

Comparison of five gridded precipitation products at climatological scales over West Africa

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Abstract The paper aimed at assessing the capabilities and limitations of five different precipitation products to describe rainfall over West Africa. Five gridded precipitation datasets of the Tropical Rainfall Measurement Mission (TRMM) Multi-Platform Analysis (TMPA 3B43v7); University of Delaware (UDEL version 3.01); Climatic Research Unit (CRU version 3.1); Global Precipitation Climatology Centre (GPCC version 7) and African Rainfall Climatology (ARC version 2) were compared and validated with reference ground observation data from 81 stations spanning a 19-year period, from January 1990 to December 2008. Spatial investigation of the precipitation datasets was performed, and their capability to replicate the inter-annual and intra-seasonal variability was also assessed. The ability of the products to capture the El Nino and La Nina events were also assessed. Results show that all the five datasets depicted similar spatial distribution of mean rainfall climatology, although differences exist in the total rainfall amount for each precipitation dataset. Further analysis shows that the three distinct phases of the mean annual cycle of the West Africa Monsoon precipitation were well captured by the datasets. However, CRU, GPCC and UDEL failed to capture the little dry season in the

month of August while UDEL and GPCC underestimated rainfall amount in the Sahel region. Results of the inter-annual precipitation anomalies shows that ARC2 fail to capture about 46% of the observed variability while the other four datasets exhibits a greater performance ($r > 0.9$). All the precipitation dataset except ARC2 were consistent with the ground observation in capturing the dry and wet conditions associated with El Nino and La Nina events, respectively. ARC2 tends to overestimate the El Nino event and failed to capture the La Nina event in all the years considered. In general GPCC, CRU and TRMM were found to be the most outstanding datasets and can, therefore, be used for precipitation assessment over West Africa.

1 Introduction

The West African region is highly sensitive to variations in rainfall amount owing to strong dependence on rainfed agriculture for sustainable economy (Omotosho 2007; Akinsanola and Ogunjobi 2014, 2015). Therefore, accurate estimates of precipitation on varying space and time scales are important not just to the weather forecaster or climate scientists, but also to a wide range of decision makers dealing with sectors such as water resources and agriculture. In view of this, rainfall knowledge is relevant to many applications as it affects our ability to determine and understand the hydrological balance, helps to improve water management in both agriculture and power generation, and also is needed for studies on drought relief and flood awareness. Huffman et al. (2007) describe precipitation as a very complicated parameter because of its high variability at small scales. Also, De Luis et al. (2000)

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referred to rainfall as one of the key climatic variables that affect both the spatial and temporal patterns of water availability. In spite of the need for rainfall products, Africa has the lowest density of rain gauges for any continent apart from Antarctica, and operational radar installations are almost non-existent Washington et al. (2006). Because of the complex terrain in West Africa, the density of rain gauge networks is seriously limited, and the distribution is unreasonable, most especially in mountainous region. Maidment et al. (2013) noted that because of the lack of ground-based observations, indirectly calculated rainfall estimates from satellite imagery, reanalysis and Numerical Weather Prediction (NWP) model outputs assume greater importance. Globally, two types of data sources are available for precipitation: direct (surface observations) and indirect measurements (e.g., satellite, radar and micro-links). Surface observations from rain gauges are the only direct measurements; however, they are affected by systematic errors, i.e., losses due to wetting, evaporation, and aerodynamic effects (Nespor and Sevruk 1999; Porcù et al. 2014). Indirect measurements offer large spatial coverage, but they must be calibrated to obtain meaningful values, though calibration might not be enough to guarantee meaningful results in satellite estimates.

Over the past decades, tremendous efforts have been made to monitor and understand precipitating systems from space. Techniques were developed to estimate precipitation from convection based on infrared channels; then, microwave channels provided an opportunity to estimate precipitation from cloud processes; it became possible to estimate precipitation proxies with the advent of high-frequency polarized channels over terrestrial regions (Arkin and Meisner 1987; Spencer et al. 1989). Globally and most especially over West Africa, there are a number of precipitation datasets with distinct characteristics at different temporal and spatial scales, and they are helpful to study the hydrological cycle and economic activities at large scale. These datasets include; Tropical Rainfall Measuring Mission Multi-satellite Precipitation Analysis (TMPA) which provides rainfall estimates based on certain merged microwave infrared estimates such as the TRMM microwave imager (TMI), visible infrared scanner (VIRS) and TRMM precipitation radar Huffman et al. (2007); University of Delaware (UDEL) precipitation dataset, (Legates and Willmott 1990); Climatic Research Unit (CRU) at the University of East Anglia precipitation datasets (New et al. 2000, Mitchell and Jones 2005); Global Precipitation and Climatology Project (GPCP) (Huffman et al. 2010); CPC Merged Analysis of Precipitation (CMAP) (Xie and Arkin 1997); Global Precipitation Climatology Centre (GPCC) (Rudolf et al. 2010) and the African Rainfall Climatology (ARC2) (Novella and Thiaw 2013) among others. However, there is need to evaluate

rigorously these products with a view regarding operational uses of rainfall data and also to improve knowledge of the African rainfall climate (Maidment et al., 2013). This will enable estimation of the extent to which the satellite and gridded precipitation products can be relied upon to give a good database needed for the analysis of rainfall variability and will also improve our understanding of the limitations and advantages of the use of satellite and other gridded products to overcome problems associated with global precipitation measurements. It will also be relevant to the use of real time rainfall data for water management (flood warnings and river flow).

The sparseness of ground-based observations makes evaluation more difficult in West Africa than elsewhere and comparisons must be carried out using methods which take into account the problems aforementioned. Several studies have been conducted with the aim to inter-compare satellite and reanalysis precipitation derived products against reference ground observation data (e.g., Dinku et al. 2007, 2008; Thorne et al. 2001; Ali et al. 2005; Jobard et al. 2007). In West Africa, efforts have been made to inter-compare some of these rainfall products in a way to reduce discrepancies, e.g., Chapa et al. (1993); Ba et al. (1995); Nicholson et al. (2003); Nicholson (2001); Ali et al. (2005); Jobard et al. (2007); Lamptey (2008); Roca et al. (2010). Jobard et al. (2011); Pierre et al. (2011); Habib et al. (2012); Thiemig et al. (2012, 2013); Gosset et al. (2013). However, most of these works focused on a specific region, limited to single or few gridded products and were performed at low spatial and temporal resolution. Notwithstanding this, products still require in-depth validation against reference ground observations. This will increase the understanding of the quality of the precipitation products and also quantify the appropriate level of confidence in their use for different applications.

Hence, the purpose of this study is to extend the work of previous authors by assessing the capabilities and limitations of five different precipitation products to describe rainfall over West Africa using a detailed statistical and climatological focused approach.

2 Study area

The study area of this research is West Africa. The region as shown in Fig. 1, broadly lies between longitude 20°W and 20°E and latitude 0° and 20°N. Geographically, the Gulf of Guinea is the southern boundary, while to the north is the northern boundary of Mauritania, Mali and Niger. Its eastern and western limits are Mount Cameroun and Atlantic Ocean, respectively. Following Omotosho and Abiodun 2007; Abiodun et al. 2012, the West Africa domain considered in this work is divided into three

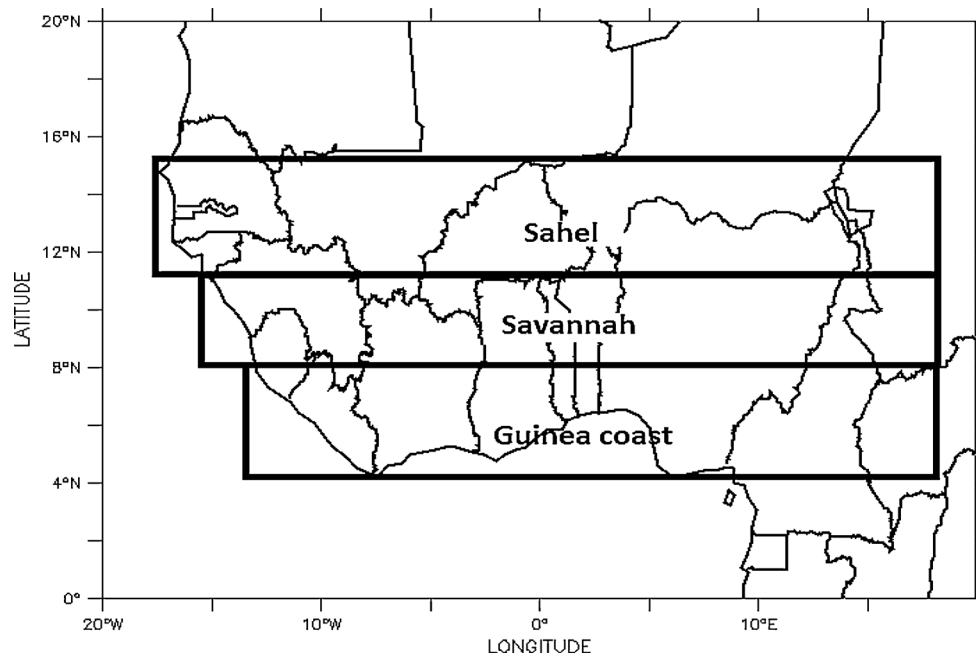


Fig. 1 West African domain divided into three climatic zones: Guinea (4°N–8°N), Savanna (8°N–11°N) and Sahel (11°N–16°N). Source: Omotosho and Abiodun (2007); Abiodun et al. (2012)

climatic zones as shown in Fig. 1: Guinea Coast (4°–8°N), Savannah (8°–11°N) and Sahel (11°–16°N). The Guinea Coast represents the southern boundary to the Atlantic Ocean which is characterized by sub-humid climate with an average annual rainfall between 1250 and 1500 mm. The Savannah zone is a semi-arid zone with an average annual rainfall between 750 and 1250 mm. However, this zone is affected by little dry season during the monsoon jump. The Sahel zone covers the northern boundary of Mauritania, Mali and Niger characterized with a single rainfall peak but short rainy season (June–September) with an annual rainfall of about 750 mm. The variability in climate of West Africa is also greatly influenced by topography and some of the most important plateaus are Fouta Djallon, Jos Plateau and the Cameroon Highland as shown in Fig. 2.

3 Data and method

3.1 Data

The precipitation products used in this study consists dataset from the: Climate Research Unit (CRU) version 3.1; Global Precipitation Climatology Centre (GPCC) version 7; University of Delaware (UDEL) version 3.01; Tropical Rainfall Measuring Mission (TRMM), Multi-Platform Analysis TMPA 3B43 version 7 and African Rainfall Climatology version 2 (ARC2). These dataset were constructed spatially and temporally by interpolation of observed and

satellite data records. In addition, the five products were selected because of the following reasons (1) they are widely used in literature and have been highlighted to be potentially useful over West Africa, (2) they have relatively high spatial resolution and long time periods (except for TRMM which was selected based on good performance as indicated in many literatures), (3) these products are easily accessible in published databases as final products.

3.1.1 Brief description of the products

The Climate Research Unit (CRU) at the University of East Anglia developed climate variables including time series of precipitation at mean monthly scales covering Earth's land areas for 1901–2014. The data is gridded to $0.5^\circ \times 0.5^\circ$ resolution and are sourced from the auspices of Global Historical Climatology Network v2 (GHCN) and CLIMAT, with approximately 4000 gauging stations globally (New et al. 1999, 2000; Mitchell and Jones 2005; Harris et al. 2014).

