

Changes in length of rainy season and rainfall extremes under moderate greenhouse gas emission scenario in the Veua catchment, Ghana

Isaac Larbi, Bessah Enoch, Clement Nyamekye, Joshua Amuzu, Gloria C. Okafor, Daniel Kwawuvi and Yaw Mensah Asare

ABSTRACT

The economic implications of extreme climate changes are found to impact sub-Saharan Africa negatively. This study aimed to analyze projected changes in length of rainy season (LRS), and rainfall extreme indices at the Veua catchment, Ghana. The analysis was performed using high-resolution simulated rainfall data from the Weather Research and Forecasting (WRF) model under moderate greenhouse gas emission scenario for the period 2020–2049 relative to the 1981–2010 period. LRS was computed from the difference between rainfall onset and cessation dates, and its trends were assessed using Mann–Kendall test and Sen’s slope estimator. Annual rainfall intensity and frequency indices were computed. Results showed an increase in mean LRS from 168 to 177 days, which was at a rate of 1 day/year in the future (2020–2049). The LRS increase would be more significant at northern and south-western parts of the catchment. Rainfall intensity and frequency indices are projected to increase at spatial scale across the catchment. Projected changes in rainfall extremes could increase the frequency and intensity of drought and flood events. Thus, it is necessary to integrate suitable climate change adaptation measures such as rainwater harvesting, flood control measures, and development of early warning systems in the planning process by decision-makers at the catchment.

Key words | length of rainy season, rainfall extreme indices, rainfall projections, regional climate model, Veua catchment

HIGHLIGHTS

- The spatio-temporal changes in length of rainy season and rainfall extreme indices were analyzed under moderate greenhouse gas emission scenario for the veua catchment.
- High resolution regional climate model was employed in this study.
- Rainfall intensity and frequency indices are projected to increase at the spatial scale across the catchment.
- Mann–Kendall test, onset and cessation of rainfall were used for the data analysis.

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INTRODUCTION

Climate change and climate variability have received attention in recent years which has resulted in increased studies on the spatial heterogeneity of the impact of climate change (e.g., Kaufmann *et al.* 2017). These studies reveal a global increase in average temperature between land and sea and low precipitation increases in high latitudes. Precipitation has been observed to continue decreasing along tropics and subtropical land regions (IPCC 2007, 2013). An increase in average temperature is projected to result in increased climate and climate variability. This will increase the frequency and severity of climate events due to the variability of weather patterns. An increase in the frequency and severity of climatic events has varied impacts on human and natural systems (IPCC 2012). For instance, the catastrophic impact of climate change and climate variability result in short or prolonged drought (Hosseinzadehtalaei *et al.* 2020) and more flooding events from high-intensity and frequency rainfall events (Pineda & Willems 2018). The socio-economic losses of these human-induced and naturally occurring impacts of climate change and climate variability are enormous (Schellnhuber *et al.* 2006; Amuzu *et al.* 2018).

The IPCC report reveals that extreme weather events will continue to increase in many parts of the world (Reay *et al.* 2007). For instance, in Africa, by the end of the year 2020, it was projected that between 75 million and 250 million people would be affected by increasing water stress as a consequence of climate change and climate variability extremes (IPCC 2012). With high confidence, the IPCC reports climate change to increase stress on water resources in Africa (IPCC 2014). As demand for water resources increases, the lives and livelihoods of many people in Africa will be adversely affected. Comparing Africa to the other continents in terms of vulnerability to climate change extremes, the IPCC (2012) notes that 'Africa is one of the most vulnerable continents because of multiple stresses and low adaptive capacity'. Water resources in Africa have been subjected to the highest hydro-climatic variability over space and time relative to other continents (IPCC 2014). This has negative implications on the continent's continuous

economic development. Adaptation strategies in Africa have been noted to be insufficient considering the projected changes in climate over the region. The impact of climate change over the African continent varies.

In West Africa, annual rainfall has been revealed to be on the decrease since the 1960s with a recorded decrease of 20 to 40% around the 1990s (IPCC 2012). The decrease in annual rainfall has caused an estimated 25–35 km southward shift of the 'Sahelian, Sudanese and Guinean ecological zones' with more projected impacts by 2030 (IPCC 2012). As the IPCC (2012) puts it, 'seventeen countries in West Africa share 25 trans-boundary rivers and many countries within the region have a water-dependency ratio of around 90%'. The 90% recorded water-dependency ratio in West Africa is the highest on the African continent. Furthermore, West Africa is the most vulnerable region on the continent to floods and drought using the 2007 floods as a point of reference (Paeth *et al.* 2011; Tall *et al.* 2012). This justifies the selection of West Africa for this study.

Additionally, research into the spatiotemporal pattern of the length of the rainy season and rainfall extremes, for instance, can aid in the development of country-specific adaptation and resilient mechanisms to be put in place relative to situations where these climatic extremes are not predicted (Willems *et al.* 2012). Indeed, in many developing countries, coarse resolution datasets have been used to make continent-scale analysis with less documented information on projected climatic extreme events at the catchment level. Most studies focus on continental-scale when undertaking studies on climate variability extremes (e.g., Nicholson 2002; Vörösmarty *et al.* 2013). However, we share the view that climate variability extremes can be highly variable even in a small space like a country or catchment-scale. The IPCC (2014) posits that 'the impacts of climate change will be superimposed onto already water-stressed catchments with complex land uses, engineered water systems, and a strong historical socio-political and economic footprint'. This justifies the choice to narrow the study area to Veia, a water catchment located in the Upper East Region (UER) of Ghana, West Africa.

Located inside the Veua catchment is the Veua irrigation dam, one of the two main dams (Veua and Tono) used for irrigation in the UER of Ghana. Many farming communities are in the Veua catchment, where intensive farming and animal-rearing activities take place. This makes the Veua catchment critical for the food security needs of UER, the northern sector, and Ghana at large. While the Veua catchment provides farmers with the opportunity to farm continuously throughout the year, it faces 'rising temperature and evapotranspiration trends' (Limantol *et al.* 2016). Studies on climate change and climate variability extreme indices at Veua are considered critical to the development of effective adaptation strategies in water resource management for food security and support of water-dependent livelihood activities. This informed the choice of the Veua catchment for this study with a focus on projected length of rainy season and rainfall extremes. Less research in projected climatic extreme events in developing countries affects policy formulation that relies on data like projected climatic events for sector-specific cases. This creates a lacuna in the effective protection of key sectors like infrastructure, food and agriculture, and potable water supply against the impact of climate change and its variability in many developing countries. This research direction is taken from recommendations from studies like those of Larbi *et al.* (2018) and Muluneh *et al.* (2017). The IPCC report recommends that 'water resources and watershed management in trans-boundary river basins are possible ways in which countries in West Africa can co-operate on a regional basis to build institutional capacity, strengthen regional networks and institutions to encourage co-operation, the flow of information and transfer of technology' (IPCC 2012).

