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Key Points:
- Ghana's climate has become progressively drier over the last century; the temperature has increased significantly across Ghana, while rainfall has declined mainly in the northern and southwestern parts of the country
- The regions with high prevelance of subsistence agriculture are those experiencing significant increases in temperature and decreases in rainfall
- Variability in total annual rainfall has declined significantly toward the northern part of the country and around the Volta Lake

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Spatiotemporal Variations in Rainfall and Temperature in Ghana Over the Twentieth Century, 1900–2014

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Abstract Climate-dependent subsistence agriculture remains the main livelihood for most populations in Ghana. The spatiotemporal variations in rainfall and temperature have influence particularly in poorly-developed agrarian regions with limited or no irrigation infrastructure. Therefore, a systematic understanding of climate patterns across space and time is important for mitigating against food insecurity and household poverty. Using over a century of high-spatial resolution data, this study examines the spatiotemporal variations in rainfall and temperature across Ghana to identify climate-stressed locations with potential effect on the production of major staple crops. The data for the analysis were drawn from the University of Delaware's Gridded Precipitation and Temperature Monthly Climatology version 4.01. The analysis was restricted to the main crop-growing periods (March to December). The Mann-Kendall nonparametric regression test was used to examine significant changes in rainfall variability and temperature at the district level. The results show that Ghana's climate has become progressively drier over the last century and prone to drought conditions. The most climate-stressed districts are clustered within the three northern regions (Upper West, Upper East, and Northern) and the Western region. The most recent census in Ghana shows that the three northern regions also have the highest prevalence of subsistence agriculture. The findings from this study have implications for targeted interventions such as the Ghanaian government's recent policy initiative aimed at alleviating rural poverty by encouraging youth participation in agriculture along with efforts to intensifying crop production using modern farming techniques.

1. Introduction

Rainfall and temperature are key climatic drivers for agricultural production. The variations in the amount of rainfall and temperature across space and time can significantly influence agricultural yields, which in turn can have a substantial effect on food security and household income. This is particularly the case in most parts of Africa, including Ghana, where climatic conditions continue to threaten agricultural production, as well as the livelihoods of people living in poor and marginalised rural communities (Antwi-Agyei et al., 2012; Barrios et al., 2008; Cooper et al., 2008; Roudier et al., 2011).

Agriculture is an important sector for social and economic development in Ghana. About one half of Ghanaian households are engaged in the agricultural sector, contributing to 22% of the country's Gross Domestic Product (Ghana Statistical Service, 2014; Kayode et al., 2014). The dependence on agriculture in Ghana varies considerably by geographical regions and rural-urban areas. According to the 2010 population and housing census, 76.1% of rural households are engaged in agricultural activities (Kayode et al., 2014). At the regional level, 84% of households in the Upper East region are engaged in agriculture compared to only 7% in Greater Accra (Kayode et al., 2014). More than 95% of agricultural households in Ghana are engaged in crop-farming (Kayode et al., 2014). Agriculture in Ghana is mostly on a subsistence basis, with about 90% of farm holdings being <2 ha (Ministry of Food and Agriculture (MoFA), 2015). Of the 7.8 million hectares of agricultural land under cultivation, only 0.4% is irrigated, with the remaining 99.6% dependent on rainfall (MoFA, 2015).

High nighttime temperatures of 32°C compared to 27°C could decrease rice yields by 90%, and under drought conditions (below two standard deviations of the mean total annual rainfall) maize yields could fall by 1.7% for each degree-day spent above 30°C (Thornton et al., 2014). Rowhani et al. (2011) showed that a simultaneous increase in mean temperatures and decrease in rainfall results in reducing maize, sorghum, and rice yields. Households engaged in agricultural activities are usually the most vulnerable in terms of coping with crop production losses attributed to uncertainty in rainfall and temperature (Wossen & Berger, 2015). However, the measurement of rainfall and temperature and related uncertainty can be methodologically challenging in terms of availability, type, and quality of robust spatial and socioeconomic data.

There is evidence to suggest that traditional societies relied on local knowledge to predict rainfall and temperature patterns, however, due to the rapidly changing climate; this is no longer effective, thus increasing the vulnerability of farmers to climate stressors such as droughts, floods, and timing of rainfall (Thornton et al., 2014). While there are many technological innovations and interventions including effective irrigation systems for enhancing agricultural production, they are out of financial reach for most Ghanaian smallholder farmers who rely solely on essential rainfall and temperature for crop production (Thornton et al., 2014). Therefore, understanding the variability in the quantity and timing of rainfall and temperature is important for predicting crop yields for smallholder farmers.

There are very limited studies that examine climate trends in Ghana. Previous studies that have analysed the spatiotemporal variations in rainfall and temperature have used station-level data with a sparse geographical mix, yielding low spatial coverage and inconsistent and missing data across space and time (Arku, 2012; Endreny & Imbeah, 2009; Lacombe et al., 2012; Le Barbé et al., 2002; Nkrumah et al., 2014; Oduro-Afriyie & Adukpo, 2009; Owusu & Waylen, 2009). Le Barbé's et al. (2002) study of West Africa analysed mean annual rainfall from 300 gauges over an area of 1,700,000 km^2 to measure the occurrence rate and magnitude of convective storms between 1950 and 1990. While their results concurred with previous studies showing a decline in rainfall from the 1970s, the selected network of gauges did not cover Ghana. However, using annual maximum rainfall from satellite precipitation bins and eight gauges (Endreny & Imbeah, 2009), standardised deviation of mean annual rainfall derived from 30 monthly rainfall gauges (Oduro-Afriyie & Adukpo, 2009), and mean annual rainfall and standard deviation derived from 15 stations (Owusu & Waylen, 2009), studies have confirmed similar patterns of declining rainfall and rainfall variability over Ghana from the 1970s. Most of these studies used interpolated station data due to the sparsely distributed network of gauges providing continuous data (daily, monthly, and yearly), and national level analyses covered only limited time periods (mostly between 1950 and the present day). These periods also correspond with the mid-twentieth century onset of extreme global temperature rise in response to high levels of greenhouse gases; however, it is unclear whether the results suggest climate change or climate variability.

