Recent climate trends for the Volta Basin in West Africa

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Introduction

Several studies have noted that West Africa – in particular, the Sahel – experienced the most profound inter-decadal climate variability in the world during the twentieth century (Speth *et al.*, 2011; Obuobie and Ofori, 2013). Similar to overall climate patterns in the region, rainfall in the Volta Basin (Figure 1) is characterised by high spatial and temporal variability which increases as one moves north from the sub-humid zones (van de Giesen *et al.*, 2001; 2010; Brown and Crawford, 2008; Pavelic *et al.*, 2013; UNEP-GEF Volta Project, 2013). Rainfall was unusually high in the 1930s and 1950s, but the region was hit by drought that lasted most of three decades (1970–2000). Rainfall partially recovered for the period 1994–2003 (Opoku-Ankomah and Amisigo, 1998; Friesen and Diekkrüger, 2002; Owusu and Waylen, 2009; McSweeney *et al.*, 2010; Ofori *et al.*, 2015). A 10% decrease in rainfall from the period 1960–2005 resulted in a 200km southward shift of isohyets (UNEP-GEF Volta Project, 2013). The West African Monsoon (WAM; Nikulin *et al.*, 2012; Christensen *et al.*, 2013) is known to influence climate variability over the region, and the WAM itself is influenced by changes in the concentrations of greenhouse gases and aerosols in the atmosphere (Christensen *et al.*, 2013).

The evidence for climate variability and climate change across the globe is unequivocal, and the data for the Volta Basin is in line with global findings. Evidence for climate change includes significant increases in ambient temperatures and the increased occurrence of extreme events such as droughts and heavy rainfall (Neumann *et al.*, 2007; Kankam-Yeboah *et al.*, 2010; 2013; van de Giesen *et al.*, 2010; Obuobie *et al.*, 2012; UNEP-GEF Volta Project, 2013). Climate change, irrespective of its cause, is expected to amplify climate variability and increase the intensity and frequency of extreme climate events (WMO, 2009; Cubasch *et al.*, 2013).

The fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2014) compared new observations for the recent climatological period with previous projections, to assess the capabilities of climate models in the simulation of the West African climate (Cubasch *et al.*, 2013). Projected changes in surface temperature were similar to the observed changes, but no trends were found for rainfall, probably due to the effects of interannual variability (McSweeney *et al.*, 2010; Christensen *et al.*, 2013; Kirtman *et al.*, 2013). Reliable projec-

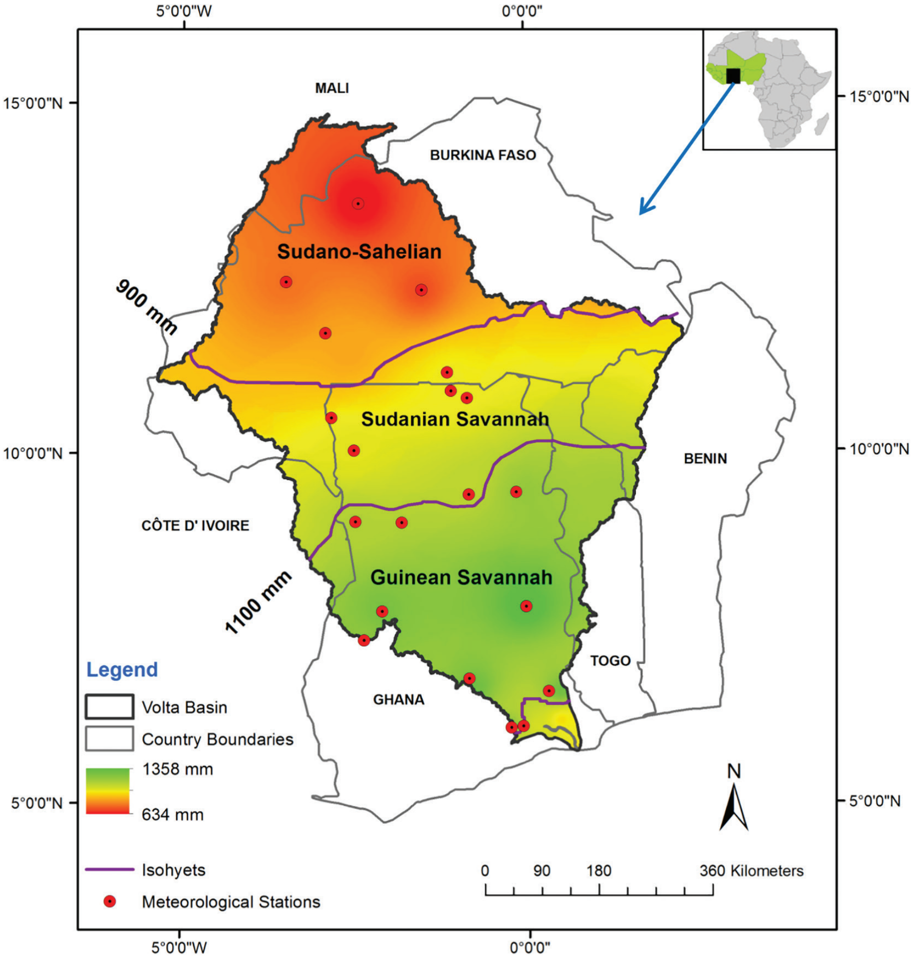

Figure 1. Map of the Volta Basin in West Africa (inset: the location of the basin within the African continent) showing the riparian countries and the climate zones. The ranges of hills that surround the basin reach an altitude between about 250m and 300m, but are generally lower in the Guinean Savannah zone.

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tion and detection of trends in rainfall and systematic changes in rainfall extremes will therefore require an accurate understanding of observations of interannual and multi-decadal climate variability. This is because climate variables, and rainfall in particular, are characterised by high spatial and temporal variability. Investigation of their trends and variability is essential to our understanding of the characteristic progression of the WAM. Adaptation strategies must not only account for future model projections but also for inter-decadal variability (low-frequency variance) in climate extremes observed for past climatological periods (Jung and Kunstmann, 2007; WMO, 2009; Bindoff *et al*., 2013).

In this paper, temperature and rainfall time series in the Volta Basin and their corresponding extreme indices are evaluated and analysed for trends over the reference period 1981–2010.

Material and methods

Study area

The Volta River Basin is located in the semi-arid and humid zones of West Africa and covers an area of about 400 000km^2 (Figure 1). It is a transboundary river basin, the majority of which is located in Ghana (41.6%) and Burkina Faso (43%), with the remainder in Togo (6.4%), Benin (3.4%), Mali (3.1%) and Cote d'Ivoire (2.5%; VBA, 2009). The climate regime is characterised by strong meridional gradients. The Inter-Tropical Convergence Zone (ITCZ) is a zone of significant convective activity and controls the climate in the basin. The rain belt associated with the movement of the ITCZ controls the amount and duration of rainfall across the basin. The migration of the ITCZ across the northern parts once and southern parts twice during the annual cycle results in the mono-modal and bimodal rainfall patterns in the northern and southern areas of the basin, respectively.