Similar to CRU, GPCC is the official precipitation data center of the World Meteorological Organization (WMO) World through the Global Telecommunication System (GTS) on near-real-time basis (Fuchs et al. 2007). To be comprehensive in its approach, the GPCC also integrates other global precipitation data collections from the Food and Agriculture Organisation (FAO), the Climate Research Unit (CRU) of the University of East Anglia, and the Global Historical Network (GHCN), as well as several regional data sets. These data undergo quality checks and correction procedures before gridding. Generally, GPCC have data for

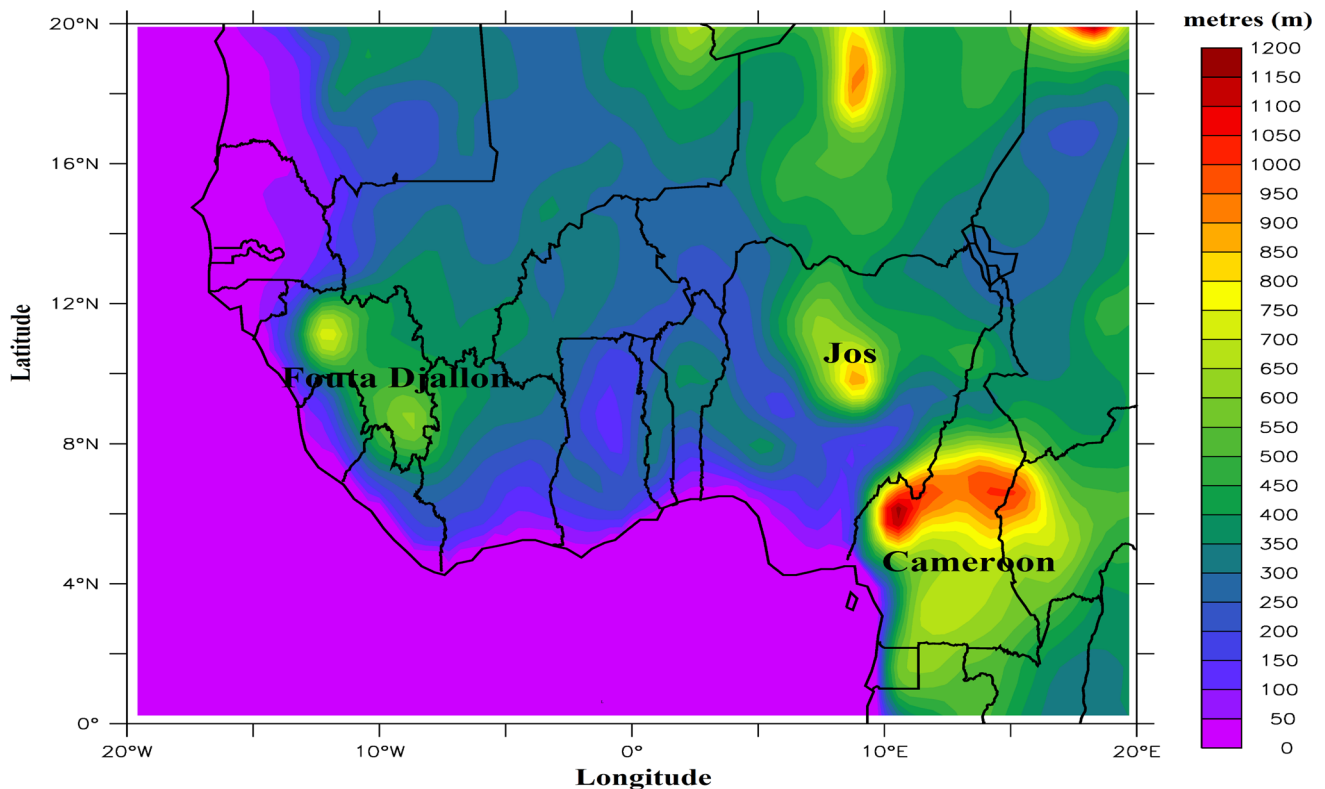


Fig. 2 The topography of the study area. [Source: Akinsanola et al. (2015)]

over 48,000 land stations and near-real-time access to 6000–7000 Synoptic Ocean Prediction (SYNOP) and conveyable low-noise infrared radiometer for measurements of atmosphere and ground surface targets (CLIMAT) reports via the WMO's GTS (Fekete et al. 2004).

Furthermore, the global precipitation dataset, UDEL was developed at the Department of Geography, University of Delaware. This dataset is based mainly on station data, ~22,000 rain gauges were used from GHCN, as well as collections of rain gauge data from a range of different data sets such as the Legates and Willmott (1990) archive for station climatologies.

The Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) version 7 (i.e., TRMMv7) dataset is a joint project between the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA). These precipitation estimates are constructed using the following procedures (1) calculation based on passive microwave measurement (PMW) systems on multiple satellites, (2) infrared measurements are used to estimate precipitation, which then is calibrated against the precipitation estimates based on PMW estimates, (3) infrared (IR) estimates are used to fill in the gaps of PMW estimates, (4) precipitation data based on ground-based radar, rain gauge and disdrometer data are incorporated and used for

calibrating the multi-satellite product from step three (Huffman et al. 2007).

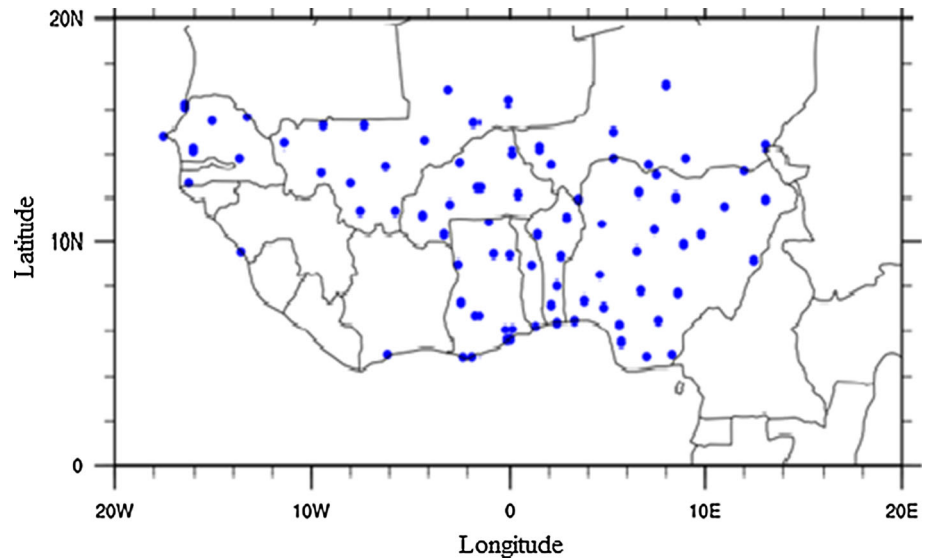
Finally, as described in (Novella and Thiaw 2013), the African Rainfall Climatology version 2 (ARC2) is a rainfall estimate with a temporal and spatial resolution of 1 day and $0.1^\circ \times 0.1^\circ$, respectively. The input to this dataset are 3-hourly infrared brightness temperature data from the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) geostationary satellites centred over Africa and the quality-controlled GTS daily rainfall reports from Africa (see Table 1 for the summary).

All the dataset used in this study were re-gridded to a spatial resolution of 0.5° by 0.5° for easy comparison using bilinear interpolation as in Nikulin et al. (2012) for easy comparison. Also to address the uniformity in the temporal span of all the dataset, the rainfall data were aggregated into monthly means over the period of 1990–2008. Furthermore, it should be noted that the averaging periods of the TRMM product is necessarily different due to the availability periods of the data (i.e., 1998–2008). However, we assume that the averaging periods of 1998–2008 is informative enough to assess systematic biases, capture year-to-year and seasonal variability, and that the observed differences between the products are dominated by the respective measurement technique rather than long-term climate variability (Hijmans et al. 2005).

Table 1 Descriptions of the data used

Product name	Data Source	Combination method	Temporal and spatial resolution	References
Reference ground observation	National meteorological services, African rainfall data base of the Institute of Geophysics and Meteorology of the University of Cologne, Germany	Quality-control	Interpolated onto a 0.5° by 0.5° grid using Thiessen polygon method, with elevation as a co-factor (1990–2008)	Sanogo et al. (2015)
Tropical Rainfall Measuring Mission (TRMM) Multi-Platform Analysis TMPA 3B43 version 7	Geo-IR, PM from TMI, SSM/I, AMSU, AMSR	Combination of PM and calibrated IR estimates, monthly scaling on ground station	Monthly 0.25° grid (1998–present)	Huffman et al. (2007)
University of Delaware (UDEL), version 3.01	GHCN2, the Atmospheric Environment Service/Environment Canada; the Hydro-meteorological Institute in St. Petersburg, GC-Net data; Greenland station records from the Automatic Weather Station Project; the National Center for Atmospheric Research (NCAR) daily India data; Sharon Nicholson's archive of African precipitation data (2001)	Quality-control, inter-comparison of the data from different sources	Monthly 0.5° grid (1900–2010)	Legates and Willmott (1990)
Climatic Research Unit (CRU) version 3.1	CLIMAT, Monthly Climatic Data for the World (MCDW), World Weather Records (WWR), National Meteorological Services, Australian Bureau of Meteorology (BoM)	Extensive manual and semi-automated quality-control measures	Monthly 0.5° grid (1901–2009)	New et al. (2000), Mitchell and Jones (2005), Harris et al. (2014)
Global Precipitation Climatology Centre (GPCC), version 7	SYNOP, CLIMAT, GHCN, CRU, FAO, national meteorological services	Quality-control, inter-comparison of the data from different sources and interpolation of the data to a regular mesh system	Monthly 0.5° grid (1901–2013)	Rudolf et al. (2010)
African Rainfall Climatology (ARC), version 2	3-hourly geostationary infrared (IR) data centered over Africa from EUMETSAT, quality-controlled Global Telecommunication System (GTS) gauge observations reporting 24-hour rainfall accumulations over Africa	Recalibration of all Meteosat First Generation (MFG) IR data, daily reprocessing using the operational RFE2 algorithm	Daily 0.1° grid (1983–present)	Novella and Thiaw (2013)

Fig. 3 Spatial distribution of the 81 ground observation precipitation data used



3.1.2 Ground observation

In a way to compare and validate the rainfall data from different products, the study used precipitation data from a reference ground observation stations. The ground observation data of 81 meteorological stations in West Africa were obtained from the archive of the African rainfall database of the Institute of Geophysics and Meteorology, University of Cologne, Germany, for the period of 1990–2008 (see Fig. 3 for the spatial distributions). This reference ground observation data have already undergone routine quality checks. However, rigorous checks were performed to further improve the quality of the data, and implemented in the following three steps: First, plots of monthly means of each station and a maximum of five neighboring stations within a radius of 100 km were inspected visually to determine if the climatology of a target station agrees with that of its neighbors. The second step involves temporal and spatial quality checks as suggested by Eischeid et al. (1995). The last part of the quality-control procedure identifies and corrects inhomogeneity in stations time series. Summarily, stations with excessive missing data, and stations whose seasonal patterns were significantly different from their closest neighbor were removed.

The quality-controlled reference ground observation data were then interpolated onto a 0.5° by 0.5° grid using Thiessen polygon method, with elevation as a co-factor. Then standardized precipitation anomalies (ratios of monthly values to the climatological mean) were interpolated using angular distance-weighted interpolation as in New et al. (2000). The interpolation techniques used here were selected after experimenting with different approaches. All the 81 stations used, passed the quality check and were used for the interpolation.

3.2 Method

Four seasons were selected to compare and study the precipitation estimates: the dry season (December–February), the pre-rainy season (March–May), the rainy season (June–August) and the post-rainy season (September–November). A comparison was performed for the three main sub-regions over West Africa in Fig. 1. For each sub-regions and season, the comparison includes a climatological description and a statistical description. The climatological description is presented by showing the spatial precipitation pattern and the time latitude cross-section, inter-annual and intra-seasonal variability and their depiction of El Nino and La Nina events. The ENSO events occurrences were sourced from the database of the Climate Prediction Center (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml).

The statistical analysis includes detailed quantitative statistics. Although wide range of evaluation statistics are available to assess data performance (Wang et al. 2003; Diro et al. 2009; Segele et al. 2008). There is, however, no single statistic that encapsulates all aspects of interest. For this reason it is useful to consider several performance statistics and also to understand the sort of information or insight they might provide. The following parameters were, therefore calculated.

3.2.1 Mean bias, MB

The mean bias provides a good indication of the mean over estimate of predictions, i.e., the difference between the sum of prediction and observation.

$$MB = \frac{1}{n} \sum_{i=1}^N M_i - O_i, \quad (1)$$

where O_i represents the i th observed value and M_i represents the i th model/satellite/gridded value for a total of n observations.