Arku's (2012) study used data between 1966 and 2005 with a subset period of 1981 and 2000 and concluded that there has not been a continuous period (of at least 10 years) of either positive or negative change, and hence, there was no change in climate. National analyses often mask the spatiotemporal variations in rainfall and temperature at the small geographic level. On the other hand, micro-level analysis of districts and regions focus on intraregional variations, with little or no systematic intraregional and interregional comparisons (Geografisk, 1997; Issahaku et al., 2016; Neumann et al., 2007; Nyatuame et al., 2014; Owusu et al., 2008). Issahaku's et al. (2016) study of rainfall and temperature variation in the Upper East region of Ghana from 1954 to 2014 used monthly average temperature and average annual rainfall station data to find increases in day and nighttime temperatures and decreases in rainfall. However, the aggregation of the data masked out the local variations between districts and agroecological areas.

The goal of this research is to investigate the spatiotemporal variations in rainfall and temperature across Ghana and identify locations with multiple climatic stresses on crop-producing areas using historical long-term data sets dating back to more than 100 years (1900–2014). In this research, climatic stress is defined by significant increases or decreases in rainfall and/or temperature over the period of the data set. To understand the potential effects of the changes in rainfall and temperature on crop production, we considered the main crop-growing months (March to December) of major staple crops in Ghana, including maize, rice, sorghum, cassava, millet, and yam (MoFA, 2015). We analysed the mean, minimum, and maximum annual temperature and the total and standard deviation of the annual rainfall using a 7-year moving average window (Amikuzuno & Donkoh, 2012; Issahaku & Maharjan, 2013; Jones & Thornton, 2003; Rowhani et al., 2011; Thornton et al., 2009, 2014). These measurement indicators enable us to conduct a systematic assessment of the quality and quantity of crop production and the likelihood of drought and flood conditions.

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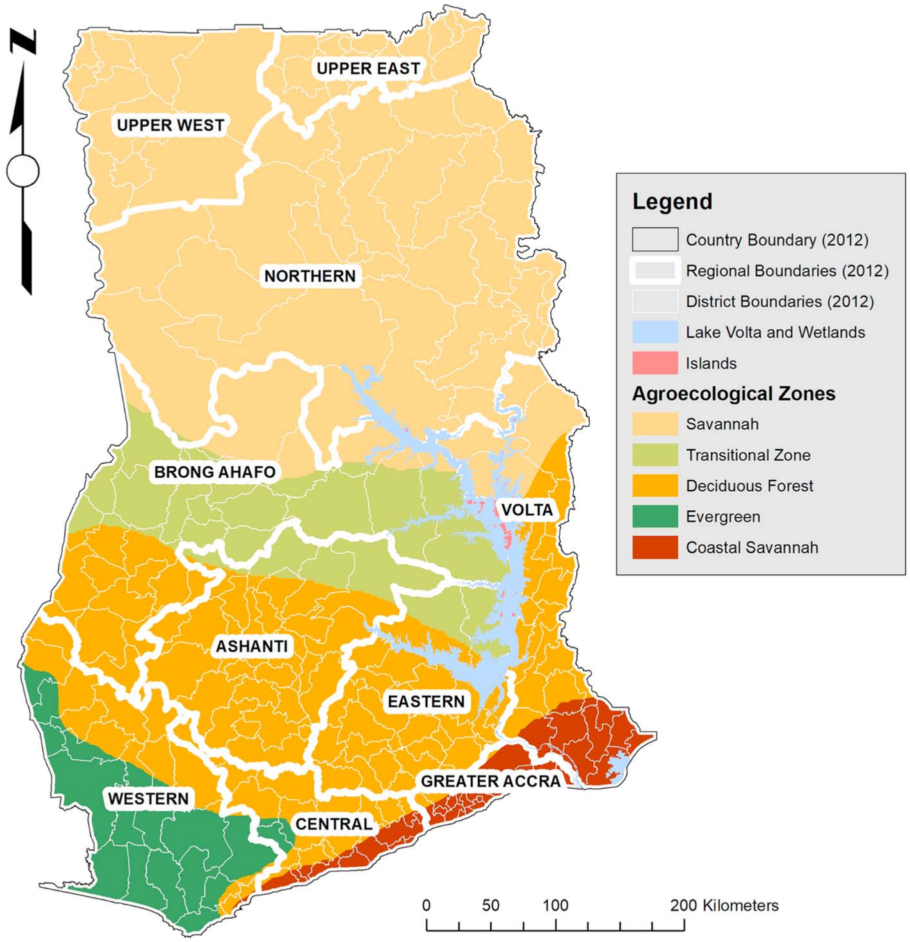

Figure 1. Agro-ecological zones of Ghana: Savannah, Transitional Zone, Deciduous Forest, Evergreen and Coastal Savannah. Source (Harvest Choice, 2005).

2. Study Area

Ghana is located on the Gulf of Guinea in West Africa covering 23,884,245 ha of land and water area between latitudes 4°N and 11°N and longitudes 4°W and 2°E (MoFA, 2015; Nkrumah et al., 2014). The country is demarcated into 10 regions and 216 districts, covering five broadly categorised agroecological (Coastal Savannah, Evergreen, Deciduous Forest, Transitional, and Savannah) zones (Figure 1). The 2010 Ghana Population and Housing Census enumerated 24,658,832 people across the whole country (Ghana Statistical Service, 2013a).

The three northern regions (Upper West, Upper East, and Northern), which are predominantly agroecologically Savannah, are the most sparsely inhabited, constituting 41% of the total land area but only 17.1% of the population. Over three quarters of households in these regions (Upper West—77.1%, Upper East—83.7%, and Northern—75.5%) are engaged in subsistence agriculture (Kayode et al., 2014). The three regions are the most poorly-developed regions in terms of extreme poverty incidence (Online et al., 2010). Ashanti, Brong Ahafo, and Eastern regions, which are mainly transitional and deciduous forest areas producing cocoa, timber, and minerals, constitute 19.4%, 9.64%, and 10.7% of the national population, respectively (Kayode et al., 2014). The share of agricultural activities is also high in these regions: Ashanti (36.6%), Brong Ahafo (68.5%), and Eastern (59.2%) (Kayode et al., 2014).

