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ORIGINAL PAPER

Trends and interannual variability of extreme rainfall indices over Ghana, West Africa

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Abstract

Rainfall plays an important role in the socio-economic development of any nation. Below or above normal rainfall amounts have serious consequences on key socio-economic sectors. This is particularly true for countries such as Ghana where rainfall plays a key role in the agriculture and energy sectors. In this study, the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS)-homogenized daily rainfall series was used to determine the variability of ten extreme rainfall indices recommended by the World Meteorological Organization-Commission for Climatology (WMO-CCL) and the research project on Climate Variability and Predictability (CLIVAR). The trends of these indices and their links to SST anomalies at oceanic basins were also explored in this study. To understand the variability at interannual to decadal time scales and links with SST forcings, the sum of the first three principal components of the indices were correlated with SST anomalies at oceanic basins. The 35 years mean of frequency indices, CDD, CWD, R10mm and R20mm were found to be in a range of 10–125, 6–14, 30–60 and 8–24 days per year, respectively. On the other hand, the mean over the same period of intensity indices PRCPTOT, R95p, R99p, SDII, RX1day and RX5day were in the range of 900–1700 mm, 200–400 mm, 40–130 mm, 9–13 mm, 30–100 mm and 90–180 mm per year, respectively. The maximum of temporally averaged intensity indices covers southwestern Ghana, while the minimum of the indices lies over northwestern and eastern coasts. A significant decreasing trend in wet indices were observed over the Volta Lake and central portions of the country (7.5°N to 9.5°N), whereas low positive trends were observed over the Northern parts of the country. Wet indices over the country showed significant positive correlations with the Atlantic Ocean SST and negative correlations with the Pacific and Indian basins SSTs. Specifically, the NINO3.4 revealed significant negative correlations with the wet indices over the west-central portions of the country. IOD was observed to have a dipole effect on rainfall indices with the central and southern parts generally covered by negative correlations, while Northern and coastal regions showed positive correlations. The impacts of Atlantic SST on wet rainfall indices are significant over most parts of the country. These results have implications on the improvement of seasonal forecast of the Ghanaian rainfall and its extremes and also provide prior knowledge for better understandings of multidecadal modulations of global interannual teleconnections.

1 Introduction

Studies reported in IPCC (2007) have highlighted on the impact of rainfall variability and its extreme on the socio-economic sectors of developing countries. According to IPCC reports (2007, 2013, 2018), rainfall is projected to be concentrated into more intense events, with longer periods of little rains in between, which will have negative consequences for rainfall dependent economies. In a developing country like Ghana, the agricultural sector is predominantly rain-fed. Therefore increasing rainfall variability would affect food production and livelihood as the agricultural sector provides employment to 70% of citizens and about 28% of the gross domestic product (GDP) (Baidu et al. 2017; Ofori-Sarpong 2001). In addition, rainfall variability affects hydro-electric power generation, which accounts for about 68% of the total energy requirement of Ghana (Kunstmann and Jung 2005). Furthermore, rainfall variability and its extremes affect integrated water resource management, a challenge to United

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Nations Development Goal (DG) 6. An evidence of the impact of extreme climate events (droughts and floods) on water resource management have been reported (e.g., Owusu and Waylen (2013), Paeth and Hense (2004)) as well as the variability of rainfall onsets, duration, and cessations (e.g., Amekudzi et al. (2015)). However, most of these studies focused on specific locations and only few on the entire country.

A number of researches on extreme rainfall trends have been carried out in some parts of West Africa with limited focus in Ghana. For example, Sanogo et al. (2015) analysed the trends in a number of extreme rainfall indices in West Africa and revealed some significant increasing trends in the annual rainfall totals in some parts of the region particularly in Sahel. In the four northeast arid zones of Nigeria, Hess et al. (1995) observed some significant decline in the annual rainfall trends within the period of 1961–1990 by a margin of 8 mm per year. Moreover, in Ghana, most of these limited studies focused on the understanding of the rainfall trends in the region with less attention on its forcings (Baidu et al. 2017; Kemausuor et al. 2011; Yengoh et al. 2010) and others on trends at specific locations (Manzanas et al. 2014).

Furthermore, various efforts in sub-Saharan Africa are devoted to understanding of the link between SST anomalies over ocean basins and rainfall (Lough 1986; Lamb and Peppler 1992; Lamb 1978a, 1978b), whereas a considerable number of these studies were in the Sahel region (Wolter 1989; Hastenrath 1990; Palmer 1986; Nicholson and Webster 2007; Lamb and Peppler 1992; Lough 1986; Janicot et al. 1996; Fontaine and Janicot 1996; Issa Lélé and Lamb 2010; Giannini et al. 2003; Bader and Latif 2003; Balas et al. 2007; Janicot et al. 1998; Fontaine and Bigot 1993) and Eastern Africa (Tsidu 2017; Bahaga et al. 2015). Studies have shown that positive SSTs over the Northern Atlantic were associated with floods, whereas positive SSTs over the eastern Pacific and Indian Oceans were linked to droughts over the West African region (Fontaine and Bigot 1993; Fontaine and Janicot 1996; Janicot et al. 1998). However, only a handful studies over Ghana has established the relationship between SST and rainfall variability (Opoku-Ankomah and Cordery 1994). These studies found a positive correlation between the equatorial Atlantic SSTs with rainfall in Ghana and negative correlation with Sahelian rainfall.

The current study seeks to investigate the spatio-temporal trends of extreme rainfall indices over Ghana using high resolution and homogenized Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS). Furthermore, the study will explore the link between SST over ocean basins and rainfall extreme in Ghana. The remaining part of the paper is structured as follows: Section 2 presents the Study area and methods, whereas Results and discussions are given in Section 3. Finally, Conclusions are presented in Section 4.

2 Study area and methods

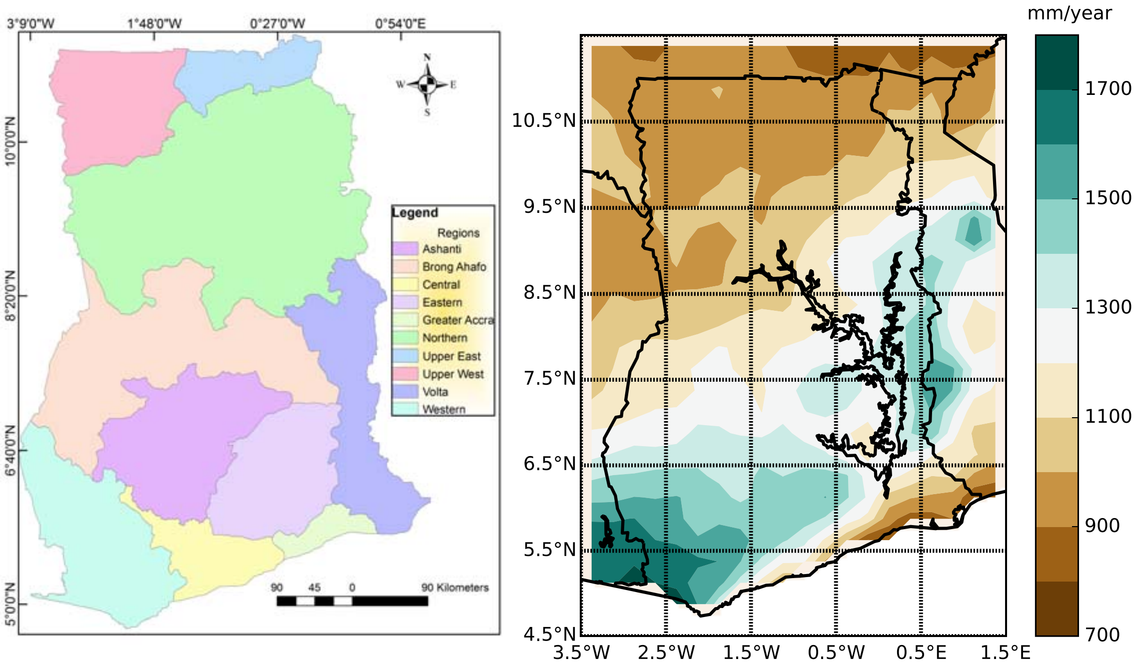
2.1 Climate of Ghana

Ghana lies in the tropics thus characterized by a typical tropical monsoonal climate system which is dominated by two seasons (wet and dry) (Amekudzi et al. 2015) with a rainfall system which is highly variable spatio-temporally (Lacombe et al. 2012; Asante and Amuakwa-Mensah 2014). Rainfall in the region is mainly associated with the evolution and migration of a cluster of thunderstorms known as mesoscale convective systems (MCSs) and modulated by the moisture advection from the lower atmosphere of the Gulf of Guinea (Sultan and Janicot 2003; Aryee et al. 2017). In addition, rainfall regimes of the region is distinguished by the meridional migration of the intertropical discontinuity (ITD) (Sultan and Janicot 2003, and references therein). This movement of the ITD brings about the unimodal and bimodal rainfall patterns observed in the Northern and southern halves of the country, respectively. Typically southern Ghana experiences its rainfall season between March–mid-November with two peaks in June and October, whereas the Northern half of the country in late April–mid-October with one peak in August (Amekudzi et al. 2015; Manzanas et al. 2014). On average, the annual rainfall total over the country ranges between 900 and 1700 mm with relatively high values in southwest and relatively low values in the north and the eastern coast (see Fig. 1b). The mean daily temperature ranges from approximately 30 °C during the daytime to about 24 °C during the night-time, whereas relative humidity is in the order of 77–85% (Asante and Amuakwa-Mensah 2014).