The region can be divided into three climate zones (Figure 1), namely, the Guinean Savannah zone (humid south) which has two distinct rainfall seasons that peak in June and September, the Sudano-Sahelian, and the Sudanian Savannah zones (northern basin) which experience mono-modal rainfall that peaks in August/September. Rainfall in the Sudano-Sahelian and Sudanian Savannah zones is unevenly distributed and is skewed towards the months of June to September, during which over 70% of the total annual rainfall occurs (Amisigo, 2005; UNEP-GEF Volta Project, 2013). In the humid south zone, rainfall is evenly distributed over the year (UNEP-GEF Volta Project, 2013).

The mean annual rainfall values are about 700mm, 1000mm and 1200mm for the Sudano-Sahelian, Sudanian Savannah and Guinean zones, respectively (Obuobie *et al*., 2017). Monthly means of daily maximum temperatures vary from 36°C in March to 27°C in August and from 30°C in March to 24°C in August in the northern and southern parts of the basin, respectively (Oguntunde, 2004). Evapotranspiration (ET) is a significant component of the water balance in the basin due to the large bodies of water found across the region (Lake Volta formed as a result of the construction of the Akosombo Dam and Bui Reservoir) and the semi-arid characteristics of the basin. The annual potential ET value varies from 2500mm in the north to about 1800mm in the southern parts of the basin. Potential ET exceeds the mean annual rainfall everywhere in the basin. Andreini *et al*. (2000) and Martin (2005) estimated that the actual ET rate is equal to 91% of the total rainfall.

Data and analyses

Daily rainfall, minimum air temperature (T_{min}) and maximum air temperature (T_{max}) data were obtained from the meteorological agencies of Ghana and Burkina Faso for 20 meteorological stations (Figure 1) in the basin for a 30-year period (1981–2010). Just 20 out of a possible 66 meteorological stations were selected due to data gaps and the poor quality of the data of some of the meteorological stations in the basin.

Monthly, seasonal and annual statistics for the mean and extreme indices were computed from daily rainfall and temperature data for each meteorological station. Spatial averages of the statistics for rainfall amounts (including the number of rainy days) and T_{min} and T_{max} were subsequently calculated for each of the climate zones. Definitions of, and equations related to, the statistics/extreme indices calculated for each of the climate variables over the reference period 1981–2010 are outlined in the following paragraphs.

The Standardised Precipitation Index (SPI) is defined as the total annual/total seasonal rainfall departure from the mean annual/mean seasonal rainfall over the reference period (μ), standardised by the mean annual/seasonal standard deviation (σ) over the same reference period. SPI is can be expressed as follows:

$$\mathrm{SPI}_i = (P_i - \mu) / \sigma \qquad (1)$$

where P_i is the annual/seasonal rainfall for year *i* for the reference period.

The definition of the aridity index (AI) is adopted from the United Nations Environmental Programme (UNEP, 1992). AI is expressed as the ratio of rainfall to potential evapotranspiration. AI is an indicator of the effective moisture available in a basin relative to the atmospheric demand under prevailing climatic conditions. Regions with AI values less than 1 are generally classified as dry, since the evaporative demand cannot be met by precipitation, and regions with AI values greater than 1 are broadly classified as wet. Under the UNEP classification scheme, regions with AI < 0.65 are defined as arid, with four sub-classes from hyper-arid to sub-humid, while regions with AI > 0.65 are classified as humid.

Potential evapotranspiration ET_o was estimated using the Hargreaves method (Hargreaves *et al*., 1985).

Empirical cumulative probability functions (CDFs) for temperature, rainfall, and the AI were developed. The CDFs of the mean annual values of the variables were used to assess their temporal distribution (i.e. the fraction of the data points which had low probability of occurrence (extreme events)).

Descriptive indices of extremes from the World Meteorological Organization's (WMO's) Expert Team on Climate Change Detection and Indices were used to assess changes in climate extremes over the reference period. Climate indices have been used as indirect indicators for monitoring changes in climate extremes such as droughts and floods (WMO, 2009; Qian *et al*., 2010; Dosio, 2016). A list of indices analysed in this work is provided in Table 1.

The climate variables and indices were analysed for trends using the non-parametric Mann-Kendall trend test. The Mann-Kendall test (Mann, 1945; Kendall, 1975; Hirsch and Slack, 1984; Hirsch *et al*., 1982) was chosen over the least-squares (Gaussian) method because it is insensitive to individual observations with high values and therefore prevents high leveraging which skews the analysis. The Mann-Kendall test statistic *S* is zero when the time series of the parameters have zero-trends or no trend. The test statistic τ (tau) tests the null hypothesis, H_o – that data is randomly ordered in time and thus there is no trend – and the alternative hypothesis, H_a – that there is a monotonic (increasing or decreasing) trend. The null hypothesis is rejected when the absolute value of τ is greater than the critical value obtained from the standard normal cumulative distribution table.

The non-parametric Theil–Sen estimator (Theil, 1950; Sen, 1968) was used to estimate the rate of increase or decrease of the trends for each variable/index over the reference period. The statistical value *P*, or calculated probability, is presented.

Results and discussion

Temperature trends

The mean annual T_{max} in the basin is generally higher in the north (the Sudano-Sahelian and Sudanian Savannah) than the south (the Guinean Savannah; Table 2). The highest T_{max} value (38°C) was observed during the April to June period (AMJ, during which the onset of rainfall occurs) over the Sahelian zone; by contrast, the highest T_{max} values for the Sudanian and Guinean zones (36.9 and

Table 1

List of extreme indices analysed in the study.

Index	*Notation*	*Definition*	*Units*
Lowest T_{min}	$T_{min}n$	Lowest daily minimum temperature over a given period	°C
Lowest T_{max}	$T_{max}n$	Lowest daily maximum temperature over a given period	°C
Highest T_{min}	$T_{min}x$	Highest daily minimum temperature over a given period	°C
Highest T_{max}	$T_{max}x$	Highest daily maximum temperature over a given period	°C
Cold nights	$T_{min}10$	Number of days on which T_{min} is lower than the calendar 10th percentile (centred on a 5-day window) of the reference period	days
Cold days	$T_{max}10$	Number of days where T_{max} is lower than the calendar 10th percentile (centred on a 5-day window) of the reference period	days
Warm nights	$T_{min}90$	Number of days on which T_{min} is higher than the calendar 10th percentile (centred on a 5-day window) of the reference period	days
Warm days	$T_{max}90$	Number of days where T_{max} is higher than the calendar 10th percentile (centred on a 5-day window) of the reference period	days
Warm spell duration index	WSDI	The number of days per year on which T_{max} is higher than the calendar 90th percentile of the reference period (centred on a 5-day window) for an interval of at least 6 days	days
Consecutive dry days	CDD	Longest number of consecutive days on which precipitation <1mm	days
Consecutive wet days	CWD	Longest number of consecutive days on which precipitation >1mm	days
Simple daily intensity index	SDII	Ratio of the annual total rainfall to the number of wet days (defined as precipitation ≥1.0mm) in the year	mm day^{-1}
Rainfall due to very wet days	R95pTOT	The total amount of rainfall in a year when the daily rainfall amount is larger than the 95th percentile (on wet days) of the reference period	mm
Fraction of annual precipitation due to very wet days	R95pTOT/PRCPTOT	Ratio of R95pTOT to the total annual rainfall	%

Table 2

Mean annual and seasonal minimum and maximum temperatures for the period 1981–2010 for each of the climatic regions of the Volta Basin.