Western region is mostly Evergreen and Deciduous Forest and highly economically active with a vibrant harbour, several large- and small-scale mines, and offshore oil fields (Online et al., 2010). About one half of households in the region are directly engaged in agricultural activities. Greater Accra (predominantly Coastal) and Ashanti (predominantly Deciduous Forest) are the most developed and urbanised regions in the country, with 16.3% and 19.4% of the national population, respectively, and the lowest in terms of agricultural activity (Greater Accra—6.6% and Ashanti—36.6%). The Volta region cuts across three agroecological (coastal, deciduous forest, and savannah) zones. It constitutes 8.6% of the population and is made up of subsistence agriculture (58.8% of households) and fishing communities (Kayode et al., 2014). Central region, primarily deciduous forest and coastal, is the fourth poorest region and constitutes 8.9% of the population, with fishing and agriculture as the main economic activities (Kayode et al., 2014; Online et al., 2010).

The mean annual temperature varies from 26.1°C at the southwest coast of Western region to 28.9°C at the northeast border of the Upper East, but can reach up to 40°C in the northeast (MoFA, 2015). Conversely, mean annual rainfall varies from approximately 1,000 mm in the northeast border of the Upper East region to 2,200 mm in the southwest coast of Western region. The coastal zone is an arid area experiencing only mean annual rainfall of 800 mm (MoFA, 2015). The three northern regions, with the highest dependence on subsistence agriculture, experience the second lowest amount of rainfall (annual average of approximately 1,000 mm) and the highest temperatures (annual average of 28.9°C; MoFA, 2015). Brong Ahafo, Ashanti, Eastern, Central, and Volta regions, also with high dependence of subsistence agriculture, experience a mean annual rainfall of 800 mm to 1,500 mm and mean annual temperatures of 26.4°C (Ghana Statistical Service, 20122013b). Given the high dependence on subsistence agriculture in Ghana and the high spatial variations in rainfall and temperature, there is a dire need to understand the spatiotemporal variations in rainfall and temperature at sufficient spatial resolution and identify climate-stressed localities.

3. Data

The data for the analysis are derived from the University of Delaware's Gridded Precipitation and Temperature Monthly Climatology version 4.01 (UoD PTMC). The UoD PTMC version 4.01 data are extracted using 12,857 air-temperature and 17,721precipitation stations across the world. Due to the uneven spread and geographically disperse nature of weather stations, Climatologically Aided Interpolation procedures were used to interpolate monthly rainfall and temperature averages to a 0.5° by 0.5° of latitude/longitude grid (Matsuura & Willmott, 2015). The Climatologically Aided Interpolation uses an enhanced distance-weighting method that reduces cross-validation errors. Cross validation of spatial and station-by-station data is carried out to check interpolation errors and to reduce network biases on cross-validation results. The results of Manzanas et al. (2014), who use a quality-controlled data set consisting of 14 gauges from the Ghana Meteorological Agency as a reference for the period from 1961 to 2010, support the use of the gauge-based UoD PTMC product. The UoD product does not correct for undercatch bias correction; however, research shows that accounting for rain gauge undercatch may not be important in Africa (Maidment et al., 2014). Furthermore, other analyses have shown that mathematically correcting for rain gauge undercatch bias produces similar results of annual and seasonal mean rainfall (Schneider et al., 2014).

The advantage of the UoD PTMC version 4.01 is the availability of high-spatial resolution data and longer temporal records with no missing observations (available for researchers at no cost). The data for the analysis consist of monthly rainfall and temperature averages from 1900 to 2014. In total, five variables were derived:

1. Total annual rainfall (sum of monthly rainfall averages)
2. Rainfall variability (standard deviation of a moving 7-year window of the total annual rainfall)
3. Mean minimum annual temperature (mean of the monthly minimum temperatures)
4. Mean annual temperature (mean of the monthly temperatures)
5. Mean maximum annual temperature (mean of the monthly maximum temperatures)

The analysis was restricted to the months March to December to coincide with major cropping period. To examine the changes in temperature, the minimum and maximum monthly temperatures were extracted for each grid (122 grids in total) by year and the mean annual temperature was computed for the months March to December for each grid. All three indicators were analysed due to their importance for crop growth (Amikuzuno & Donkoh, 2012; Issahaku & Maharjan, 2013; Jones & Thornton, 2003; Rowhani et al., 2011; Thornton et al., 2009, 2014). The total rainfall and the standard deviation of the total rainfall for March to December were computed for each grid by year. West African rainfall variability operates on three dominant time scales: multidecadal (>20 years), quasi-decadal (8–18 years), and interannual (2–8 years; Dieppois et al., 2015). A number of studies (Koranteng & McGlade, 2001; Mawunya et al., 2012; Opoku-Ankomah & Cordery, 1994; Owusu & Waylen, 2009) have shown a link between sea surface temperatures, rainfall, and El Niño–

Southern Oscillation (which operates on a 4–7-year cycle) across Ghana. In order to identify any break periods that indicate a shift in rainfall trends, we chose the finer-resolution interannual time scales, which also correspond to the El Niño–Southern Oscillation cycle. To calculate rainfall variability, the standard deviation of total annual rainfall was calculated using a moving window to smooth out irregularities and capture the overall direction of the trend. Moving windows of analysis of 4, 5, 6, and 7 years were tested on annual rainfall using the (runsd(df, year)) function in the R programming language, and the 7-year window showed the strongest line of best fit. The computation of 108 standard deviations (1900–1906, 1901–1907, 1902–1908 … 2008–2014) was performed. The Mann-Kendall trend test was then applied to these values (mk.test(x)) in order to test the trend in variability over time.

4. Methodology

To examine interannual and decadal variability in total rainfall over the study period, the Lamb index (Kouakou et al., 2016) was used. The Lamb index I_i determines whether precipitation in a given year of the study period is excess, normal, or deficit. The index is computed using equation (1)

$$I_i = \frac{P_i - P}{\sigma} \tag{1}$$

where I_i is the Lamb index for year i, P_i is the value of the annual rainfall of the year i, and P and σ are the average rainfall and standard deviation computed over the study period. I_i greater than 0.5 is classified as excess rainfall, I_i between -0.5 and 0.5 is classified as normal rainfall, while I_i less than -0.5 is classified as deficit rainfall. In addition, in order to assess interdecadal variability in mean annual rainfall and mean annual temperatures over the study period, the decadal means and the decadal mean ratios were computed. The decadal mean ratios were evaluated by using the period 2005–2014 as the reference period, with ratios less than 1 signifying a deficit in either recent rainfall or temperature. Ratios greater than 1 signify an increase in either recent rainfall or temperature.