3.2.2 Root mean squared error, RMSE

The RMSE is a commonly used statistic that provides a good overall measure of how close modelled values are to predicted values.

$$RMSE = \left[\frac{\sum_{i=1}^n (M_i - O_i)^2}{n} \right]^{\frac{1}{2}}, \tag{2}$$

where all symbols are as explained in Eq. 1.

3.2.3 Correlation coefficient, r

The (Pearson) correlation coefficient is a measure of the strength of the linear relationship between two variables. If $r = 1$, then there is a perfect positive relationship between two variables while $r = -1$ implies perfect negative relationship. A correlation coefficient of 0 means that there is no linear relationship between the variables. Mathematically, the correlation coefficient (r) is given as

$$r = \frac{1}{(n-1)} \sum_{i=1}^n \left(\frac{M_i - \bar{M}}{\sigma_M} \right) \left(\frac{O_i - \bar{O}}{\sigma_O} \right), \tag{3}$$

where σ_M, σ_O represents the standard deviation of the gridded and reference ground observation data, respectively, and all other symbols are as explained in Eq. 1.

3.2.4 Coefficient of efficiency, C

There have been many suggestions for measuring model performance over the years, but the COE is a simple formulation which is easy to interpret. A perfect model has a $COE = 1$. As noted by Legates and McCabe (2012) although the COE has no lower bound, a value of $COE = 0.0$ has a fundamental meaning. It implies that the model is no more able to predict the observed values. Therefore, since the model can explain no more of the variation in the observed values than can the observed mean, such a model can have no predictive advantage. For negative values of COE, the model is less effective than the observed mean in predicting the variation in the observations.

The coefficient of efficiency based on Legates and McCabe (1999).

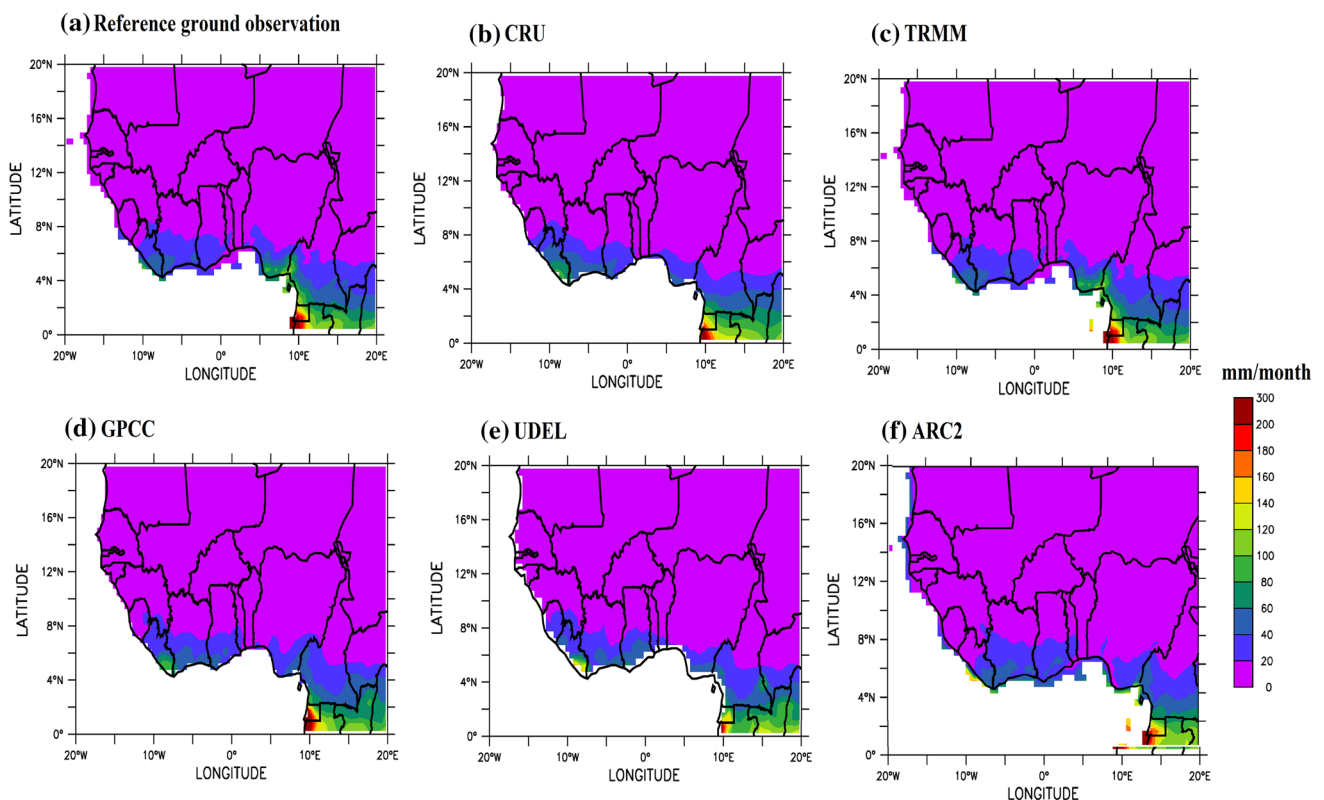


Fig. 4 Spatial pattern of mean DJF precipitation (mm/month) for **a** reference ground observation, **b** CRU, **c** TRMM, **d** GPCC, **e** UDEL, **f** ARC2 from 1990 to 2008