Time scale	*Sudano-Sahelian*			*Sudanian Savannah*			*Guinean Savannah*		
	Mean (°C)	*Std. Dev. (degC) [CV] (%)*	*Trend ($degCyr^{-1}$) [P-value]*	*Mean (°C)*	*Std. Dev. (degC) [CV] (%)*	*Trend ($degCyr^{-1}$) [P-value]*	*Mean (°C)*	*Std. Dev. (degC) [CV] (%)*	*Trend ($degCyr^{-1}$) [P-value]*
Mean minimum temperature									
Annual	22.3	0.4 [2]	0.034 [<0.0001]	22.6	0.3 [2]	0.024 [0.001]	22.4	0.3 [1]	0.016 [0.011]
JFM	20.4	1.0 [5]	0.048 [0.017]	22.5	0.7 [3]	0.03 [0.038]	22.6	0.5 [2]	**0.02 [0.064]**
AMJ	26.1	0.5 [2]	0.029 [0.002]	24.8	0.4 [2]	**0.01 [0.301]**	23.4	0.3 [1]	**0.006 [0.432]**
JAS	22.7	0.3 [1]	0.021 [0.012]	22.4	0.3 [1]	0.013 [0.035]	21.9	0.2 [1]	0.011 [0.005]
OND	20.2	0.7 [4]	0.044 [0.005]	21.0	0.6 [3]	0.031 [0.012]	21.8	0.4 [2]	0.019 [0.038]
Mean maximum temperature									
Annual	35.7	0.5 [1]	0.029 [0.005]	34.4	0.3 [1]	0.021 [0.004]	32.0	0.4 [1]	0.028 [0.000]
JFM	36.0	0.9 [3]	0.062 [0.001]	36.9	0.7 [2]	0.042 [0.007]	34.7	0.5 [1]	0.031 [0.003]
AMJ	38.0	0.6 [2]	0.024 [0.032]	35.2	0.6 [2]	**0.012 [0.392]**	32.2	0.5 [1]	0.024 [0.012]
JAS	32.4	0.6 [2]	**–0.004 [0.858]**	30.7	0.4 [1]	**0.008 [0.318]**	29.2	0.4 [1]	0.029 [<0.0001]
OND	35.6	0.8 [2]	0.041 [0.022]	35.1	0.6 [2]	**0.026 [0.087]**	32.2	0.5 [2]	0.042 [<0.0001]

Values in bold are statistically significant ($P < 0.05$).

34.7°C, respectively) were observed in the January to March period (JFM – the driest and warmest season). The lowest T_{max} values were observed during the July to September period (JAS – the rainfall season) for all three climatic zones. The lowest mean annual T_{min} value was also observed in the Sahelian zone (Table 2). The lowest value of T_{min} was observed during the October to December period (OND – during which the rainfall season ends), while the highest values were observed during the period AMJ for all three climatic zones. Similar patterns were also observed in the T_{max} and T_{min} variability over the basin. The seasonal variation was more pronounced in the north of the basin than the south. The T_{min} and T_{max} variability was highest for the Sahelian zone, within which the highest variation (with a coefficient of variation CV~5%) occurred during JFM, as observed for the other climatic zones.

The direction of change for T_{min} and T_{max} is very clear over the entire basin, with l increasing trends observed on both inter-annual and seasonal timescales (Table 2). Where these trends are statistically significant (*P*-value < 0.05), these are marked in bold. The average rate of increase for mean annual T_{min} was highest for the Sahelian zone (+0.34 degC per decade) and lowest for the Guinean zone (+0.16 degC per decade). The average rate of increase for mean annual T_{max} was also highest for the Sahelian zone (+0.29 degC per decade) and lowest for the Guinean zone (+0.21 degC per decade).

Seasonally, the rate of increase for T_{min} was highest during JFM over the Sahelian zone (+0.48 degC per decade) and lowest during JAS for the other two climate zones (+0.21 degC per decade; Table 2). The rate of increase for T_{max} was also highest during JFM over the Sahelian zone (+0.60 degC per decade) and lowest during AMJ in the Sudanian and Guinean zones (+0.24 degC per decade; Table 2). The almost unanimous trends over the basin were consistent with findings reported in past climate studies for the region (Oguntunde *et al.*, 2006; Neumann *et al.*, 2007; McSweeney *et al.*, 2010).

Rainfall trends

The periods during which the rainfall seasons occur over the basin are well known, but the onset of the rainy season is unpredictable (van de Giesen, 2010; Kankam-Yeboah *et al.*, 2010). The meridional (north–south) gradient of rainfall over the basin is confirmed by the mean annual and seasonal values shown in Table 3. The mean annual rainfall for the reference period was 749mm, 971mm and 1224mm for the Sahelian, Sudanian and Guinean zones, respectively. During the period 1981–2010, statistically significant increasing trends (*P*-value < 0.05) occurred over the Sahelian zone only for the annual mean and JAS-period rainfall. The average rate of increase for mean annual rainfall was 7.6mm per year (10% per decade). Apparent increasing trends in the annual mean and seasonal rainfall were observed in the other climate zones (Table 3).

A statistically significant rainfall trend for JAS was found only for the Sahelian zone. The rate of increase was 6.1mm per year (equivalent to ~ 12% per decade). Thus, the annual mean trend observed for the Sahelian zone is a result of the significant increase in the rainfall trend for the JAS-period, during which the zone receives the majority of its annual rainfall (mono-modal rainfall pattern). Rainfall amounts in the Guinean zone appeared to be increasing during the main rainfall season, although there was no statistical trend in the data series except for OND (Table 3). The average rate of increase was 2.3mm (14% per decade). The increasing trend in the mean annual rainfall and JAS seasonal rainfall over the Sahelian zone and the increasing trend during OND were consistent with significant increasing trends observed in the data for the number of rainy days (Table 4). There was no evidence of trends for the number of rainy days in AMJ and JAS for the Sudanian and Guinean zones (Table 4). The apparent decreasing trends in the number of rainy days in AMJ and JAS for the Sudanian zone and in JAS for the Guinean zone appear to support findings from past studies (Kankam-Yeboah *et al.*, 2010; Pavelic *et al.*, 2013) which may indicate that the late start and/or shortening of the rainy season are consequences of climate change.