The Mann-Kendall nonparametric regression test was used to examine significant changes ($p < 0.05$) in rainfall variability (total and average 7-year moving window standard deviation) and temperature (mean, minimum, and maximum; Lacombe et al., 2012). The Mann-Kendall nonparametric regression analyses the sign of the difference between the later-measured observation and all earlier-measured observations. This results in a total of $n(n-1)/2$ possible pairs of data, where n is the total number of observations:

$$\text{Let} \quad \theta = y_{i+1} - y_i \tag{2}$$

where y_i is observation at time i and θ is the difference between the observations at time i and time $i+1$. The test statistic S is then given by (3), the sum of the integers,

$$S = \sum_{i}^{n-1} \sum_{i+1}^{n} \quad \text{sgn}\left(y_{i+1} - y_i\right) \tag{3}$$

where n is the number of observations and sgn(θ) is given by (4),

$$\text{sgn}(\theta) = \begin{cases} 1 \text{ if } \theta > 0 \\ 0 \text{ if } \theta = 0 \\ -1 \text{ if } \theta < 0 \end{cases} \tag{4}$$

The mean of S is $E[S]S = 0$, and the variance σ^2 is

$$\sigma^2 = \left\{n(n-1)(2n+5) - \sum_{i+1}^{p} t_{i+1}(t_{i+1}-1)(2t_{(i+1)+5})\right\}/18 \tag{5}$$

where p is the number of the tied groups in the data set and t_{i+1} is the number of data points in the $i + 1th$ tied groups (Gilbert, 1987). Tied groups refer to observations in the data set that have the same values.

A large positive value of S indicates an increased trend, and a large negative S indicates a decreased trend, whereas a small S is an indication of no trend. To test for significant changes over time, a τ test statistic with a range of -1 to +1 is calculated

$$\tau = \frac{S}{n(n-1)/2} \tag{6}$$

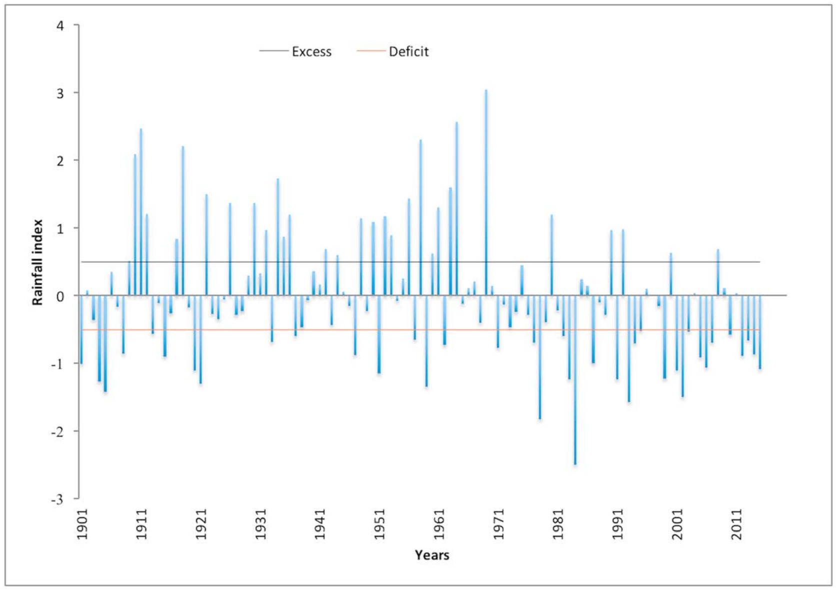

Figure 2. Interannual variability of precipitation rates using the Lamb index, Ghana, 1900–2014.

where both s and τ are significantly different from 0 ($p < 0.05$), then this is an indication of a significant change in rainfall and temperature. The p value is calculated as in Fisher (1992) for $n > 40$. We considered areas with significant ($p < 0.05$) changes in rainfall or temperature as climate stressed.

5. Results

5.1. Temporal Variations in Rainfall

Over the last century, Ghana's climate during the crop-growing seasons has become drier and more prone to drought conditions. Based on the Mann-Kendall nonparametric regression on data from 1900 to 2014, the mean annual rainfall and rainfall variability in the growing seasons have declined significantly, $p = 0.014$ and $p = 0.002$, respectively. The decadal mean has declined from a high of 1,308 mm in the 1960s to 1,147 mm for the period 2005–2014. The decadal mean ratios show that the current climate (2005–2014) is the driest and that there was a significant wet period in the 1960s. The ratio of mean decadal precipitation between 2005–2014 and 1960–1969 is 0.88 indicating a comparative deficit in recent rainfall. Analysis of rainfall indices shows that mean annual rainfall in the growing season of Ghana's major staple crops is characterised by high interannual variability of rainfall at the national scale (Figure 2). Two major rainfall periods can be identified: an excess period from 1900 to 1970, where the estimated Lamb rainfall indices are generally both positive and in excess, suggesting a wet climate prone to heavy rains and floods (1969 and 1964 are the wettest years in the index), and the second period from the 1970s marked by a sudden shift to a drier climate with rare years in excess (1980, 1990, 1992, 2000, and 2008 only). The estimated Lamb rainfall indices are generally negative, indicating a tendency toward drought (25 of the last 45 years have been in rainfall deficit), particularly in the years 1978, 1983, 1984, 1991, 1993, 1999, and 2002.

5.2. Temporal Variations in Temperature

Mean, minimum, and maximum temperatures have all increased significantly over time ($p = 0.017$, $p = 0.012$, and $p = 0.022$, respectively). The mean decadal temperature has increased by 0.6°C from 26.8°C (1900–1910) to 27.4°C (2006–2015). The first half of the twentieth century (1900 to 1950) is characterised by multidecadal oscillations in the mean temperature (Figure 3), followed by a prolonged drop in the decadal mean temperature from the 1940s (26.9°C) of 0.2 to 0.3°C, respectively, throughout the 1950s (26.7°C) and 1960s (26.6°C). The shift toward the current warmer climate commences in the 1970s. Since 2000 the mean annual and decadal temperatures have consistently been in excess of 27°C, prior to which the mean decadal temperature