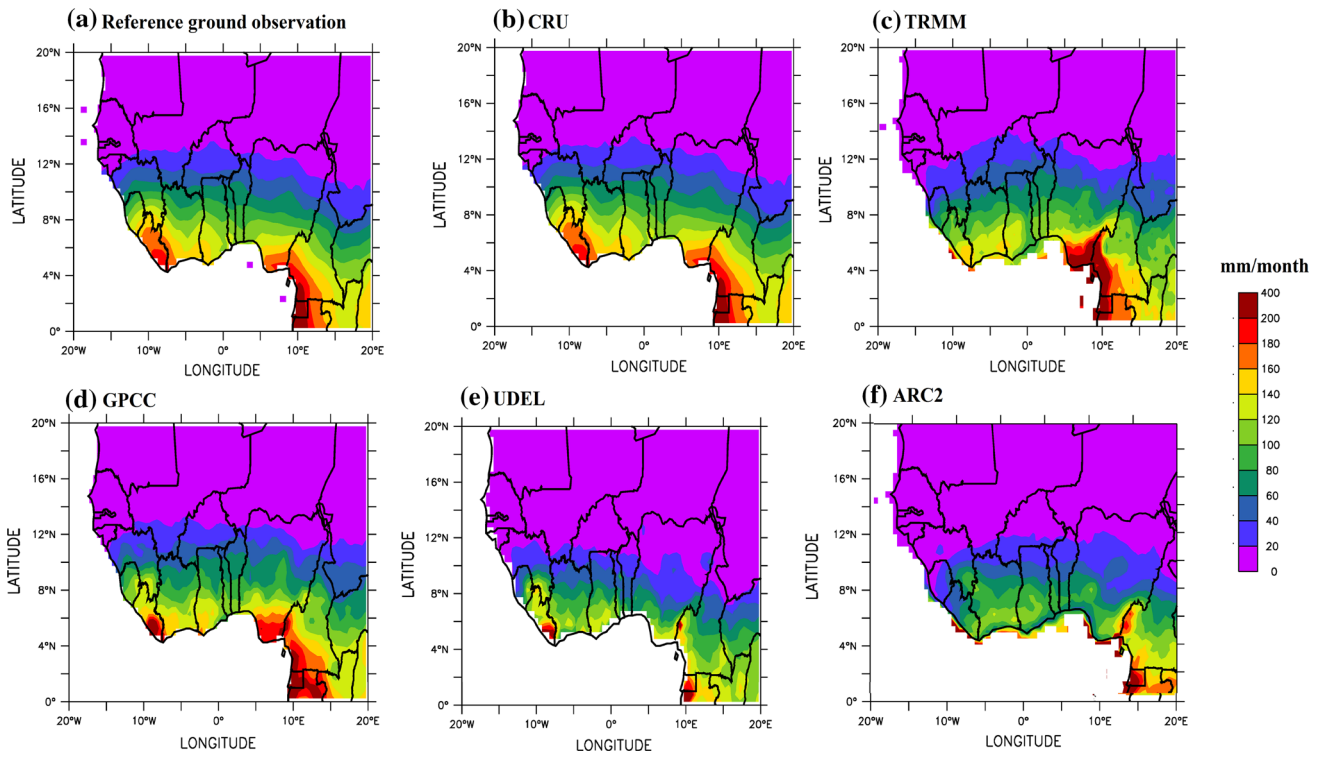


Fig. 5 Same as Fig. 4 but for MAM

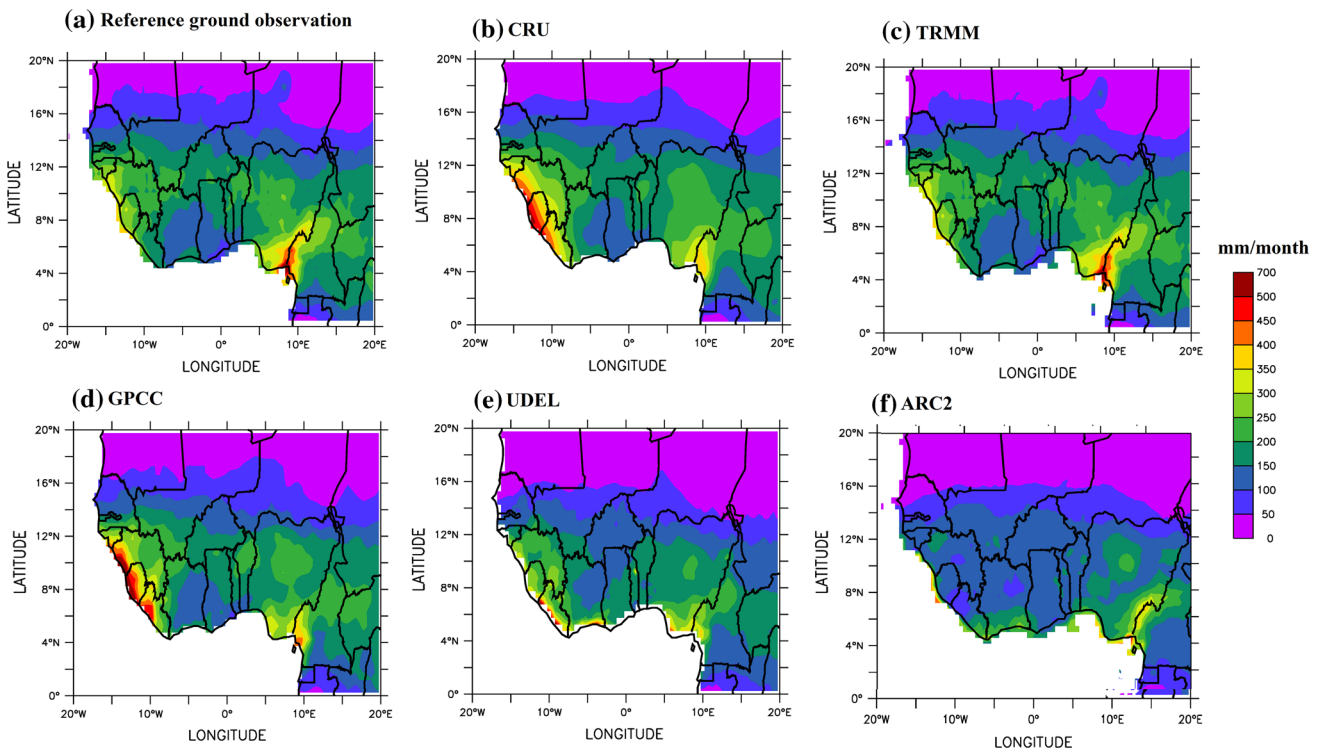


Fig. 6 Same as Fig. 4 but for JJA

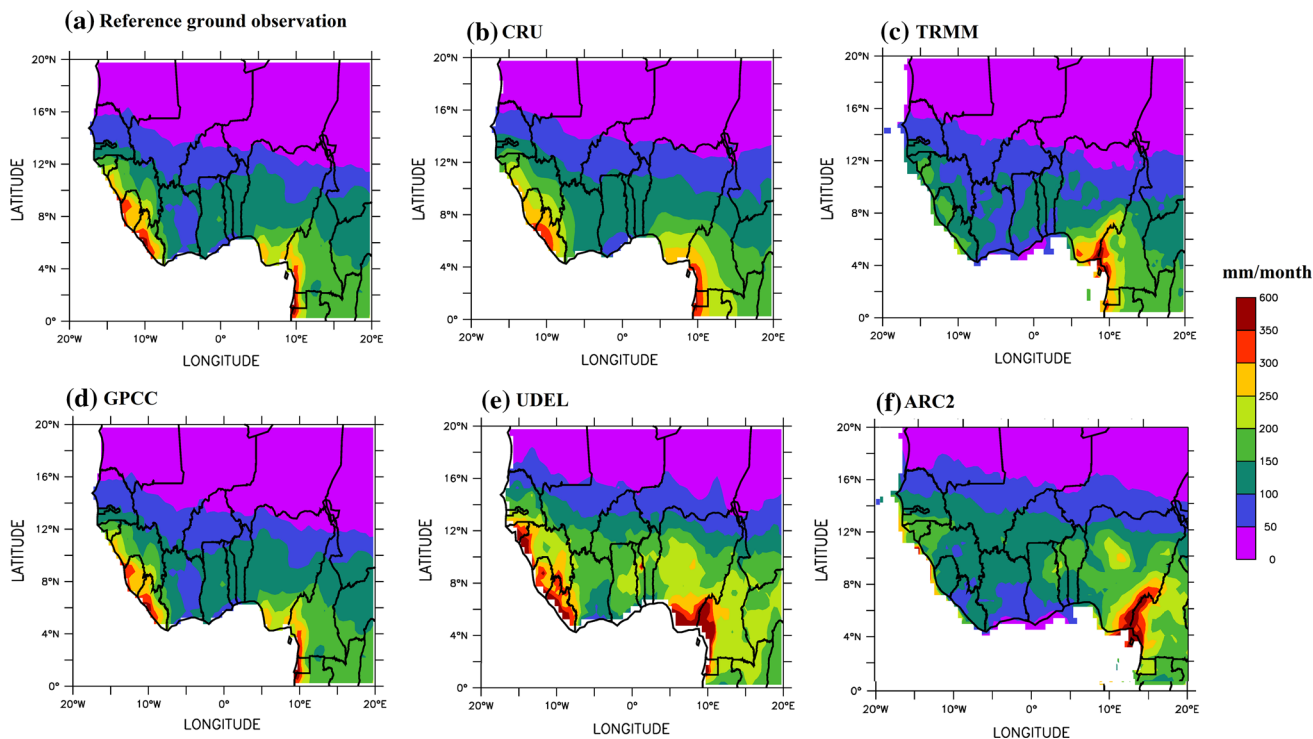


Fig. 7 Same as Fig. 4 but for SON

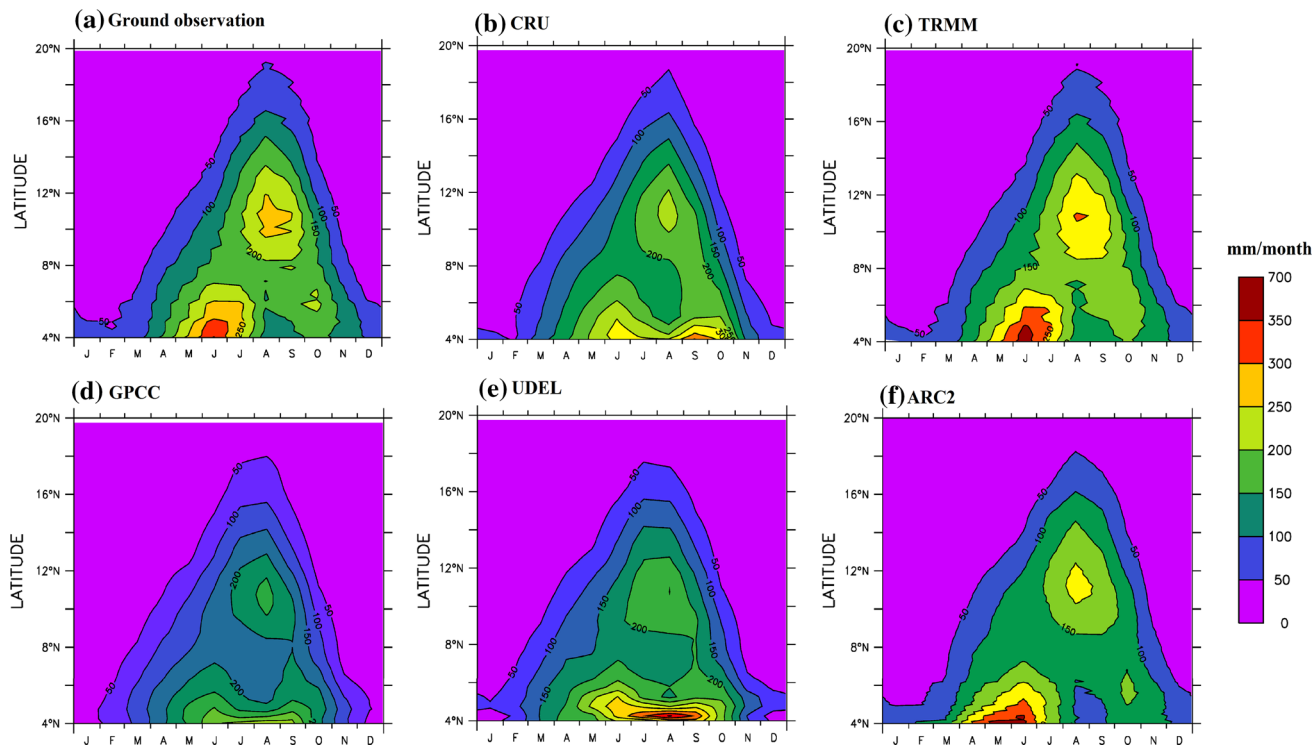


Fig. 8 Time-latitude cross-section of mean monthly rainfall (mm/month) for a reference ground observation, b CRU, c TRMM, d GPCC, e UDEL, f ARC2 from 1990 to 2008

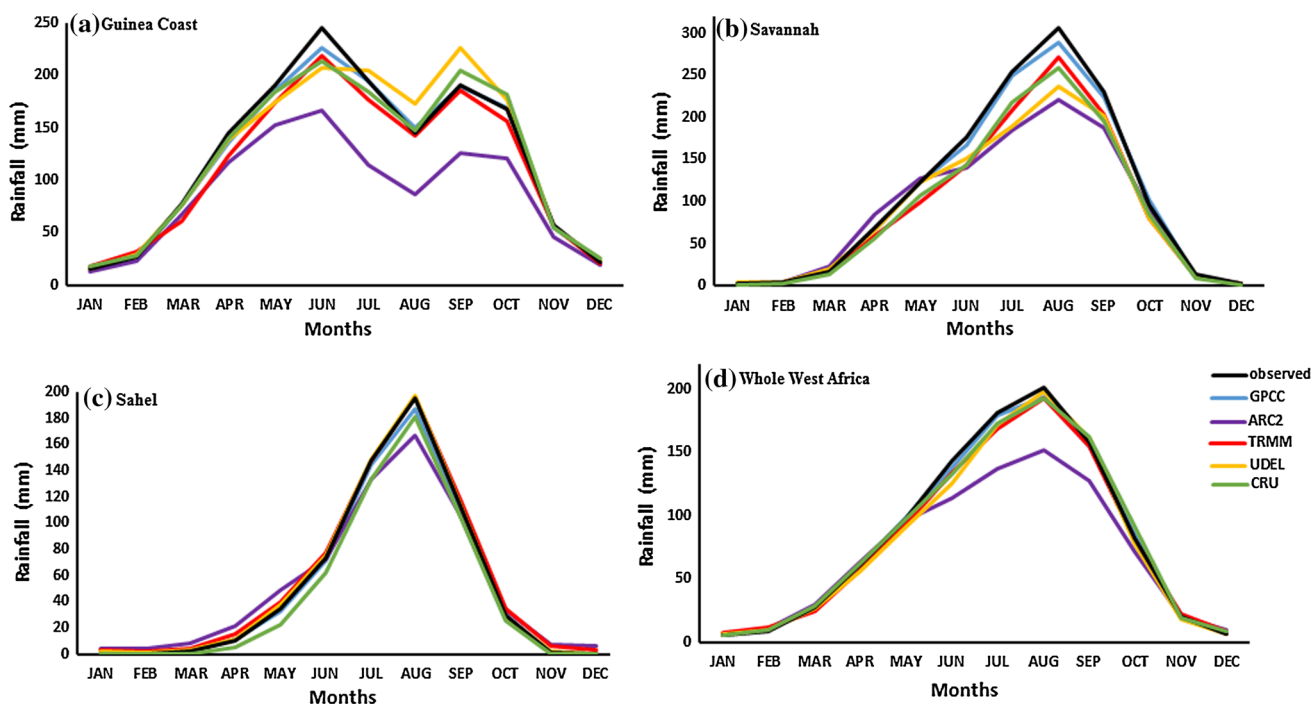


Fig. 9 Mean monthly variation of precipitation (mm) for the Reference ground observation and gridded products over a Guinea Coast, b Savannah, c Sahel, d whole West Africa from 1990 to 2008

$$COE = 1.0 - \frac{\sum_{i=1}^n |M_i - O_i|}{\sum_{i=1}^n |O_i - \bar{O}|}, \tag{4}$$

where all symbols are as explained in Eq. 1.

Also, to assess extreme events, the standardized precipitation value was calculated for all the years using the long-term mean, yearly mean and the standard deviation. The standardized anomalies reduce the influence of the mean and facilitate comparison between different areas or nonhomogeneous regions. This was done using equation

$$\varphi = \frac{x - \bar{x}}{\sigma}, \tag{5}$$

where φ represents the standardized precipitation index, x is the actual value of each parameters (rainfall), \bar{x} is the long-term mean value of each parameters (rainfall), σ is the standard deviation.

The expressions for all these statistics can be found in Wilks (2006), also the statistics were presented in Taylors diagram following, Taylor (2001).

