Journal of Environmental Protection, 2025, 16(6), 627-645
https://www.scirp.org/journal/jep
ISSN Online: 2152-2219
ISSN Print: 2152-2197

# Trend Analysis of Rainfall, Temperature and Relative Humidity Using Non-Parametric Tests in the Tamale Metropolis of Northern Ghana

**Abu Iddrisu[1], Ibrahim Yakubu Seini[2], Wilhelmina Asare[3]**

[1]Department of Sustainability Studies, Faculty of Natural Resources and Environment, University for Development Studies, Tamale, Ghana
[2]Department of Mathematics, Faculty of Physical Sciences, University for Development Studies, Tamale, Ghana
[3]Department of Sustainability Sciences, University for Development Studies, Tamale, Ghana
Email: abuiddrisu161@gmail.com

**How to cite this paper:** Iddrisu, A., Seini, I.Y. and Asare, W. (2025) Trend Analysis of Rainfall, Temperature and Relative Humidity Using Non-Parametric Tests in the Tamale Metropolis of Northern Ghana. *Journal of Environmental Protection*, **16**, 627-645.
https://doi.org/10.4236/jep.2025.166032

**Received:** May 4, 2025
**Accepted:** June 27, 2025
**Published:** June 30, 2025



## Abstract

This study investigates the trends and variations in rainfall, temperature, and relative humidity over a 33-year period (1990-2023) in the Tamale metropolis, using data from the five (5) data stations of Ghana Meteorological Agency (GMeT). Statistical trend analyses were performed using the Mann-Kendall test, followed by the Theil Sen slope test, to assess the direction and magnitude of changes in annual, monthly, and seasonal patterns. Between May and August (raining season), increasing temperatures are observed in May and July. Minimum temperatures are observed for every month of the year. However, there were increasing rainfalls in March but decreasing in August and September. Relative humidity exhibited decreasing trends in all months except March. To overcome the consequences of these, there is need to develop heat-tolerant crop varieties, adjust planting dates and schedules, promote agroforestry practices and enhance pest and disease management techniques.

## Keywords

Temperature, Rainfall, Relative Humidity, Trends, Agroforestry

## 1. Introduction

The impact of climate change on agricultural sustainability has garnered scientific attention, prompting efforts to understand their patterns and behaviors to mitigate their effects [1]. Climate change has far-reaching consequences on land, water, and the environment, threatening human existence due to food insecurity, water scarcity, farming failures, extreme events, infectious diseases, biodiversity loss, and displacement [2]. Rainfall and temperature are commonly used indicators of climate change impacts on water resources. Studies have consistently shown monotonic changes in temperature and rainfall trends over the past decades [3]. For instance, a study [4] detected an increasing trend in rainfall during the 20th century, while another [5] reported a 0.37˚C and 0.32˚C increase in surface temperatures during 1925-1944 and 1978-1997, respectively.

Seasonal rainfall patterns in the country vary, with mean rainfall ranging from 20 - 80 mm in December to February, 60 - 200 mm in March to May, 100 - 220 mm in June to August and 40 - 180 mm in September to November [6]. The southwestern region experiences high-intensity rainfall. Trend analysis reveals: increasing consecutive dry days in Transition, Forest, and Coastal zones, but decreasing in Savannah; decreasing consecutive wet days in Savannah, Transition, and Coastal zones, but increasing in Forest; slight increases in heavy rainfall days in Savannah, Forest, and Transition zones, but decreases in Coastal; slight increases in very heavy rainfall days in all zones except Transition and annual wet day rainfall totals increase in Savannah and Forest, but decrease in other zones [6].

Climate projections in Ghana align with global trends, indicating a continued rise in temperatures [7] [8]. Studies suggest that mean temperature increases will range from 1.5˚C to 3.0˚C by 2080 in most agro-ecological zones during the dry season [9]. The Government of Ghana also projected temperature increases, with average annual temperatures expected to rise by up to 0.8˚C by 2020 and 5.4˚C by 2080 across all zones [10] [11]. Notably, there is significant spatial variation in projected temperatures, with northern Ghana (above 8˚N) expected to warm at a faster rate than the coastal regions [12] [13].

Ghana's climate is tropical with regional and seasonal variations in humidity. The country has two main rainy seasons, with the north experiencing only one season from May to September. Accra, the capital, has high humidity (83% average) throughout the year, with the highest in August (87%) and lowest in January (78%). The hottest months (March to May) see increased rainfall. The average daily high temperature in Accra is 31˚C with high humidity, making it feel tropical and muggy temperatures [14]. In contrast, Northern Ghana has a more moderate humidity level (40% - 60%) during warm months, but still experiences a muggy sensation due to absolute humidity levels. Overall, Ghana's climate is characterized by high temperatures and humidity, with regional variations.

Ghana's Third National Communication highlights the northern half of the country as a hotspot for climate change vulnerability [15]. Multiple studies confirmed its heightened exposure due to various factors, including limited access to climate information, precipitation and temperature variability, poverty, and low literacy rates, which amplify its sensitivity to extreme weather events [16]-[18]. Notably, MESTI reports significant temperature increases in the northern region over a decade, with minimum temperatures rising by 20% and maximum temperatures by 29.6% [8].

Although there had been previous research on trends and periodicities in rainfall, temperature, and relative humidity datasets over Ghana [19], rising temperature and declining rainfall being a threat to water security in northern region of Ghana [20] and projected temperature increases over northern Ghana [21]. To the best of the author's knowledge, no report has been sighted on the interplay of climate variation, air quality and relative humility in Tamale and its environs. This study will analyze the trends in rainfall, temperature, and relative humidity in a tropical climate region of Tamale using 33 years of data. The non-parametric Mann-Kendall test and Theil-Sen slope test were employed to identify trends, and estimate their magnitudes. This study will contribute to understanding climate trends in the Tamale metropolis, and provide valuable insights for policymakers to develop adaptive strategies for a changing climate.

## 2. Materials and Methods

### 2.1. The Study Area

Tamale is the capital city of the Northern Region which used to be the largest region by land size. Due to its proximity to the Sahel and the Sahara, the region has a dry and hazy atmosphere with high temperature for a larger part of the year. Landscapes are mostly grasslands with groups of drought-resistant trees such as baobabs, neem and acacias trees. The dry season lasts from January to March [22]. The rainy season lasts from July to October, and it usually rains 750 to 1050 mm (30 to 40 inches) a year. During the day, it can be 40˚C (104˚F) and at night, it can be 14˚C (59˚F) [22].

The air quality in the region is of significant interest, particularly in relation to cooking and biomass burning, which impact regional air quality. According to the 2021 Population and Housing Census, the northern region has a population of 2,310,934 consisting of 1,143,439 males and 1,167,495 females (**Figure 1**).