Previous studies have contributed to the literature by studying the past characteristics of the length of the rainy season (e.g., Amekudzi *et al.* 2015) and extreme climatic events' frequencies and intensities indices (e.g., Sunyer *et al.* 2012). We share the view that these studies may not provide a complete understanding of the dynamics of these climatic events since precipitation captures other elements like evapotranspiration which varies over time. In essence, using observed and simulated rainfall data to make projections into the future under high-resolution datasets using the regional climate model will aid in the provision of a

better understanding of future climatic extremes and water availability for agricultural activities. Studying the length of the rainy season and rainfall extreme indices, for instance, helps in the provision of objective and meaningful information on trends, averages, variability, and other statistics on rainfall extremes needed to inform policy formulation (Muluneh *et al.* 2017; Pineda & Willems 2018). Another contribution of this study is to help inform policy and research towards the development of more strategies for effective flood and drought management in the Veua catchment. This is in support of the IPCC (2014) recommendation that 'strategies that integrate land and water management, and disaster risk reduction, within a framework of emerging climate change risks, would bolster resilient development in the face of projected impacts of climate change'. The aim of this study was, therefore, to analyze the projected changes in the length of the rainy season, and rainfall extreme indices (frequency and intensity) in the Veua catchment in the UER of Ghana using high-resolution datasets.

METHODS

Study area

The Veua catchment is one of the sub-catchments within the White Volta Basin in Ghana and is located between latitudes 10° 30'N–11° 08'N and longitudes 1° 15'W–0° 50'E (Figure 1). It has a total land area of about 305 km² and covers mainly the Bongo and Bolgatanga districts in the UER of Ghana. It is characterized by fairly low relief with elevation ranging between 89 m and 317 m (Figure 1) and is mainly dominated by cropland followed by grassland and forest/mixed vegetation (Larbi *et al.* 2019). Located in a semi-arid agro-climatic zone, the catchment covers three agro-ecological zones: the savanna and Guinea savanna zones in Ghana, and north Sudanian savanna zone in Burkina Faso. The climate of the catchment is controlled by the movement of the inter-tropical discontinuity (ITD) over the land which controls the climate of the entire West African region (Obuobie 2008). The rainfall regime in the catchment is uni-modal from April/May to October with a mean annual rainfall of 957 mm which normally peaks in August (Larbi *et al.* 2018). The temperature is

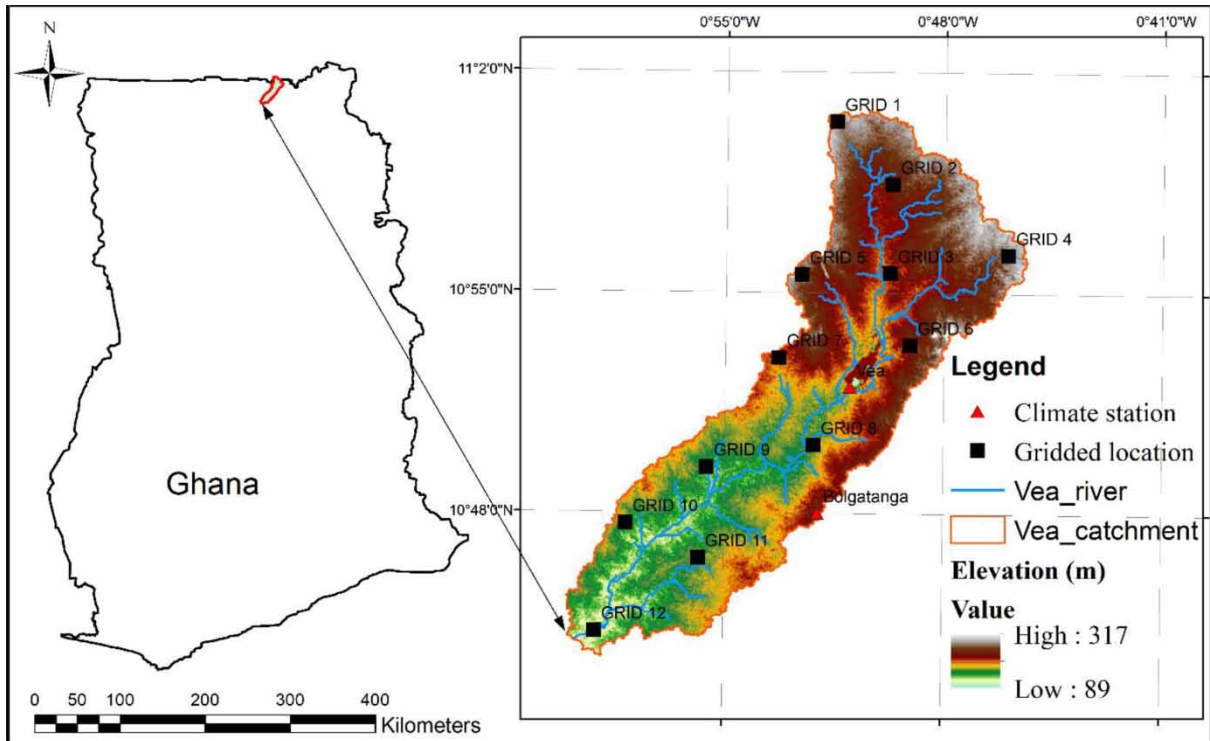


Figure 1 | Map of the Veia catchment in Ghana showing the station and gridded precipitation locations, and elevation within a 12 km regional climate model grid.

uniformly high with a mean value of 28.5 °C while potential evapotranspiration in the study area exceeds monthly rainfall for most of the year, except the three wettest months of July, August, and September (Larbi *et al.* 2020a).

Data sources

Station and satellite-based rainfall data at daily timescale from 1981 to 2010 for 14 locations (Figure 1) were used as observed data for this study. The station (Bolgatanga and Veia) data were obtained from the Ghana Meteorology Agency while the satellite-based rainfall data come from the Climate Hazards Group Infrared Precipitation Station (CHIRPS) data. The CHIRPS precipitation dataset is a product of the United States Geological Survey (USGS) and the Climate Hazards Group at the University of California, Santa Barbara (UCSB) which is available at horizontal resolution 5 km (Funk *et al.* 2015). The station and CHIRPS data quality control, and validation over the Veia catchment have been performed and documented in a previous study by Larbi *et al.* (2018). It was found that an extremely high

seasonal correlation coefficient ($r = 0.99$), Nash–Sutcliffe efficiency (0.98), and percentage bias (4.4% and -8.1%) exist between the CHIRPS and station records. Daily minimum and maximum temperature, relative humidity, wind speed, and solar radiation data were also obtained from the NASA Langley Research Center (LaRC) POWER project (NASA POWER 2018). These climate variables were used to compute the potential evapotranspiration at each climate station. The NASA POWER data ability in reproducing well the climate pattern of station data have been previously demonstrated (Larbi *et al.* 2018).

To assess the future evolution of length of rainy season (LRS) and rainfall extremes in the Veia catchment, the outputs of a near future projection of rainfall simulated with the Weather Research and Forecasting Model (WRF) regional climate model (RCM) was used (Heinzeller *et al.* 2017). This near future projection of rainfall data was produced under the framework of the West African Science Service Center on Climate Change and Adapted Land Use (WASCAL) program over the West African region. The WRF model simulation was driven by the General Fluid

Dynamics Laboratory Earth System Model (GFDL-ESM2M) and produced at a horizontal resolution of 12 km. A detailed technical description of this WRF model simulation (henceforth WRF-GFDL) is reported in Heinzeller *et al.* (2017). The performance of the selected WRF-GFDL model has been evaluated, and the model indicates remarkable skills in reproducing the climatology of the Veua catchment for the period 1981–2005 (Larbi *et al.* 2020b). The WRF-GFDL rainfall data for the Veua catchment have already been bias-corrected using the local intensity (LOCI) scaling method in Larbi *et al.* (2020b). The output used for this study consists of daily simulated rainfall data for the period (2020–2049) under the Representative Concentration Pathway (RCP4.5) scenario. The RCP4.5 is a medium-range emission scenario which is equivalent to 650 ppm CO₂ and stabilizes after 2,100 (van Vuuren *et al.* 2011). The scenario assumes that carbon in natural vegetation will be factored into climate policies, thereby showing a turning point in the global land use contribution to carbon emissions. This scenario was selected not only because the simulated WRF-GFDL output is limited to RCP4.5 but because the scenario is also considered as a threat to the West Africa climate.