2.2 Data source

The rainfall data applied in this study is the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS V2) obtained from the International Research Institute of Climate and Society (IRI) data website. The CHIRPS rainfall data is quasi-global with a daily temporal resolution and a spatial resolution of 0.25° × 0.25° spanning a climatological period of 1981–2015. The product is as a result of the joint collaboration between scientists in the US Geological Survey (USGS), Earth Resources Observation and Science (EROS) Center with the aim of providing rainfall data suitable for climate impact studies like floods and drought monitoring and trend analysis (Funk et al. 2015). This rainfall product is a combination of satellite imageries with resolution of 0.05° and in situ station datasets whose algorithm incorporates various temporal resolutions of cold cloud duration (CCD) based precipitation for the period of 1981–2015. Further details of the CHIRPS rainfall data is given in Funk et al. (2015).

The SST data employed in this study is the National Oceanic and Atmospheric Administration extended



(a) (b)

Fig. 1 The study area (**a**) and the mean annual rainfall climatology over Ghana for the period of 1981–2015 (**b**)

reconstructed SST data (ERSST V5). ERSST V5 is the current version of SST data with a monthly temporal resolution and a spatial resolution of 2°×2°. It includes the newly released SST from the International Comprehensive Ocean-Atmosphere Dataset (ICOADS). The annual averages for the period of 1981–2015 were used in this study. Further details on the product can be found in Huang et al. (2017). The dipole mode index (DMI) also known as the Indian Ocean Dipole (IOD) is a coupled ocean-atmosphere phenomenon occurring in Indian Ocean (Diatta and Fink 2014) which describes the SST anomalous difference between the western parts of the equatorial Indian Ocean (50–70°E and 10°S-10°N) and the south eastern equatorial Indian Ocean (90–110°E and 10°S-0°N) (Vinayachandran et al. 2002). Monthly fields of DMI were obtained from the NOAA, Global Climate Observing System (GCOS) for a period of 1870–2017. However, the data was averaged to have annual means covering the period of 1981–2015 to match the rainfall indices along time axis for further analysis.

The NINO3.4 is the average SST anomalies in the NINO3.4 region (5°N to 5°S, from 170°W to 120°W) (Barnston and Tippett 2013). Monthly fields of the NINO3.4 were obtained from NOAA for the period of 1948–2018. Annual means for 1981–2015 were computed from the monthly fields and applied for this study. More details on NINO3.4 can be found in Trenberth and Stepaniak (2001).

The Atlantic Multidecadal Oscillation (AMO) index is a basin-scale mode of observed multidecadal climate variability which describes the average SSTs in the north of Atlantic (0°–70°N) (Enfield et al. 2001, and references therein). It is based on the Kaplan SST data with spatial resolution 5° × 5° spanning the period from 1856 to 2018. More information on the AMO index is found in Enfield et al. (2001), Rayner et al. (2003).

2.3 Methodology

Daily rainfall fields for a total of 560 grid points over Ghana were extracted from the CHIRPS rainfall data and thereafter subjected to a homogenisation process using RHtestsV4 package described in Wang and Feng (2010). Although CHIRPS rainfall data is already homogenized, the procedure is carried out as a matter of software requirement. The homogenisation technique employs the two-phase regression model to detect changepoints in the input time series. Details on the two-phase regression model is found in Lund and Reeves (2002) and Wang and Feng (2010). Afterwards, the ten selected rainfall indices (see Table 1) were computed for all 560 grid points.

The mean climatologies for the ten rainfall indices at all grids were computed by averaging over a period of 35 years. The linear trends for the rainfall indices were computed for each grid point with the aid of the non-parametric, rank-based procedure, the Mann-Kendall (MK) test described in (Tsidu 2017; Manzanas et al. 2014, and references therein). Furthermore, the significance of the trends was tested by computing the p values for all grid points which were later compared to a predefined significant value of 0.05 (95% confidence level). Grid points with p values less than the significant value were considered significant, whereas those greater than the significant value were insignificant.

In order to investigate the correlation between the rainfall indices over the entire country and the SST anomalies over the oceanic basins, the Pearson correlation coefficients were computed between the SST anomalies for each grid (5° × 5°grid spacing) and the sum of first three principal components (PCs) of the rainfall indices over Ghana.

Furthermore, the Pearson correlation coefficients were computed between the SST indices and the rainfall indices. The extreme rainfall indices analysed in this study are recommended by the World Meteorological Organization-Commission for Climatology (WMO-CCI) and the research program on Climate Variability and Predictability (CLIVAR) and the Joint WMO-CCI Technical Commission for Oceanography and Marine Meteorology (JCOMM) and have been used in several studies (e.g., Zhang et al. (2001), dos Santos et al. (2012), Manzanas et al. (2014)). Table 1 presents details of the selected extreme rainfall indices explored in this study.

3 Results and discussions

3.1 Mean climatology of rainfall indices

The results of the mean climatologies of the ten selected rainfall indices, CDD, CWD, R10mm, R20mm, PRCPTOT, R95p, R99p, SDII, RX1day and RX5day are presented here. Figure 2 represents the climatologies of the frequency indices over Ghana derived from data covering a period of 35 years (1981–2015). From this figure, it is observed that the consecutive dry days (CDD) over Ghana are between 10 and 125 days per annum on average. In general, the number of rainy days is relatively longer in the South than in the North; thus, one expects that the number of consecutive dry days would be more pronounced in the North than in the South of the country. As observed, consecutive dry days in the Northern half were about 80–120 days per annum and about 10–80 days per annum in the southern half of the country.

The wet frequency indices thus heavy rainfall days (R10mm), very heavy rainfall days (R20mm), and consecutive wet days (CWD) showed similar spatial patterns throughout the entire country (see Fig. 2). This is expected as the North is generally drier than South of the country. The R10mm, which describes the annual counts of the days with rainfall exceeding 10 mm, has an annual mean value in the range of 30–60 days per annum over the entire country. The southwestern parts of Ghana, areas around the Volta Lake of Ghana and the entire southern parts of the country (latitudes 5–8°N and longitudes 0.5°W-1.5°E), enjoy relatively high number of heavy rainfall days (40–60 days). The least heavy rainfall days of about 30–40 days per annum are found in most parts of Northern Ghana.

On the other hand, the consecutive wet days (CWD) is in the range of 6–14 days per year. The highest rainy days is observed over areas around the Volta Lake stretching southwards to cover most parts of Southern Ghana (at latitudes 5–8 N and longitudes 0.5 W-1.5 E of the country) with an average number of CWD of about 10 days per annum. The lowest consecutive wet days are observed over the Northern and the eastern coastal parts of Ghana with an average of about 7 days per year.

The annual frequency of very heavy rainfall days (R20mm) has a range of 8–24 days per year over the entire country. Southern Ghana was found to have 10–24 days per annum of very heavy rainfall days which is relatively higher than those of the Northern parts of the country (about 9–15 days per annum); these findings are consistent with other studies in Manzanas et al. 2014, Aryee et al. 2018. Southwestern Ghana experiences the highest number of days with very heavy rainfall (> 20 days per annum) throughout the year.

Figure 3 displays the mean climatologies of the intensity indices over Ghana. These are the annual mean of total rainfall (PRCPTOT), very wet day (R95p), the simple daily rainfall index (SDII), extremely wet day (R99p), daily maximum rainfall (RX1day) and the 5-day maximum rainfall (RX5day) over a period of 35 years. The annual rainfall total (PRCPTOT)

Table 1 Table showing the ten selected rainfall indices computed over Ghana

Indices	Name	Computation	Definition	Units
CDD	Consecutive dry days	$RR_{ij} < 1mm$	Maximum number of consecutive days with $\mathrm{RR} < 1$ mm	Days
CWD	Consecutive wet days	$RR_{ij} > 1mm$	Maximum number of consecutive days with $\mathrm{RR} \geq 1$ mm	Days
R10mm	Number of heavy rainfall days	$RR_{ij} > 10mm$	Annual count of days when days $\mathrm{RR} > 10$ mm	Days
R20mm	Number of very heavy rainfall	$RR_{ij} > 20mm$	Annual count of days when days $\mathrm{RR} > 20$ mm	Days
PRCPTOT	Annual wet-day rainfall total	$\sum_{i=1}^{n} RR_{ij}$	Annual total rainfall in wet day ($\mathrm{RR} > 1$ mm)	mm
R95p	Very wet day	$\mathrm{R95p}_j = \sum_{i=1}^{N} RR_{ij}$	Annual total rainfall when $\mathrm{RR} > 95$ percentile	mm
R99p	Extremely wet day	$\mathrm{R99p}_j = \sum_{i=1}^{N} RR_{ij}$	Annual total rainfall when $\mathrm{RR} > 99$ percentile	mm
SDII	Simple daily intensity index	$\mathrm{SDII}_i = \frac{\sum_{i=1}^{N} RR_j}{N}$	Annual mean rainfall with ($\mathrm{RR} \geq 1$ mm)	mm
RX1day	Daily maximum rainfall	$\mathrm{Rx1day} = \max(RR_{ij})$	Annual maximum 1-day rainfall	mm
RX5day	5-day maximum rainfall	$\mathrm{Rx5day} = \max(RR_{ij})$	Annual maximum 5-day rainfall	mm