Brown and Crawford (2008) and Oyebande and Odunuga (2010) reported that the Sahelian region was hit by the worst drought on record from the 1970s onwards, until the 1970s until a partial recovery of rainfall in the 1990s. Evidence from this study supports the findings of past studies that indicate the reversal of decreasing rainfall trends to normal levels, or even towards wetter conditions, under the effects of anthropogenic climate change (Brown and Crawford, 2008; Schewe and Levermann, 2017). These effects (i.e. increased temperatures and CO_2 concentrations) could cause a northward shift of the WAM, resulting in the establishment of a positive feedback loop between the increased rainfall amounts and the increase in vegetation cover (a process known as the 'greening' of the Sahel). A recent publication by Schewe and Levermann (2017) points to an abrupt intensification of rainfall (i.e. more frequent heavy rainfall) in the Sahelian region occurring under a gradual increase in sea surface temperature (SST) in the tropical Atlantic and Mediterranean moisture source regions, accompanied by an increase in near-surface wind speed from the former. They advance the argument that rainfall is non-linearly related to SST. Thus, beyond a certain SST threshold above pre-industrial levels, a gradual increase in oceanic moisture avail-

Table 3

Mean annual and seasonal rainfall amounts for the period 1981–2010 for each of the climatic regions of the Volta Basin.

Time scale	*Sudano-Sahelian*			*Sudanian Savannah*			*Guinean Savannah*		
	Mean total (mm)	*Std. Dev. (mm) [CV](%)*	*Trend [P-value]*	*Mean annual (mm)*	*Std. Dev. (mm) [CV] (%)*	*Trend [P-value]*	*Mean annual (mm)*	*Std. Dev. (mm) [CV] (%)*	*Trend [P-value]*
Annual	749	105 [14]	**7.6 [0.001]**	971	114 [12]	3.6 [0.187]	1224	167 [14]	3.3 [0.372]
JFM	6	7 [127]	−0.04 [0.475]	27	17 [61]	−0.09 [0.643]	86	30 [35]	−0.30 [0.721]
AMJ	181	43 [24]	0.98 [0.094]	302	47 [15]	1.55 [0.08]	420	59 [14]	0.93 [0.335]
JAS	524	90 [17]	**6.09 [0.003]**	567	74 [13]	1.36 [0.521]	554	102 [18]	0.35 [0.915]
OND	38	24 [62]	0.5 [0.164]	74	30 [40]	0.63 [0.432]	163	41 [25]	**2.30 [0.008]**

Values in bold are statistically significant (*P* < 0.05).

Table 4

Mean annual and seasonal numbers of rainy days in the annual cycle, based on the 1981–2010 period.

Time scale	*Sudano-Sahelian*			*Sudanian Savannah*			*Guinean Savannah*		
	Mean total (days) (daysday	*Std. Dev. (days) [CV] (%)*	*Trend [P-value]*	*Mean total (days)*	*Std. Dev. (days) [CV] (%)*	*Trend [P-value]*	*Mean total (days)*	*Std. Dev. (days) [CV] (%)*	*Trend [P-value]*
Annual	66	7 [11]	**0.4 [0.01]**	75	7 [10]	−0.1 [0.775]	98	8 [8]	0.2 [0.134]
JFM	1	1 [92]	−0.01 [0.58]	3	1 [53]	−0.02 [0.748]	7	2 [32]	0.01 [0.817]
AMJ	19	2 [13]	0.05 [0.392]	23	3 [12]	−0.04 [0.521]	31	3 [8]	0.01 [0.817]
JAS	41	5 [12]	**0.31 [0.004]**	42	4 [10]	−0.04 [0.721]	44	5 [12]	−0.02 [0.887]
OND	5	2 [44]	0.06 [0.212]	8	3 [36]	0.041 [0.412]	16	3 [17]	**0.19 [0.001]**

Values in bold are statistically significant ($P < 0.05$).

Table 5

Mean annual and seasonal AI, based on the 1981–2010 period.

Time scale	*Sudano-Sahelian*			*Sudanian Savannah*			*Guinean Savannah*		
	Mean	*Std. Dev. [CV] (%)*	*Trend [P-value]*	*Mean*	*Std. Dev. [CV] (%)*	*Trend [P-value]*	*Mean*	*Std. Dev. [CV] (%)*	*Trend [P-value]*
Annual	0.4	0.1 [14]	**0.004 [0.0034]**	0.5	0.1 [12]	0.002 [0.175]	0.9	0.1 [14]	0.002 [0.521]
JFM	0.04	0.1 [129]	~0 [0.412]	0.2	0.1 [62]	~0 [0.617]	0.7	0.3 [36]	−0.003 [0.617]
AMJ	1.0	0.3 [26]	0.004 [0.125]	1.9	0.3 [17]	0.01 [0.125]	3.0	0.5 [15]	0.003 [0.669]
JAS	3.7	0.7 [19]	**0.043 [0.011]**	4.3	0.6 [14]	0.007 [0.669]	4.8	0.9 [18]	~0 [0.972]
OND	0.3	0.2 [64]	0.004 [0.254]	0.4	0.2 [41]	0.003 [0.432]	1.7	0.4 [26]	**0.023 [0.011]**

Values in bold are statistically significant ($P < 0.05$).

ability could trigger an intensification of monsoon rainfall in the Sahelian region via self-amplifying thermo-dynamical feedback.

In line with the UNEP classification scheme, the Sudano-Sahelian and Sudanian Savannah zones are classified as 'semi-arid', and the Guinean zone is classified as 'humid' (Table 5). In a warm-climate region such as the Volta Basin, an increase in soil moisture following increased rainfall leads to increases in the amount of water that is subject to the ET process. Considering the increasing temperature trends over the basin, the increases in both rainfall amounts and the number of rainy days in the Sahelian and Guinean zones should be offset by high ET rates. However, there is no evidence that indicates that the region is becoming more arid (i.e. there are no decreasing rainfall trends); in fact, increasing rainfall trends are observed in JAS, and this increasing trend is reflected in the mean annual data for the Sahelian zone (Table 5). The results of this study support the findings of Schewe and Levermann (2017), which indicate that the Sahelian zone is becoming less dry, at least over recent decades (i.e. water availability is increasing). A trend was also observed for the Guinean zone that was consistent with a seasonal increasing trend for rainfall during OND. However, the increasing trend in OND rainfall is not reflected in the annual pattern, and it cannot, therefore, be concluded that the Guinean zone is getting wetter. The general lack of trends detected in the rainfall data for the Guinean zone and, in particular, the Sudanian may have accounted for a lack of trends for AI in most parts of the basin. It is possible that increasing or decreasing trends are masked by the high degree of variability in rainfall characteristics observed over the region (WMO, 2009).

