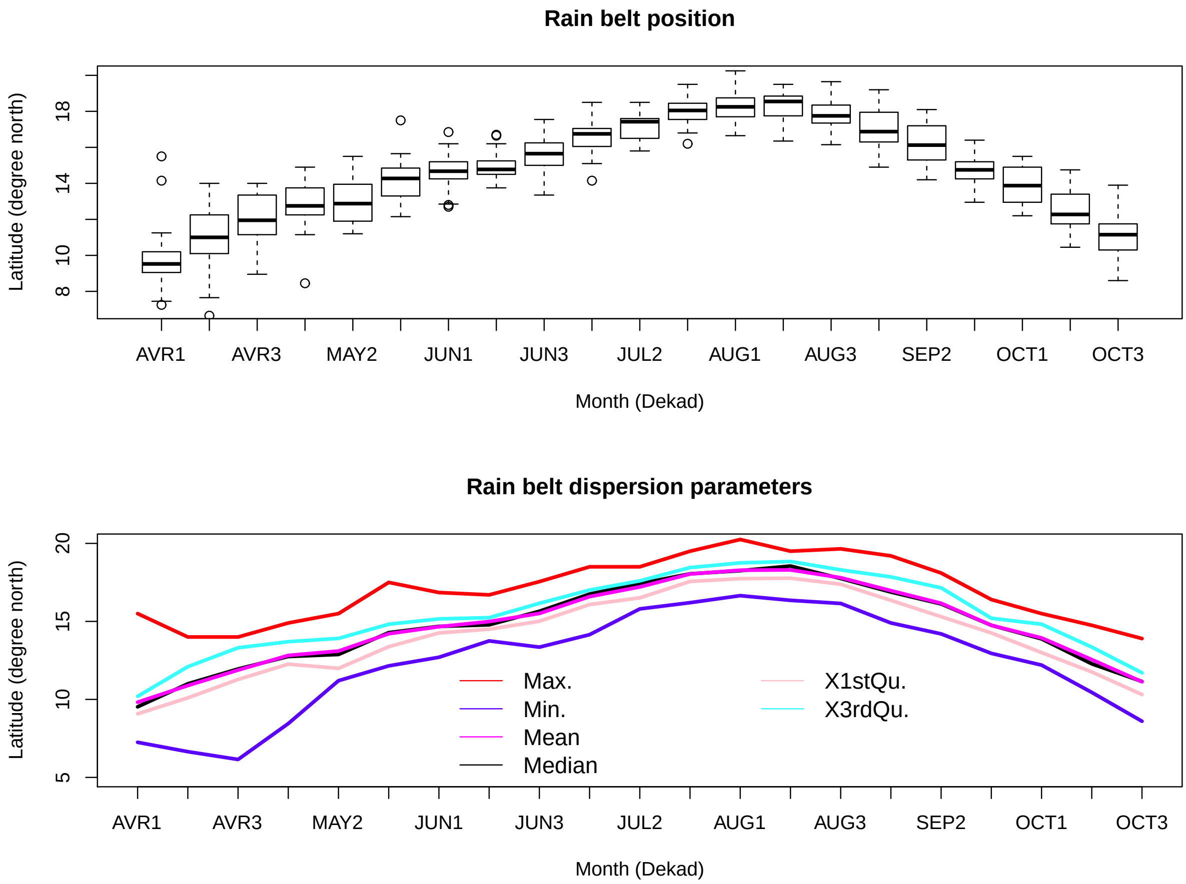

Fig. 6. Mean monthly tropical rain belt position over Cameroon for the period 1990 to 2015 between april and october (from november to early march, the tropical rain belt is localized around 5°N, its southernmost position).