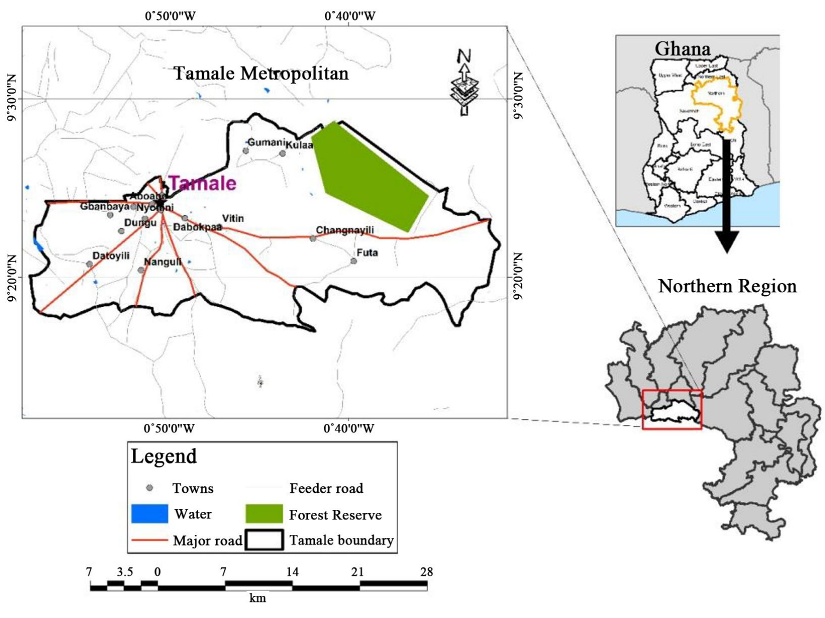


**Figure 1.** Map of Tamale Metropolitan.

## 2.2. Data Set

Long-term rainfall, temperature and relative humidity data (observed daily for 23 years) were investigated to detect trends between 1990 and 2023 in Tamale. The daily temperature, rainfall, and relative humidity data were obtained from the Ghana Meteorological Agency for the periods 1990 to 2023. Tables 1-4 summarized the monthly central tendency and dispersion measures for $T_{max}$, $T_{min}$, rainfall and relative humidity (average). The annual rainfall was maximum with the value of 1608.12 mm in 1991 and yearly minimum rainfall amounting to 878.96 mm was obtained in 2015. The analysis of the current investigation is the monthly and annual minimum temperature ($T_{min}$) and the maximum temperature ($T_{max}$) during 1990-2023. Annually maximum temperature observed was 41.58˚C in 2016, whereas the minimum temperature was found in 1991. Relative humidity ($RH_{aveg}$) analysis showed that monthly average minimum and maximum values were found to be 71 and 135 in 2020 and 1991, respectively.

**Table 1.** Monthly values of measures of central tendency for maximum temperature (Tmax) (˚C).

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| count | 34.00 | 34.00 | 34.00 | 34.00 | 34.00 | 34.00 | 34.00 | 34.00 | 34.00 | 34.00 | 34.00 | 34.00 |
| mean | 35.52 | 37.44 | 37.92 | 36.29 | 34.30 | 32.02 | 30.45 | 29.94 | 30.78 | 32.90 | 35.34 | 35.39 |
| min | 33.29 | 35.83 | 36.77 | 34.62 | 31.76 | 31.10 | 29.51 | 29.27 | 29.46 | 31.01 | 32.07 | 33.59 |
| 25% | 35.01 | 37.10 | 37.52 | 35.51 | 33.85 | 31.49 | 30.17 | 29.70 | 30.64 | 32.53 | 35.04 | 35.09 |
| 50% | 35.58 | 37.43 | 37.92 | 36.44 | 34.40 | 32.08 | 30.43 | 29.90 | 30.81 | 32.99 | 35.54 | 35.44 |
| 75% | 36.09 | 37.83 | 38.36 | 36.93 | 34.88 | 32.41 | 30.64 | 30.19 | 31.07 | 33.27 | 35.76 | 35.74 |
| max | 37.30 | 38.46 | 39.57 | 37.97 | 35.95 | 33.61 | 31.76 | 30.67 | 31.65 | 34.47 | 36.62 | 36.78 |
| std | 0.88 | 0.61 | 0.69 | 0.91 | 0.79 | 0.60 | 0.51 | 0.32 | 0.48 | 0.67 | 0.86 | 0.75 |

**Table 2.** Monthly values of measures of central tendency for minimum temperature (Tmin) (˚C).

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| count | 34.00 | 19.96 | 18.18 | 19.29 | 19.98 | 20.49 | 21.85 | 0.86 | 34.00 | 19.96 | 18.18 | 19.29 |
| mean | 34.00 | 23.03 | 20.34 | 22.47 | 23.35 | 23.77 | 24.93 | 1.07 | 34.00 | 23.03 | 20.34 | 22.47 |
| min | 34.00 | 25.41 | 23.77 | 25.04 | 25.54 | 25.78 | 26.78 | 0.70 | 34.00 | 25.41 | 23.77 | 25.04 |
| 25% | 34.00 | 25.52 | 24.35 | 25.09 | 25.50 | 25.88 | 26.91 | 0.60 | 34.00 | 25.52 | 24.35 | 25.09 |
| 50% | 34.00 | 24.64 | 23.48 | 24.26 | 24.58 | 24.92 | 25.62 | 0.53 | 34.00 | 24.64 | 23.48 | 24.26 |
| 75% | 34.00 | 23.46 | 22.66 | 23.18 | 23.50 | 23.79 | 24.55 | 0.49 | 34.00 | 23.46 | 22.66 | 23.18 |
| max | 34.00 | 22.92 | 22.21 | 22.53 | 22.86 | 23.29 | 24.03 | 0.47 | 34.00 | 22.92 | 22.21 | 22.53 |
| std | 34.00 | 22.69 | 21.87 | 22.39 | 22.63 | 22.97 | 24.00 | 0.45 | 34.00 | 22.69 | 21.87 | 22.39 |