LRS computation

The LRS was computed by taking the difference between rainfall onset and cessation dates for the historical (1981–2010) and near future (2020–2049) periods. For each station, the rainfall onset and cessation dates were computed using the Instat+ application (Nyembo *et al.* 2020). The onset date is defined as the date (after 1st April) with a total of

at least 25 mm of rainfall within 5 days, in which the starting day must be wet (at least 0.85 mm rainfall recorded), followed by 7 or more consecutive days of no dry periods (Stern *et al.* 1981). The cessation date was also computed based on the concept of the water balance developed by Stern *et al.* (1981) (i.e., the first date the soil water balance becomes zero after 1st October). These definitions were selected for this study due to their reliability in determining the onset and cessation of rainfall over West Africa (Kumi & Abiodun 2018). In computing cessation date, mean daily reference evapotranspiration (ET_o) for each station is required. The ET_o was computed for each station at daily scale based on the Penman–Monteith method (Monteith 1965).

Rainfall extremes indices analysis

Several rainfall indices have been developed by the Expert Team on Climate Change Detection Monitoring Indices (ETCCDMI) for understanding climate extremes and have been widely applied in several regions (Larbi *et al.* 2018). In this study, six of the rainfall indices categorized into intensity and frequency indices were adopted and computed using RCLindex (Larbi *et al.* 2018). These indices were selected due to their direct impact on water resources and agriculture (Hadri *et al.* 2020). Table 1 shows the description of the selected rainfall indices calculated and analyzed in this study. Three intensity and three frequency indices were selected and analyzed. The consecutive dry days (CDD) are described as a useful indicator for short-term drought (Frich *et al.* 2002) and drought tendencies

Table 1 | Rainfall extreme indices

	Indices	Descriptive name	Definition	Units
Intensity	PRCPTOT	Annual total wet-day precipitation	Annual total precipitation from days ≥ 1 mm	mm
	R95p	Very wet days	Annual total precipitation on the days when daily PRCP >95th percentile	mm
	RX5day	Max-5-day precipitation amount	Annual maximum consecutive 5-day rainfall	mm
Frequency	CWD	Consecutive wet days or Longest wet period	Maximum number of consecutive days with PRCP ≥ 1 mm	days
	CDD	Consecutive dry days or Longest dry period	Maximum number of consecutive days with PRCP <1 mm	days
	R20 mm	Number of very heavy rainfall days	Annual counts of days when rainfall ≥ 20 mm	days

(Orlowsky & Seneviratne 2012) and indicate enhanced dryness and high risk for seasonal droughts.

Trend and spatial distribution analysis

The non-parametric Mann–Kendall (MK) test was used for the trend detection in the LRS. The MK test has been utilized in several studies (e.g., Okafor *et al.* 2017; Larbi *et al.* 2018; Nyembo *et al.* 2020) and has proven to be suitable for non-normally distributed hydro-meteorological data. The MK test assumes a null hypothesis (H_0) that there is no trend which is tested against the alternative hypothesis (H_1) of the presence of a trend (Önöz & Bayazit 2003). Positive and negative values of the MK test indicate increasing and decreasing trends, respectively. The magnitude of the trend was estimated using the Theil–Sen slope estimator modified by Hirsch *et al.* (1982). The MK test and Sen's slope estimator computation for the length of rainy season were conducted at 5% significance level. At this significance level, a negative trend is significant when its p -value ≤ 0.05 , and a positive trend is significant when its p -value ≥ 0.05 . Details on the computation of MK test and Sen's slope estimator can be found in the studies by Larbi *et al.* (2018) and Nyembo *et al.* (2020).

The inverse distance weighting (IDW) interpolation technique (Feng-Wen & Chen-Wuing 2012) was used to interpolate the computed LRS and rainfall indices over the entire catchment at annual timescale from the individual locations. The changes are obtained by the difference between the near future period minus the historical period. The IDW approach minimizes interpolation errors during predictions by using semi-variogram models and considers more observations to achieve the predictions (Oliver & Webster 1990). It assumes that closer things are more similar than those farther apart and uses measured values surrounding an unmeasured location to predict its value.

RESULTS

Projected changes and trends in LRS

Figure 2 and Table 2 show the temporal distribution and basic statistics of the LRS, respectively. The results show a

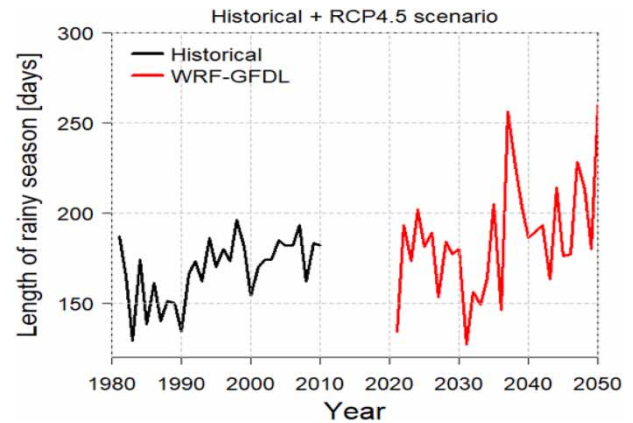


Figure 2 | Inter-annual variability in the length of rainy season over the Veia catchment for the historical (1981–2010) and near future (2020–2049) periods under RCP4.5 scenario.

clear variation in the LRS across the stations (Table 2). The shortest and longest LRS were found to be in the range of 113 to 201 days for the historical period, and from 96 to 241 days in the near future (Table 2). The computed coefficient of variation (CV) values also revealed a relatively low variability in the LRS among the studied stations. Relatively low variability of 9.7 and 12.4% in the LRS for the historical and near future period, respectively, was found for the entire catchment. The time series showed the LRS in the range of 129 to 196 days for the historical and in the early part (up to the year 2035) of the near future period (Figure 2). The mean annual LRS for the entire catchment is projected by the WRF-GFDL model to increase from 168 to 177 days in the near future. The MK test results show a mixed pattern of upward and downward trends in the LRS within the individual locations for the 1981–2010 period. Most locations did not experience significant trends, but the whole catchment saw an increasing trend of LRS at 5% significant level (Table 2). The near future period, however, showed an increasing trend in the LRS at all stations and the entire catchment.