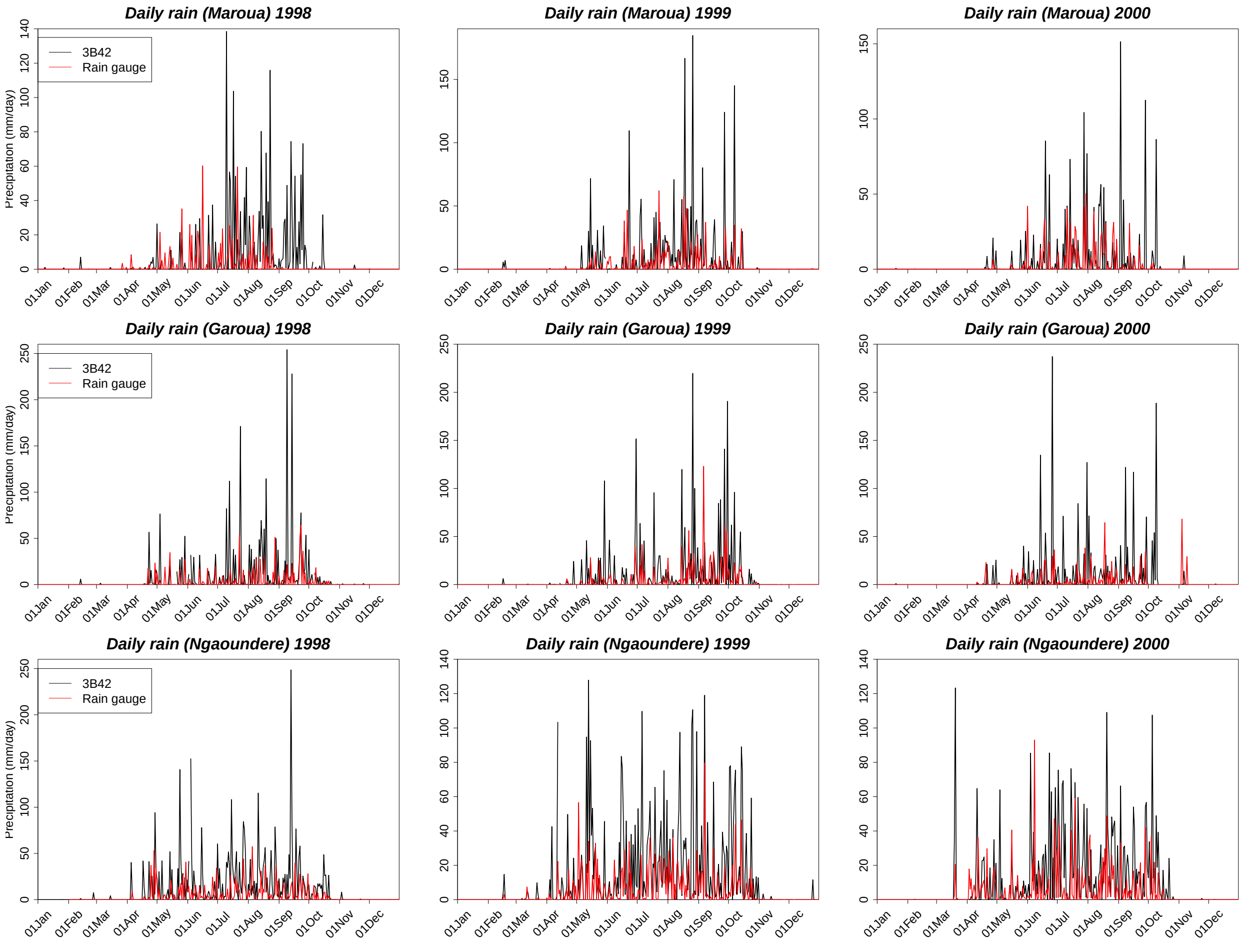

Fig. 7. Daily time series of accumulated rainfall over Maroua, Garoua and Ngaoundere for the years 1998, 1999 and 2000.