4 Results and discussion

4.1 Assessing the spatial distribution of mean annual rainfall

In this section, the mean spatial rainfall climatology from the different precipitation products (CRU, TRMM, GPCC,

UDEL and ARC2) were assessed and compared with the reference ground observation data. The spatial distribution of the mean December–January–February (DJF) precipitation from (1990 to 2008) over West Africa is shown in Fig. 4a–f for reference ground observation and the comparison datasets. Large area of West Africa is having rainfall below 20 mm (north of latitude 8°N). However, rainfall was observed to be highest around the eastern part of the Guinea coast (about longitude 10°E). All the precipitation datasets used were consistent in capturing the decreasing rainfall from south to north. Figure 5 shows the same pattern as in Fig. 4 but for the months of March–April–May (MAM). Rainfall amount over the larger part of West Africa is observed to have increased reaching the savannah region (about 11°N), however, little or no rainfall is still highly predominant over the Sahel. The zone of highest rainfall is observed to be around the coastal part extending from Liberia towards the south eastern part of Nigeria. This observed region of low and high rainfall amount is consistent in all the datasets but the amount of rainfall attributed varies systematically to a very large extent. Furthermore, the June–July–August (JJA) precipitation pattern shown in Fig. 6 reveals that rainfall is observed over the entire West Africa domain with the Guinea coast having the highest rainfall amount. An interesting feature observed was that the zone of maximum rainfall is localized on major West Africa highlands (i.e., over the Fouta Djallon, Cameroon Mountains and Jos

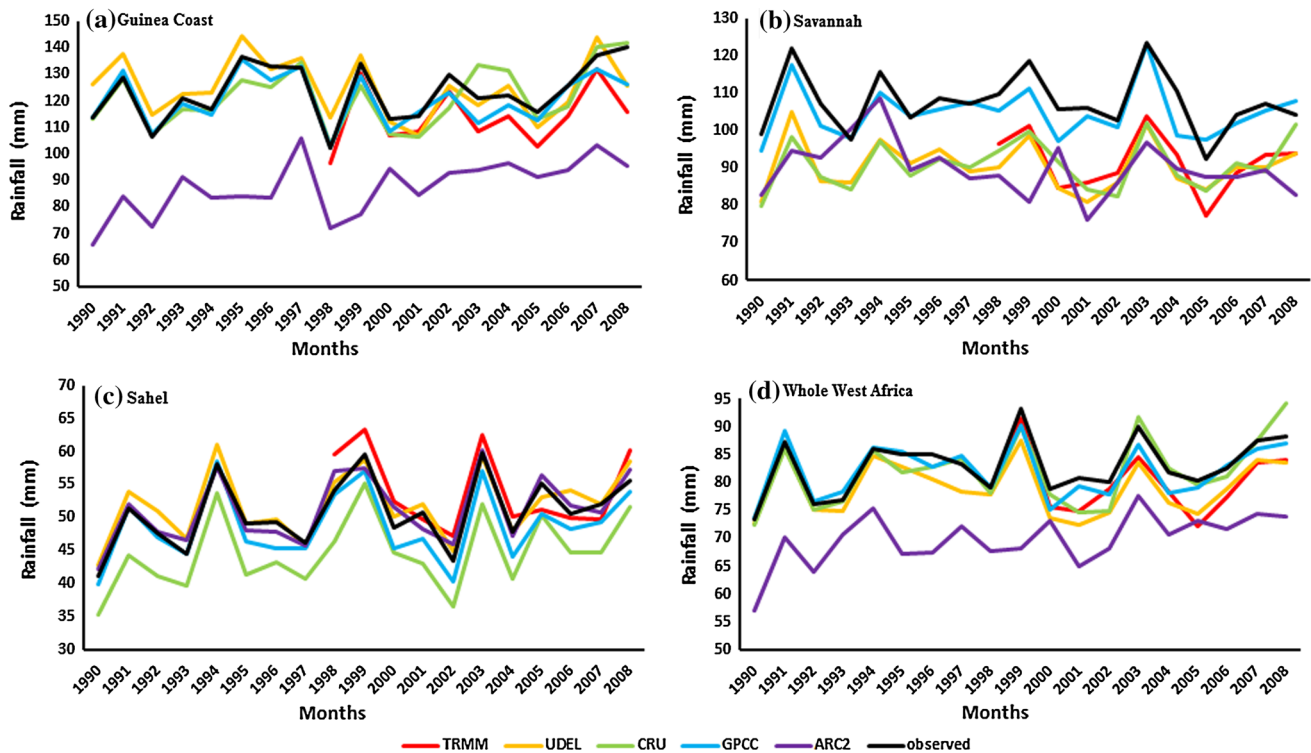


Fig. 10 Inter-annual variation of mean monthly precipitation (mm) for the Reference ground observation and gridded products over **a** Guinea Coast, **b** Savannah, **c** Sahel, **d** whole West Africa from 1990 to 2008

Table 2 Results of the trend line equation of the precipitation dataset used

Data	Guinea coast	Savannah	Sahel	West Africa
Reference ground observation	$y = 0.5955x - 1067$	$y = -0.1599x + 427.48$	$y = 0.3456x - 640.05$	$y = 0.3127x - 542.07$
CRU	$y = 0.7434x + 114.09$	$y = 0.1976x + 88.929$	$y = 0.3531x + 41.211$	$y = 0.4304x + 77.705$
GPCC	$y = 0.155x + 119.03$	$y = 0.0328x + 104.57$	$y = 0.1913x + 46.878$	$y = 0.148x + 80.665$
TRMM	$y = 0.9344x + 100.91$	$y = -0.4147x + 97.569$	$y = -0.4857x + 61.002$	$y = -0.0286x + 80.329$
UDEL	$y = -0.2919x + 128.01$	$y = -0.0716x + 91.314$	$y = 0.2676x + 49.281$	$y = 0.051x + 78.639$
ARC2	$y = 1.2039x + 75.799$	$y = -0.4495x + 94.512$	$y = 0.3543x + 47.658$	$y = 0.4691x + 65.237$

Plateau in Nigeria). In the months of September–October–November (SON) shown in Fig. 7. The amount of rainfall is observed to have reduced drastically compared to that of JJA. The orographic related rainfall maximum found over the Cameroon Mountains extends northeast–southwest, with an anvil-like shape encompassing Nigeria on the left and Lake Chad to the right. CRU, TRMM and GPCC are in near perfect mutual agreement with the observed features.

It can be concluded that rainfall decreases northward as far as the southern fringe of the Sahelian region about 16°N throughout the season. Also orography plays an important role in West Africa precipitation patterns as supported by (Jenkins et al. 2002; Jones et al. 2011; Abiodun 2003). However, it is obvious that uncertainties exist between the different precipitation dataset used, this can be attributed to the variation in the spatial resolution of the dataset and

also, strong degree of rainfall enhancement by coastal effects (Ba et al. 1995; McCollum et al. 2000; Nicholson et al. 2003).

4.2 Intra-seasonal and inter-annual variability of West African climate

The West Africa monsoon exhibits three distinct phases: the onset, the high rain period and the eventual southward withdrawal of the monsoon rain band (Le Barb'e et al. 2002; Sultan and Janicot 2003; Zhang 2007). Such behavior is best characterized by a time latitude cross-section (Hovmoller diagram). Figure 8 shows the time-latitude cross-section of the monthly mean rainfall from latitude 4° to 20°N, averaged between longitude 20°W and 10°E from 1990 to 2008. The plots provide a robust

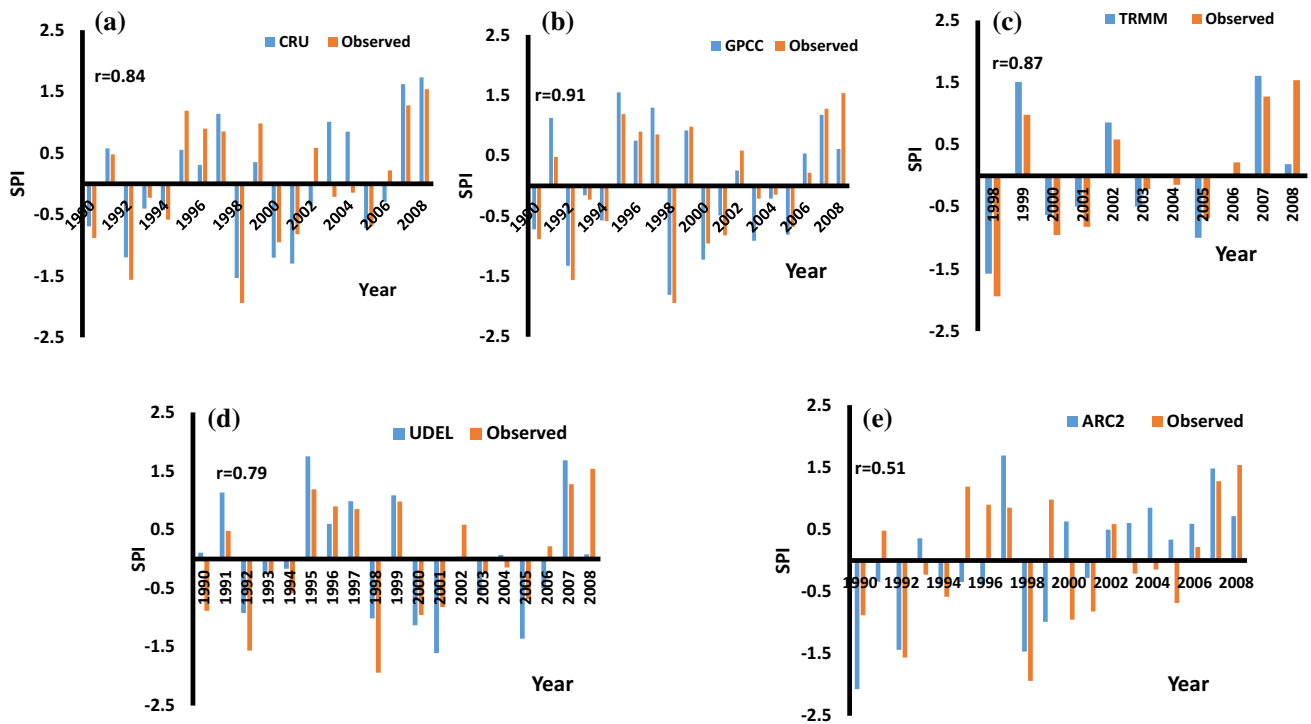


Fig. 11 Inter-annual variability of standardized precipitation anomalies of the reference ground observation data compared with **a** CRU, **b** GPCC, **c** TRMM, **d** UDEL, **e** ARC2 over the Guinea coast from 1990 to 2008