**Table 3.** Monthly values of measures of central tendency for rainfall (mm).

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| count | 34.00 | 34.00 | 34.00 | 34.00 | 34.00 | 34.00 | 34.00 | 34.00 | 34.00 | 34.00 | 34.00 | 34.00 |
| mean | 19.96 | 23.03 | 25.41 | 25.52 | 24.64 | 23.46 | 22.92 | 22.69 | 22.57 | 22.70 | 21.55 | 19.61 |
| min | 18.18 | 20.34 | 23.77 | 24.35 | 23.48 | 22.66 | 22.21 | 21.87 | 21.73 | 21.75 | 18.46 | 17.71 |
| 25% | 19.29 | 22.47 | 25.04 | 25.09 | 24.26 | 23.18 | 22.53 | 22.39 | 22.27 | 22.36 | 21.16 | 18.88 |
| 50% | 19.98 | 23.35 | 25.54 | 25.50 | 24.58 | 23.50 | 22.86 | 22.63 | 22.53 | 22.71 | 21.53 | 19.66 |
| 75% | 20.49 | 23.77 | 25.78 | 25.88 | 24.92 | 23.79 | 23.29 | 22.97 | 22.82 | 22.95 | 22.31 | 20.22 |
| max | 21.85 | 24.93 | 26.78 | 26.91 | 25.62 | 24.55 | 24.03 | 24.00 | 23.83 | 23.91 | 23.69 | 22.32 |
| std | 0.86 | 1.07 | 0.70 | 0.60 | 0.53 | 0.49 | 0.47 | 0.45 | 0.50 | 0.52 | 1.10 | 1.03 |

**Table 4.** Monthly values of measures of central tendency and dispersion for relative humidity.

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| count | 32.00 | 32.00 | 32.00 | 32.00 | 32.00 | 32.00 | 32.00 | 32.00 | 32.00 | 32.00 | 32.00 | 32.00 |
| mean | 66.24 | 76.70 | 96.32 | 123.18 | 138.74 | 147.30 | 151.89 | 153.24 | 148.44 | 135.00 | 105.14 | 78.90 |
| min | 27.25 | 44.44 | 62.90 | 81.37 | 63.38 | 63.73 | 63.07 | 65.48 | 32.47 | 29.50 | 46.35 | 31.18 |
| 0.25 | 57.17 | 65.17 | 84.43 | 115.36 | 137.80 | 145.86 | 152.11 | 150.57 | 134.79 | 117.73 | 86.46 | 60.88 |
| 0.5 | 67.29 | 75.60 | 99.44 | 125.31 | 141.47 | 153.32 | 161.75 | 165.05 | 162.78 | 151.67 | 118.75 | 85.65 |
| 0.75 | 75.78 | 89.69 | 105.59 | 133.92 | 145.77 | 158.36 | 163.43 | 166.79 | 163.91 | 153.93 | 126.12 | 94.06 |
| max | 96.63 | 109.77 | 127.21 | 141.45 | 160.75 | 163.10 | 167.22 | 171.00 | 166.37 | 160.90 | 134.79 | 113.29 |
| std | 14.68 | 17.57 | 16.11 | 13.89 | 17.17 | 19.34 | 22.64 | 25.33 | 28.57 | 30.31 | 28.41 | 20.69 |

## 3. Methodology

Trend analysis, a technique for determining the spatio-temporal variations in several climate parameters, is the simplest procedure to detect the variation of variables in the data time series. This is indeed a critical problem for a country such as Ghana, as the country's economy relies primarily on rain-fed agriculture. Hence, any shift in the rainfall pattern will have devastating effects on the nation's farming prospects. Consequently, trend analysis has the potential to resolve global climate variability challenges. Twenty-three years of meteorological observations were analyzed to examine rainfall and temperature data patterns. The MK test was conducted to detect the trend, and the magnitude of slopes was analyzed by employing the Theli-Sen technique. The MK is a popular technique used to identify trends in a time series dataset. The method finds a monotonic trend in the investigation parameter during the specific period. A monotonic upward (downward) trend shows that the variable continuously rises (falls) over the period. The Theli-Sen technique is utilized to compute the magnitude of the slope after the trend tests. Furthermore, the Pettitt test was executed to determine the time series' change point [23]. Pettitt's method is widely utilized in identifying shifting points in variables time series values. The flow chart for the methodology is presented in **Figure 2**.

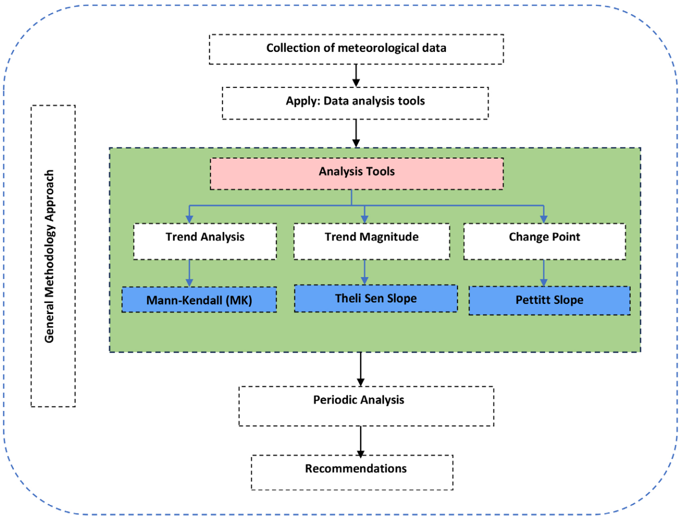


**Figure 2.** Flow diagram of the methodology (Adopted from Rajput *et al.*) [24]

# 4. Results and Discussions

## 4.1. Temperature Trend Analysis

The annual and monthly temperature data (maximum and minimum) showed a considerable variation in the annual maximum temperature during the investigation period. After the MK test had identified the trends, the Theli Sen slope was estimated to quantify the magnitude of the slope. The MK Test value and Theli Sen slope for maximum temperature are shown in **Table 5**. Monthly temperature trends exhibited the following patterns:

- Minimum temperature: A consistent statistically increasing trend was observed across all 12 months, from January (month 1.0) to December (month 12.0) (**Figure 3**, A-L; representing the months January to December respectively).

- Maximum temperature: Trends varied by month, with statistically significant increases observed in January, February, May, July, November, and December. No discernible trends were detected in March, April, June, and October. A statistically significant decreasing trend was noted in September.

The analysis of annual and monthly temperature data revealed notable variations in maximum temperature over the study period. The Mann-Kendall (MK) test was employed to identify trends, and the Theil-Sen slope estimator was used to quantify their magnitudes. Results showed that minimum temperatures exhibited a statistically consistent upward trend across all twelve months, while maximum temperatures demonstrated a more heterogeneous pattern. Specifically, significant increases in maximum temperature were observed in January, February, May, July, November, and December. Conversely, no clear trends were found in March, April, June, and October, and a significant decreasing trend was observed in September.

These findings are consistent with several studies conducted in Ghana and across Africa, though they also reveal nuanced differences. The consistent rise in minimum temperatures aligns with the work of Owusu and Waylen (2009) [25], who documented a general warming trend in minimum temperatures across northern Ghana over a similar temporal scale. Similarly, Nkrumah *et al*. (2014) [26] reported that minimum temperatures in southern Ghana have shown a persistent increase, attributing this pattern to urbanization and land surface changes. These observations suggest that nighttime warming is a widespread phenomenon, likely driven by increased heat retention in modified land surfaces and the broader effects of climate change.