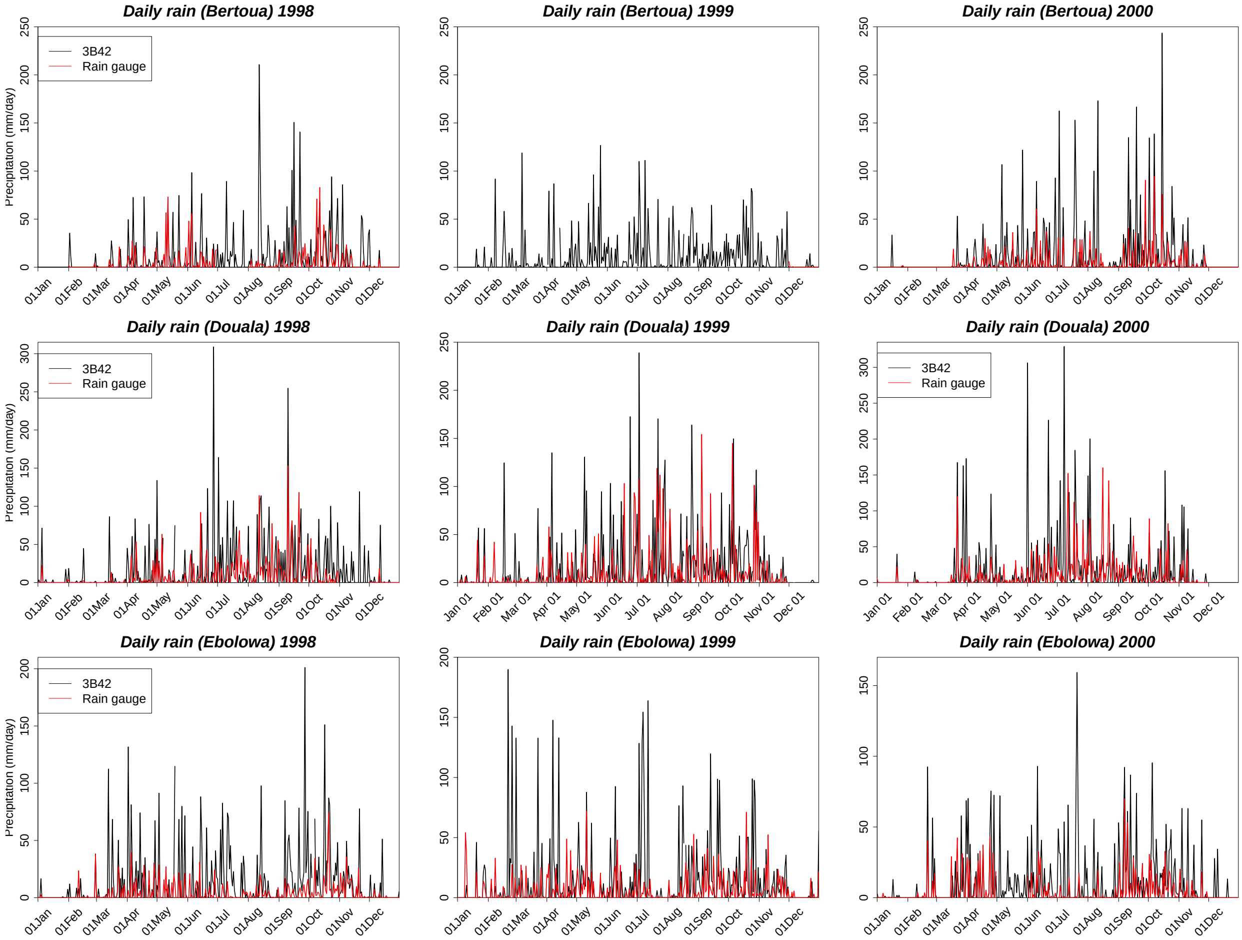

Fig. 8. Daily time series of accumulated rainfall over Bertoua, Douala and Ebolowa for the years 1998, 1999 and 2000.