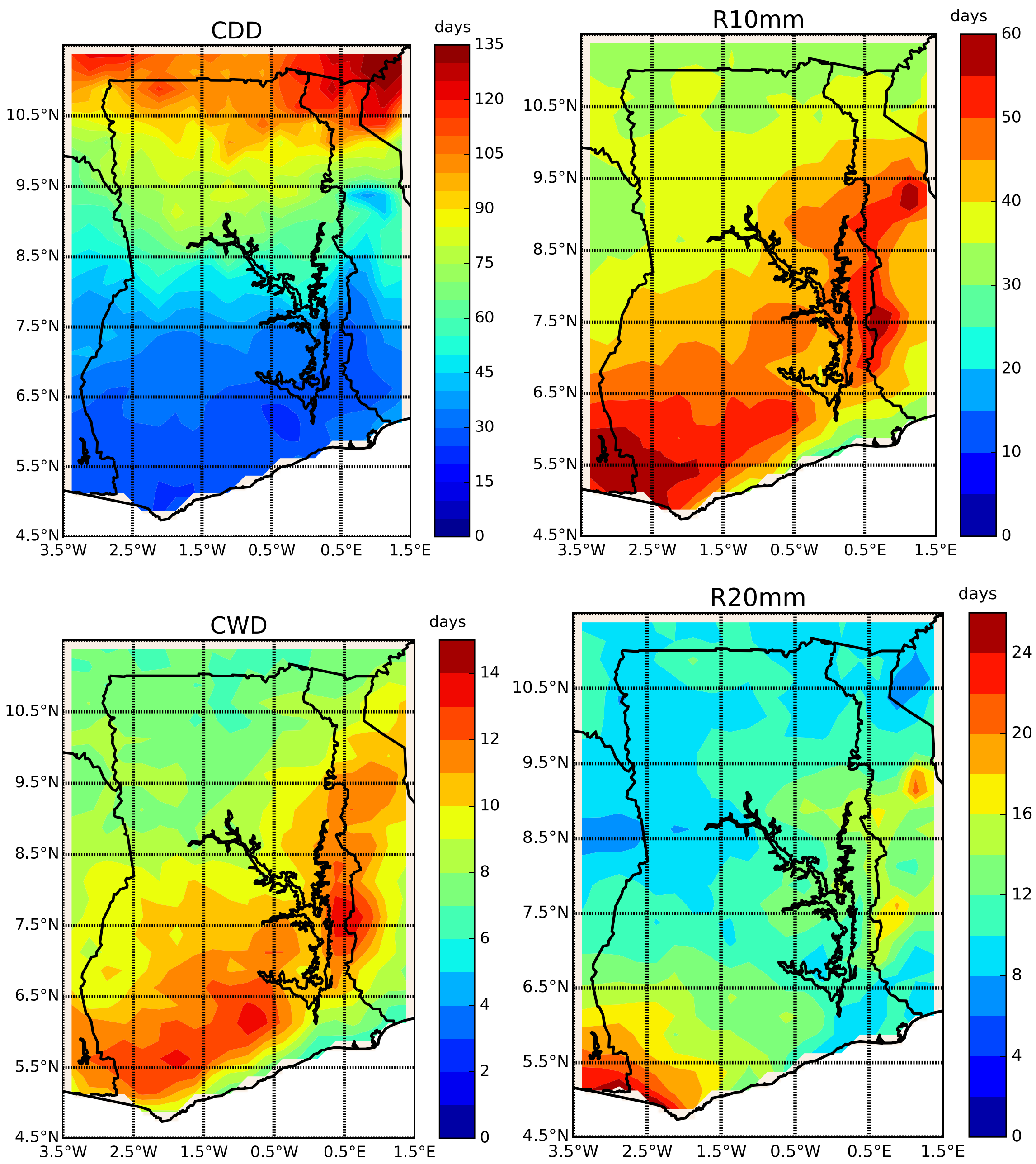


Fig. 2 Mean climatology of frequency indices for the period of 1981–2015 over Ghana. **a** CDD; **b** R10mm; **c** CWD; **d** R20mm

over the entire Ghana has a range between 900 and 1700 mm per year. The highest annual rainfall total in the range of 1300–1700 mm are found in the southwestern and eastern parts of the Volta Lake, which is possibly because of relief rainfall, while relatively low values, between 900 and 1100 mm, are observed over the northwestern and eastern coasts of the country. These observations are in agreement with findings in Baidu et al. (2017).

It is observed that the very wet days (R95p) and extremely wet days (R99p) are highest over southwestern Ghana, while lowest values dominate most of the Northern and parts of the eastern coasts of the country. The R95p index ranges between 200 and 400 mm per year, while the R99p index on the other hand ranges between 40 and 130 mm per year over the entire country. Furthermore, the spatial patterns of the simple daily intensity index (SDII) ranges between 6 and 14 mm per year. Relatively high daily rainfall intensities (9–14 mm) are seen to dominate over southwestern Ghana, while the lowest daily intensities (6–8 mm) stretches westwards towards the North from the Volta Lake region. The annual RX1day and the annual RX5day indices range between 30 and 100 mm and 90 and 180 mm per year, respectively, over the entire country (see Fig. 3). The lowest intensities (averagely 30 mm) of daily maximum rainfall amount dominate over small portions of

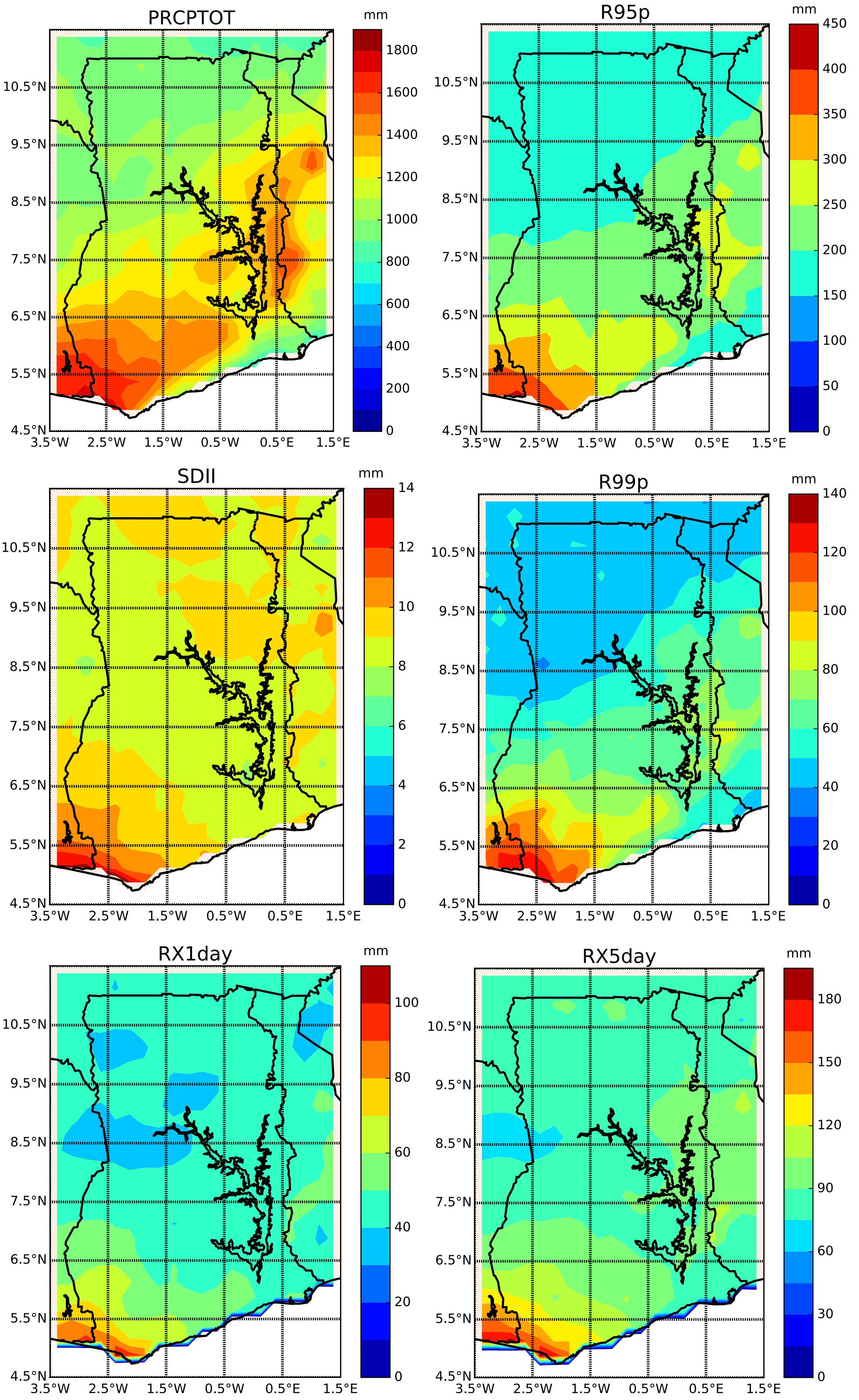


Fig. 3 Mean climatology of intensity indices for the period of 1981–2015 over Ghana. **a** PRCPTOT; **b** R95p; **c** SDII; **d** R99p; **e** RX1day; **f** RX5day

Northern Ghana (8.2–9.0°N), central Ghana (9–9.6°N) and parts of northwestern Ghana (9.6–10.3°N). In addition, most of central Ghana extending to higher latitudes towards Northern Ghana experience medium range (averagely 55 mm) daily maximum rainfall amount, while the highest amount is observed over the southwestern Ghana (averagely 95 mm). Similarly, the 5-day maximum rainfall amount has high intensities over southwestern Ghana and low intensities over the eastern coasts and northwestern parts of Ghana. A mean value of about 160 mm per year of 5-day maximum rainfall amount dominants over most of southwestern Ghana, while the lowest mean values (about 65 mm per year) is observed over western mid-Ghana (8.2–9.00°N). Most of central Ghana including the Northern parts have a mean value of about 80 mm per year of the 5-day maximum rainfall amount.