In contrast with the temperature data, the annual and seasonal rainfall cycles vary considerably on an interannual scale (Tables 2 and 3). The annual and seasonal CV (coefficient of variation) for rainfall ranged from 12% to 14% and from 13% to 127%, respectively. The annual CV for T_{min} and T_{max} ranged from 1% to 2% and the seasonal T_{min} and T_{max} CV ranged from 1% to 5%. The interannual and seasonal variability findings for temperature (T_{min} and T_{max}) are similar in the Sahelian and Sudanian zones, and they are the two most variable zones (Table 2). Rainfall was most variable in the Sahelian and Guinean zones, and their mean annual variability was identical. The high mean annual rainfall variability in the Guinean zone is probably due to the shorter rainy season (fewer rainy days in JAS) - Table 4. The high rainfall variability may be masking a decreasing trend during JAS and a shift towards increased rainfall in the minor rainy season (i.e. an increasing trend in rainfall amounts and rainy days during OND; Table 4). These changes in the annual mean rainfall cycle may account for the high variability of the mean annual rainfall.

Rainfall variability (as expressed by the CV) is notably high during JFM (the dry and warm season) and OND (the end of the rainy season) especially in the Sahelian and the Sudanian zones. Rainy days are clearly rare during these seasons (Table 4), and the amounts of rainfall, and the rainfall pattern, will therefore be erratic. Aridity (the ratio of rainfall to ET) was also found to be highly variable (Table 5). Considering the fact that potential ET is estimated from temperature, its variability will be largely accounted for by rainfall variability, which is generally high over the entire basin (Table 3). Rainfall is particularly difficult to simulate for the Sahelian zone, so confidence in the projections of the WAM is likely to be low. Confidence in projections made for the West African region based on simulations of the ITCZ is low to moderate (Christensen *et al*., 2013; Kim *et al*., 2013; IPCC, 2014).

The SPI values indicate that the 1980s were generally dry, though the magnitudes of the values for individual dry years across this decade vary between climate zones. Rainfall recovered in the subsequent decade (1991–2000) in the Sahelian zone and from the late 1980s to the early 2000s in the Sudanian and Guinean zones (Figures 2 and 3). Jung and Kunstmann (2007) and Oguntunde *et al*. (2006) reported that the 1980s were the driest period of the twentieth century in West Africa but that there was a recovery of rainfall in the Sahel, particularly in western Sahel, in the late 1990s to early 2000s.

For the three examined regions, the mean annual and seasonal rainfall exhibit clear decadal variability over the reference period (Figures 2 and 3). In the Sudano-Sahelian zone, rainfall exhibits a clear inter-decadal trend that is not replicated the Sudanian and Guinean zones. The trends in decadal variability confirm that rainfall has recovered over the last two decades. Significant trends evident in the data for JAS and mean annual rainfall suggest that the Sahelian zone is getting wetter, at least compared with the drought-hit 1980s, and so possibly extreme rainfall events may increase in the future (Christensen *et al*., 2013; Schewe and Levermann, 2017). Even though individual years in the last decade were wet, the observed trends point towards an increase in the variability of rainfall interannually and in JAS (7% for both). Consequently, future rainfall may be erratic and highly variable at both timescales. In the Sudanian Savannah zone, rainfall recovered over the decade 1991–2000, but over the following decade incremental decreases are observed. Rainfall variability appeared to increase over the two decades from 1981, decrease in the early 2000s, and remain more-or-less the same thereafter, especially in terms of the mean annual rainfall in JAS and OND (Figures 2 and 3). Over the Guinean Savannah zone, the annual rainfall regime are mostly dry for the 1980s and average for the 1990s and 2000s. Unlike the Sahelian zone, no clear overall rainfall trend was evident; although there was an increasing trend (2%) observed for OND, it was not reproduced in the mean annual SPI, and it is therefore reasonable to conclude that rainfall variability may remain unchanged.

Temporal distribution of climate variables

The temporal distributions of temperature, rainfall and AI indicate that the probability of recurrence was relatively high for each of these variables, such that the mean annual value calculated for the total period of study would be expected to be exceeded on average only once every 1 to 2.5 years. In the Sudano-Sahelian zone, the mean annual T_{min} and T_{max} values would be expected to be exceeded on average every 1.6 and 1.8 years, respectively, with 57% of annual mean values found to be above the mean annual value for the study period. For T_{min} and T_{max}, temperatures ≥22.8°C and ≥36.1°C, respectively, were found to have a low probability of occurrence (moderate to rare events) with at least a 5-year return period. The mean annual values of rainfall and AI had recurrence periods of 2 and 1.3 years, respectively. Half of the annual rainfall values were found to be above the mean annual value for the study period, and 73% of the annual AI values were above the mean annual value. Mean annual rainfall values ≥845mm and AI values ≥0.48 were considered to be moderate to rare events in the region. The relatively high annual mean data points for AI, and the high plotting probabilities, suggest that the annual mean