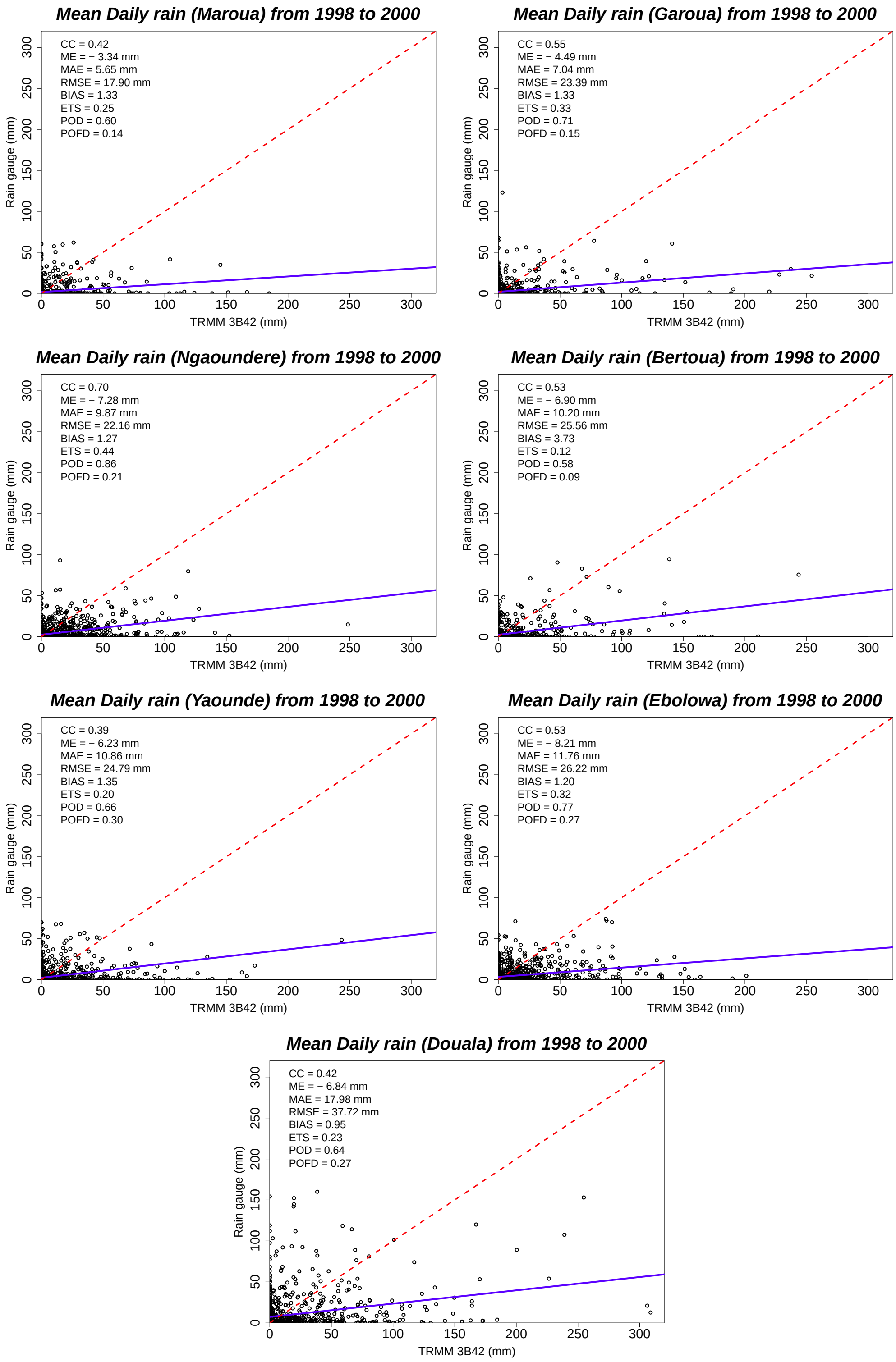

Fig. 9. Categorical indices for daily rainfall and linear regression fitting (scatter plots) for years 1998 to 2000 for different stations. Plots are shown with a threshold of 1mm/day