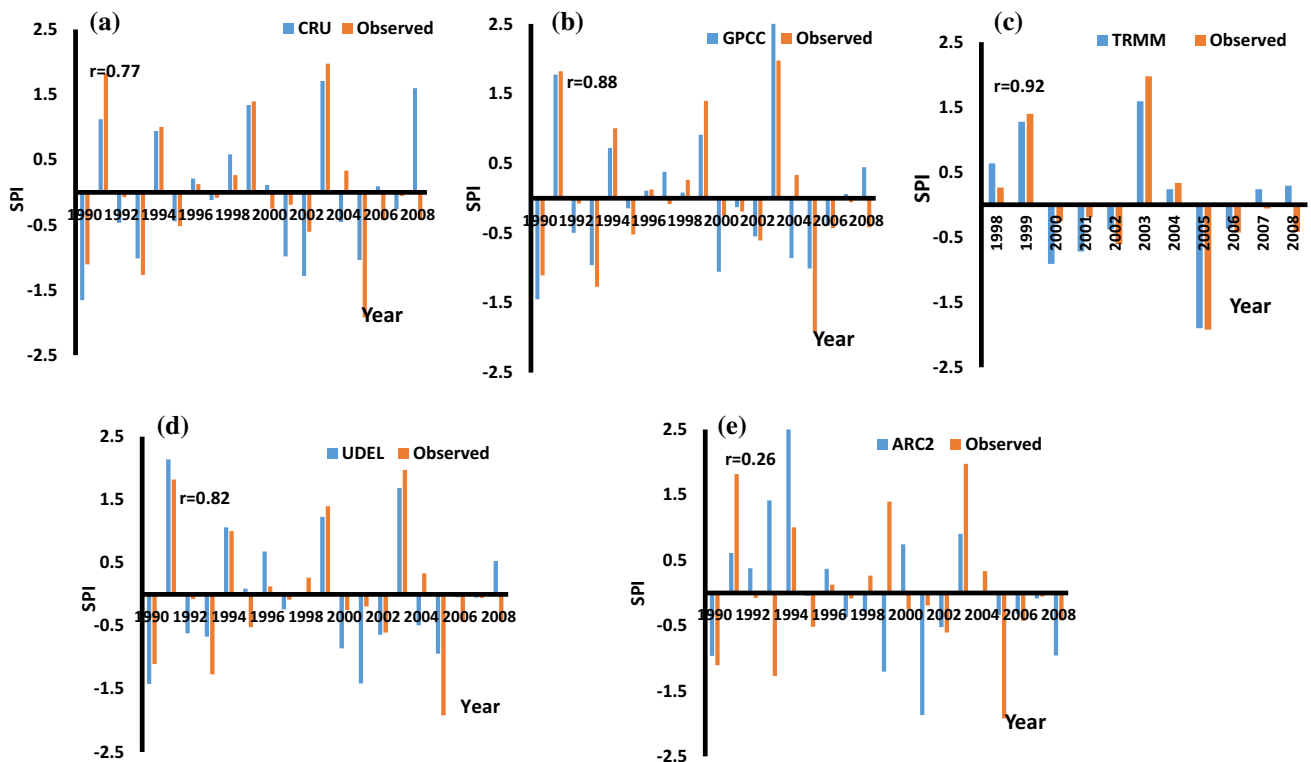


Fig. 12 Same as Fig. 11 but for Savannah

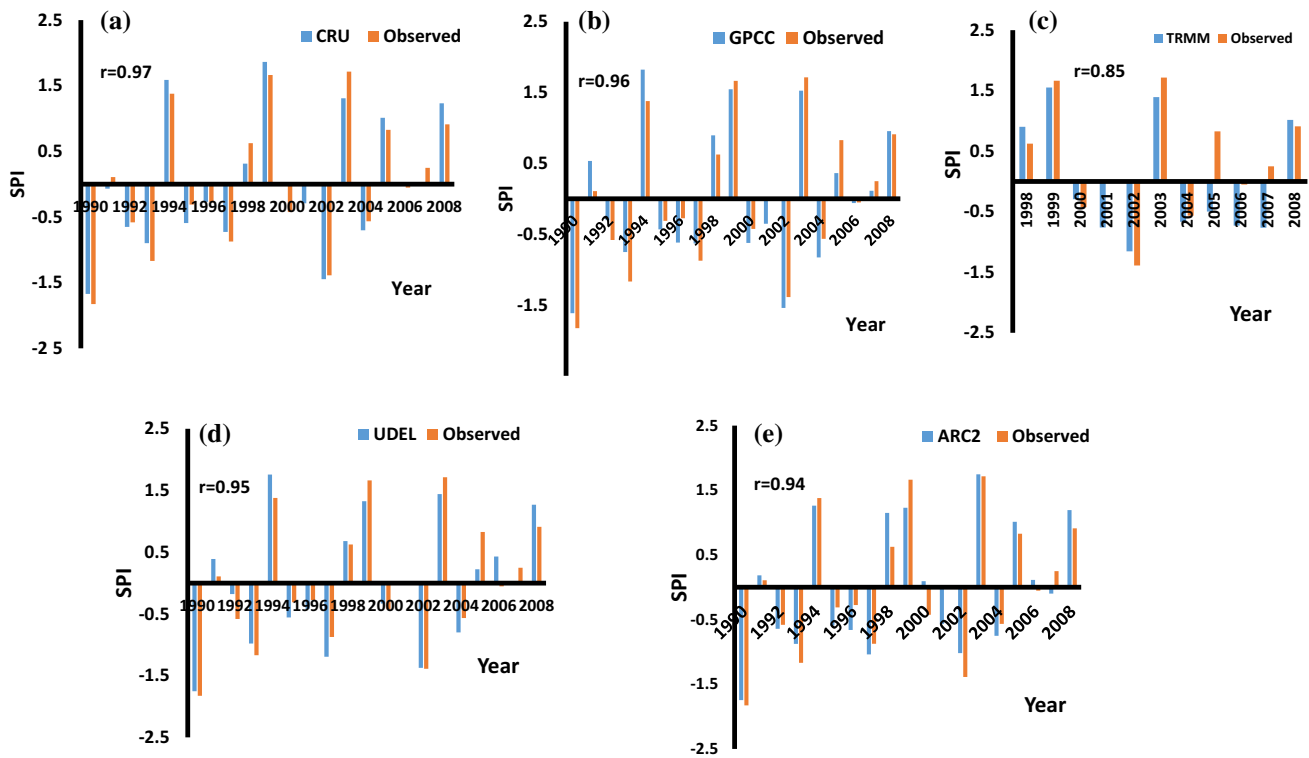


Fig. 13 Same as Fig. 11 but for Sahel

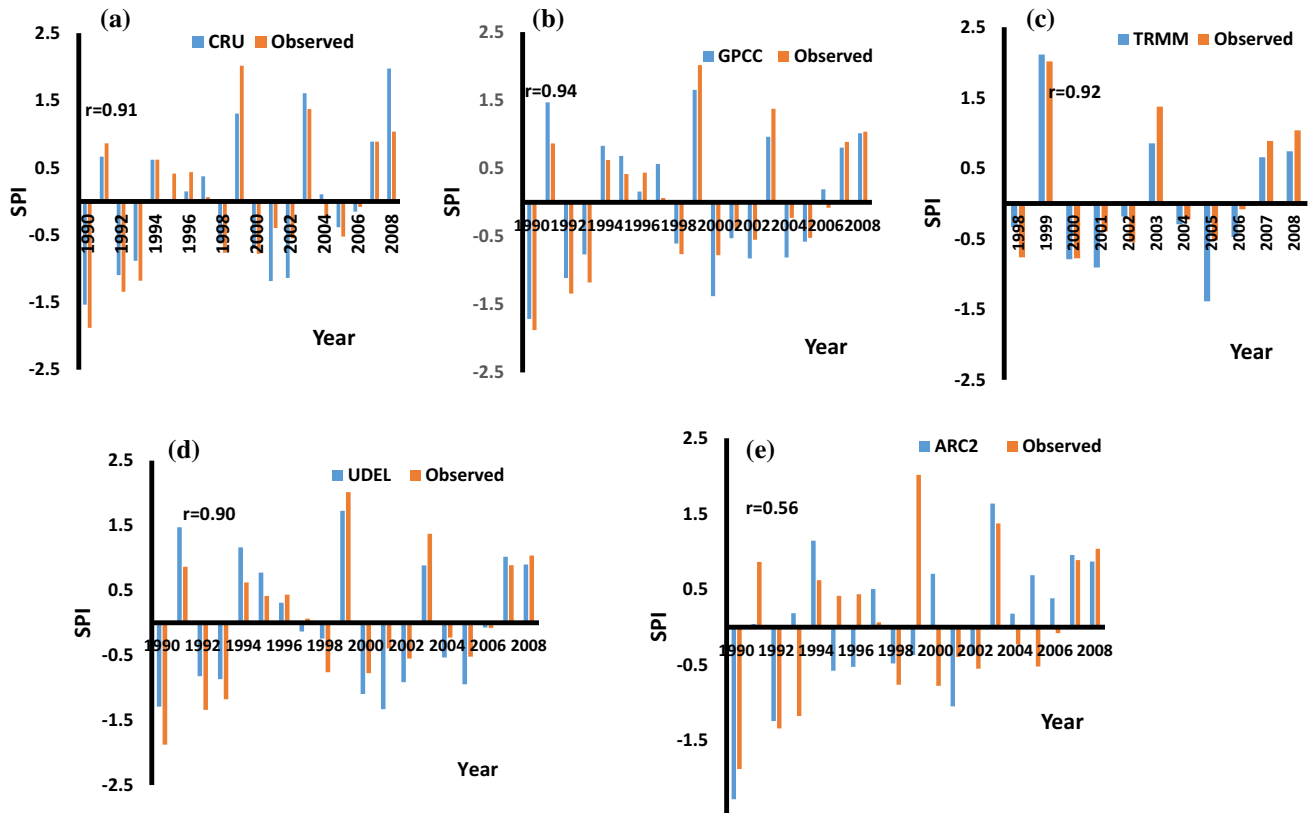


Fig. 14 Same as Fig. 11 but for the whole West Africa domain

framework to assess gridded precipitation product skills in replicating seasonal and intra-seasonal variations of the West Africa Monsoon, and thus the mechanisms of the region's rainfall (Hourdin et al. 2010). The reference ground observation data depicts an onset period between late March and early May with a gradual extension of the rain belt from coast to about 8°N. A break was observed known as the monsoon jump (Sultan and Janicot 2000, 2003; Gbobiyan et al. 2013) which occurs in the rain band between June and July leading to the northward shift of the monsoon precipitation to about 10°N. This monsoon jump result into high rainfall amounts in the Sahel region of West Africa accompanied by abrupt cessation in precipitation intensities along the Guinean coast. Moreover, in September, the rain band experiences a southward shift towards the Guinea coast accompanied by a decrease in rainfall amount over the Sahel. Generally, two peaks of rainfall were observed in June and September with a little dry season in August. Relative to the reference ground observation data, only ARC2 and TRMM captured the little dry season very well in August while other datasets CRU, GPCC and UDEL failed to capture the August break. The first peak of rainfall was observed around July and August in UDEL and GPCC and also, the two datasets were found to systematically underestimate rainfall amount in the Sahel region. Generally the three distinct phases of the mean annual cycle of the West Africa Monsoon precipitation are well captured by the datasets.

Furthermore, a more detailed additional assessment of the annual cycle was carried out considering the zonal-averaged monthly rainfall using ground observation data (81 stations) as the reference over Guinea coast, Savannah, Sahel and the whole West Africa domain for precipitation products from 1990 to 2008 and shown in Fig. 9. This

helps to better identify rainfall minima and peaks, and thus to further gain insights about the capability of the different precipitation dataset to capture variations in specific homogenous zones. Over the Guinea Coast, the reference ground observation data exhibits two peaks of rainfall (bi-modal pattern), a primary maximum in June, and a secondary one in September. Also observed is a relative mid-summer low (minimum) rainfall in August as the monsoon rain band seasonally migrates in the north–south direction in the Guinea Coast. The bi-modal pattern of precipitation was well captured by all the datasets, but considerable variability exists in the magnitude of the products, predominantly during the peaks of rainfall. It is worth noting that ARC2 underestimated rainfall to a large extent in Guinea coast. In the Savannah, the length of rainy season extends from May to September, however, rainfall exhibit a unimodal pattern, having its peak in the month of August. All the dataset captured the pattern but underestimated the rainfall amount during the summer months. Furthermore, in the Sahel, the length of rainy season is less than four months between July and September while August has the highest rainfall amount which is well captured by all the dataset. However, taking into consideration the whole West Africa domain, July–September was observed to have the highest rainfall and this is consistent in the datasets although there are variations in the total amount attributed when compared with the reference ground observation. These differences observed in the different precipitation datasets maybe due to the reasons discussed by McCollum et al. (2000), which include the interpolation technique (or area-averaging technique). Area averaging of ground observation data introduces spatial sampling errors that depend primarily on the number and distribution of the stations within the grid point used.

Fig. 15 Standardized Precipitation Index for JJA associated with El Nino events of 1991/1992, 1997/1998 and 2002/2003

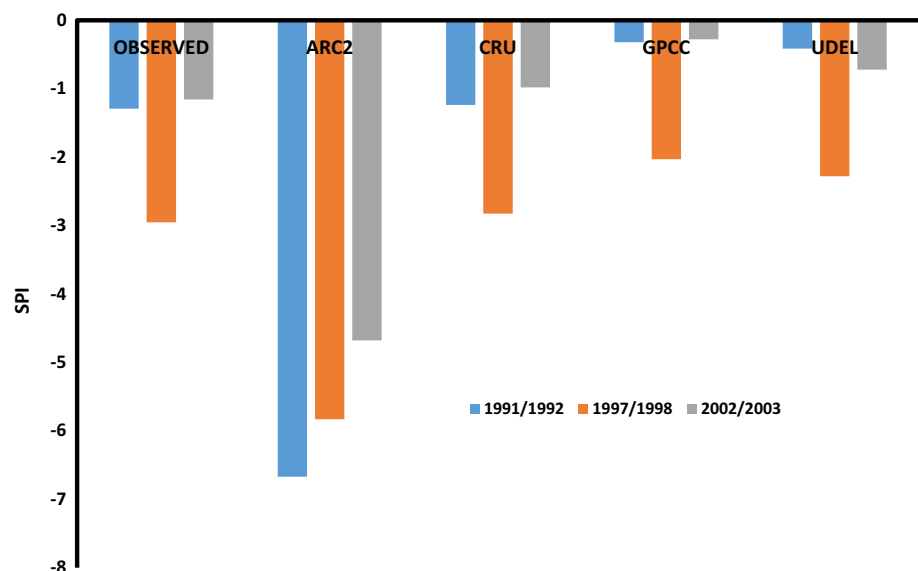


Fig. 16 Standardized Precipitation Index for JJA associated with La Nina events of 1998/1999, 1999/2000, 2000/2001