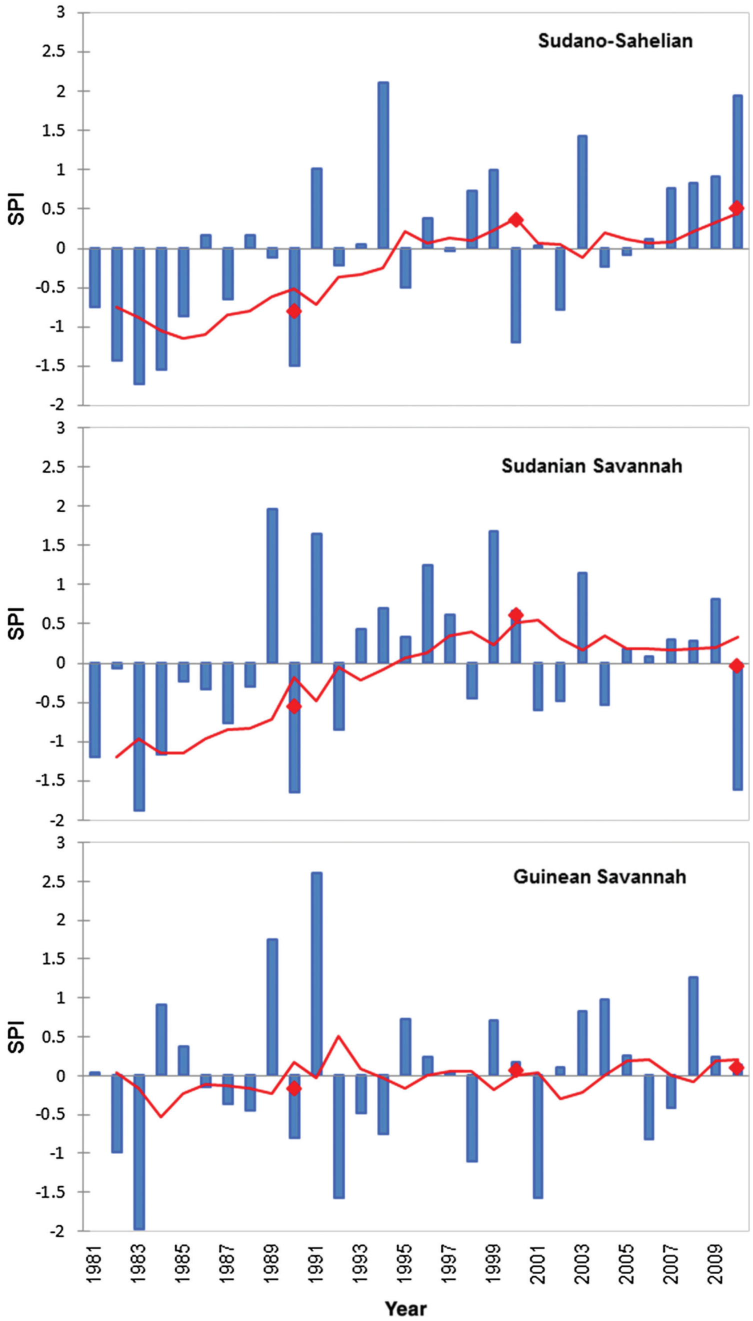

Figure 2. Standardised precipitation indices for annual mean rainfall for all three climate zones over the reference period 1981–2010. Red spline line indicates exponential smoothing of the annual mean values. Red diamond-shaped dots represent the decadal SPI values.

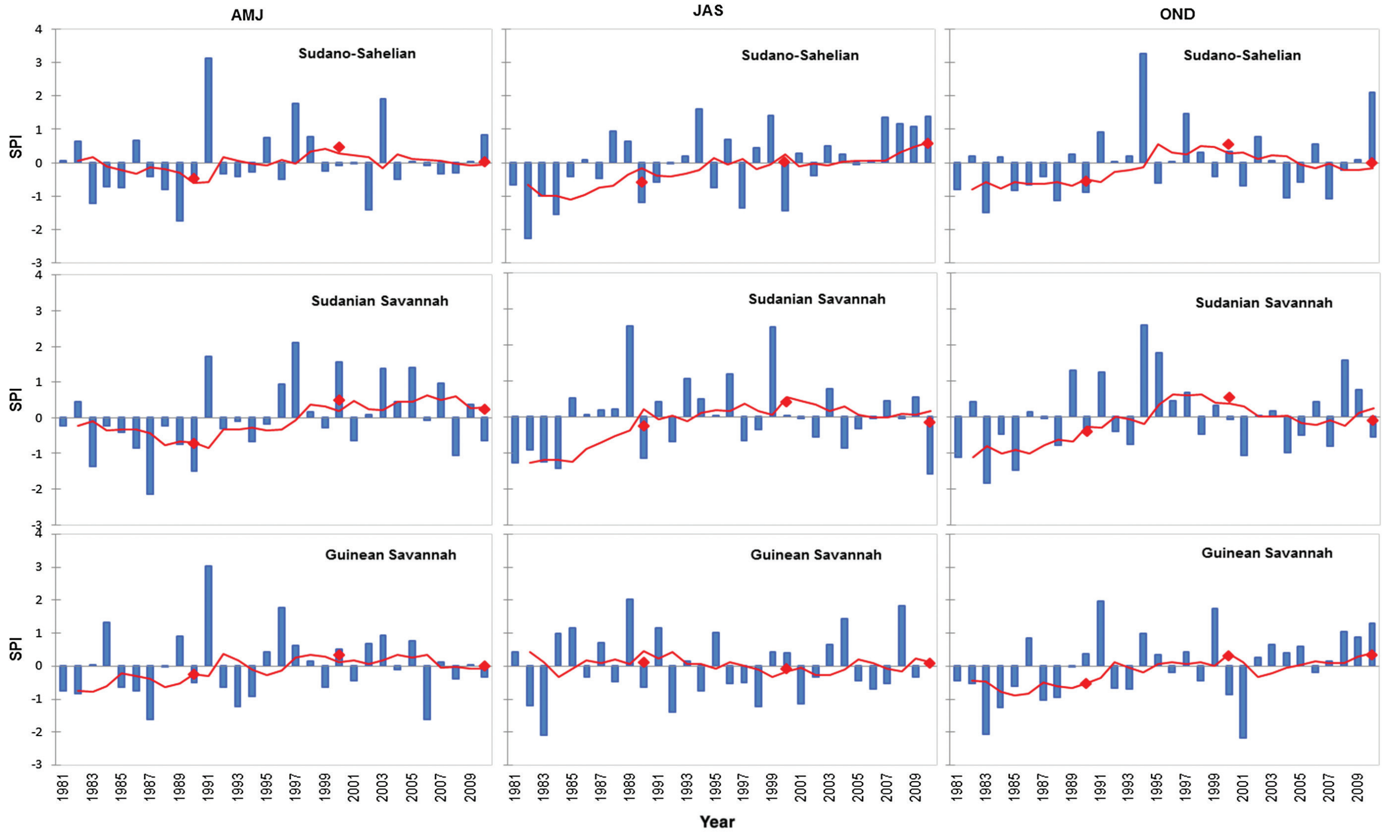

Figure 3. Standardised precipitation indices for seasonal mean rainfall (excluding January–March) for all three climate zones over the reference period 1981–2010. Red spline line indicates exponential smoothing of the annual mean values. Red diamond-shaped dots represent the decadal SPI values.

values are moving incrementally in the direction of becoming extreme events (in this case towards wet/dry sub-humid conditions).

The recurrence periods for T_{min} and T_{max} were 1.8 and 1.7 years for the Sudanian zone and 2 and 1.7 years for the Guinean zone. In the Sudanian zone 57% of annual mean values were found to be above the mean annual value for the study period. In the Guinean zone, 60% and 40% of the annual mean values exceeded the mean annual T_{min} and T_{max}, respectively. T_{min} values ≥22.9°C and T_{max} values ≥34.8°C in the Sudanian zone and T_{min} ≥22.7°C and T_{max} ≥32.3°C in the Guinean zone were considered to be moderate to rare. For rainfall and aridity, analysis of the temporal distribution showed that 53% and 57% of the annual mean values, respectively, were above the mean annual values in the Sudanian zone. In the Guinean zone, 57% of the annual mean rainfall and 40% of the aridity indices exceeded the mean annual values. The recurrence periods for rainfall and AI were shorter than 2.5 years. Rainfall and AI values ≥1064mm and ≥0.56 in the Sudanian zone and ≥1363mm and ≥0.96 in the Guinean zone were considered to be moderate to rare.