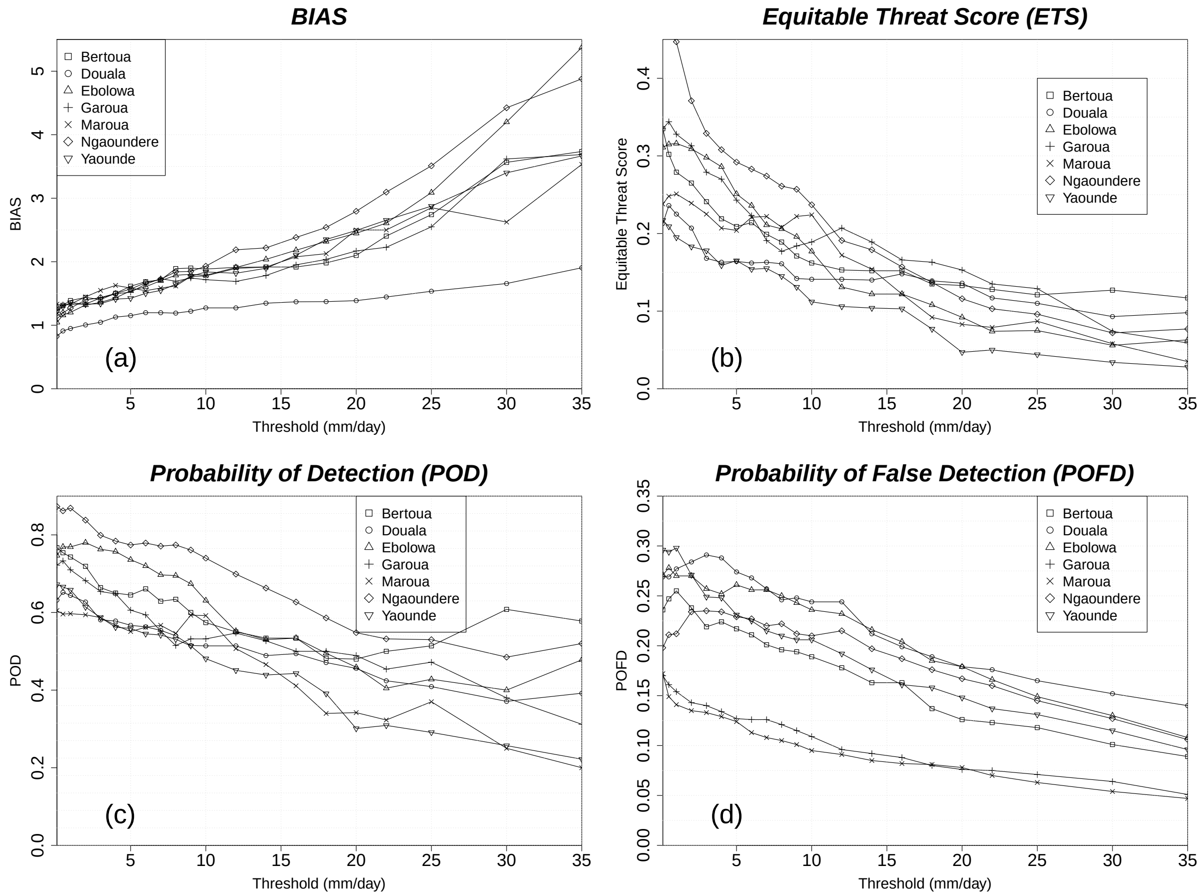

Fig. 10. Sensitivity of categorical indices (a: BIAS (frequency bias), b: ETS, c: POD and d: POFD) with different daily precipitation thresholds. Indices are computed for the available stations for the period 1998 to 2000 according to the contingency table presented in Table 2.