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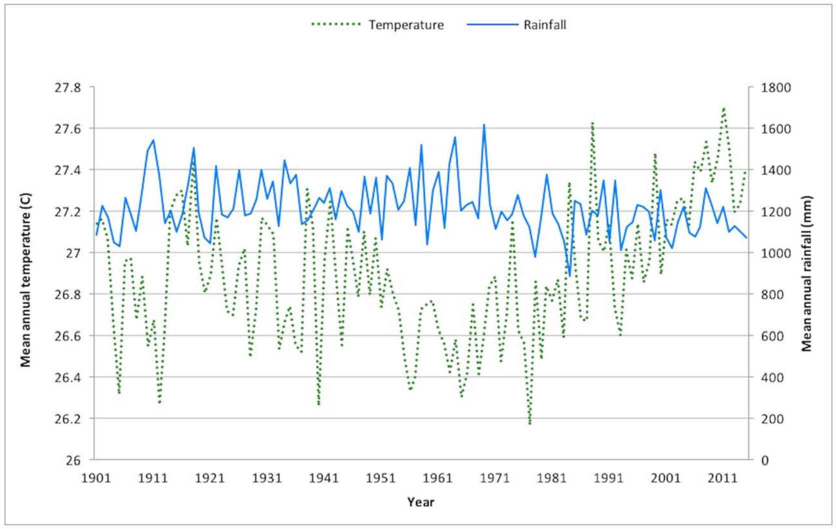

Figure 3. Mean annual rainfall and temperature over Ghana, 1900–2014 (rainfall—solid line; temperature—broken line).

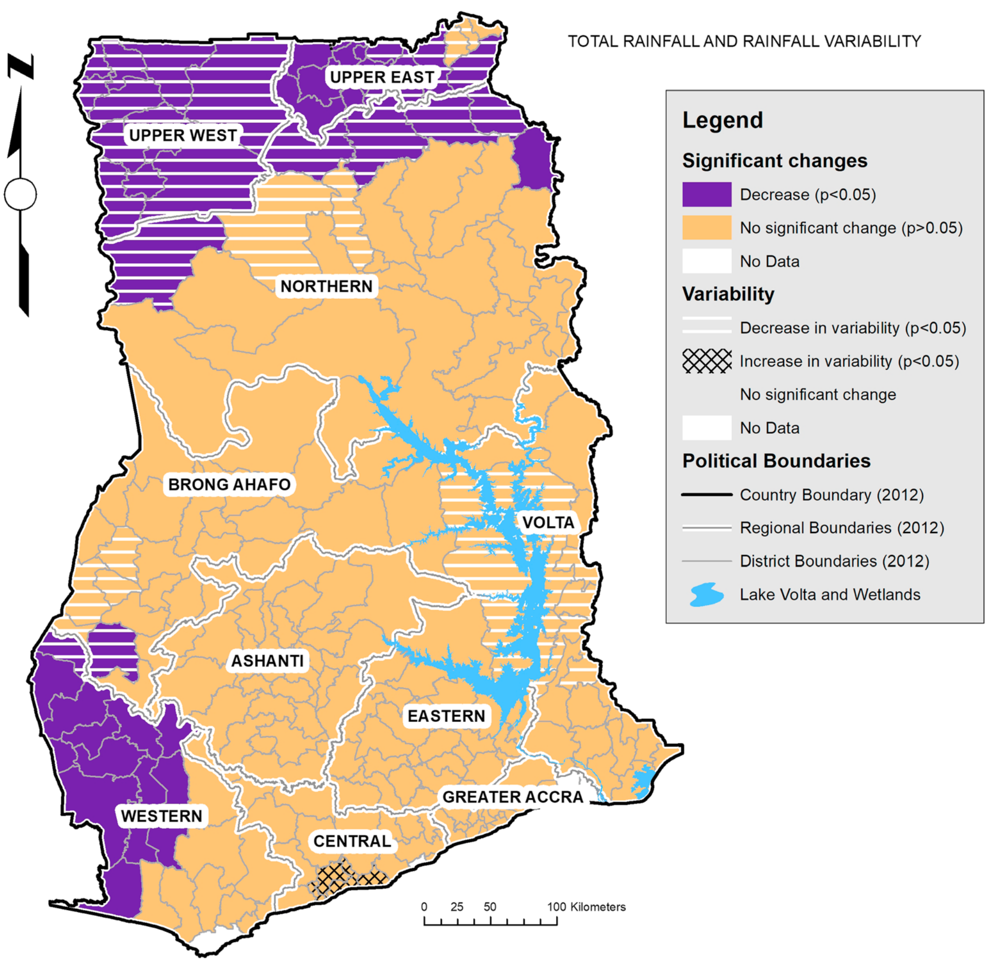

Figure 4. Mann-Kendall spatial analysis of total annual rainfall and rainfall variability.

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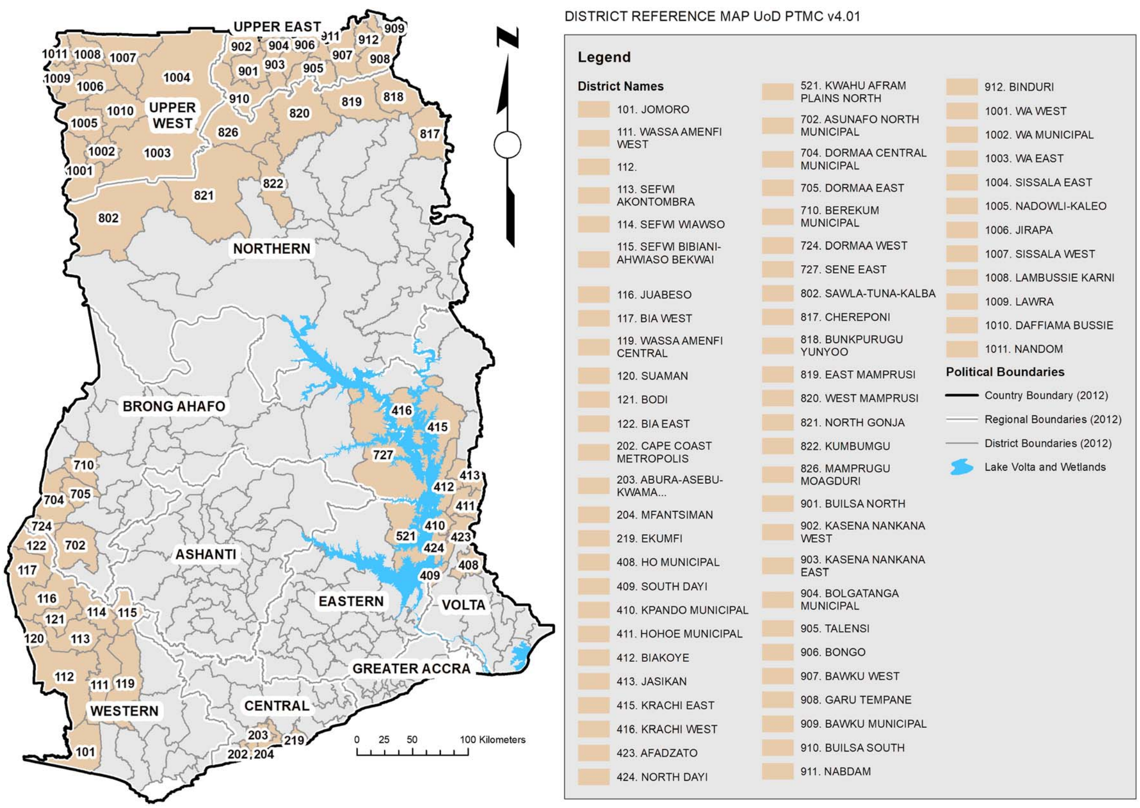