Trends in climate extremes

Increasing trends were evident in the temperature extreme indices in all three climatic zones (Tables 6 and 7). Trends were established for the coldest daily minimum temperature, T_{min_n} (i.e. the lowest daily minimum temperature each year), interannually and seasonally in all climatic zones. The rate of increase of T_{min_n} was +0.05 degC per year (+0.5 degC per decade) for the Sahelian and Guinean zones and +0.03 degC per year (+0.3 degC per decade) for the Sudanian zone (Table 6). The highest rate of increase for T_{min_n} was +0.6 degC per decade and was observed for JFM over the Sahelian zone. Rates of +0.43 degC per decade and +0.38 degC per decade were observed for the same period over the Sudanian and Guinean zones. Significant increasing trends were seen for all seasons over the Sahelian zone. The warmest daily minimum temperature (i.e. the highest daily minimum temperature each year, T_{min_x}) was observed in JAS and OND in the Guinean zone. The highest rate of increase for T_{min_x} was +0.4 degC per decade and was observed in the Sahelian zone. The highest rates of increase for the warmest daily maximum temperature (annual maximum daily maximum temperature, T_{max_x}) were observed in the Sahelian and Sudanian zones in JFM (+0.3 degC and +0.5 degC per decade, respectively), and in JAS (+0.3 degC per decade) and OND (+0.2 degC per decade) over the Guinean zone. No trends were observed in the time series for the coldest daily maximum temperature T_{max_n} (the lowest daily maximum temperature each year) or the warm spell duration index (WSDI) over the entire basin (Tables 6 and 7). The typical approach to assessing the intensity and frequency of rare extremes is to fit statistical models to the annual time series of the extreme quantiles (T_{min_n}, T_{max_n}, T_{min_x} and T_{max_x}). However, observed trends in the indices for extreme quantiles are first indications of possible changes in rare extremes.

The frequency of 'warm' days has increased significantly interannually and in JFM over the entire basin, as well as in JAS and OND over the Guinean zone only (Table 6). The frequency of 'warm' nights has also significantly increased interannually over the entire basin, as well as for all four seasons over the Sahelian zone, and for JAS and OND over the Guinean zone (Table 6). Over the period of study, the number of 'warm' days has increased by an average of 10 days per year over the entire basin. Interannually, the largest rate of increase was 3.9%, for the Guinean zone, compared with 2.1% for the Sahelian zone and 2.6% for the Sudanian zone. Seasonally, changes in the frequency of 'warm' days were most pronounced in JFM over the Sahelian (4.5%) and Sudanian (4.9%) zones, and in OND over the Guinean zone (5.1%). The number of 'warm' nights increased by an average of 10 nights per year over the entire basin. The rate of increase in the number of 'warm' nights was highest in the Guinean zone, in JAS (6% per year) and interannually (5%). In the Sahelian zone, the rate of increase was highest in OND (5%), whereas in the Sudanian zone no trends were evident for any season.

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Decreasing trends were observed for the frequency of 'cold' days and nights – the opposite of the results documented above for the frequency of 'warm' days and nights. The average number of 'cold' days decreased by 10 days per year in the Sudanian and Guinean zones, and in the Sahelian zone decreased by 11 days per year. The rate of decrease was significant for the annual mean data series over all the three zones. In the Guinean zone the rate of decrease was significant for all seasons except AMJ. The rate of decrease was high in the Guinean zone (5%), relative to the Sahelian and Sudanian zones (~1.6%). The average number of 'cold' nights interannually was about 10 days in all three zones. The rate of decrease in the number of 'cold' nights was highest in seasonal terms for the Guinean zone (~5% in JAS) and in interannual terms over the Guinean and Sahelian zones (3% each).

Increasing trends in the mean annual and seasonal T_{min} and T_{max} as well as the extreme temperature indices (especially the T_{min} component/extreme indices) are consistent with rapid warming in the basin. T_{min} is the temperature component most sensitive to global warming in climate change studies (Kim *et al*., 2013). Consequently, the diurnal temperature difference will reduce, the ambient environment will be consistently warmer, and numerous processes and functions of the natural environment that depend on the diurnal heating and cooling cycle will be altered.

Significant trends (*P*-value < 0.05) were found for the indicies of rainfall extremes (i.e. CDD, SDII, R95pTOT/RPCPTOT) only in the Sahelian zone, as shown in Table 7. The SDII increased even as the number of rainy days increased, providing confirmation of an increasing trend in heavy rainfall events. Considering that the R95pTOT/PRCPTOT is not sensitive to changes in the number of wet days, the presence of positive trends alongside an increase in the total annual rainfall indicates that extremes are increasing disproportionately relative to annual total rainfall (WMO, 2009). Van de Giesen *et al*. (2010) revealed that although there have been wet and dry decades, the changes in the total amount of rainfall are not significant; however, there has been an increase in the intensity and frequency of extreme events with related high variance. IPCC (2007) and WMO (2009), in their assessments of extreme events, revealed that there has been an increase in heavy precipitation events since the mid-twentieth century, leading to a larger proportion of annual total rainfall occurring during heavy precipitation events in different regions of the world, including West Africa.

Conclusions

Temperature, rainfall, and climate indices of extremes for the Volta Basin were analysed for trends over the reference period 1981–2010. We further evaluated the temporal and

Table 6

Mean and trend values for temperature extremes indices (calculated at seasonal and annual timescales for the reference period 1981–2010).

Time scale	*Sudano-Sahelian*		*Sudanian Savannah*		*Guinean Savannah*	
	Mean	*Trend [P-value]*	*Mean*	*Trend [P-value]*	*Mean*	*Trend [P-value]*
T_{min}n (°C)						
Annual	13.2	**0.05 [0.041]**	15.7	**0.03 [0.049]**	20.2	**0.05 [0.021]**
JFM	19.7	**0.06 [0.009]**	20.8	**0.04 [0.011]**	21.7	**0.04 [0.012]**
AMJ	26.3	**0.03 [0.009]**	22.4	0.0 [0.901]	22.2	0.01 [0.211]
JAS	20.9	**0.02 [0.001]**	20.9	**0.02 [0.008]**	21.2	**0.02 [0.004]**
OND	18.8	**0.05 [0.002]**	19.9	0.003 [0.061]	21.6	**0.04 [0.002]**
T_{min}x (°C)						
Annual	30.4	0.02 [0.245]	28.8	0.0 [0.900]	25.8	0.01 [0.388]
JFM	24.2	**0.09 [0.006]**	25.7	0.04 [0.069]	24.5	0.02 [0.074]
AMJ	29.2	**0.03 [0.031]**	27.4	0.02 [0.317]	25.0	0.01 [0.143]
JAS	25.2	**0.02 [0.028]**	24.1	0.01 [0.115]	22.8	**0.02 [0.004]**
OND	23.2	**0.04 [0.011]**	23.3	0.02 [0.143]	23.2	**0.02 [0.009]**
T_{max}n (°C)						
Annual	26.1	−0.002 [0.943]	25.6	−0.04 [0.153]	25.9	0.02 [0.217]
JFM	30.8	0.06 [0.164]	32.4	0.03 [0.475]	31.7	0.01 [0.721]
AMJ	32.4	0.04 [0.943]	29.8	0.001 [0.986]	28.6	0.01 [0.486]
JAS	27.9	−0.03 [0.318]	26.4	−0.04 [0.104]	26.6	0.004 [0.642]
OND	31.8	0.05 [0.205]	31.6	0.04 [0.239]	30.1	**0.04 [0.002]**
T_{max}x (°C)						
Annual	42.6	0.01 [0.681]	41.2	**0.03 [0.033]**	37.3	0.02 [0.463]
JFM	39.5	**0.03 [0.046]**	39.7	**0.05 [0.005]**	36.5	0.03 [0.059]
AMJ	41.3	0.02 [0.187]	38.4	0.01 [0.655]	34.1	0.02 [0.063]
JAS	35.9	0.01 [0.762]	33.7	0.01 [0.158]	31.1	**0.03 [0.002]**
OND	37.9	0.01 [0.254]	37.3	0.01 [0.284]	33.4	**0.02 [0.012]**
T_{min}10 (days)						
Annual	10.2	**−0.33 [0.000]**	10.1	**−0.22 [0.007]**	10.0	**−0.35 [0.000]**
JFM	10.5	−0.28 [0.071]	10.6	−0.25 [0.112]	10.3	**−0.31 [0.007]**
AMJ	10.0	**−0.26 [0.02]**	9.8	−0.12 [0.269]	9.8	**−0.23 [0.019]**
JAS	9.9	**−0.35 [0.002]**	9.9	−0.17 [0.074]	9.8	**−0.46 [0.002]**
OND	10.3	**−0.42 [0.017]**	10.0	**−0.30 [0.031]**	10.2	**−0.38 [0.013]**