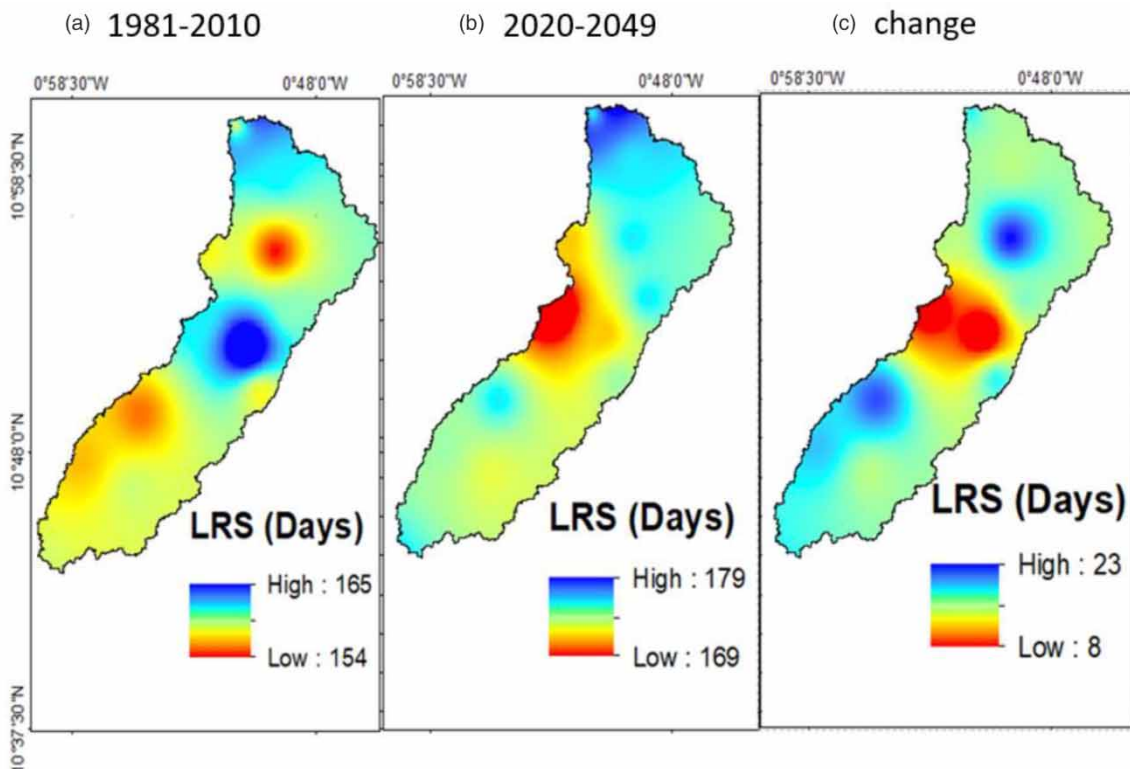
The spatial distribution of the LRS for the historical and near future periods and the projected changes between the two periods is shown in Figure 3. The historical period shows mean annual LRS in the range of 154 to 165 days, with the highest values found at the central part of the catchment. The LRS is expected to increase in the near future with the highest increase found in the northern part of the

Table 2 | Basic statistics and Mann–Kendall trend analysis of LRS (days) for the historical (1981–2010) and near future period

Station	Min	Max	Mean	CV (%)	MK test	Sen's slope
GRID 1	113 (127)	191 (235)	158 (177)	11.8 (13.0)	−1.05 (0.46)	−0.41 (0.27)
GRID 2	114 (116)	194 (215)	160 (176)	12.8 (12.4)	−0.68 (0.64)	−0.40 (0.33)
GRID 3	113 (137)	193 (241)	154 (177)	13.0 (14.5)	−1.07 (1.48)	−0.50 (0.88)
GRID 4	114 (124)	193 (219)	159 (176)	12.3 (13.3)	−0.43 (0.50)	−0.20 (0.27)
GRID 5	114 (120)	193 (227)	157 (174)	12.9 (14.6)	−0.62 (1.12)	−0.35 (0.74)
GRID 6	114 (125)	193 (226)	159 (177)	12.2 (14.5)	−0.42 (1.39)	−0.17 (0.86)
GRID 7	129 (103)	193 (217)	160 (169)	10.8 (16.7)	0.20 (0.91)	0.07 (0.67)
GRID 8	115 (125)	192 (225)	157 (177)	12.4 (14.4)	−0.36 (1.38)	−0.17 (0.90)
GRID 9	120 (123)	192 (215)	155 (177)	11.7 (13.1)	−0.73 (0.16)	−0.28 (0.14)
GRID 10	129 (123)	192 (215)	156 (177)	11.6 (13.1)	0.00 (0.12)	0.00 (0.10)
GRID 11	120 (122)	192 (214)	158 (176)	11.9 (13.1)	0.71 (0.14)	0.31 (0.13)
GRID 12	120 (124)	192 (213)	158 (175)	11.1 (13.1)	0.73 (0.16)	0.25 (0.14)
Veia	106 (96)	201 (227)	166 (174)	13.6 (17.0)	2.11* (0.04)	1.0 (0.09)
Bolgatanga	120 (127)	196 (240)	171 (181)	11.2 (17.0)	2.43* (0.191)	1.0 (1.28)
Catchment	129 (125)	196 (214)	168 (177)	9.7 (12.4)	2.56* (1.91)	1.07 (1.28)

The values for the near future period are in parentheses.

Note: CV indicates coefficient of variation; * indicates statistically significant at 5%.

**Figure 3** | Length of rainy season (LRS) over the Veia catchment for (a) historical (1981–2010), (b) near future (2020–2049), and (c) projected changes.

catchment. The projected change in LRS shows an increase in the LRS in the range of 8 to 23 days, which is more visible at the northern and south-western part of the catchment (Figure 3(c)).

Annual changes in extreme rainfall

The projected changes and time series of the intensity (PRCPTOT, RX5day, and R95p) and frequency (CWD, CDD, and R20 mm) rainfall indices in the Veia catchment are shown in Table 3 and Figure 4, respectively. All three intensity indices are projected to increase in the near

future relative to the historical period (Table 3). The mean annual total wet-day precipitation (PRCPTOT) is projected to increase by 40.2 mm, while annual maximum consecutive 5-day rainfall (RX5day) and very wet days (R95p) are projected to increase by 30.6 mm and 86.1 mm, respectively. The maximum number of consecutive wet days (CWD) and consecutive dry days (CDD) would increase in the near future by 18 and 41 days, respectively. On the other hand, the annual mean value for the number of heavy rainfall days (R20 mm) is projected to decrease by 2 days in the catchment (Table 3).

At the spatial scale (Figure 5), PRCPTOT would increase in most parts of the catchment, especially the southern part, but would decrease in the central part of the catchment. A similar result is found in RX5day, which is also projected to increase across the catchment, with a major increase found at the southern part of the catchment. The R95p is projected to increase in all parts of the catchment, with a more pronounced increase at the southern part of the catchment. The CWD is projected to increase in the range of 18 to 35 days with the highest increase at the southern part of the catchment (Figure 5). A similar result is observed in the CDD, which generally increases over the catchment. In the case of R20 mm, an increase in the range of 13 to 25 days is projected in the entire catchment (Figure 5).