Figure 5. Map of districts referenced in section 5.

peaked at 26.9°C in the 1940s. Figure 3 clearly shows that from the 1970s, Ghana has been experiencing increasing temperature coupled with decreasing total rainfall.

5.3. Spatial Variations in Total Rainfall and Rainfall Variability

Figure 4 shows that total annual rainfall has declined significantly in the Upper West, Upper East, and Western regions as well as in the districts of Northern region that border the Upper West and Upper East. In the Upper West, the mean decadal rainfall from 1900 to 1909 was 1,122 mm but declined to 1,068 mm between 1950 and 1959 and further declined to 964 mm between 2005 and 2014. The Upper West experienced significant decreases ($p < 0.05$) in total rainfall as well as in rainfall variability in all districts (Figure 4). In the Upper East, the decline in total rainfall was mainly observed from the 1960s. Between 1950 and 1959, the mean decadal rainfall was 1,081 mm but declined to about 979 mm between 2005 and 2014. In the Upper East region, all the districts except Pusiga experienced either a significant decline in total rainfall or rainfall variability or both. Builsa North, Builsa South, Kasena Nankana East, and Kasena Nankana West districts experienced significant declines in total annual rainfall only; Bawku and Binduri districts experienced significant declines in rainfall variability only, while Bawku West, Bolgatanga Municipal, Bongo, Garu Tempane, Nabdam, and Talensi districts experienced significant declines in both. In Northern region, Bunkpurugu Yunyoo, East Mamprusi, Mamprugu Moagduri, Sawla-Tuna-Kalba, and West Mamprusi districts observed both significant declines in total annual rainfall and rainfall variability; Chereponi district experienced a significant decline in total annual rainfall, while Kumbumgu and North Gonja districts experienced significant declines in rainfall variability (see Figure 5).

In Southern Ghana, a significant decline in total rainfall was observed mostly among districts in Western region—which has been experiencing a decadal average decline in total rainfall since the 1960s from 1,716 mm between 1960 and 1969 to 1,374 mm between 2005 and 2014. Twelve out of the 22 districts in Western region experienced significant declines in total annual rainfall. However, only Bia East experienced significant declines in both total annual rainfall and rainfall variability. The only district to

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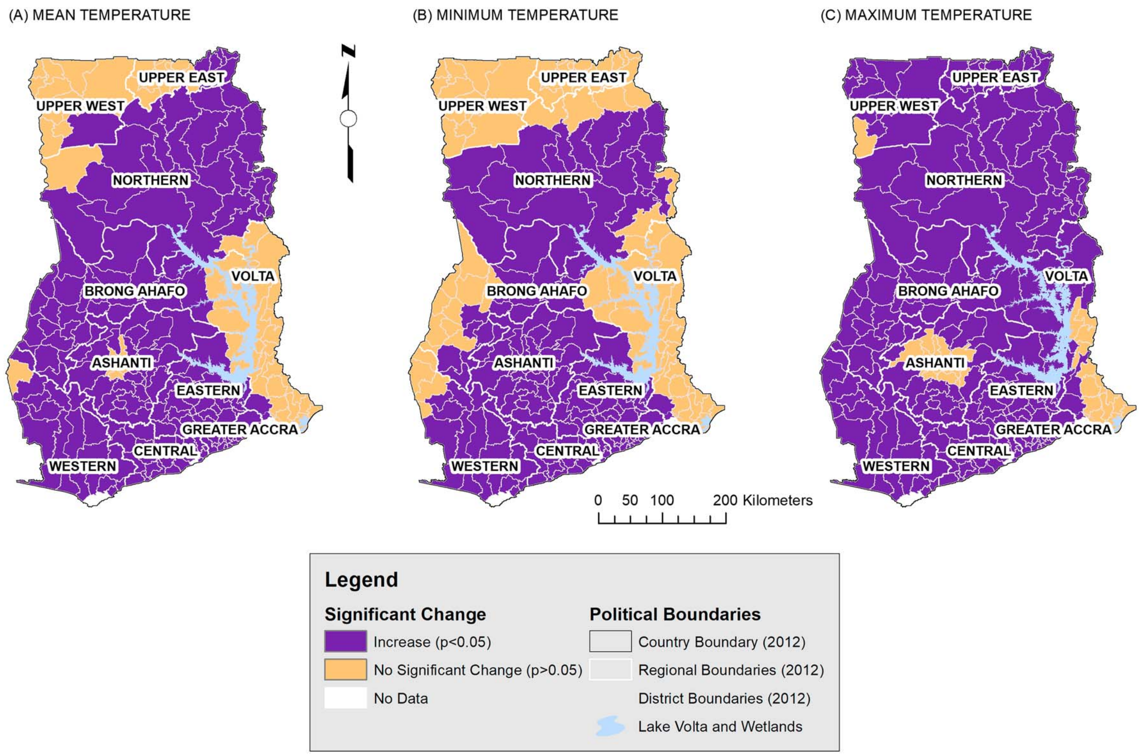

Figure 6. Visualised results of the Mann-Kendall spatial analysis of mean, minimum, and maximum annual temperature changes over Ghana between 1900 and 2014.

experience significant decline in both total annual rainfall and rainfall variability in the region of Brong Ahafo was the Asunafo North Municipal district. However, neighbouring districts to Asunafo North Municipal experienced significant declines in rainfall variability. Although localities around the Volta Lake did not experience significant declines in total annual rainfall, they did experience significant declines in rainfall variability. A significant increase in rainfall variability was observed only in the districts of Abura-Asebu-Kwamankese, Cape Coast Metropolis, Ekumfi, and Mfantsiman in Central region.