Comparatively, studies from other African contexts echo similar trends. For instance, Gebrechorkos *et al*. (2019) [27], in a study covering Eastern Africa, noted consistent upward trends in minimum temperatures across various climate zones, emphasizing the regional nature of nocturnal warming. Likewise, Boko *et al*. (2007) [28] in the IPCC Fourth Assessment Report identified rising minimum temperatures as a key feature of climate change impacts in sub-Saharan Africa, with implications for health, agriculture, and energy consumption.

In contrast, maximum temperature trends presented more complexity. The observed intra-annual variability, with both increasing and decreasing trends, reflects findings by Asante and Amuakwa-Mensah (2015) [29], who also identified spatial and temporal inconsistencies in maximum temperature changes across Ghana. Their study noted that while certain agro-ecological zones recorded increasing maximum temperatures, others showed either stable or declining trends, particularly during the minor rainy seasons. Similarly, Klutse *et al.* (2018) [30] identified varied monthly patterns of maximum temperature trends in West Africa, highlighting the influence of local climatic systems, vegetation cover, and atmospheric circulation patterns.

The significant decreasing trend in maximum temperature during September may be linked to the peak of the rainy season in many parts of Ghana, where increased cloud cover and precipitation reduce solar radiation. This has also been noted by Owusu and Waylen (2009) [25], who observed a seasonal modulation of temperature patterns due to rainfall distribution. On the other hand, the increasing maximum temperatures in the dry season months such as January and February coincide with the Harmattan period, during which clear skies and low humidity promote higher daytime temperatures, a phenomenon corroborated by studies from Nyatuame, Kasei, and Martey (2014) [31].

These temperature trends have important human dimensions. Rising minimum temperatures, for example, can alter the growing periods for staple crops, influence disease vector activity, and affect human thermal comfort, especially at night. The variability in maximum temperatures, particularly the extremes, poses challenges for outdoor labor productivity, food preservation, and energy demand for cooling. The observed trends also reflect local perceptions of climate variability reported in several qualitative studies among Ghanaian farming communities, where shifts in temperature patterns are associated with declining agricultural productivity and changing livelihood strategies.

The implications of rising minimum temperatures are multidimensional. Firstly, shifts in the timing of flowering and fruiting due to warmer nights can disrupt the phenological synchrony of crops. Secondly, increased nocturnal respiration rates can reduce net photosynthesis, contributing to lower yields. Thirdly, higher night temperatures elevate water demand due to increased evapotranspiration, thereby compounding challenges in water-scarce areas. These results are consistent with the conclusions of Owusu and Waylen (2009) [25], who emphasized that temperature increases in Ghana's northern belt significantly affect soil moisture regimes and crop performance.

In contrast, the variable trends in maximum temperature offer a more nuanced outlook. The rainy season months of May through August showed mixed patterns. While May and July recorded rising trends, June and August exhibited no significant change, and September experienced a decline. These results mirror the seasonal patterns reported by Adiku *et al.* (2015) [32], who noted an intensification of heat during the onset of the rains but relative thermal stability mid-season. Likewise, Kasei *et al.* (2010) [33] reported increased maximum temperatures in northern Ghana between May and July, attributing them to early cessation of rainfall and delayed planting, which have knock-on effects on crop performance.

Increased maximum temperatures during the early rainy season, particularly in May, can accelerate evaporation, reduce soil moisture, and affect seedling emergence and establishment. This is especially problematic for early-maturing crops like groundnuts and maize. July's rising temperature can support photosynthesis but may induce thermal stress if thresholds are exceeded. These findings resonate with those of Laube *et al.* (2012) [34], who linked similar patterns of increasing Tmax in northern Ghana with heat stress impacts on maize. On the other hand, the lack of discernible trends in June and August suggests windows of relative climatic stability, beneficial for crop development. This finding supports the work of Yiran and Stringer (2016) [18], who argued that intra-seasonal temperature stability is critical for ensuring crop resilience in northern Ghana.

The decreasing maximum temperature in September is particularly noteworthy and somewhat atypical. While few studies report declining Tmax during this period, similar patterns were observed by Apata *et al.* (2016) [35] in parts of Nigeria, where late-season cooling was attributed to increased cloud cover and delayed rainfall events. However, in Ghana, the implications may vary depending on crop type and harvest schedules.

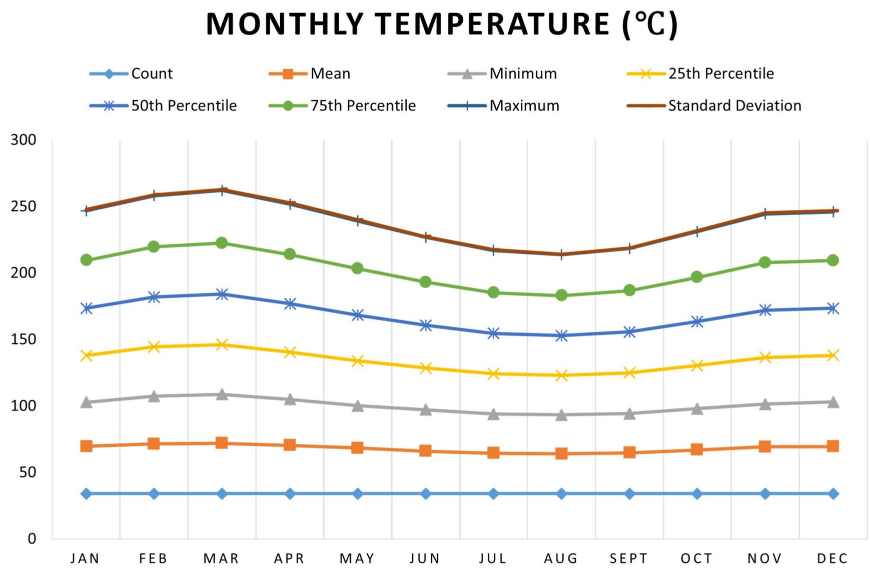


**Figure 3.** Monthly trend plots of maximum temperature.

Increasing minimum temperatures across all months in a tropical region like Ghana can have significant implications for crop production:

1) Changes in growing seasons: Warmer nights can lead to earlier flowering and fruiting, potentially disrupting the synchronization of growth stages and impacting yields;

2) Heat stress: Higher minimum temperatures can cause heat stress in crops, especially those sensitive to temperature fluctuations, leading to reduced growth,

yields, and quality;

3) Water requirements: Increased temperatures can enhance evapotranspiration, leading to higher water demands for crops, potentially straining water resources;

4) Shifts in suitable crop zones: Rising temperatures can cause areas to become more or less suitable for specific crops, potentially requiring adjustments in crop selection and farming practices;

5) Pest and disease dynamics: Changes in temperature regimes can alter the distribution, prevalence, and behavior of pests and diseases, potentially impacting crop health;

6) Yield reductions: Overall, increasing minimum temperatures can lead to reduced crop yields, decreased quality, and lower productivity.