3.2 Trends of rainfall indices

In this section, the spatial trends of the ten rainfall indices for the period of 1981–2015 are shown in Figs. 4 and 5. The consecutive dry days show insignificant to negative trends over most of Ghana with the exceptions of Northern Ghana and some isolated pockets along 0.5 W between latitude 7.5 and 9 N that exhibit increasing trend in the number of annual consecutive dry days (i.e., an increase of 3 to 10 days per decade in the last nearly four decades) (see Fig. 4a). Despite increase in consecutive dry days over these regions, the annual counts of days with rainfall exceeding 10 mm has been increasing over the Northern half of the country and southwestern Ghana during the 1981–2015 period (see Fig. 4b). The consecutive wet days show negative trends over most of the country with the exceptions of the isolated pocket over southwestern and central-eastern Ghana (see Fig. 4c). The decrease in consecutive dry days did not lead to an increase in CWD suggesting that the changes in rainfall frequency indices are mainly reflected in the increase in rainfall events with heavy and very heavy rainfall over most parts of Ghana.

The annual wet-day rainfall total shows drying trends over the entire Volta Lake extending westwards to most parts of central, western (i.e., between latitudes 7–9°N) and eastern coasts of Ghana (see Fig. 5a). Interestingly, southwestern Ghana with the highest annual rainfall total exhibits a positive trend. Positive trends similar to those over southwestern Ghana are observed over most parts of Northern Ghana. The very wet and extremely wet day indices (see Fig. 5b, d) have similar spatial trends over the entire country. Negative trends dominate the entire country except for areas lying south of 6.5 N which are dominated by normal to positive trends. In addition, the simple daily rainfall intensity over Ghana shows negative trends over central Ghana between latitudes 7–9.3 N, while positive trends dominate the rest of the country (see Fig. 5c). Furthermore, southeastern Ghana is dominated by positive trends in daily maximum rainfall amount, whereas negative trends are found to cover almost all other parts of the country (see Fig. 5e). Similarly, positive trends in 5-day maximum rainfall amount are observed in Southern and northwestern Ghana, whereas negative trends dominate the remaining parts of the country (see Fig. 5e).

3.3 Correlations of SST anomalies and the rainfall indices over Ghana

3.3.1 Relation between global SST and rainfall indices

The link between the ten rainfall indices over Ghana and SSTs are presented here. Specifically, the first three principal components (which contributed to more than 70% of the total variance) of the ten rainfall indices were computed and correlated (grid-wise) with the SSTs (see Fig. 6). Correlations that are statistically insignificant at 95% confidence level are masked in these figures. Generally, the results reveal some appreciably significant correlations between the combined principal components of some rainfall indices and the SSTs over parts of the Pacific, Atlantic and Indian Oceans.

No or few significant correlations were observed between SSTs and rainfall indices (CDD, CWD, RX1day, RX5day and SDII), thus indicating the frequency of these rainfall indices over the region are probably more driven by seasonal scale variability than interannual variability in SSTs over oceanic basins. It could also be that the variability in these indices is driven by local scale than large-scale SST variability.

The number of heavy rainfall days over Ghana is observed to have negative correlation (− 0.7 to – 0.3) with SSTs over the equatorial Pacific and the Indian Oceans, whereas positive correlations are observed over parts of the Atlantic Ocean. Similarly, the number of very heavy rainfall days had negative correlations with SSTs in the Pacific (equatorial and Northern) and the Indian Oceans, while Southern Indian Ocean is dominated by positive correlations. These current findings are consistent with earlier studies which revealed similar interrelationship with rainfall over varied locations and the SSTs in oceanic basins (e.g., Diatta and Fink (2014), Clark et al. (2003), Bader (2005)).

Positive correlations are observed between the annual wet-day precipitation total and SSTs over the Atlantic Ocean, whereas negative correlations are found in the equatorial Indian and Pacific Oceans which is consistent with findings by Gadgil et al. (2004) who confirmed warm SSTs over equatorial Indian and Pacific to be associated with negative rainfall anomalies over Ghana and vice versa. The very wet day index has also revealed positive correlation with SSTs in the Northern Atlantic equatorial, Indian and some parts of the Pacific Oceans. In contrast, negative correlations are prevalent over parts of the Atlantic and Southern Indian Oceans. These results are in line with findings by Lough (1986) which revealed contrasting

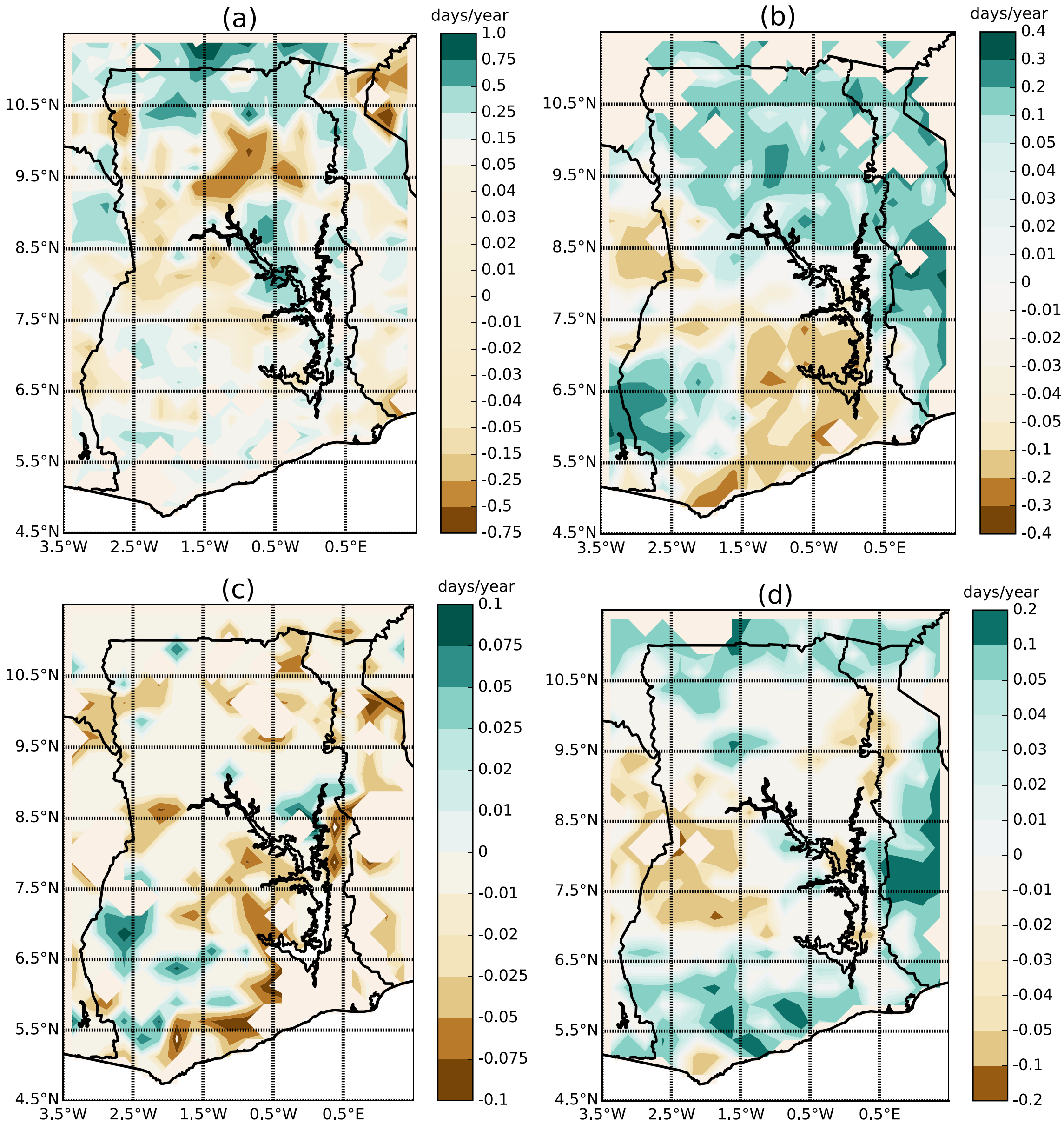


Fig. 4 Trends of intensity indices for the period of 1981–2015 over Ghana. **a** CDD; **b** R10mm; **c** CWD; **d** R20mm

relationship between rainfall over Sahel and SST departures over the southeastern tropical Atlantic Ocean.