5.4. Spatial Variations in the Mean, Minimum, and Maximum Temperatures

Figure 6 shows significant increases in mean, minimum, and maximum temperatures in most parts of Ghana. The districts that have not experienced significant increases in mean temperature were concentrated in the Upper East, Upper West, and Volta regions. Similar spatial patterns were observed for minimum temperatures in addition to districts in Brong Ahafo and Western regions. All districts except a few in Ashanti and Volta regions have experienced significant increases in maximum temperature.

Examining decadal averages from 1900 to 2014, the results show that the largest increase in mean temperature of 1.34°C (from 26.03°C between 1900 and 1909 to 27.37°C between 2005 and 2014) was recorded in Greater Accra. The smallest increases in mean temperature were recorded in the three warmest regions (Upper West [1900–1909 = 27.67°C, 2005–2014 = 28.04°C, and Δ = 0.37°C], Upper East [1900–1909 = 28.19°C, 2005–2014 = 28.77°C, and Δ = 0.58°C], and Northern [1900–1909 = 27.74°C, 2005–2014 = 28.32°C, and Δ = 0.58°C]). The results show that as we move from the warmer northern climate to the cooler climate of the South the increase in mean temperatures becomes larger.

5.5. Spatial Intersection Between Total Annual Rainfall, Rainfall Variability, and Mean Temperature

To identify potential climate-stressed areas, we examined the spatial intersection between total annual rainfall, rainfall variability, and mean temperature (Figure 7). We grouped them into four broad categories: (a) decrease in rainfall ($p < 0.05$) and no change in temperature, (b) increase in temperature ($p < 0.05$) and no change in rainfall, (c) decrease in rainfall ($p < 0.05$) and increase in temperature ($p < 0.05$), and (d) no

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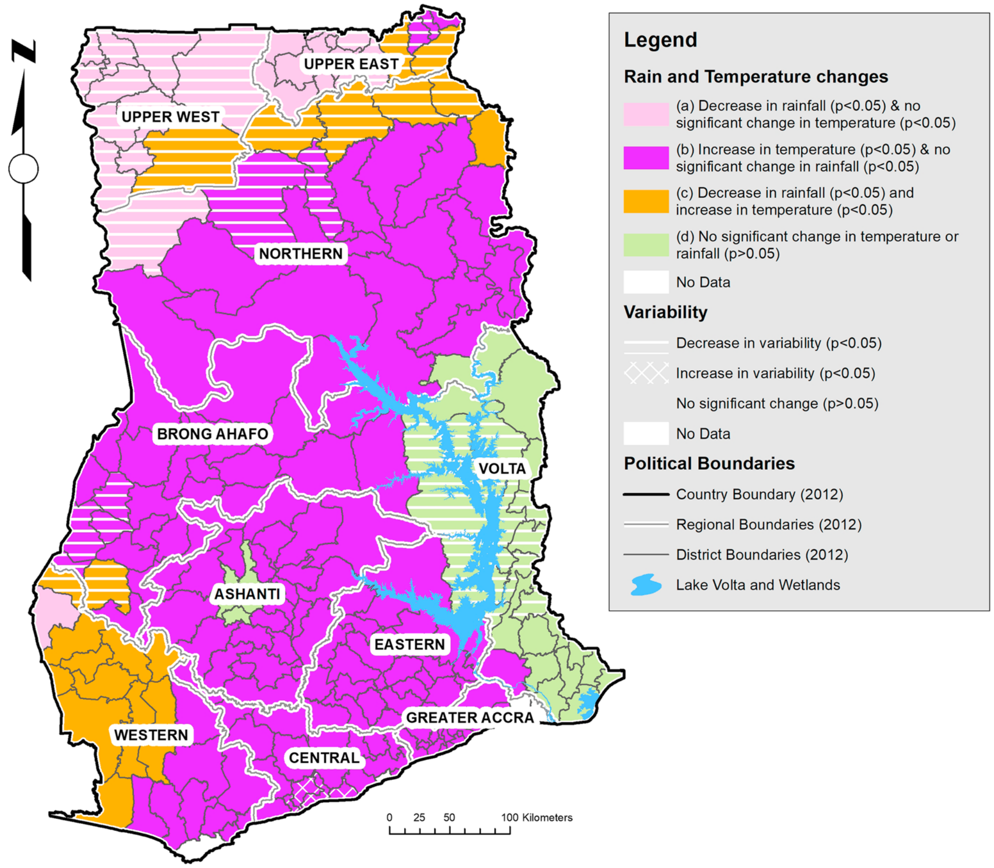

Figure 7. Intersection analysis of both significant and no significant changes in total annual rainfall, rainfall variability, and mean annual temperatures for the identification of climate-stressed localities in Ghana, 1900–2014.

significant change in temperature or rainfall. The results show that most parts of Ghana are climate-stressed. The Upper West showed a significant decline in rainfall, whereas the districts in the north of Northern region comprise one of the highly-susceptible areas showing a decline in rainfall and an increase in temperature. Bunkpurugu Yunyoo, East Mamprusi, West Mamprusi, and Mamprugu Moagduri districts in Ghana's Northern region have experienced significant decreases in total annual rainfall and significant increases in mean temperature (c) plus significant declines in rainfall variability. These changes were also observed for Garu Tempane and Bawku West districts in the Upper East, Wa East district in the Upper West, Bia East district in Western region, and Asunafo North Municipality in Brong Ahafo. Although a number of districts in the western area of Western region (Jomoro, Sefwi Akontombra, Sefwi Bibiani-Ahwiaso Bekwai, Sefwi Wiawso, Aowin, Suaman, Bodi, Juabeso, Wassa Amenfi West, and Wassa Amenfi Central) and Chereponi district in Northern region have also experienced significant decreases in total annual rainfall and increases in mean temperature (c), they did not observe significant changes in rainfall variability.

Kasena Nankana West, Kasena Nankana East, Builsa South, and Builsa North districts in the Upper East and Bia West district in Western region recorded significant decreases in total annual rainfall but no significant change in mean temperature (a). Similar results were found in Bolgatanga Municipal, Bongo, Talensi, and Nabdam districts in the Upper East; Wa Municipal, Jirapa, Sissala West, Lambussie Karni, Wa West, Sissala East, Nadowli-Kaleo, Daffiama Bussie, Lawra, and Nandom districts in the Upper West; and Sawla-Tuna-Kalba districts in Northern region. However, these districts experienced significant decreases in rainfall variability in addition.