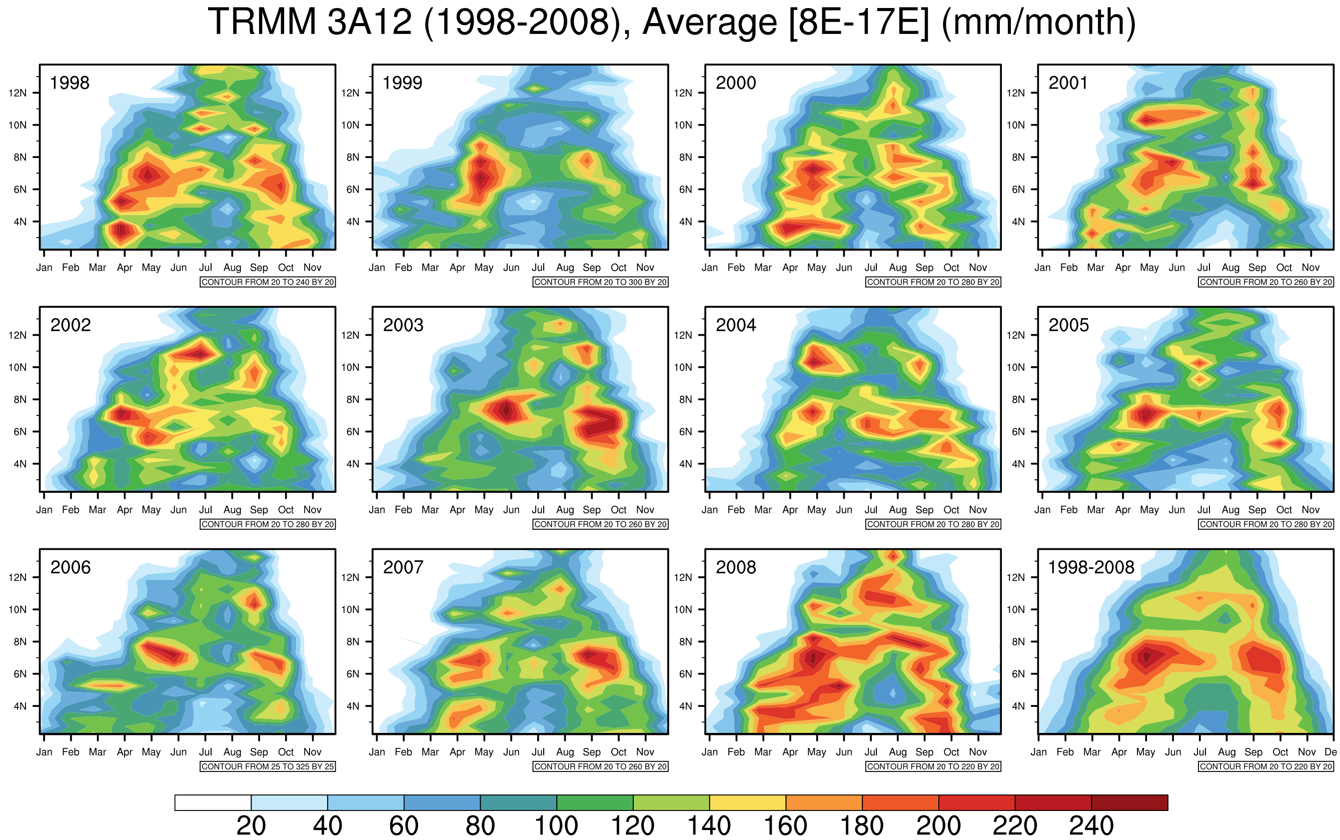

Fig. 11. Interannual Hovmöller diagrams of the monthly accumulated convective rainfall and climatology (1998-2008) from TRMM 3B12 products averaged over 8°E–17°E.