On average, it is observed that the Atlantic SST has a more pronounced and direct positive link, whereas the Pacific SST has a negative link with wet indices in Ghana. This implies that the warmer the SSTs in the Atlantic Ocean, the more rainfall are expected in the region and vice versa. On the other hand, the warmer the SSTs in the Pacific Ocean, the less the likelihood of wetness in the country and vice versa. The Indian ocean SST generally has no direct impact on the rainfall in Ghana as this mainly depends on the presence of the Mascarene high which pumps moisture into the Congo basin, and thus how much moisture is available and pumped into the West African region would then determine how wet or dry the region would be.

These current findings are consistent with earlier studies by Balas et al. (2007) who found the rainfall variability over west-central Africa to be linked to the SST fluctuations especially over Pacific Nino regions and the western Indian Ocean particularly during the boreal summer season.

3.3.2 NINO3.4

In Section 3.3.1, it has been noted that the equatorial Indian Ocean and Pacific SST anomalies are negatively correlated with wet indices, while equatorial Atlantic Ocean SST anomalies correlate positively with some wet indices (PRCPTOT, R10mm, R20mm and R95p). However, these correlations are the average of the whole country and do not indicate which

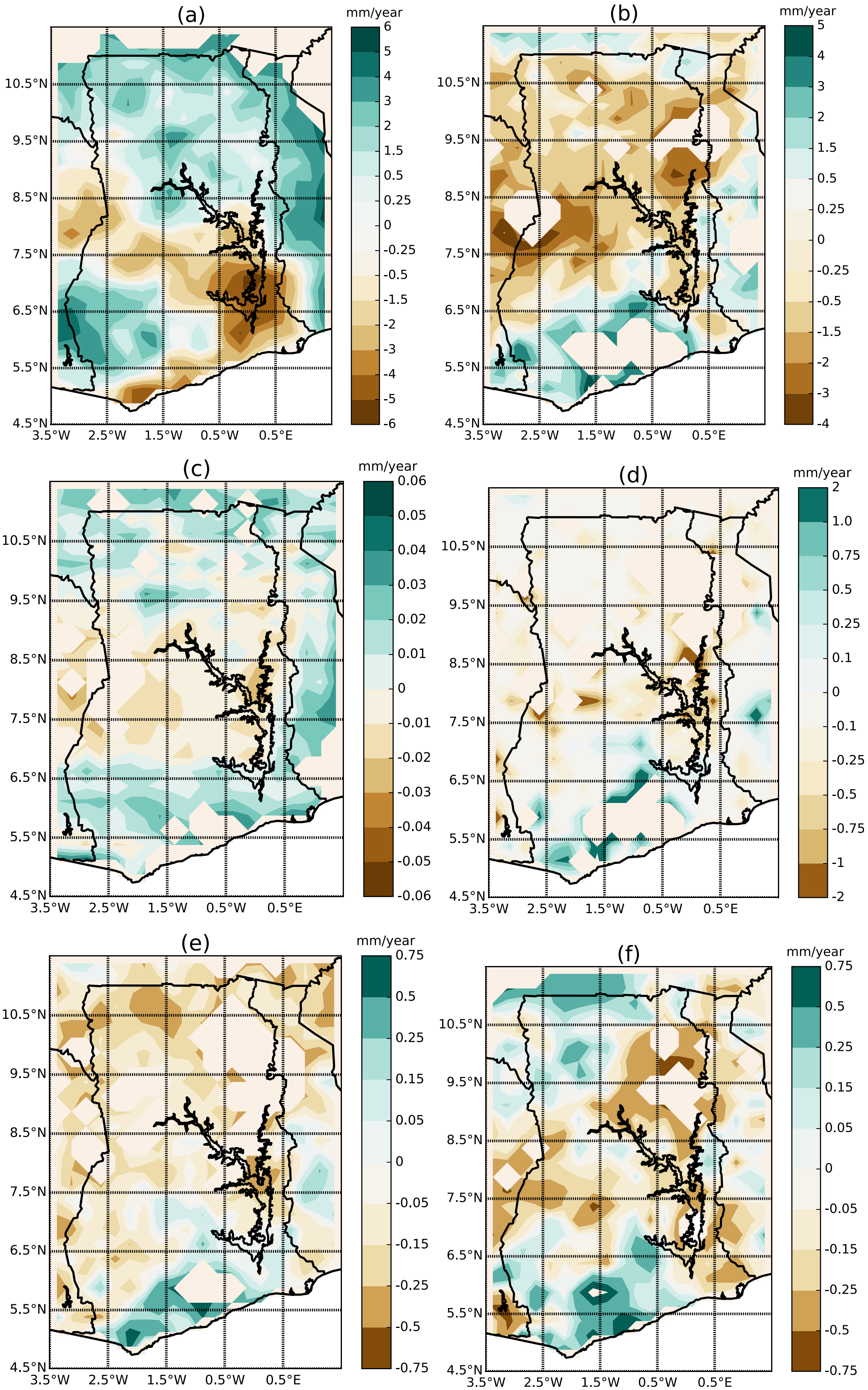
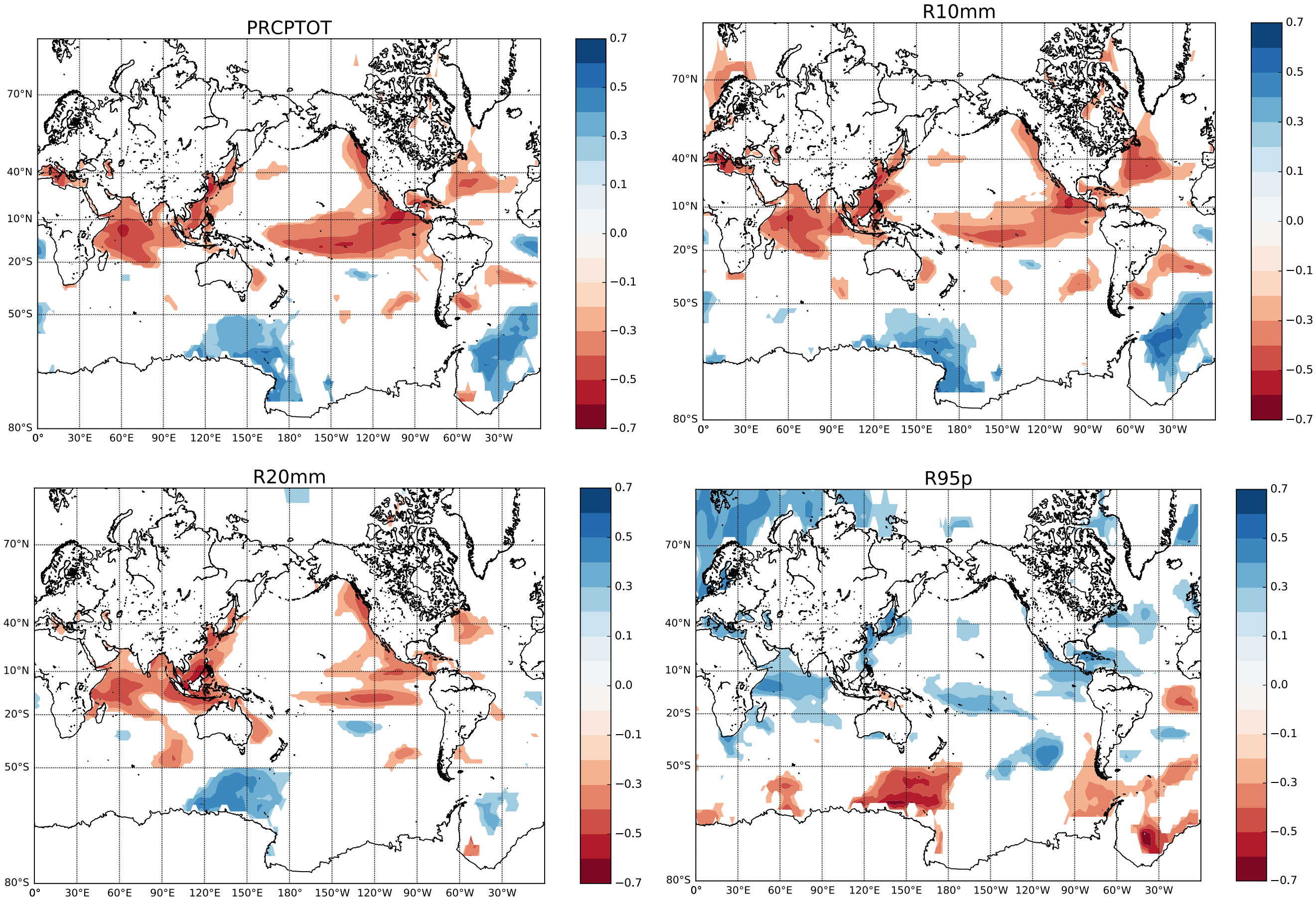


Fig. 5 Trends of intensity indices for the period of 1981–2015 over Ghana. **a** PRCPTOT; **b** R95p; **c** SDII; **d** R99p; **e** RX1day; **f** RX5day


PRCPTOT

R10mm

R20mm

R95p

Fig. 6 Significant correlation between global SST and wet indices (PRCPTOT and R10mm) in Ghana for the period of 1981–2015

parts of the country are influenced and the extent to which the various parts of the country are controlled by interannual SST variability. To answer this question, NINO3.4, IOD and AMO indices that represent equatorial Pacific, Indian and Atlantic Oceans, respectively, are used for correlations with grid point extreme rainfall indices (PRCPTOT, R10mm, R20mm and R95p) that exhibit strong positive/negative correlations.