Table 3 | Mean projected changes in the intensity and frequency of rainfall extreme indices at the Veia catchment between the historical and near future (2020–2049) period

Rainfall extreme indices	Historical (1981–2010)	WRF-GFDL (2020–2049)	Change
PRCPTOT (mm)	937.1	977.3	40.2
R95p (mm)	193.3	279.2	86.1
Rx5day (mm)	87.9	118.5	30.6
CWD (days)	8	26	18
CDD (days)	102	143	41
R20 (days)	9	7	–2

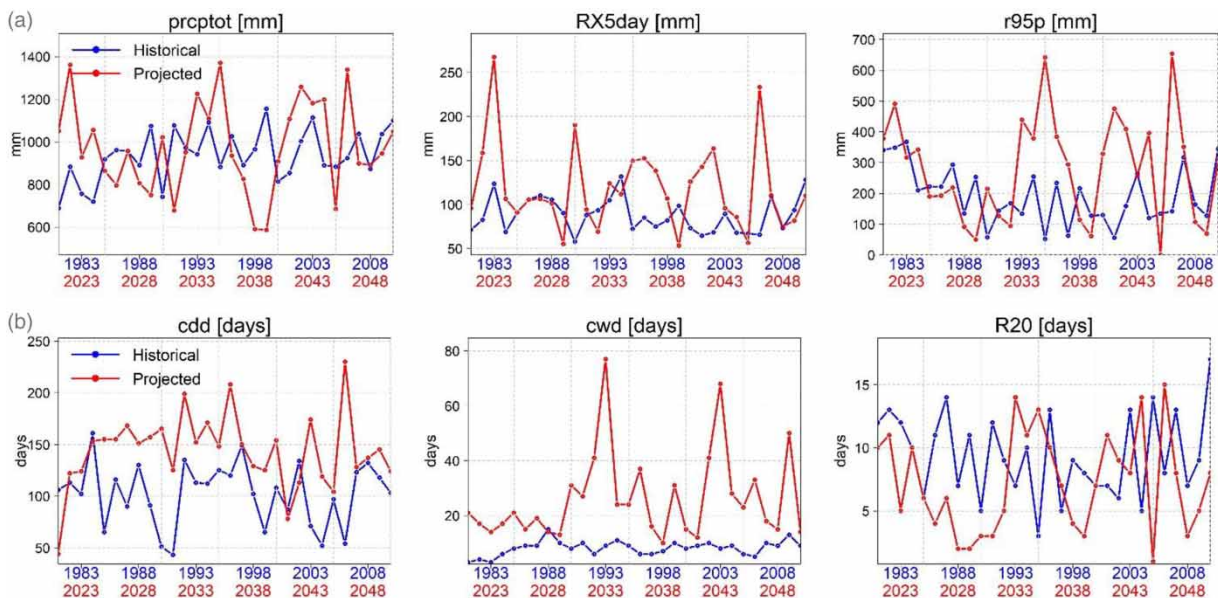


Figure 4 | (a) Intensity and (b) frequency of rainfall extreme indices for the historical (1981–2010) and near future (2020–2049) under RCP4.5 emission scenario.

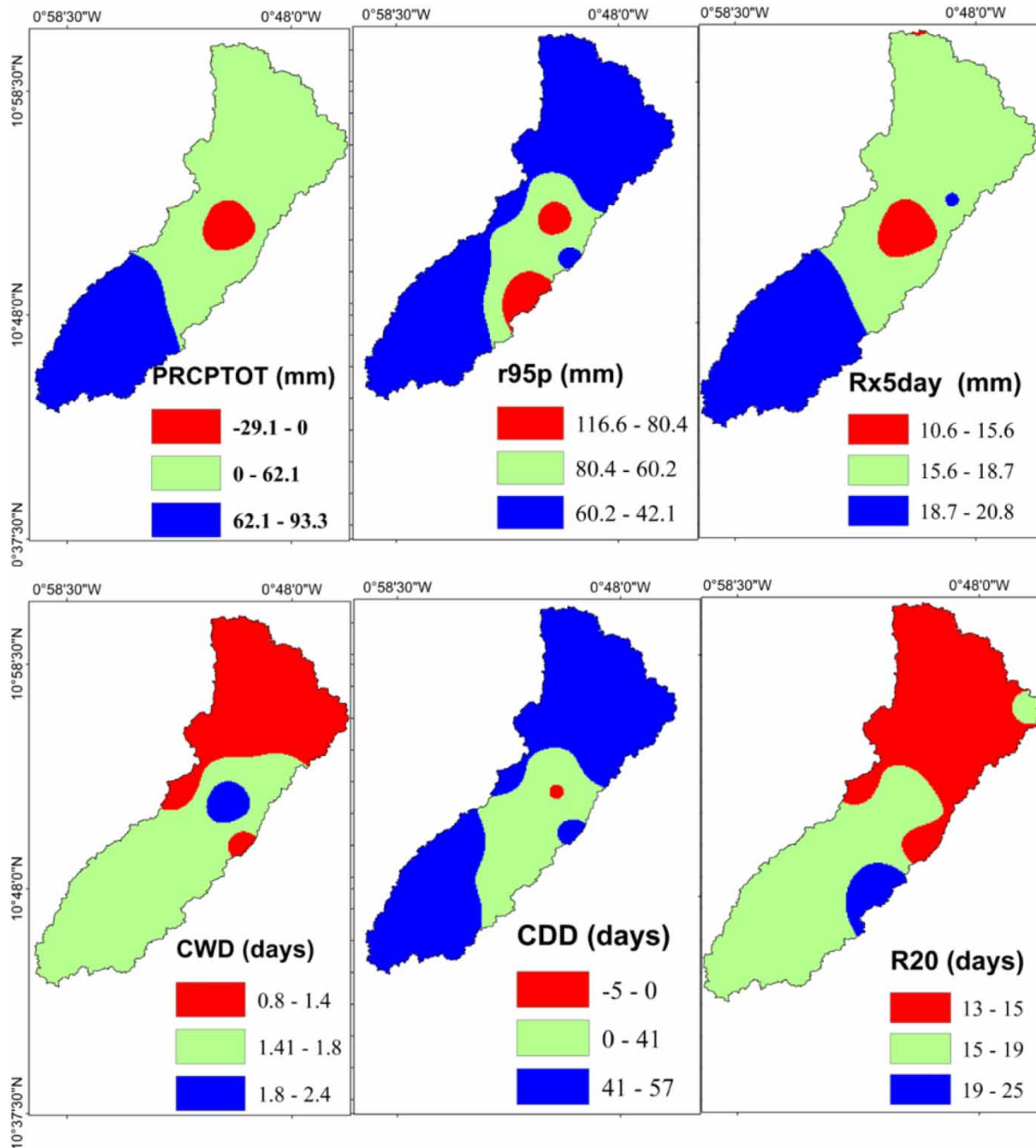


Figure 5 | Spatial distribution of changes in the intensity (PRCPTOT, RX5day, and R95p) and frequency (CWD, CDD, and R20 mm) of extreme rainfall indices in 2020–2049 under RCP4.5 compared to the 1981–2010 period in the Veia catchment.