The implications for the trends in Tmax for the rainy season period of May to August are:

1) May: increasing temperatures can lead to faster evaporation of water from the soil, potentially reducing soil moisture and affecting seed germination and early growth stages of crops;

2) June: no trend in temperature suggests stable conditions, which is beneficial for crop growth and development;

3) July: increasing temperatures can enhance crop growth, but excessive heat can lead to heat stress, particularly for crops sensitive to temperature fluctuations;

4) August: no trend in temperature indicates stable conditions, allowing crops to mature and ripen normally (**Figure 3**).

Overall, these temperature trends may impact: crop water requirements and soil moisture levels; growth and development stages of crops; heat stress and crop yields and timing of planting and harvesting. It should be pointed out that these implications are specific to the rainy season in the Tamale Metropolis and may vary depending on local conditions and crop types.

### 4.2. Rainfall Trend Analysis

Based on our analysis, the implications for Tamale and its environs are:

1) No trend in rainfall (Jan, Feb, Apr, May, Jun, Jul, Sep, Oct, Nov)—Stable rainfall patterns, allowing for predictable agricultural planning and water resource management.

2) Increasing rainfall in March—Potential for: improved crop yields and vegetation growth; replenished water sources and improved water security; increased flood risk, potentially affecting settlements and infrastructure.

3) Decreasing rainfall in August and December—Potential for: water scarcity and drought impacts on crops and livestock; reduced water availability for domestic and industrial use and increased risk of bush fires and land degradation (**Figure 4**).

Overall, these trends may impact: agricultural productivity and food security, water resource management and availability, flood and drought risk management and ecosystem health and biodiversity. In Tamale and its environs, these implications may be particularly significant for:

- Agriculture: Impacts on crop yields, livestock productivity, and food security.
- Water resources: Impacts on water availability, quality, and management.
- Ecosystems: Impacts on vegetation, wildlife, and biodiversity.
- Human settlements: Impacts on flood risk, water access, and livelihoods.

Stakeholders, including farmers, water managers, and policymakers, may need to adapt strategies to address these implications, such as: implementing climate-smart agriculture practices, enhancing water harvesting and storage infrastructure, improving flood and drought early warning systems and promoting ecosystem conservation and restoration efforts.

The analysis of rainfall trends in Tamale and its environs reveals a complex yet critical pattern with implications for agriculture, water resources, ecosystems, and human settlements. The data suggest no significant trends in rainfall for most months, indicating relative stability that supports predictable agricultural activities and effective water resource management. This aligns with the findings of Kasei *et al.* (2010) [36], who noted stable intra-annual rainfall in the Northern Region, conducive to traditional cropping cycles. However, this contrasts with Nyadzi *et al.* (2015) [37], whose regional study indicated erratic rainfall patterns in some areas of northern Ghana, suggesting that microclimatic variations remain important in local planning.

An observed increase in rainfall in March could benefit agricultural productivity through improved soil moisture and early planting opportunities. Similar findings were reported by Owusu and Waylen (2009) [25], who observed early onset of rains in parts of northern Ghana, enhancing maize and sorghum yields. On the other hand, Yiran and Stringer (2016) [18] argued that while increased rainfall can improve vegetation cover, it can also raise the risk of localised flooding, particularly in peri-urban areas with poor drainage. This dual effect highlights the need to balance opportunities for agricultural expansion with risks to infrastructure and settlement, especially for vulnerable populations living in flood-prone zones.

Conversely, the decreasing rainfall in August and December raises concerns about water scarcity and the health of ecosystems. A reduction in August rainfall, a typically wet month, may disrupt crop maturation and livestock water access. In agreement, Antwi-Agyei *et al.* (2012) [16] highlighted how rainfall deficits during critical months severely affect farming communities, leading to food insecurity and reduced income. Similarly, Dietz *et al.* (2004) [38] noted that such changes can trigger seasonal migration and alter household labour allocation in northern Ghana. The decline in December rainfall also has implications for dry-season farming and domestic water supply, echoing observations by Gbetibouo and Hassan (2005) [39] in semi-arid regions of South Africa, where late-year rainfall decline led to increased vulnerability of smallholder farmers to water stress.

The broader implications of these rainfall changes span across agricultural productivity, water availability, and ecological balance. With erratic rainfall in some months and reductions in others, crop planning becomes more uncertain. This supports the arguments made by Laube *et al.* (2012) [34], who emphasised that climate variability significantly undermines rainfed agriculture in West Africa. The consequence for human livelihoods is substantial, especially for subsistence farmers whose yields are directly tied to rainfall performance. Water resources may also be affected, not only in terms of quantity but also quality, as observed by Adjei *et al.* (2020) [40], who reported increased sedimentation in water bodies during heavy rains and reduced recharge during dry spells.

Moreover, ecosystem degradation resulting from irregular rainfall and extended dry periods may lead to biodiversity loss, a concern raised by Ntiamoa-Baidu (2008) [41], who linked habitat fragmentation in Ghana to climate-induced vegetation changes. Human settlements are not spared, as shifts in rainfall increase the risks of both flooding and droughts. According to Tschakert *et al.* (2010) [42], such climatic extremes disproportionately affect the poor, who often reside in poorly planned or informal settlements with limited access to adaptive infrastructure.

To respond to these emerging challenges, the involvement of stakeholders—farmers, water managers, local authorities, and policymakers—is essential. Approaches such as climate-resilient agriculture, rainwater harvesting, and early warning systems for extreme weather events should be prioritised. These interventions are consistent with the recommendations by Ampadu *et al.* (2021) [43], who highlighted the value of community-based adaptation strategies in northern Ghana. Additionally, efforts to restore degraded lands and conserve native vegetation may help improve ecosystem resilience, as suggested by Mertz *et al.* (2009) [44] in their broader study on Sahelian adaptation.