Figure 7 reveals association of low (high) PRCPTOT and R10mm indices with warm (cold) Nino3.4 SST indices over most of Ghana with exception of small latitude bands in the North of the country. However, these negative association shrinks to central Ghana in the western half and to 6.5–10.5 N in the eastern half of the country in the cases of R20mm and R95p indices. The strongest influence of equatorial Pacific SST anomalies on rainfall indices is apparent over western-central Ghana and Volta Lake region as noted from negative correlation exceeding 0.6. These findings are in agreement with previous studies by Diatta and Fink (2014), Clark et al. (2003) who have shown negative correlations between the Nino3.4 and parts of West African rainfall. This negative correlation between parts of the Ghanaian rainfall and the Nino3.4 is possibly attributable to the positive Pacific SSTs coinciding with subsistence within the tropics as highlighted by Janicot et al. (1998). Thus, a warm Pacific SST is tantamount to less rainfall events, whereas cold Pacific SST will likely induce more rainfall events within western-central and Volta Lake region of Ghana.

3.3.3 Indian Ocean Dipole (IOD)

The IOD index generally has a dipole effect on the rainfall indices over Ghana characterized by no or negative correlations over central Ghana and isolated pockets of positive correlations over the Northern and Southern border areas of the country as shown in Fig. 8. For instance, the PRCPTOT showed negative correlations over the central western Ghana and some parts of the Volta Lake. In contrast, positive correlations are observed far North of the country.

Similarly, for the R10mm, the northwestern portion of the country is dominated by positive correlations, while central Ghana and Southern Volta Lake are dominated by negative correlation. In addition, mid-Northern and greater portions of central Ghana are marked by negative correlations, while far northwestern and eastern coast of the country are dominated by positive correlations between the IOD and the R20mm index. Most of central and northwestern Ghana are mainly dominated by

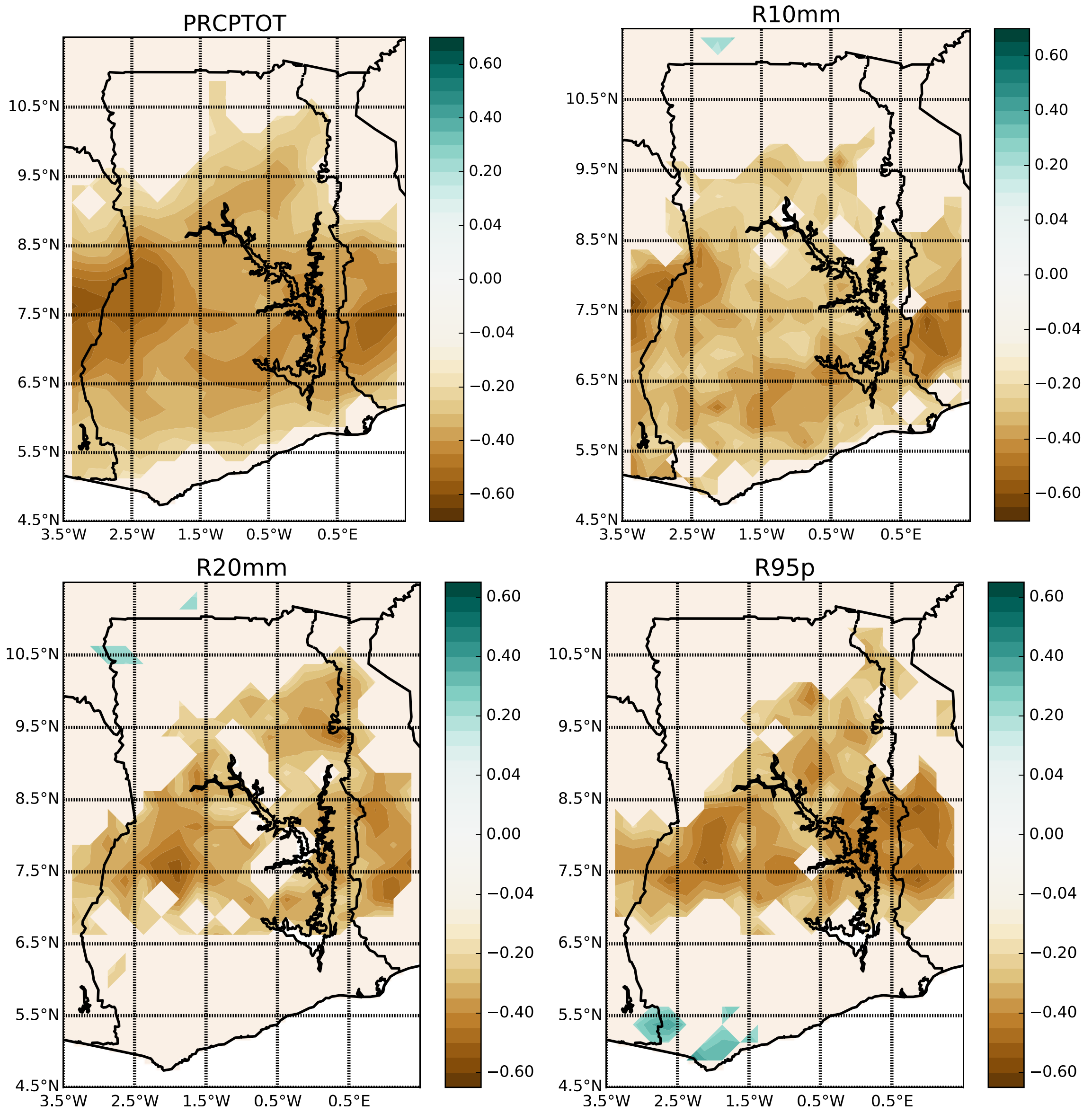


Fig. 7 Correlation between NINO3.4 index and the PRCPTOT, R10mm and R20mm rainfall indices for the period of 1981–2015 over Ghana

negative correlations, whereas the coastal zones and far north-eastern Ghana are influenced by positive correlations.

On average, throughout the entire country, negative correlations exists between wet indices and SSTs anomalies in the Indian Ocean. The argument of Fontaine and Janicot (1996), Bader and Latif (2003) and Lu (2009) that increasing SSTs in the Indian Ocean induced a reduction of precipitation over sub-Saharan West African and Sahel area explains these observations. The correlations of rainfall indices over Ghana with IOD is in agreement with previous understanding that warm SST in the Indian Ocean shifts the rising branch of walker circulation towards Indian Ocean thereby inhibiting rainfall over West Africa. In addition, the positive phase of the IOD index (warm SSTs) creates atmospheric teleconnections mid-tropospheric large-scale subsidence in sub-Saharan West Africa thereby leading to the observed interrelationship over the country (Bader 2005).

3.3.4 AMO index

As established in Figs. 6, SSTs anomalies over the equatorial Atlantic Ocean have positive correlation with wet indices in Ghana. Figure 9 depicts the grid-wise correlation between the PRCPTOT, R10mm, R20mm and R95p indices and the AMO index country-wide. The annual wet-day rainfall total is observed to correlate positively (0.2–0.6) with the AMO index over the entire country which is in agreement with the findings by Diatta and Fink (2014) who reported positive correlations between the AMO index and rainfall over the Sahel. In addition, the results are consistent with findings by Opoku-