DISCUSSION

Analysis of spatiotemporal changes of LRS, intensity and frequency of rainfall extremes in the Veia catchment under

RCP4.5 scenario using the WRF-GFDL model were conducted. The mean annual LRS showed variability and a mixed pattern of increasing and decreasing temporal trends. This means that the LRS would be uncertain, such

that in some parts of the catchment the rains start early while in others they arrive very late. As a result, the inter-annual variability would make it difficult for agriculturists to determine the planting dates, the selection of the crop type and crop varieties (Amadou *et al.* 2015). Results of the LRS support the increasing evidence that temperature is continuously increasing while rain becomes less predictable and shorter in duration (Maddison 2006; Thornton *et al.* 2006). The variations and increasing trend of LRS over the Veia catchment for both the historical and future periods may be attributed to the variability in the rainfall onsets and cessation dates. Rainfall is regarded as one of the most significant climatic parameters affecting human activities (Vogel 2000), hence knowledge of rainfall variability is crucial for the effective planning and management of water resources (Oloruntade *et al.* 2018). Weather information is also necessary for the effective implementation of climate change adaptation strategies (Kamagaté 2006). Additionally, the LRS is very important to small-scale farmers in the Sudano-Sahel region of West Africa where the Veia catchment is situated. In addition, Modarres & da Silva (2007) have also revealed that drier locations, just like the Veia catchment location, experience higher rainfall uncertainties that affect agricultural production. This information could help with the year-to-year selection of crop cultivars adapted to the variability in the LRS (Hachigonta *et al.* 2008). The projected increase of LRS (within a range of 8–23 days) in the catchment provides substantial information and guidance to farmers, particularly on which type of crop to select for planting.

The frequency and intensity of extreme rainfall indices are projected to vary in space and time in the near future. The projected increase in the CDD in the northern and southern parts of the Veia catchment suggests a dry tendency. The drier conditions in the future at the northern part of the catchment can be attributed to the decrease in annual total rainfall (PRCPTOT) over this area. Abdullah (2015) stated that the effects of climate change on extreme rainfall events will be greater in regions that are more fragile and thus vulnerable to climate change. Katz & Brown (1992) also maintain that even a small change in the mean rainfall due to global warming can cause significant changes in extreme rainfalls. The projected changes in CDD and CWD could lead to an uneven temporal distribution of rainfall which could have a devastating impact on agriculture

(FAO *et al.* 2015; Wiebe *et al.* 2017). Similarly, the adverse changes in the R20 m over the Veia catchment may lead to a reduction in surface water and groundwater resources. These outcomes are very likely associated with global warming, since the atmosphere can hold more water vapor in a warmer climate (Chu *et al.* 2014). The increase in rainfall extremes is larger than changes in mean rainfall in a warmer climate, because extreme precipitation relates to increases in moisture content of the atmosphere (Kharin & Zwiers 2005). This, therefore, raises serious concern for the catchment as it could suffer from the risk of a climate disaster (such as drought) in the near future. In a similar study, Kanlisi & Arkum (2013) found that the study region has witnessed periodic extreme climate shocks and disasters, such as highly variable and erratic rainfall and long spells of droughts, over the past years. According to the Environmental Protection Agency (EPA 2007), such extreme weather events are expected to intensify in the region by 2080 which is in line with the projected increase in intensity and frequency of extreme rainfall in this study.

Both intensity and frequency of rainfall extremes globally were reported by Myhre *et al.* (2019) to have increased due to global warming. An earlier study in the Veia catchment reported a 1.3 °C increase in temperature under RCP4.5 scenario for the period 2020–2049 (Larbi *et al.* 2020b). Consequently, the projected increase in intensity (PRCPTOT, RX5day, and R95P) and frequency (CWD and CDD) of rainfall extreme indices could reflect the projections of future climate change for the catchment (Kharin & Zwiers 2005; Boko *et al.* 2007). The projected changes in rainfall extremes could negatively affect the livelihoods of smallholder farmers in the Veia catchment involved in only rain-fed agriculture (Abeygunawardena *et al.* 2003; Fosu-Mensah *et al.* 2012). Although rainfall is considered one of the key climate elements which regulate and determine agricultural activities and production throughout the world (Katunzi *et al.* 2016), higher rainfall intensities could have adverse impacts on agriculture. Thus, it will increase the rate of erosion and loss of particulate nutrients from arable soils, eventually reducing the fertility and productivity of soils (Fraser *et al.* 1999). Fowler & Hennessy (1995) also opined that increase in the intensity of rainfall may increase the risk of flood frequency and severity which will eventually destroy cultivated crops.

CONCLUSIONS

This study assessed the changes in the LRS, the intensity and frequency of rainfall extreme indices in the Veia catchment using observation and high-resolution simulated rainfall data from the WRF model under the RCP4.5 emission scenario. The analysis showed clear variation in the LRS across the catchment, and the mean value is projected to increase by 9 days in the near future relative to the historical period. The extreme rainfall indices also revealed an increase in the intensity and frequency in the near future. Drier conditions are expected, particularly in the northern part of the Veia catchment, due to the projected decrease in rainfall and an increase in consecutive dry days over that area. However, the southern part of the catchment would experience wetter conditions with both total wet-day precipitation and maximum consecutive 5-day rainfall projected to increase. These rainfall extremes results suggest that the Veia catchment would be vulnerable to the risk of climate disasters such as drought and floods which could have consequences for socio-economic activities. Thus, there is a need for decision-makers to reorient adaptation and mitigation strategies in the context of climate change and extremes in the study area. Adaptation policies such as rainwater harvesting, weather and climate information services, flood control measures and the development of early warning systems are necessary to mitigate the effects of future extreme climate events in the Veia catchment. The LRS and rainfall extreme assessment in this study was only based on one regional climate model, which when compared to multi-model mean will have high uncertainty in the future projection, making it a limitation of this study. Further studies need to be conducted in this field using multi-model mean and also under extreme climate change scenario (i.e., RCP8.5 scenario).

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DATA AVAILABILITY STATEMENT

All relevant data are available from <https://www.power.larc.nasa.gov/dataaccess-viewer> and <http://chg.geog.ucsb.edu/data/chirps>.

REFERENCES

- Abdullah, G. Y. 2015 The effects of climate change on historical and future extreme rainfall in Antalya, Turkey. *Hydrological Sciences Journal* **60** (12), 2148–2162.
- Abeygunawardena, P., Vyas, Y., Knill, P., Foy, T., Harrold, M., Steele, P. & Sperling, F. 2003 *Part 1. Poverty and Climate Change: Reducing the Vulnerability of the Poor Through Adaptation*. World Bank, Washington DC, USA. Available from: <http://agris.fao.org/agris-search/search.do?recordID=US2012416506> (accessed 28 August 2019).
- Amadou, M. L., Villamor, G. B., Attua, E. M. & Traoré, S. B. 2015 Comparing farmers' perception of climate change and variability with historical climate data in the Upper East Region of Ghana. *Ghana Journal of Geography* **7** (1), 47–74.
- Amekudzi, L., Yamba, E., Preko, K., Asare, E., Aryee, J., Baidu, M. & Codjoe, S. 2015 Variabilities in rainfall onset, cessation and length of rainy season for the various agro-ecological zones of Ghana. *Climate* **3**, 416–434. <http://dx.doi.org/10.3390/cli3020416>.
- Amuzu, J., Jallow, B., Kabo-Bah, A. & Yaffa, S. 2018 The climate change vulnerability and risk management matrix for the coastal zone of the Gambia. *Hydrology* **5** (1), 14. <https://doi.org/10.3390/hydrology5010014>.
- Boko, M., Niang, I., Nyong, A., Githeko, C. A., Medany, M., Osman-Elasha, B., Tabo, R. & Yanda, P. 2007 *Africa. Climate Change 2007: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK and New York, USA.
- Chu, P.-S., Chen, D.-J. & Lin, P.-L. 2014 Trends in precipitation extremes during the typhoon season in Taiwan over the last 60 years. *Atmospheric Science Letters* **15**, 37–43. doi:10.1002/asl2.464.
- EPA 2007 Climate change and the Ghanaian economy. In: *Policy advice series*, Vol 1. Environmental Protection Agency of Ghana, Accra, Ghana.