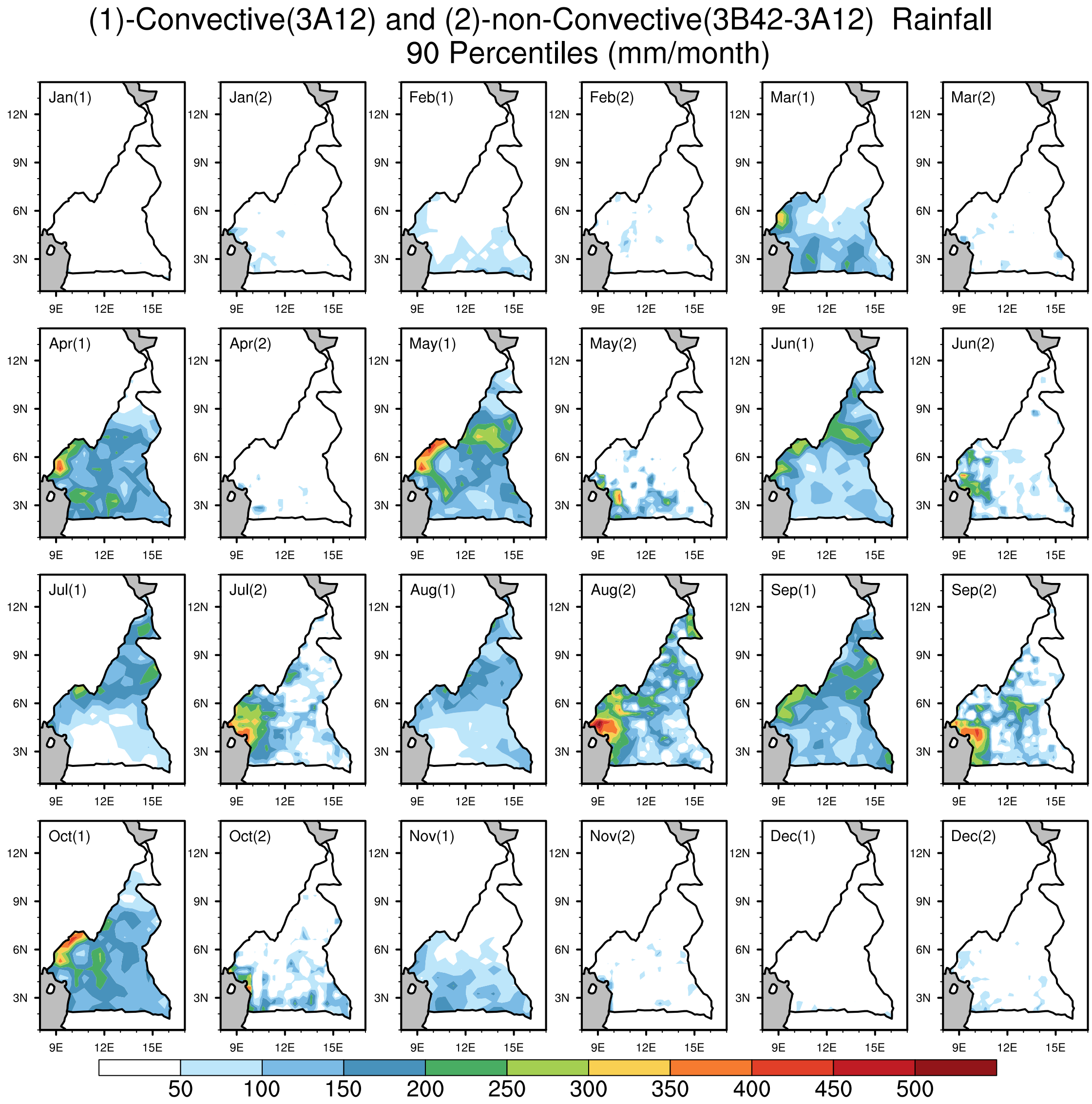

Fig. 12. Spatiotemporal distribution of the 90th percentile of the monthly accumulated convective rainfall climatology (3A12) and monthly accumulated non-convective rainfall climatology (3B42 - 3A12). The climatology is computed from 1998–2008. (1) refers to convective rainfall and (2) refers to non-convective rainfall or large scale rainfall (difference between 3B42 and 3A12).