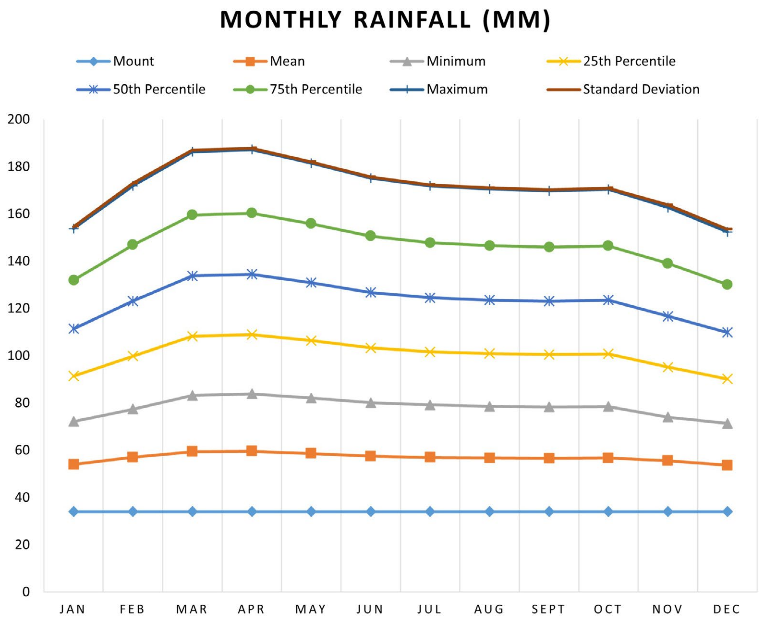


**Figure 4.** Monthly trend plots of rainfall.

### 4.3. Relative Humidity Trend Analysis

Decreasing relative humidity (RH) every month, except March (**Figure 5**), in a tropical area like northern Ghana has several implications for the environment and crop production:

(1) Environmental Implications:

a) Increased evaporation: Lower RH leads to faster evaporation from water bodies, soil, and plants, potentially altering the water cycle.

b) Drier air: Decreased RH can lead to drier air, potentially increasing the risk of bush fires and land degradation.

c) Disrupted ecosystems: Changes in RH can impact ecosystems, potentially affecting biodiversity and wildlife habitats.

(2) Crop Production Implications:

a) Water stress: Decreased RH can lead to increased water loss through transpiration, potentially causing water stress in crops.

b) Reduced yields: Water stress can result in reduced crop yields, decreased quality, and lower productivity.

c) Shifts in growing seasons: Changes in RH can disrupt growing seasons, potentially requiring adjustments in planting dates and crop selection.

d) Increased pest and disease pressure: Drier conditions can lead to increased pest and disease pressure, potentially impacting crop health.

In Tamale and its environs, these implications may be particularly significant for:

1) Agriculture: Impacts on crop yields, quality, and productivity.

2) Water resources: Impacts on water availability, quality, and management.

3) Ecosystems: Impacts on biodiversity, wildlife habitats, and ecosystem services.

Stakeholders may need to adapt strategies to address these implications, such as:

1) Irrigation management: Implementing efficient irrigation systems to mitigate water stress.

2) Crop selection: Choosing drought-tolerant crop varieties or adjusting planting dates.

3) Soil conservation: Implementing conservation agriculture practices to reduce soil moisture loss.

4) Ecosystem restoration: Restoring degraded lands and promoting ecosystem service.

The observed monthly decrease in relative humidity (RH), with the exception of March, in northern Ghana particularly in Tamale and its environs has far-reaching implications for environmental stability and crop production. As relative humidity plays a key role in maintaining ecological balance and supporting agricultural activities, its steady decline presents a pressing concern. These changes are particularly significant in tropical zones where smallholder agriculture and natural ecosystems are highly sensitive to climate variability.

Environmentally, reduced RH enhances evaporation rates from water bodies and soil surfaces. According to Nkrumah *et al*. (2020) [45], prolonged low humidity increases evaporation in northern Ghana, thereby reducing the retention of moisture in soil and open water sources critical for both agriculture and domestic use. Similarly, Anyadike (2009) [46] notes that in arid regions of West Africa, declining RH leads to increased atmospheric dryness, which in turn escalates the risk of bushfires and contributes to the degradation of vegetation cover. These findings are consistent with observations by Owusu and Waylen (2013) [25], who highlight that lower RH disrupts natural moisture cycles and can diminish ecosystem resilience in the savannah ecological zone. Compared to areas in southern Ghana where higher RH levels contribute to more stable microclimates [47], the north is evidently more vulnerable to climatic extremes, making environmental management more urgent.

From an agricultural perspective, decreasing RH results in increased crop water loss through transpiration, which places considerable water stress on crops. According to Antwi-Agyei *et al*. (2012) [16], low RH conditions exacerbate water stress and significantly affect maize and sorghum productivity in the Upper East Region. Similarly, Sarr (2012) [48] identifies that in the Sahelian belt, reduced RH coupled with higher temperatures leads to shorter growing periods, thereby reducing yield potential. These results are echoed in the work of Laube *et al*. (2012) [34], who found that in northern Ghana, water stress during the growing season frequently leads to crop failure, particularly among resource-poor farmers. Compared with areas like southern Nigeria where RH remains relatively stable and supports longer growing seasons [49], the north faces a more constrained agricultural calendar, making traditional farming practices less reliable.

Furthermore, decreasing RH affects pest and disease dynamics. Drought-like conditions often favour the spread of certain pests such as the fall armyworm, as observed by Tambo *et al*. (2021) [50] in Ghanaian maize fields. In contrast, wetter environments tend to favour fungal and bacterial infections. Waha *et al*. (2013) [51] corroborate this finding in their regional climate-agriculture analysis across Sub-Saharan Africa, noting that reduced RH can shift the pest population spectrum and increase vulnerability to outbreaks, especially when coupled with poor adaptive capacity among smallholder farmers.

The implications of these changes are human as well as ecological. In Tamale and nearby communities where agriculture serves as the primary livelihood, reduced RH directly translates into food insecurity, income loss, and heightened poverty. Access to water becomes more constrained, and communities reliant on rain-fed farming struggle to sustain productivity. As Acheampong *et al*. (2014) [52] argue, climate-related stresses such as humidity fluctuations disproportionately affect rural populations with limited access to irrigation and adaptive technologies.

In response, adaptation strategies must be locally relevant and scientifically informed. Efficient irrigation systems, such as drip irrigation promoted by Badu-

Apraku *et al.* (2010) [53], can help manage water stress, while the adoption of drought-tolerant crop varieties as suggested by Partey *et al.* (2018) [54] offers a longer-term solution. Soil conservation measures, including mulching and zero tillage, can also improve moisture retention and buffer the effects of RH decline. On the ecological front, restoring degraded lands and protecting tree cover activities emphasized by Codjoe and Owusu (2011) [55] can help moderate microclimates and sustain biodiversity.