- FAO, IFAD & WFP 2015 *The State of Food Insecurity in the World: Meeting the 2015 International Hunger Targets: Taking Stock of Uneven Progress*. FAO, Rome, Italy. Available from: www.fao.org/3/a4ef2d16-70a7-460a-a9ac-2a65a533269a/i4646e.pdf
- Feng-Wen, C. & Chen-Wuing, L. 2012 Estimation of the spatial rainfall distribution using inverse distance weighting (IDW) in the middle of Taiwan. *Paddy Water Environment* **10**, 209–222. doi:10.1007/s10333-012-0319-1.
- Fosu-Mensah, B. Y., Vlek, P. L. G. & MacCarthy, D. S. 2012 Farmers' perception and adaptation to climate change: a case study of Sekyedumase district in Ghana. *Environment, Development and Sustainability* **14**, 495–505.
- Fowler, A. M. & Hennessy, K. J. 1995 Potential impacts of global warming on the frequency and magnitude of heavy precipitation. *Natural Hazards* **11**, 283–303. <http://www.springerlink.com/content/w7q445p545h78g38/>.
- Fraser, A. I., Harrod, T. R. & Haygarth, P. M. 1999 The effect of rainfall intensity on soil erosion and particulate phosphorus transfer from arable soils. *Water Science and Technology* **39** (12), 41–45.
- Frich, P., Alexander, L. V., Della-Marta, P., Gleason, B., Haylock, M., Klein Tank, A. M. G. & Peterson, T. 2002 Observed coherent changes in climatic extremes during the second half of the twentieth century. *Climate Research* **19** (3), 193–212.
- Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S. & Michaelsen, J. 2015 The climate hazards infrared precipitation with stations – a new environmental record for monitoring extremes. *Scientific Data* **2**, 150066. <https://doi.org/10.1038/sdata.2015.66>.
- Hachigonta, S., Reason, J. C. & Tadross, M. 2008 An analysis of onset date and rainy season duration over Zambia. *Theoretical and Applied Climatology* **91**, 229–243.
- Hadri, A., Saidi, M. E. M., Saouabe, T. & El Fels, A. A. 2020 Temporal trends in extreme temperature and precipitation events in an arid area: case of Chichaoua Mejate region (Morocco). *Journal of Water and Climate Change*. doi: 10.2166/wcc.2020.234.
- Heinzeller, D., Dieng, D., Smiatek, G., Olusegun, C., Klein, C., Hamann, I., Salack, S. & Kunstmann, H. 2017 The WASCAL high-resolution regional climate simulation ensemble for West Africa: concept, dissemination, assessment. *Earth System Science Data Discussions* **10**, 813–835. <https://doi.org/10.5194/essd-2017-93>.
- Hirsch, R. M., Slack, J. R. & Smith, R. A. 1982 Techniques of trend analysis for monthly water quality data. *Water Resour. Res.* **18**, 107–121.
- Hosseinzadehtalaei, P., Tabari, H. & Willems, P. 2020 Climate change impact on short-duration extreme precipitation and intensity–duration–frequency curves over Europe. *Journal of Hydrology* **590**, 125249. <https://doi.org/10.1016/j.jhydrol.2020.125249>.
- IPCC 2007 The physical science basis – summary for Policymakers. Contribution of WG1 to the Fourth assessment report of the Intergovernmental Panel on Climate Change. <http://www.ipcc.ch/ipccreports/ar4-wg1.htm>
- IPCC 2012 Managing the risks of extreme events and disasters to advance climate change adaptation. In: *A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* (C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G.-K. Plattner, S. K. Allen, M. Tignor & P. M. Midgeley, eds). Cambridge University Press, Cambridge, NY, USA.
- IPCC 2013 *Climate Change 2013: The Physical Science Basis. In: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex & P. M. Midgley, eds). Cambridge University Press, Cambridge, UK and New York, NY, USA. doi:10.1017/CBO9781107415324.
- IPCC 2014 *Climate Change 2014: Synthesis Report. In: Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (C. W. Team, R. K. Pachauri & L. A. Meyer, eds). IPCC, Geneva, Switzerland, p. 151.
- Kamagaté, B. 2006 *Hydrological Functioning and Origins of Flows on A Watershed in A Tropical Environment From Basement to Benin: Watershed of Donga (Upper Ouémé Valley)*. Ph.D. thesis, University of Montpellier II, Montpellier, France.
- Kanlisi, K. S. & Arkum, T. A. 2013 Builsa community vulnerability and capacity assessment in the Upper East Region of Ghana. *European Scientific Journal* **9** (29), 144–164. e-ISSN: 1857–7431.
- Katunzi, W., Bushesha, M. S. & Mwakalila, S. 2016 Examining rainfall and temperature pattern change over time: a case of Kishapu District, Shinyanga Region in Tanzania. *Climate Change* **2** (8), 557–572.
- Katz, R. W. & Brown, B. G. 1992 Extreme events in a changing climate: variability is more important than averages. *Climatic Change* **21**, 289–302. doi:10.1007/BF00139728.
- Kaufmann, R. K., Mann, M. L., Gopal, S., Liederman, J. A., Howe, P. D., Pretis, F., Tang, X. & Gilmore, M. 2017 Spatial heterogeneity of climate change as an experiential basis for skepticism. *Proceedings of the National Academy of Sciences of the United States of America* **114** (1), 67–71.
- Kharin, V. V. & Zwiers, F. W. 2005 Estimating extremes in transient climate change simulations. *Journal of Climate* **18**, 1156–1173. Available from: http://www.cccma.bc.ec.gc.ca/papers/skharin/pdf/ev_cgcm2.pdf
- Kumi, N. & Abiodun, B. J. 2018 Potential impacts of 1.5°C and 2°C global warming on rainfall onset, cessation and length of rainy season in West Africa. *Environmental Research Letters* **13** (5), 055009.
- Larbi, I., Hountondji, F. C. C., Annor, T., Agyare, W. A., Gathenya, J. M. & Amuzu, J. 2018 Spatio-temporal trend analysis of rainfall and temperature extremes in the Veia catchment. *Climate* **6**, 1–17. doi:10.3390/cli6040087.
- Larbi, I., Forkuor, G., Hountondji, F. C. C., Agyare, W. A. & Mama, D. 2019 Predictive land use change under business as usual and afforestation scenarios in the Veia Catchment, West Africa. *International Journal of Advanced Remote Sensing*