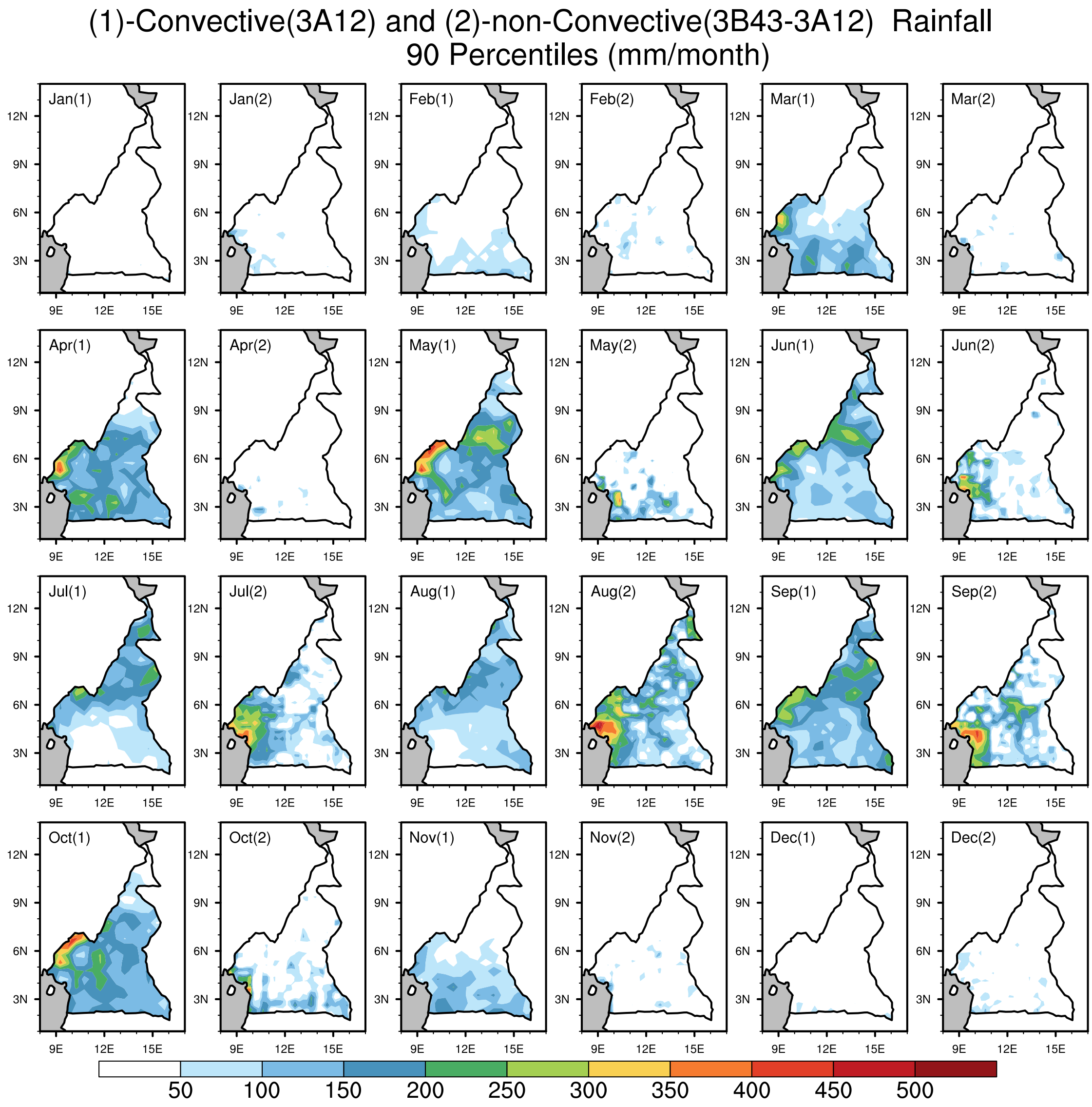

Fig. 13. Same as Fig. 12, but for 3B43.

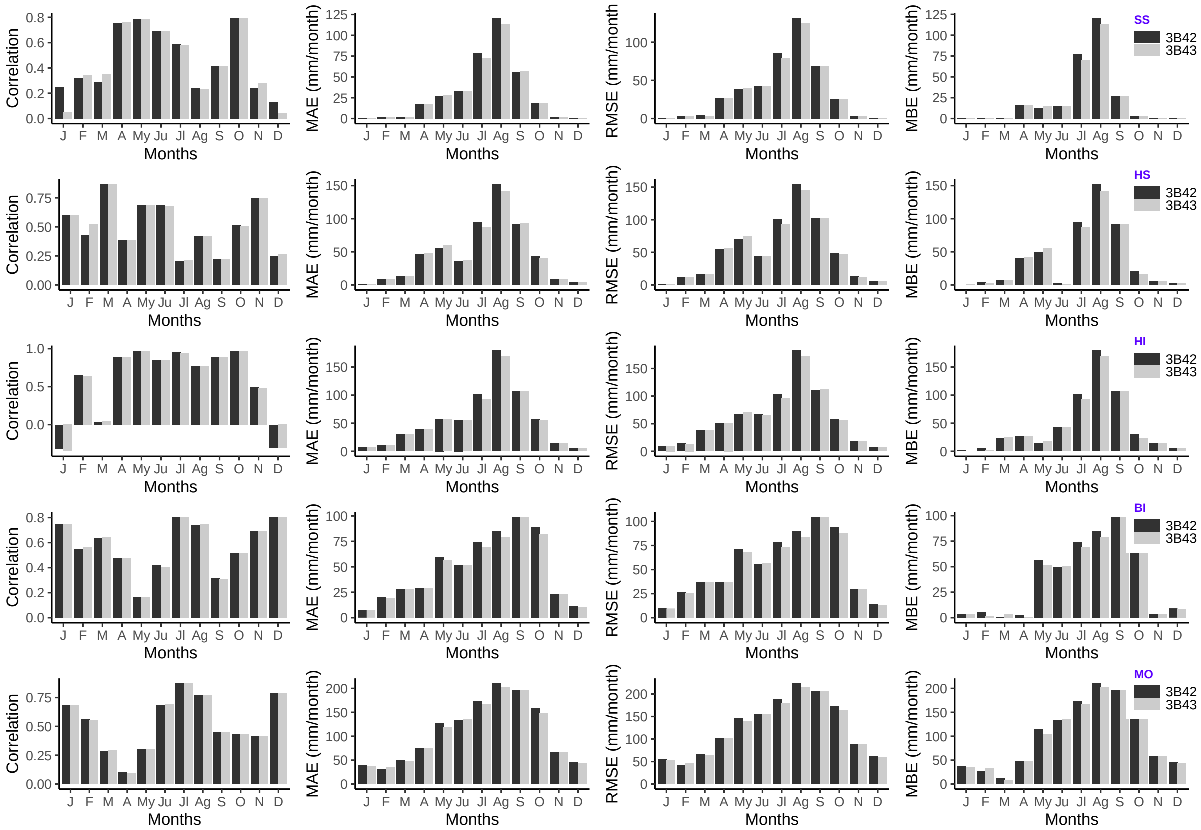

Fig. 14. Correlation, mean absolute error (MAE), root mean square error (RMSE) and the mean bias between the mean monthly accumulated convective rainfall (3A12) and mean monthly accumulated total rainfall from 3B42 and 3B43. SS : Sudano-sahelian zone, HS : Highers Savannahs zone, HI : Highlands zone, BI : Bi-modal forests zone, MO : Mono-modal forests zone