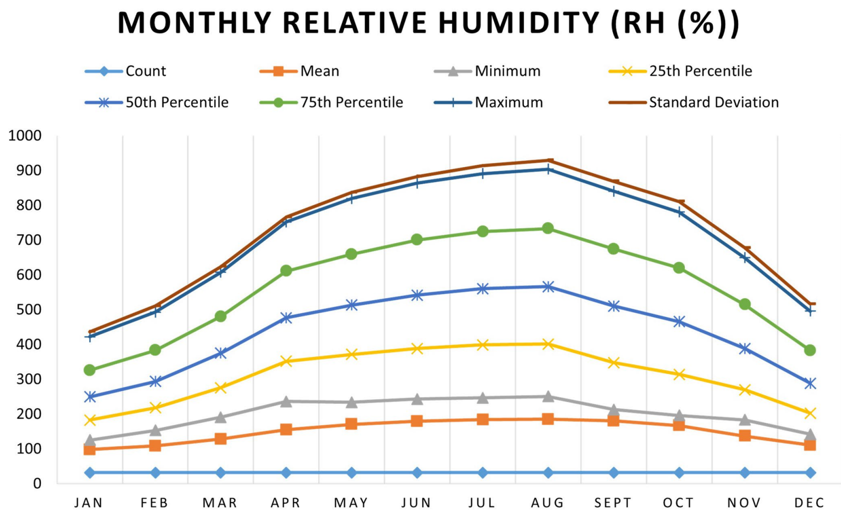


**Figure 5.** Monthly trend plots of relative humidity.

**Table 5.** Trend analysis of temperature, rainfall and relative humidity.

| Month | Tmax | | | Tmin | | | Rainfall | | | Average relative humidity | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | M-K Test Value (S) | Theli Sen Slope | Trend | M-K Test Value (S) | Theli Sen Slope | Trend | M-K Test Value (S) | Theli Sen Slope | Trend | M-K Test Value (S) | Theli Sen Slope | Trend |
| Jan | 93.00 | 0.00 | + | 84.00 | 0.00 | + | −39.00 | 0.00 | N | −82.00 | 0.00 | − |
| Feb | 62.00 | 0.00 | + | 218.00 | 0.00 | + | 33.00 | 0.00 | N | 140.00 | 0.00 | − |
| Mar | −112.00 | 0.00 | N | 246.00 | 0.00 | + | 91.00 | 0.00 | + | 118.00 | 0.00 | N |
| Apr | 45.00 | 0.00 | N | 155.00 | 0.00 | + | −39.00 | 0.00 | N | 36.00 | 0.00 | − |
| May | 55.00 | 0.00 | + | 303.00 | 0.00 | + | −173.00 | 0.00 | N | −4.00 | 0.00 | − |
| Jun | 25.00 | 0.00 | N | 351.00 | 0.00 | + | −11.00 | 0.00 | N | −152.00 | 0.00 | − |
| Jul | 77.00 | 0.00 | + | 380.00 | 0.00 | + | 41.00 | 0.00 | N | −227.00 | 0.00 | − |
| Aug | 58.00 | 0.00 | N | 426.00 | 0.00 | + | −79.00 | 0.00 | − | −248.00 | 0.00 | − |
| Sept | −63.00 | 0.00 | − | 377.00 | 0.00 | + | 49.00 | 0.00 | N | −252.00 | 0.00 | − |
| Oct | −14.00 | 0.00 | N | 330.00 | 0.00 | + | −42.00 | 0.00 | N | −198.00 | 0.00 | − |
| Nov | 112.00 | 0.00 | + | 234.00 | 0.00 | + | −41.00 | 0.00 | N | −212.00 | 0.00 | − |
| Dec | 135.00 | 0.00 | + | 107.00 | 0.00 | + | −56.00 | 0.00 | − | −212.00 | 0.00 | − |

N = "no trend", + = "Increase trend", − = "negative trend"

## 5. Conclusions

The trend analysis of minimum temperature, maximum temperature, rainfall, and relative humidity in Tamale and its environs reveals significant changes in the local climate. The findings indicate: a consistent increase in minimum temperatures, with implications for heat stress and crop development, variable trends in maximum temperatures, with increases in some months and no trends in others, no significant trends in rainfall, except for increases in March and decreases in August and December, decreasing relative humidity throughout the year, except for no trend in March. These changes have important implications for agriculture, water resources, and ecosystems in the region. The observed trends suggest a need for: climate-smart agriculture practices to address heat stress and changing rainfall patterns, enhanced water management strategies to adapt to changing rainfall and humidity conditions, ecosystem conservation and restoration efforts to maintain biodiversity and ecosystem services. This study contributes to the understanding of climate trends in northern Ghana and provides valuable insights for policymakers, agricultural practitioners, and environmental managers to develop adaptive strategies for a changing climate.

In conclusion, the study provides compelling evidence of evolving climatic patterns in Tamale and its surrounding areas, marked by distinct shifts in temperature, rainfall, and relative humidity. Minimum temperatures have shown a consistent upward trend throughout the year, suggesting widespread nocturnal warming. This development carries implications for agricultural productivity, water use, and human health, especially in regions where livelihoods are closely tied to climate-sensitive sectors. The trends in maximum temperature, while less uniform, reflect a seasonal and spatial complexity that underscores the dynamic nature of local climate systems. The rise in maximum temperatures during the dry season and early rainy months contrasts with the decreasing trends observed in September, hinting at the influence of broader atmospheric and land surface changes.

Rainfall trends appear largely stable across most months, though isolated increases and decreases highlight localized shifts that can influence farming schedules, water availability, and food security. Notably, the decline in rainfall during key months such as August and December points to a growing challenge in managing agricultural and domestic water needs, particularly among communities that lack irrigation infrastructure or alternative water sources. The increased rainfall in March, while potentially beneficial, may not offset deficits in later months, complicating crop planning and threatening harvest reliability.

The observed decline in relative humidity is particularly concerning, given its central role in maintaining soil moisture, reducing plant water stress, and regulating local climate stability. Lower humidity not only exacerbates evapotranspiration and crop desiccation but also alters the distribution and severity of pests and diseases, compounding the risks to agricultural output. For human populations in the study area, these changes translate into greater exposure to food insecurity, water scarcity, and economic vulnerability.

The Northern Regional Directorate of the Ministry of Food and Agriculture should implement a climate-smart extension program that aligns farming practices with the observed increases in temperature, declining humidity, and shifting rainfall patterns in Tamale. This should include promoting heat- and drought-tolerant crop varieties, moisture conservation techniques, and timely agronomic advice based on local climate data. Engaging farmers through participatory approaches will ensure that adaptation strategies are practical and rooted in their lived experiences.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

## References

[1] Kushwaha, N., Bhardwaj, A. and Verma, V. (2016) Hydrologic Response of Takarla-Ballowal Watershed in Shivalik Foot-Hills Based on Morphometric Analysis Using Remote Sensing and GIS. *Journal of Indian Water Resources Society*, **36**, 17-25.