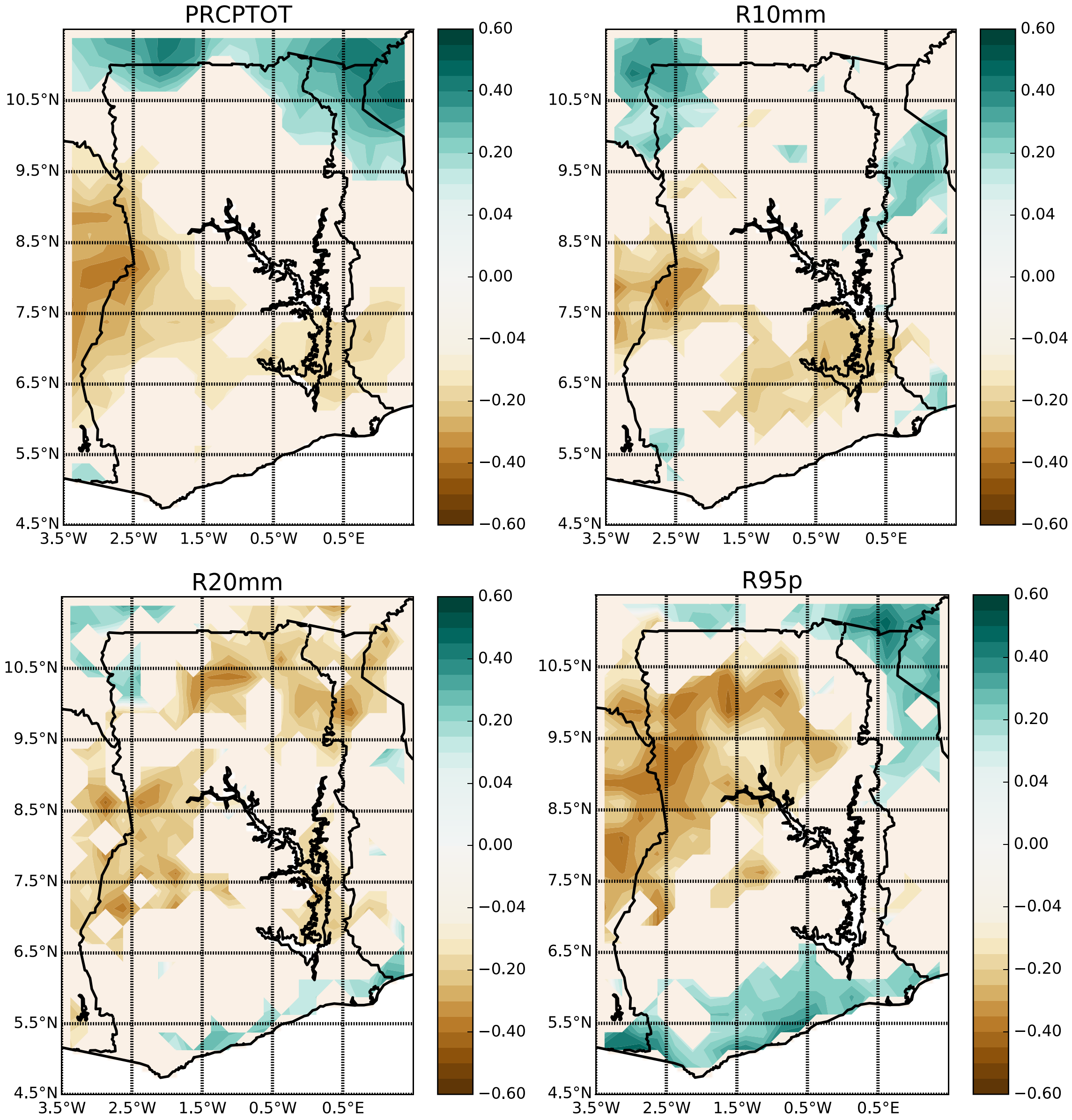


Fig. 8 Correlation between IOD index and the PRCPTOT, R10mm and R20mm rainfall indices for the period of 1981–2015 over Ghana

Ankomah and Cordery (1994) who found the SST anomalies over the equatorial Atlantic to correlate positively with the Ghanaian rainfall.

The number of heavy rainfall days, the number of very heavy rainfall days and very wet day indices are observed to also show positive correlations with the AMO index in most parts of the county except for some isolated pockets in central parts of the country. This could possibly be due to abnormally warm SSTs persistent over the south Atlantic that can reduce meridional Atlantic SST gradients located south of the ITCZ, which weakens the intensity of the Hadley circulation (Opoku-Ankomah and Cordery 1994; Palmer 1986). As a result, the intensity of rainfall/moisture over the West African region is reduced.

4 Conclusions

The spatio-temporal variability of rainfall over West Africa continues to pose challenge to food security and other socio-economic activities. This study presents a comprehensive analysis of the rainfall climatology, trends and drivers of ten extreme rainfall indices using the spatially high resolution CHIRPS-homogenized daily rainfall series for the period of 1981–2015 over Ghana. The mean climatology of the CDD was found to range between 10 and 125 days per year with maximum values over the Northern and minimum values over the southwestern parts of the country. Similar spatial patterns of mean climatologies were observed for the CWD and R10mm indices which range between 6 and 14 days per year and 30–60 days per year, respectively, whereas the R20mm

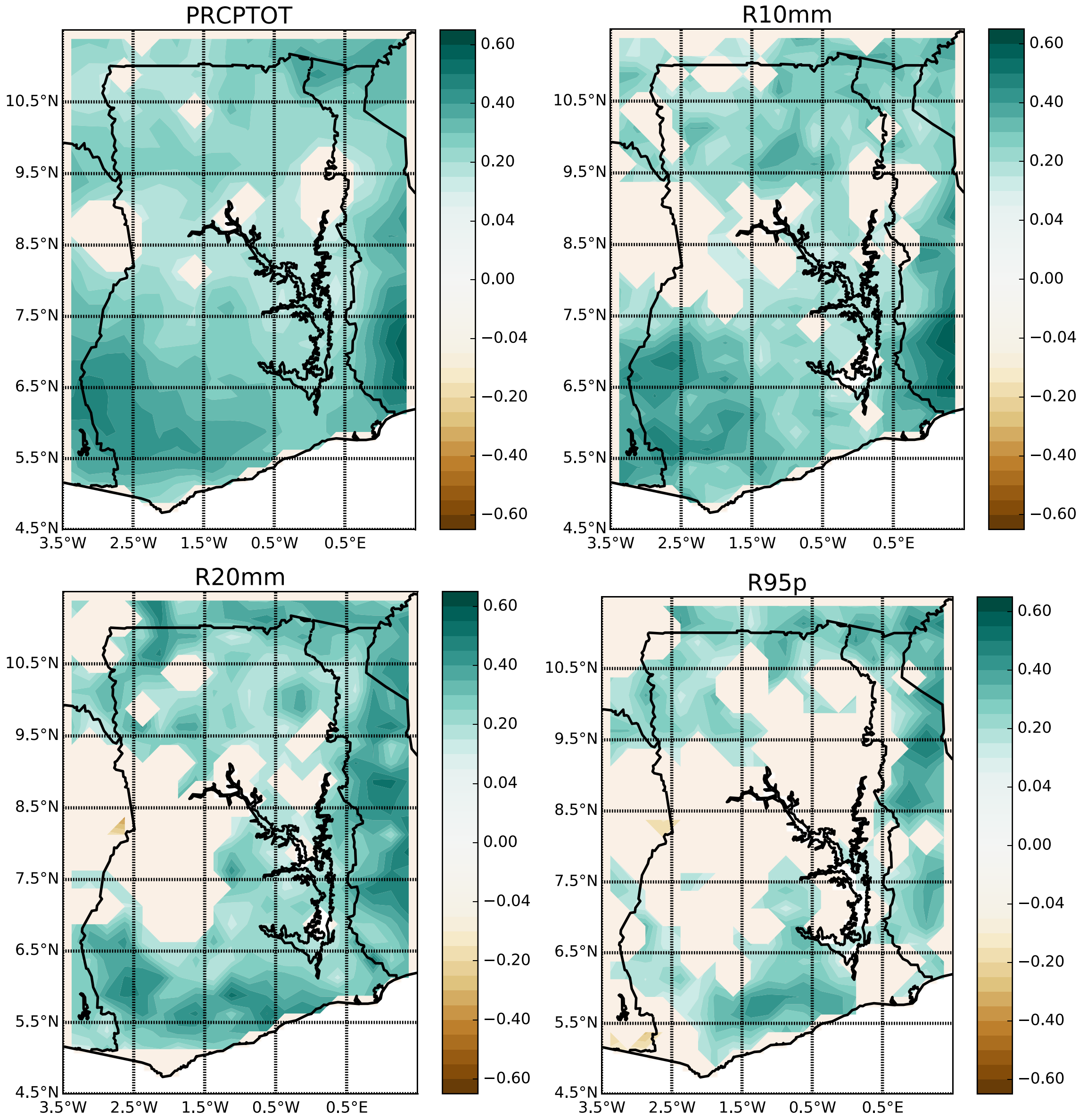


Fig. 9 Correlation between AMO index and the PRCPTOT and R95p rainfall indices for the period of 1981–2015 over Ghana

and SDII indices were range from 8–24 mm and 9–13 mm per year with highest intensities dominating the southwestern Ghana and lowest intensities over Northwestern Ghana. Furthermore, the PRCPTOT, R95p and R99p showed similar patterns with values ranging between 900 and 1700 mm, 200–400 mm and 40–130 mm per year, respectively.

The spatial patterns of the RX1day and RX5day indices were observed to be almost indistinguishable which range between 30 and 100 mm and 90–180 mm per year, respectively, with highest intensities over southwestern Ghana and lowest intensities over Northeastern and eastern coasts. The mean climatology of the SDII index ranges between 7 and 14 mm per year over the entire country with most parts of central Ghana showing medium-range daily intensities and the southwestern parts dominated by the highest daily intensities. In addition, trends of rainfall indices were significant over most parts of the country with negative trends dominating parts of the Volta Lake and central Ghana, whereas weak positive trends were observed over southwestern Ghana for wet indices.

The results for the link between the rainfall indices and SST anomalies over Oceanic basins revealed very few significant correlation between the SST anomalies over oceanic basins, and the CDD, CWD, RXIday, RX5day and SDII indices thus indicating the frequency of daily indices over the region are probably more driven by seasonal scale variability than interannual variability in SSTs over the ocean basins. Generally the SSTs anomalies at the Pacific and Indian Oceans had negative correlations with wet rainfall indices, whereas the Atlantic SSTs had positive correlations with wet indices over Ghana. Specifically, the NINO3.4 had negative correlations with indices particularly over central and Northern parts of the country. This is likely because warm Pacific SSTs as highlighted by Janicot et al. (1998) coincides with subsistence within the tropics leading to the negative correlations between Pacific SSTs and wet indices over the country. IOD on the other hand had a dipole effect on rainfall indices where central and Southern parts generally revealed negative correlations, whereas Northern and coastal zones, positive correlations. More so, the negative correlation between Atlantic SSTs and parts of Ghana could be attributed to the fact that during the negative phase of the Atlantic SSTs, the southward displacement of the West African rain belt becomes intensified thus resulting in rainfall deficits. Central portion of the country was influenced by negative correlations, while positive correlations were dominant far Northern Ghana for the AMO index. This is likely due to the fact that, during the negative phase of the Atlantic SSTs, the southward displacement of the West African rain belt is intensified resulting in rainfall deficits over those locations.