Table 6

Continued

Time scale	*Sudano-Sahelian*		*Sudanian Savannah*		*Guinean Savannah*	
	Mean	*Trend [P-value]*	*Mean*	*Trend [P-value]*	*Mean*	*Trend [P-value]*
T_{min}90 (days)						
Annual	10.3	**0.37 [0.000]**	10.1	**0.24 [0.007]**	9.5	**0.43 [0.001]**
JFM	10.7	**0.42 [0.016]**	10.6	0.28 [0.100]	9.9	0.27 [0.111]
AMJ	10.2	**0.36 [0.005]**	9.9	0.23 [0.158]	9.5	0.20 [0.159]
JAS	10.1	**0.36 [0.016]**	9.7	0.22 [0.143]	9.1	**0.57 [0.000]**
OND	10.2	**0.53 [0.004]**	10.2	0.30 [0.077]	9.6	**0.47 [0.003]**
T_{max}10 (days)						
Annual	10.5	**−0.17 [0.038]**	10.4	**−0.15 [0.038]**	10.3	**−0.27 [0.005]**
JFM	11.0	−0.22 [0.164]	10.9	−0.22 [0.108]	10.4	**−0.36 [0.002]**
AMJ	10.2	−0.05 [0.422]	10.2	−0.05 [0.708]	10.3	−0.20 [0.054]
JAS	10.3	0.01 [0.886]	10.0	0.0 [0.986]	10.1	**−0.23 [0.037]**
OND	10.6	−0.27 [0.097]	10.5	−0.29 [0.059]	10.5	**−0.53 [0.001]**
T_{max}90 (days)						
Annual	10.5	**0.22 [0.044]**	10.2	**0.26 [0.012]**	9.8	**0.38 [0.001]**
JFM	10.5	**0.47 [0.004]**	10.1	**0.50 [0.002]**	10.2	**0.28 [0.029]**
AMJ	10.4	0.28 [0.090]	10.3	0.07 [0.642]	9.8	0.25 [0.125]
JAS	10.2	0.02 [0.901]	10.0	0.21 [0.100]	9.5	**0.49 [0.000]**
OND	10.9	0.29 [0.169]	10.3	0.23 [0.080]	9.8	**0.50 [0.001]**

Values in bold are statistically significant ($P < 0.05$).

Table 7

Mean and trend values for other indices of extremes (calculated at an annual timescale for the reference period 1981–2010).

Time scale	*Sudano-Sahelian*		*Sudanian Savannah*		*Guinean Savannah*	
	Mean	*Trend [P-value]*	*Mean*	*Trend [P-value]*	*Mean*	*Trend [P-value]*
WSDI	4.2	0.0 [0.167]	2.4	0.0 [0.122]	3.3	0.22 [0.478]
CDD	148	**1.3 [0.012]**	94	−0.21 [0.817]	50	−0.6 [0.138]
CWD	7.8	0.0 [0.785]	9.7	−0.09 [0.215]	14.9	0.0 [0.900]
SDII	8.2	**0.07 [0.003]**	7.5	0.01 [0.390]	7.4	0.03 [0.076]
R95pTOT	136	**4.8 [0.005]**	160	0.51 [0.617]	239	3.7 [0.064]
R95pTOT/ PRCPTOT	18	**0.01 [0.004]**	19	0.001 [0.354]	19	0.003 [0.064]

Values in bold are statistically significant ($P < 0.05$).

spatial variability of temperature and rainfall at different timescales. Significant increasing trends were observed for the mean and extreme temperatures. The highest rate of increase in mean temperature was observed for the Sahelian zone. Rates of change for trends in temperature extremes were highest for the Sahelian and Guinean zones, for the threshold-based temperature extreme indices. Trends for the threshold-based temperature extremes indicate that there have been significant decreases in the frequencies of 'cold' days and 'cold' nights, while the frequencies of 'warm' days and 'warm' nights show significant positive trends. The rates of change for the T_{min} component and T_{min} extreme indices on both interannual and seasonal scales were very high in comparison to the T_{max} data. Considering that T_{min} is the temperature component most sensitive to global warming, it seems likely that a decrease in diurnal temperature differences is occurring. As a consequence, the ambient environment will be consistently warmer, which may alter the balance of ecosystems that depend on the diurnal cycle of heating and cooling.

For the annual mean rainfall time series, trends are observed only for the Sahelian zone; this is a result of the significant increasing trends in the JAS rainfall, when the zone receives most of its annual rain. In the Guinean zone, a trend was also evident in the minor rainy season, with apparently increasing rainfall amounts (and decreasing numbers of rainy days) during the main rainy season. This indicates that the main rainy season may be shorter, and that there is a possible skew of rainfall towards the minor rainy season. Trends in extreme rainfall indices (amounts and intensity) were significant only in for the Sahelian zone of the basin. The significant trends in the extreme indices are indicative of future climate change in extremes. The significant positive trends in the mean and extreme rainfall, as well as in the SPI, suggest that the fraction of rainfall due to very heavy rainfall events is increasing disproportionately relative to the annual total rainfall over the Sahelian zone. Thus, the Sahelian zone is getting wetter, at least compared with the drought-prone 1980s, and could possibly become wetter still in the future. However, rainfall is also highly variable in the Sahelian and Guinean zones, especially in comparison with temperature variability, which is low across the entire basin. The observed positive trends in the SPI point to an incremental advance towards an increase in the variability of rainfall interannually and intra-annually over the Sahelian zone. Consequently, future rainfall may be erratic at both of these time-scales. The combination of increasing trends in the frequency, intensity and variability of the mean and extreme rainfall events could have significant effects on rain-fed agriculture and essential ecosystem services, particularly in the Sahelian part of the basin.

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