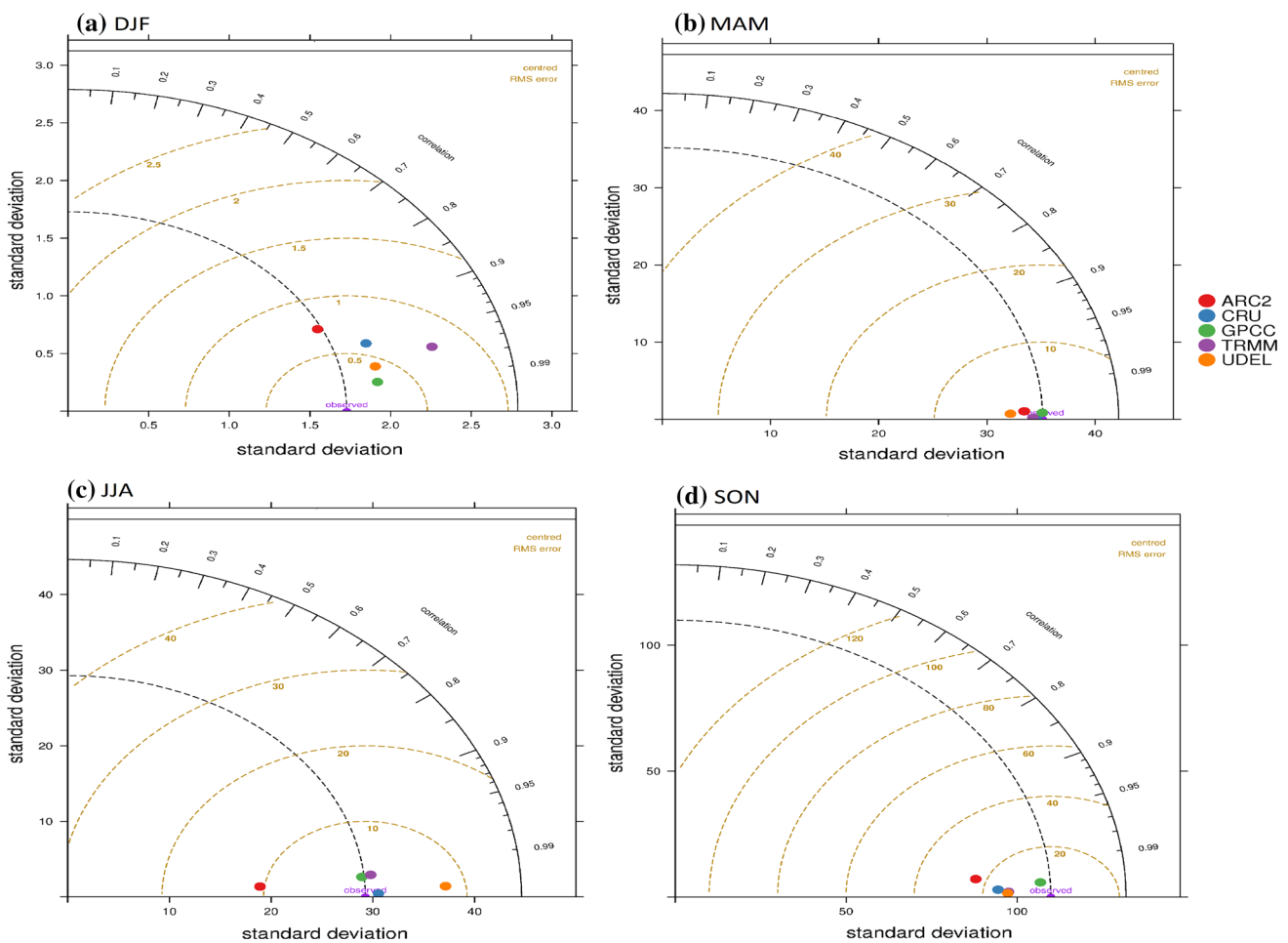
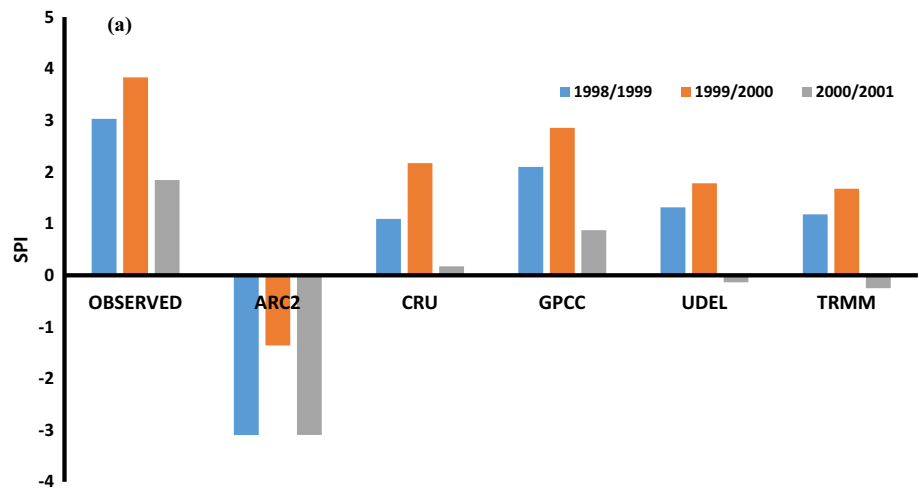


Fig. 17 Taylor diagram for mean precipitation over Guinea Coast

The inter-annual variability of precipitation is of particular importance over West Africa, because the region is mostly covered by semi-arid zones known for unreliable rainfall regime (Le Barb'e et al. 2002; Nicholson and Webster 2007). Figure 10 shows the inter-annual variation

of mean precipitation over the three sub-regions and whole West Africa domain from 1990 to 2008 while the trends for each time series are presented in Table 2. The inter-annual cycle of rainfall is well reproduced by most of the precipitation dataset used although they exhibit variation is

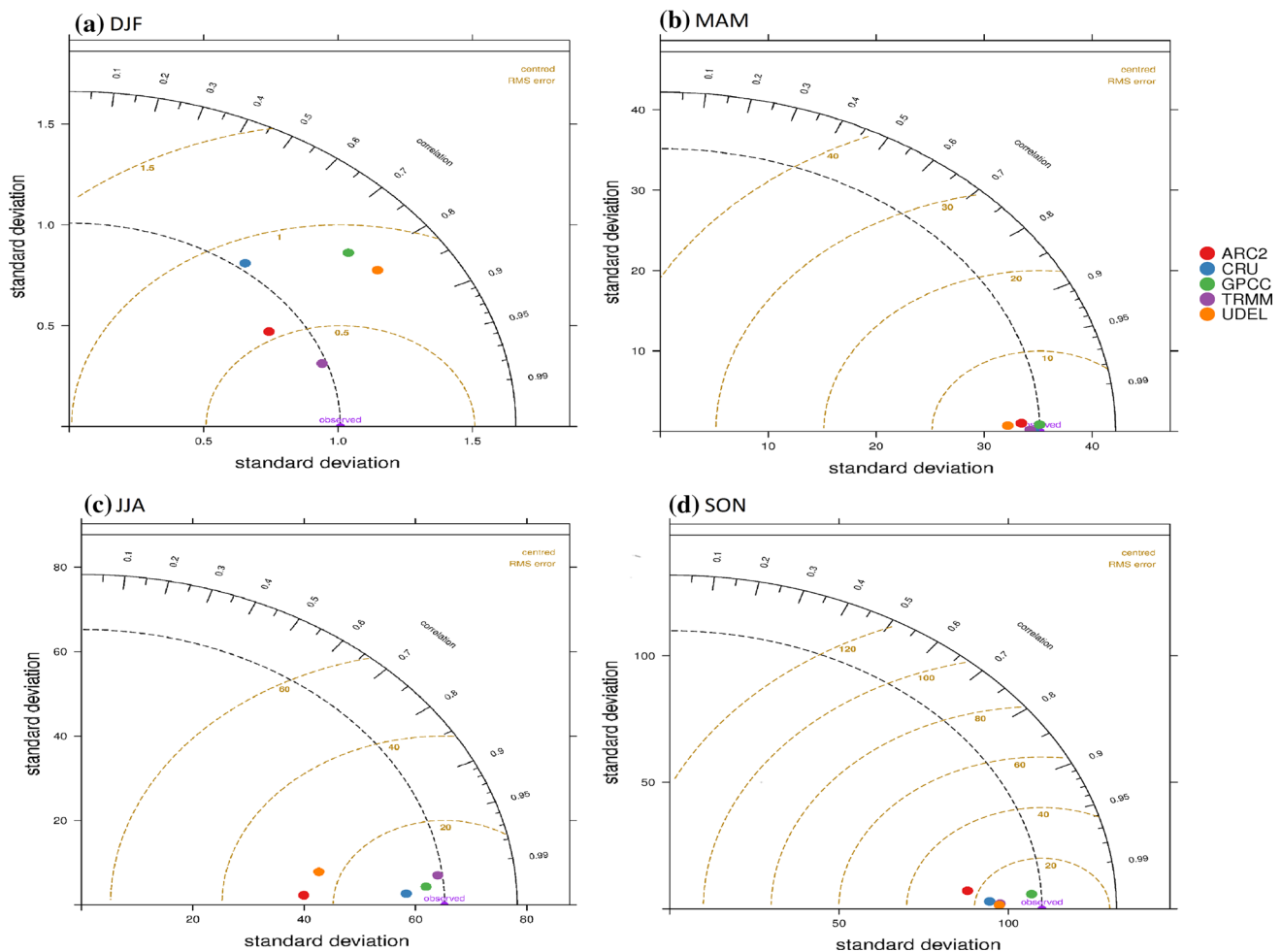


Fig. 18 Same as Fig. 17 but for Savannah

trend across the sub-regions. The reference ground observation data depicts an increasing trend of about 0.59 mm/year in the guinea coast, 0.345 mm/year in the Sahel and 0.31 mm/year over the whole West Africa domain with a decline of -0.16 mm/year in the savannah. The positive trend was well captured by majority of the data. However, it is worth noting that UDEL and TRMM failed to capture this increasing trend over the Guinea coast and the Whole West Africa domain while GPCC and CRU failed to capture the decreasing trend in the Savannah. Moreover, the magnitude of increase and decrease was over and under estimated by some of the data. These findings is consistent with the works of (Le Barb'e et al. 2002; Maloney and Shaman 2008; Akinsanola and Ogunjobi 2014) who observed separately that rainfall trends is on the increase in majority of West Africa sub-regions.