Furthermore, the results show that large parts of Ghana experienced significant increases in mean temperature but no change in total annual rainfall (b) nor a change in rainfall variability, except for Bawku Municipal and Binduri districts in the Upper East; North Gonja and Kumbumgu in Northern region; and Dormaa East,

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Berekum Municipal, Dormaa West, and Dormaa Central Municipality in Brong Ahafo. It is interesting to note that only the districts around the Volta Lake experienced significant declines in rainfall variability with no significant change in temperature or rainfall (d). The coastal districts of Abura-Asebu-Kwamankese, Cape Coast Metropolis, Mfantsiman, and Ekumfi in Central region experienced a significant increase in mean temperature and an increase in rainfall variability.

6. Discussion

Using gridded climate data, this study systematically analysed the historical changes in temperature and rainfall in Ghana and identified climate-stressed localities that may have a potential effect on crop production. Our study is the first of its kind to examine the spatial intersection between total annual rainfall, rainfall variability, and temperature at the national level in Ghana. The results of the study are consistent with previous subnational-level analysis (Issahaku et al., 2016; Neumann et al., 2007; Ofori-Sarpong & Annor, 2001), national studies (Arku, 2012; Geografisk, 1997; Lacombe et al., 2012; Nkrumah et al., 2014; Oduro-Afriyie & Adukpo, 2009; Owusu & Waylen, 2009; Paeth & Hense, 2004), and regional-level results (Giannini et al., 2008), although none of these has examined the spatial interaction of all three indicators: total rainfall, rainfall variability, and temperature. However, it is important to note that the effect of these indicators on crop yield is not independent (Issahaku & Maharjan, 2013).

This research is timely given that the Government of Ghana has recently prioritised agriculture as one of the key sectors for development with the aim of alleviating poverty through modernization and improved productivity (Ministry of Finance, 2017). The Government's strategy includes the provision of improved seeds, dams, extension services, supply of fertilizers, marketing, and e-agriculture as well as encouraging youth participation in the sector. The findings of this study provide rich information on climate-stressed areas affected by variations in rainfall and temperature across space and indicators for food production interventions and effective allocation of agricultural resources.

The findings clearly establish evidence that districts in the Upper West, Upper East, and Northern and Western regions are the most climate-stressed areas in Ghana. These districts in the last 115 years have experienced significant and different patterns of declines in rainfall, rainfall variability, and increases in temperature. The results show that most parts of Ghana experienced significant increases in temperature but not in rainfall or rainfall variability. The largest increase in temperature was observed in the cooler southern parts (Greater Accra, Central and Eastern regions) of the country, while the changes were smaller in the warmer northern parts of the country. It is interesting to note that the districts of Abura-Asebu-Kwamankese, Cape Coast Metropolis, Ekumfi, and Mfantsiman in Central region were the only districts to experience a significant increase in rainfall variability. Another interesting finding from the study was that although most districts in close proximity to the Volta Lake did not experience significant changes in total rainfall or temperature, they did experience significant declines in rainfall variability.

In the three northern regions (Savannah agroecological zone) where we have identified significant declines in total annual rainfall, rainfall variability, and increase in temperature, there could be a potential negative effect on millet, sorghum, and yam yields, which are important staples in the region. Crop models have been used to simulate sorghum and millet yield changes under 35 possible future climate conditions (combinations of −20% to 20% precipitation anomalies and + 0 to 6°C temperature anomalies) in West Africa (MoFA, 2015; Sultan et al., 2013). Simulation results showed that in almost all cases (31/35) yields were negatively affected and that when warming increased beyond +2°C, a change in rainfall no longer counteracted the negative effect warming is known to have on yields. In the Evergreen and Deciduous Forest agroecological zones of Western region, most districts experienced declines in rainfall and increases in temperature. There could be a potential reduction in rice yields in these zones as a result, while at the same time research shows that warming could benefit maize yields (Thornton et al., 2009). Additional evidence demonstrates that these changes could result in a reduction in yam yields but may increase maize and cassava yields (Amikuzuno & Donkoh, 2012; Issahaku & Maharjan, 2013, 2014).

7. Conclusions

These results clearly demonstrate that the pattern of changes in rainfall and temperature is spatially heterogeneous, and mitigating these effects would require developing a local-scale adaptation policy. Given the findings from this study, it is important that further research is undertaken to examine how the changes, especially at the intersection of rainfall, rainfall variability, and temperature variations, have affected crop production in Ghana and the resultant effects on the livelihoods and well-being of the population, particularly marginalised rural communities mainly dependent on subsistence agriculture. This will help the government to design and implement targeted interventions linking agricultural sectors with other development sectors.

8. Data Limitations

The UoD PTMC v4.01 product has some limitations. The dataset's accuracy is dependent upon the spatial coverage of the station record network and relies on the background climatology in station sparse areas. The GHCN documents records from 18 data stations 1973–2017. However, there is no detail on the longevity and consistency of the records.

Nevertheless, the product has been verified against other global-gridded products such as the CRU, GPCC, and UDEL (UoD) datasets over China in Sun et al. (2014) and the CRU, ETH, and CHCAM data sets over the European alpine region in Efthymiadis et al. (2006). These studies show that prior to the 1920s to 1930s the global station records were sparser, and while there are differences between the datasets' temporal-scale results, the trends are the same.

The scope of the paper did not encompass the correction of the precipitation records for cross-validation errors. Over Ghana cross-validation errors range over space and time (months) between 0 and 50 (mm) (Matsuura & Willmott, 2015).

Despite these limitations, the results of this paper's analysis of the long-term cumulative changes in climate support the existing body of evidence that shows the break in rainfall regime in the 1960s to 1970s and the decline in rainfall and rainfall variability post-1970 (Oduro-Afriyie & Adukpo, 2009; Ofori-Sarpong & Annor, 2001; Owusu & Waylen, 2009). The authors also conducted a spatially-disaggregated validation of the UoD PTMC v4.01 country-wide total annual rainfall against the CHIRPS v2.0. Despite different methods of measurement and different spatial aggregations of the data set, we found a statistically significant correlation between the two.

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