The rainfall deficits in the Volta Lake serve as a strong warning, as it threatens the hydro-electric energy generation in Ghana. In addition, the decreasing rainfall trends in the central portions of the country is also a serious warning which requires policy action, as those parts serve as the food basket of the country.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Amekudzi LK, Yamba EI, Preko K, Asare EO, Aryee J, Baidu M, Codjoe SN (2015) Variabilities in rainfall onset, cessation and length of rainy season for the various agro-ecological zones of Ghana. Climate 3(2):416–434

Aryee J, Amekudzi L, Quansah E, Klutse N, Atiah W, Yorke C (2017) Development of high spatial resolution rainfall data for Ghana. Int J Climatol

Aryee J, Amekudzi L, Atiah W, Osei M, Agyapong E (2018) Overview of surface to near-surface atmospheric profiles over selected domain during the qweci project. *Meteorog Atmos Phys* 131:1067–1108 1-15

Asante FA, Amuakwa-Mensah F (2014) Climate change and variability in Ghana: stocktaking. Climate 3(1):78–99

Bader, J. (2005), `The role of the tropical indian ocean in global climate'

Bader J, Latif M (2003) The impact of decadal-scale indian ocean sea surface temperature anomalies on sahelian rainfall and the North Atlantic oscillation. Geophys Res Lett 30(22)

Bahaga T, Mengistu Tsidu G, Kucharski F, Diro G (2015) Potential predictability of the sea-surface temperature forced equatorial east african short rains interannual variability in the 20th century. Q J R Meteorol Soc 141(686):16–26

Baidu M, Amekudzi LK, Aryee JN, Annor T (2017) Assessment of long-term spatio-temporal rainfall variability over Ghana using wavelet analysis. Climate 5(2):30

Balas N, Nicholson S, Klotter D (2007) The relationship of rainfall variability in west central africa to sea-surface temperature fluctuations. Int J Climatol 27(10):1335–1349

Barnston AG, Tippett MK (2013) Predictions of nino3.4 sst in cfsv1 and cfsv2: a diagnostic comparison. Clim Dyn 41(5–6):1615–1633

Clark CO, Webster PJ, Cole JE (2003) Interdecadal variability of the relationship between the Indian ocean zonal mode and east African coastal rainfall anomalies. J Clim 16(3):548–554

Diatta S, Fink AH (2014) Statistical relationship between remote climate indices and west African monsoon variability. Int J Climatol 34(12): 3348–3367

dos Santos CAC, de Brito JI, da Junior CHS, Dantas LG (2012) Trends in precipitation extremes over the northern part of brazil from era40 dataset (tendências nos extremos de precipitação sobre a parte norte do brasil através dos dados do era40). Revista Brasileira de Geografia Física 5(4):836–851

Enfield DB, Mestas-Nuñez AM, Trimble PJ (2001) The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental us. Geophys Res Lett 28(10):2077–2080

Fontaine B, Bigot S (1993) West African rainfall deficits and sea surface temperatures. Int J Climatol 13(3):271–285

Fontaine B, Janicot S (1996) Sea surface temperature fields associated with west African rainfall anomaly types. J Clim 9(11):2935–2940

Funk C, Peterson P, Landsfeld M, Pedreros D, Verdin J, Shukla S, Husak G, Rowland J, Harrison L, Hoell A et al (2015) The climate hazards infrared precipitation with stations-a new environmental record for monitoring extremes. Scientific Data 2:150066

Gadgil S, Vinayachandran P, Francis P and Gadgil S (2004), `Extremes of the Indian summer monsoon rainfall, ENSO and equatorial Indian Ocean oscillation', Geophys Res Lett 31(12)

Giannini A, Saravanan R, Chang P (2003) Oceanic forcing of Sahel rainfall on interannual to interdecadal time scales. Science 302(5647):1027–1030

Hastenrath S (1990) Decadal-scale changes of the circulation in the tropical Atlantic sector associated with Sahel drought. Int J Climatol 10(5):459–472

Hess T, Stephens W, Maryah U (1995) Rainfall trends in the north east arid zone of Nigeria 1961-1990. Agric For Meteorol 74(1–2):87–97

Huang B, Thorne PW, Banzon VF, Boyer T, Chepurin G, Lawrimore JH, Menne MJ, Smith TM, Vose RS, Zhang H-M (2017) Extended reconstructed sea surface temperature, version 5 (ersstv5): upgrades, validations, and intercomparisons. J Clim 30(20):8179–8205

IPCC (2007) The physical science basis. contribution of working group i to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Issa Lélé M, Lamb PJ (2010) Variability of the intertropical front (itf) and rainfall over the west African Sudan-Sahel zone. J Clim 23(14): 3984–4004

Janicot S, Moron V, Fontaine B (1996) Sahel droughts and ENSO dynamics. Geophys Res Lett 23(5):515–518

Janicot S, Harzallah A, Fontaine B, Moron V (1998) West African monsoon dynamics and eastern equatorial Atlantic and pacific sst anomalies (1970-88). J Clim 11(8):1874–1882

Kemausuor F, Dwamena E, Bart-Plange A, Kyei-Baffour N (2011) Farmers' perception of climate change in the Ejura-sekyedumase district of Ghana. ARPN J Agr Biol Sci 6(19):26–37

Kunstmann H and Jung G (2005), Impact of regional climate change on water availability in the Volta basin of west africa. Regional hydrological impacts of climate variability and change, in `proceedings of symposium S6 for the seventh IAHS scientific assembly. Foz de Iguacu, Brazil'

Lacombe G, McCartney M, Forkuor G (2012) Drying climate in Ghana over the period 1960-2005: evidence from the resampling-based Mann-Kendall test at local and regional levels. Hydrol Sci J 57(8): 1594–1609

Lamb PJ (1978*a*) Case studies of tropical Atlantic surface circulation patterns during recent sub-Saharan weather anomalies: 1967 and 1968. Mon Weather Rev 106(4):482–491

Lamb PJ (1978*b*) Large-scale tropical Atlantic surface circulation patterns associated with subsaharan weather anomalies. Tellus 30(3):240–251

Lamb PJ, Peppler RA (1992) Further case studies of tropical Atlantic surface atmospheric and oceanic patterns associated with sub-Saharan drought. J Clim 5(5):476–488

Lough J (1986) Tropical Atlantic Sea surface temperatures and rainfall variations in subsaharan africa. Mon Weather Rev 114(3):561–570

Lu J (2009) The dynamics of the Indian ocean sea surface temperature forcing of Sahel drought. Clim Dyn 33(4):445–460

Lund R, Reeves J (2002) Detection of undocumented changepoints: a revision of the two-phase regression model. J Clim 15(17):2547–2554

Manzanas R, Amekudzi L, Preko K, Herrera S, Gutiérrez J (2014) Precipitation variability and trends in Ghana: an intercomparison of observational and reanalysis products. Clim Chang 124(4):805–819

Nicholson SE, Webster PJ (2007) A physical basis for the interannual variability of rainfall in the Sahel. Q J R Meteorol Soc 133(629): 2065–2084

Ofori-Sarpong E (2001) Impact of climate change on agriculture and farmers coping strategies in the upper east region of Ghana. West Afr J App Ecol 2:21–35

Opoku-Ankomah Y, Cordery I (1994) Atlantic Sea surface temperatures and rainfall variability in Ghana. J Clim 7(4):551–558

Owusu K, Waylen PR (2013) The changing rainy season climatology of mid-Ghana. Theor Appl Climatol 112(3–4):419–430

Paeth H, Hense A (2004) Sst versus climate change signals in west African rainfall: 20th-century variations and future projections. Clim Chang 65(1):179–208

Palmer T (1986) Influence of the Atlantic, pacific and Indian oceans on Sahel rainfall. Nature 322(6076):251

Rayner N, Parker DE, Horton E, Folland C, Alexander L, Rowell D, Kent E, Kaplan A (2003) Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. J Geophys Res-Atmos 108(D14)

Sanogo S, Fink AH, Omotosho JA, Ba A, Redl R, Ermert V (2015) Spatio-temporal characteristics of the recent rainfall recovery in west Africa. Int J Climatol 35(15):4589–4605

Sultan B, Janicot S (2003) The west african monsoon dynamics. Part ii: the “preonset” and “onset” of the summer monsoon. J Clim 16(21): 3407–3427

Trenberth KE, Stepaniak DP (2001) Indices of El Niño evolution. J Clim 14(8):1697–1701

Tsidu GM (2017) Secular spring rainfall variability at local scale over Ethiopia: trend and associated dynamics. *Theor Appl Climatol* 130(1–2):91–106

Vinayachandran P, Iizuka S, Yamagata T (2002) Indian ocean dipole mode events in an ocean general circulation model. Deep-Sea Res II Top Stud Oceanogr 49(7–8):1573–1596

Wang XL and Feng Y (2010), Rhtestsv3 user manual, Climate Research Division. Atmospheric Science and Technology Directorate. Science and Technology Branch, Environment Canada 24

Wolter K (1989) Modes of tropical circulation, southern oscillation, and Sahel rainfall anomalies. J Clim 2(2):149–172

Yengoh GT, Armah FA, Onumah EE, Odoi JO (2010) Trends in agriculturally-relevant rainfall characteristics for small-scale agriculture in northern Ghana. J Agric Sci 2(3):3

Zhang X, Hogg W, Mekis É (2001) Spatial and temporal characteristics of heavy precipitation events over Canada. J Clim 14(9):1923–1936