- and *GIS* 8 (1), 2320–0243. <https://doi.org/10.23953/cloud.ijarsg.416>.
- Larbi, I., Obuobie, E., Verhoef, A., Julich, S., Feger, K.-H., Bossa, A. & Macdonald, D. M. J. 2020a [Water balance components estimation under scenarios of land use/land cover change in the Veia catchment, West Africa](#). *Hydrological Sciences Journal* 65 (13). doi:10.1080/02626667.2020.1802467.
- Larbi I., Nyamekye, Hountondji, C., Okafor, F. C.C. & Odoom, G. C., P.E.R. 2020 [Climate change impact on climate extremes and adaptation strategies in the Veia catchment, Ghana](#). In: African Handbook of Climate Change Adaptation (W. Leal Filho, N. Ogugu, L. Adelake, D. Ayal & I. da Silva, eds.). Springer Nature, Cham, Switzerland. http://dx.doi.org/10.1007/978-3-030-42091-8_95-1.
- Limantol, A. M., Keith, B. E., Azabre, B. A. & Lennartz, B. 2016 Farmers' perception and adaptation practice to climate variability and change: a case study of the Veia catchment in Ghana. *SpringerPlus* 5 (1), 830.
- Maddison, D. 2006 [The perception of and adaptation to climate change in Africa](#). Policy Research Working Paper; No. 4308. World Bank, Washington, DC. <https://openknowledge.worldbank.org/handle/10986/7507> License: CC BY 3.0 IGO.
- Modarres, R. & da Silva, V. d. P. R. 2007 Rainfall trends in arid and semi-arid regions of Iran. *Journal of Arid Environments* 70, 344–355.
- Monteith, J. L. 1965 Evaporation and environment. *Symposia of the Society for Experimental Biology* 19, 205–234.
- Muluneh, A., Bewket, W., Keesstra, S. & Stroosnijder, L. 2017 [Searching for evidence of changes in extreme rainfall indices in the Central Rift Valley of Ethiopia](#). *Theoretical and Applied Climatology* 128 (3–4), 795–809. <https://doi.org/10.1007/s00704-016-1739-4>.
- Myhre, G., Alterskjær, K., Stjern, C. W., Hodnebrog, Ø., Marelle, L., Samset, B. H., Sillmann, J., Schaller, N., Fischer, E., Schulz, M. & Stohl, A. 2019 [Frequency of extreme precipitation increases extensively with event rareness under global warming](#). *Scientific Reports* 9, 16063. <https://doi.org/10.1038/s41598-019-52277-4>.
- NASA POWER. 2018 [Agroclimatology](#). National Aeronautics and Space Administration (NASA) Prediction of Worldwide Energy Resources (POWER). Available from: https://power.larc.nasa.gov/common/php/POWER_AboutAgroclimatology.php (accessed 15 December, 2017)
- Nicholson, S. 2002 A review of climate dynamics and climate variability in Eastern Africa. In: *The Limnology, Climatology and Paleoclimatology of the East African Lakes* (T. C. Johnson, ed.). Routledge, London.
- Nyembo, O. L., Larbi, I. & Rwiza, M. J. 2020 [Temporal and spatial climate variability and change in a shallow tropical lake of Tanzania](#). *Journal of Water and Climate Change* 12, 469–483. doi:10.2166/wcc.2020.197.
- Obuobie, E. 2008 [Estimation of Groundwater Recharge in the Context of Future Climate Change in the White Volta River Basin](#). PhD dissertation, Rheinische Friedrich Wilhelms Universität, Bonn, Germany.
- Okafor, G. C., Jimoh, O. D. & Larbi, K. I. 2017 Detecting changes in hydro-climatic variables during the last four decades (1975–2014) on downstream Kaduna River catchment, Nigeria. *Atmospheric and Climate Sciences* 7, 161–175.
- Oliver, M. A. & Webster, R. 1990 Kriging: a method of interpolation for geographical information systems. *International Journal of Geographical Information Systems* 4 (3), 313–332.
- Oloruntade, A. J., Mogaji, K. O. & Imoukhuede, O. B. 2018 Rainfall trends and variability over Onitsha, Nigeria. *Ruhuna Journal of Science* 9 (2), 127–139.
- Önöz, B. & Bayazit, M. 2003 The power of statistical tests for trend detection. *Turkish Journal of Engineering and Environmental Sciences* 27, 247–251.
- Orlowsky, B. & Seneviratne, S. I. 2012 Global changes in extreme events: regional and seasonal dimension. *Climate Change* 110, 669–696.
- Paeth, H., Fink, A. H., Pohle, S., Keis, F., Mächel, H. & Samimi, C. 2011 [Meteorological characteristics and potential causes of the 2007 flood in sub-Saharan Africa](#). *International Journal of Climatology* 31 (13), 1908–1926. <https://doi.org/10.1002/joc.2199>.
- Pineda, L. E. & Willems, P. 2018 [Rainfall extremes, weather and climate drivers in complex terrain: a data-driven approach based on signal enhancement methods and EV modeling](#). *Journal of Hydrology* 563, 283–302. <https://doi.org/10.1016/j.jhydrol.2018.05.062>.
- Reay, D., Sabine, C., Smith, P. & Hymus, G. 2007 [Spring-time for sinks](#). *Nature* 446 (7137), 727–728. <https://doi.org/10.1038/446727a>.
- Schellnhuber, H. J., Cramer, W., Nakicenovic, N., Wigley, T. & Yohe, G. 2006 [Avoiding Dangerous Climate Change](#). Cambridge University Press. Available from: www.cambridge.org/9780521864718www.frameworks-city.ltd.ukwww.charontec.com
- Stern, R. D., Dennett, M. D. & Garbutt, D. J. 1981 The start of the rains in West Africa. *International Journal of Climatology* 1, 59–68.
- Sunyer, M. A., Madsen, H. & Ang, P. H. 2012 [A comparison of different regional climate models and statistical downscaling methods for extreme rainfall estimation under climate change](#). *Atmospheric Research* 103, 119–128. <https://doi.org/10.1016/j.atmosres.2011.06.011>.
- Tall, A., Mason, S. J., van Aalst, M., Suarez, P., Ait-Chellouche, Y., Diallo, A. A. & Braman, L. 2012 [Using seasonal climate forecasts to guide disaster management: the Red Cross experience during the 2008 West Africa floods](#). *International Journal of Geophysics* 2012, 1–12. <https://doi.org/10.1155/2012/986016>.
- Thornton, P., Jones, P., Owiyo, T., Kruska, R., Herrero, M., Kristjansson, P., Notenbaert, A., Bekele, N. & Omolo, A. 2006 Mapping Climate Vulnerability and Poverty in Africa. In: *Report to the Department for International Development*. ILRI, Nairobi, Kenya.

- Vogel, C. 2000 Usable science: an assessment of long-term seasonal forecasts amongst farmers in rural areas of South Africa. *South African Geographical Journal* **82**, 107–116.
- Vörösmarty, C. J., Bravo de Guenni, L., Wollheim, W. M., Pellerin, B., Bjerklie, D., Cardoso, M., D'Almeida, C., Green, P. & Colon, L. 2013 Extreme rainfall, vulnerability and risk: a continental-scale assessment for South America. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **371** (2002), 20120408.
- Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J. F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J. & Rose, S. K. 2011 The representative concentration pathways: an overview. *Climatic Change* **109** (1–2), 5–31. <https://doi.org/10.1007/s10584-011-0148-z>.
- Wiebe, K., Sulser, T. & Mason-D'Croz, D. 2017 *The Effects of Climate Change on Agriculture and Food Security in Africa*. International Food Policy Research Institute (IFPRI), Washington DC, USA. Available from: www.africaportal.org/publications/effects-climate-changeagriculture-and-food-security-africa/
- Willems, P., Arnbjerg-Nielsen, K., Olsson, J. & Nguyen, V. T. V. 2012 Climate change impact assessment on urban rainfall extremes and urban drainage: methods and shortcomings. *Atmospheric Research* **103**, 106–118. <https://doi.org/10.1016/j.atmosres.2011.04.003>.

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