The Inter-annual anomalies of rainfall averaged over Guinea Coast, Savannah, Sahel and the whole West Africa domain were shown in Figs. 11, 12, 13 and 14. The anomalies were calculated with mean precipitation derived

from a period of 19-year from (1990 to 2008). The standard deviation derived from the time series is used to normalize the area averaged precipitation anomalies. Also, the ground observation data was used as the reference data to calculate the correlation coefficient between the different precipitation dataset used. Over the Guinea coast and Savannah, most of the dataset reproduces the magnitude and the sign of the anomalies to a very good extent compared to the reference ground observation data with correlation coefficients exceeding 0.7 at 95% level of significance. However, ARC2 exhibit the weakest performance over this region having correlation coefficient of 0.51 and 0.26 over Guinea coast and Savannah, respectively. In the Sahelian region, all the data show relatively higher correlation coefficient (above 0.85) with the reference ground observation data implying a strong ability to reproduce perfectly the sign and magnitude of the observed anomalies and the overall variability of the Sahel rainfall. Over the entire West African domain comprising the Guinea coast, Savannah and the Sahel, only ARC2 fail to capture up to about 46%

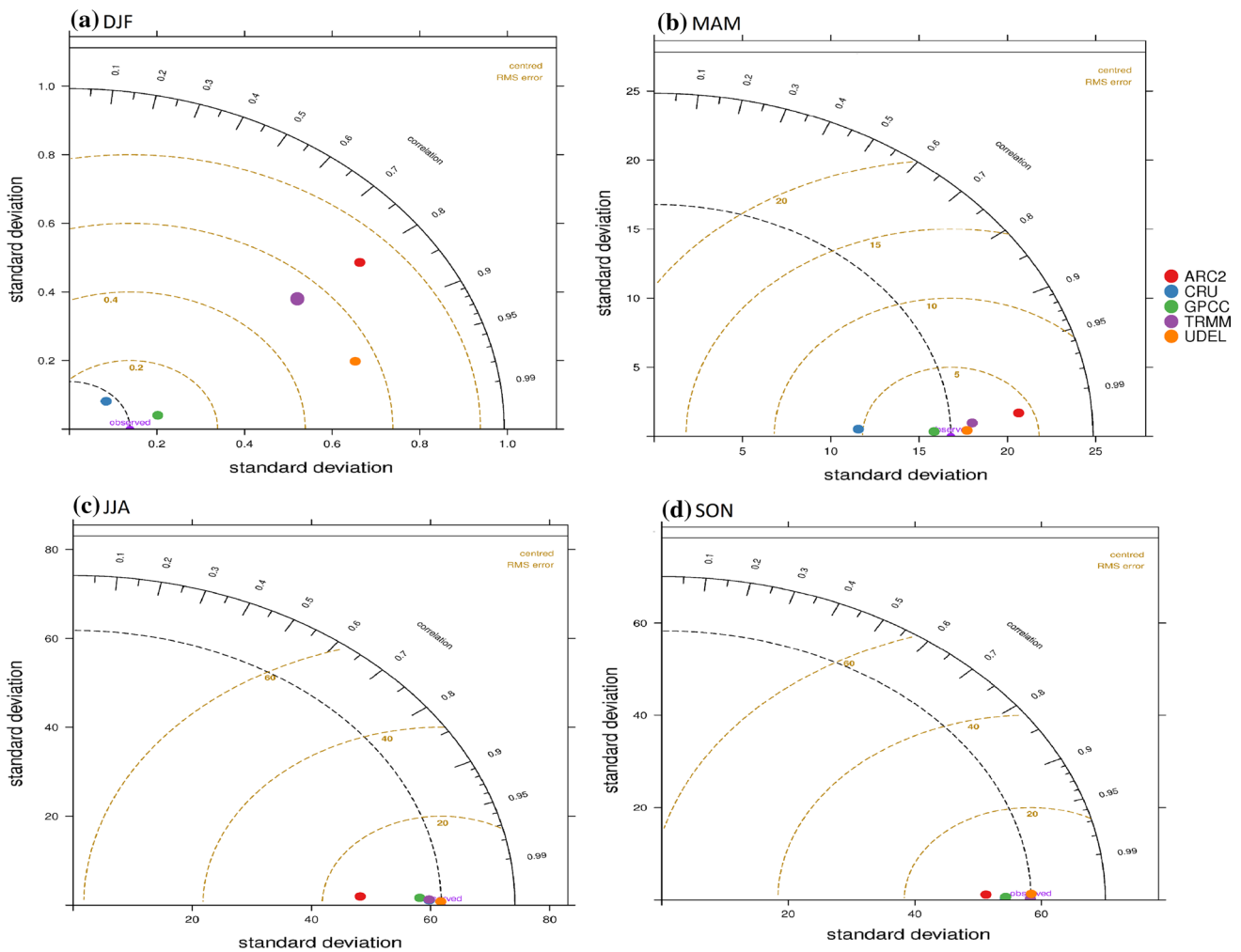


Fig. 19 Same as Fig. 17 but for Sahel

of the observed variability having a correlation coefficient of about 0.56 while other precipitation products exhibit a greater performance with correlation coefficient of more than 0.90.

4.3 Assessing the El Nino and La Nina events

A number of studies have evaluated the influence of the El Nino-Southern Oscillation phenomenon on rainfall in West Africa (see review in Moron and Ward 1998). Nicholson and Entekhabi 1986; Ropelewski and Halpert 1987, 1989; Nicholson and Kim 1997) suggest that the influence is minimal, others (e.g., Semazzi et al. 1988; Wolter 1989; Hastenrath 1990; Bhatt 1989; Moron and Ward 1998) suggest that ENSO tends to reduce rainfall in the Sahel during the summer months, while La Nina tends to increase rainfall. This study examines rainfall anomalies over West Africa during the summer months June–July–August (JJA) of 1991/1992, 1997/1998 and 2002/2003 associated with El Nino years (Fig. 15) and 1998/1999, 1999/2000 and

2000/2001 associated with La Nina years (Fig. 16) and were compared to the reference ground observation data. Negative anomalies were observed during the El Nino years which imply dry conditions. All the data captures these observed features, although ARC2 tends to overestimate the event to a very large extent. During the La Nina events, positive anomalies were observed implying a wet condition. Only ARC2 failed to capture the event in all the years considered. The failure of ARC2 to capture the La Nina events associated with wetness maybe related to underestimation of precipitation in the product during the summer months. UDEL and TRMM failed to capture the La Nina event of 2000/2001 with CRU and GPCC performing very well.

4.4 Statistical validation

The results of the statistical validation are presented in the form of Taylors diagram are shown in Figs. 17, 18, 19 and 20. The results show that there is generally a good

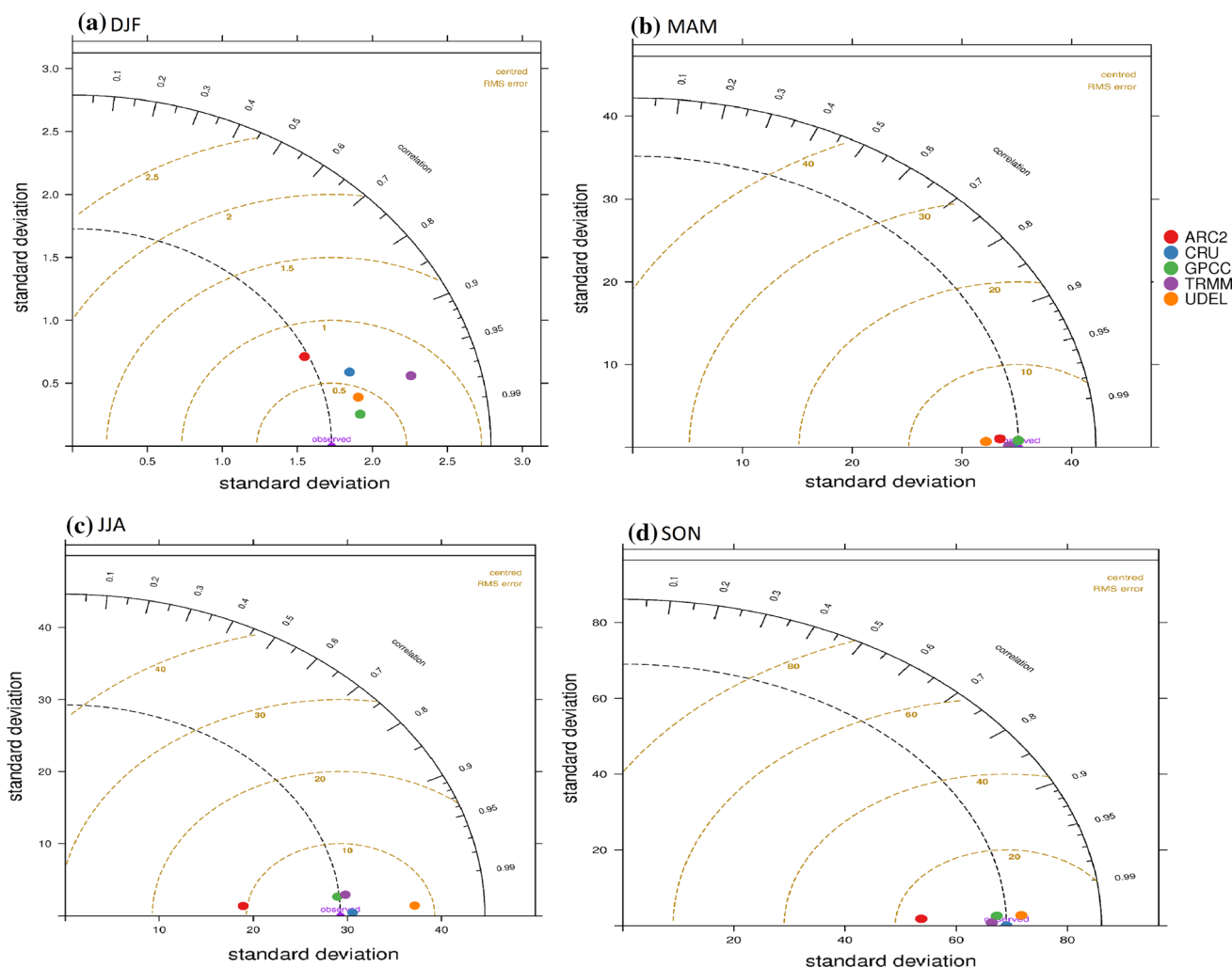


Fig. 20 Same as Fig. 17 but for the whole West Africa

agreement between the reference ground observation data and the other precipitation products with correlation coefficient greater than 0.90 over the Guinea Coast. The observed correlation is significant at 95% confidence interval, however, ARC2 was not significant in DJF and JJA hence failed to reproduce the amplitude and phase of inter-annual variability. CRU was observed to be the most outstanding data in all the seasons having standard deviations which is very close to the reference ground observation data. However, in the Savannah region the correlation is lower in DJF seasons when compared with other seasons with correlation coefficient above 0.63 in all seasons. GPCC dataset was observed to be the best data in this region owing to the lowest RMSE values and the standard deviation is similar to reference ground observation. Furthermore, in Sahel, in all the seasons, the products shows a good performance owing to their high correlation value which is statistically significant at 95% confidence interval with very low RMSE and standard deviation

values close to the reference ground observation data. However, TRMM and ARC2 failed to capture the amplitude and variability of the observed features in DJF. Generally over West Africa, datasets from GPCC, CRU and TRMM were the most outstanding.

5 Conclusion

A precipitation comparison of five different datasets (CRU, TRMM, GPCC, UDEL and ARC2) was performed over three major sub-regions in West Africa being the Guinea Coast, the Savannah and Sahel. Results show that the different precipitation products indicate broadly similar spatial distribution of rainfall. Rainfall decreases northward, as far as the southern fringe of the Sahelian region about 16°N. It was also observed from the study that orography plays an important role in West Africa precipitation patterns. However, it is worth noting that differences exist in

the amount of rainfall attributed the products. Furthermore, analysis of the intra-seasonal and inter-annual variability depicts that the three distinct phases of the mean annual cycle of the West Africa Monsoon precipitation were well captured by the products. Although discrepancies occurs in the precipitation products for instance CRU, GPCC and UDEL failed to capture the little dry season while UDEL and GPCC underestimated rainfall amount in the Sahelian region. The reference ground observation shows an increasing trend of about 0.59 mm/year in the Guinea coast, 0.345 mm/year in the Sahel and 0.31 mm/year over the whole West Africa domain with a decline of -0.16 mm/year in the Savannah. These observations were well replicated in majority of the products. Although differences were observed in UDEL and TRMM as they both failed to capture the observed increasing trend over the Guinea Coast and the Whole West Africa domain while GPCC and CRU failed to capture the decreasing trend in the Savannah. Only ARC2 fail to capture about 46% of the observed variability in the inter-annual precipitation anomalies with other products exhibiting a greater performance. During El Nino and La Nina events all the products were consistent with the reference ground observed in capturing the respective dry and wet conditions observed except ARC2 which tends to overestimate the El Nino event to a very large extent and failed to capture the La Nina event in all the years considered.

In summary GPCC, CRU and TRMM were the most outstanding out of the five precipitation products considered and analyzed and can, therefore, be used to monitor precipitation in West Africa for spatial distribution of mean annual and seasonal rainfall. These three most outstanding products can further be used to assess the sign of the anomaly of the inter-annual variability of rainfall and in monitoring the response in West African summer precipitation to El Nino and La Nina events until adequate, sufficient and reliable reference ground observation data become easily accessible and available.

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