[2] Kushwaha, N.L., Rajput, J., Shirsath, P.B., Sena, D.R. and Mani, I. (2022) Seasonal Climate Forecasts (SCFs) Based Risk Management Strategies: A Case Study of Rain-fed Rice Cultivation in India. *Journal of Agrometeorology*, **24**, 10-17. https://doi.org/10.54386/jam.v24i1.775

[3] Pingale, S.M., Khare, D., Jat, M.K. and Adamowski, J. (2014) Spatial and Temporal Trends of Mean and Extreme Rainfall and Temperature for the 33 Urban Centers of the Arid and Semi-Arid State of Rajasthan, India. *Atmospheric Research*, **138**, 73-90. https://doi.org/10.1016/j.atmosres.2013.10.024

[4] New, M., Todd, M., Hulme, M. and Jones, P. (2001) Precipitation Measurements and Trends in the Twentieth Century. *International Journal of Climatology*, **21**, 1889-1922. https://doi.org/10.1002/joc.680

[5] Jones, P.D., New, M., Parker, D.E., Martin, S. and Rigor, I.G. (1999) Surface Air Temperature and Its Changes over the Past 150 Years. *Reviews of Geophysics*, **37**, 173-199. https://doi.org/10.1029/1999rg900002

[6] Amekudzi, L.K., Atiah, W.A., Quansah, E. and Preko, K. (2019) The Spatio-Temporal Variability of Rainfall over the Agro-Ecological Zones of Ghana. *Atmospheric and Climate Sciences*, **9**, 527-544.

[7] De Pinto, A., Demirag, U., Haruna, A.K.J. and Asamoah, M. (2012) Climate Change, Agriculture, and Foodcrop Production in Ghana (Policy Note 3). International Food Policy Research Institute. http://www.ifpri.org/publication/climate-changeagriculture-and-foodcrop-production-ghana

[8] MESTI (2015) Ghana's Third National Communication to the UNFCCC. UNFCCC. http://unfccc.int/resource/docs/natc/ghanc3.pdf

[9] Stanturf, J., Warren, M., Charnley, S., Polasky, S.C., Goodrick, S.L., Armah, F. and Nyako, Y.A. (2011) Ghana Climate Change Vulnerability and Adaptation Assessment. United States Agency for International Development.

[10] MESTI (2012) Ghana's Second National Communication to the UNFCCC. UNFCCC. http://unfccc.int/resource/docs/natc/ghanc2.pdf

[11] Minia, Z. and Agyemang-Bonsu, W. (2008) Climate Change Scenario Development. Ghana Climate Change Impacts, Vulnerability and Adaptation Assessments. Envi-

ronmental Protection Agency.

[12] Bank, W. (2010) Economics of Adaptation to Climate Change. Ghana Country Study. World Bank.

[13] McSweeney, C., New, M., Lizcano, G. and Lu, X. (2010) The UNDP Climate Change Country Profiles. *Bulletin of the American Meteorological Society*, **91**, 157-166. https://doi.org/10.1175/2009bams2826.1

[14] Asante, F. and Amuakwa-Mensah, F. (2014) Climate Change and Variability in Ghana: Stocktaking. *Climate*, **3**, 78-99. https://doi.org/10.3390/cli3010078

[15] UNDPI (2015) Ghana's Third National Communication Report to the UNFCCC. Environmental Protection Agency (EPA), Ministry of Environment, Science, Technology and Innovation (MESTI).

[16] Antwi-Agyei, P., Fraser, E.D.G., Dougill, A.J., Stringer, L.C. and Simelton, E. (2012) Mapping the Vulnerability of Crop Production to Drought in Ghana Using Rainfall, Yield and Socioeconomic Data. *Applied Geography*, **32**, 324-334. https://doi.org/10.1016/j.apgeog.2011.06.010

[17] Saito, O., Kranjac-Berisavljevic, G., Takeuchi, K. and Gyasi, E.A. (2017) Strategies for Building Resilience against Climate and Ecosystem Changes in Sub-Saharan Africa. Springer.

[18] Yiran, G.A.B. and Stringer, L.C. (2016) Spatio-Temporal Analyses of Impacts of Multiple Climatic Hazards in a Savannah Ecosystem of Ghana. *Climate Risk Management*, **14**, 11-26. https://doi.org/10.1016/j.crm.2016.09.003

[19] Martey, F. and Anane-Fenin, K. (2021) Trends and Periodicities in Rainfall, Temperature, and Relative Humidity Datasets over Ghana. *Earth & Environmental Science Research & Reviews*, **4**, 44-54.

[20] Emmanuel, A. (2014) Rising Temperature and Declining Rainfall—A Threat to Water Security in Northern Region of Ghana. *British Journal of Applied Science & Technology*, **4**, 4721-4730. https://doi.org/10.9734/bjast/2014/13031

[21] Klutse, N.A.B., Owusu, K. and Boafo, Y.A. (2020) Projected Temperature Increases over Northern Ghana. *SN Applied Sciences*, **2**, 1-14. https://doi.org/10.1007/s42452-020-3095-3

[22] Ghana Statistical Service (2021) 2021 Population and Housing Census General Report. Accra, Ghana Statistical Service.

[23] Pettitt, A.N. (1979) A Non-Parametric Approach to the Change-Point Problem. *Applied Statistics*, **28**, 126-135. https://doi.org/10.2307/2346729

[24] Rajput, J., Kushwaha, N., Sena, D., Singh, D. and Mani, I. (2023) Trend Assessment of Rainfall, Temperature and Relative Humidity Using Non-Parametric Tests in the National Capital Region, Delhi. *Mausam*, **74**, 593-606. https://doi.org/10.54302/mausam.v74i3.4936

[25] Owusu, K. and Waylen, P. (2009) Trends in Spatio-Temporal Variability in Annual Rainfall in Ghana (1951-2000). *Weather*, **64**, 115-120. https://doi.org/10.1002/wea.255

[26] Nkrumah, F., Klutse, N.A.B., Adukpo, D.C., Owusu, K., Quagraine, K.A., Owusu, A., *et al*. (2014) Rainfall Variability over Ghana: Model versus Rain Gauge Observation. *International Journal of Geosciences*, **5**, 673-683. https://doi.org/10.4236/ijg.2014.57060

[27] Gebrechorkos, S.H., Hülsmann, S. and Bernhofer, C. (2018) Changes in Temperature and Precipitation Extremes in Ethiopia, Kenya, and Tanzania. *International Journal*

*of Climatology*, **39**, 18-30. https://doi.org/10.1002/joc.5777

[28] Boko, M., Niang, I., Nyong, A., *et al*. (2007) Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the IPCC.

[29] Armah, F.A., Odoi, J.O., Yengoh, G.T., *et al*. (2011) Food Security and Climate Change in Drought-Sensitive Savanna Zones of Ghana. *Mitigation and Adaptation Strategies for Global Change*, **16**, 291-306. https://doi.org/10.1007/s11027-010-9263-9

[30] Klutse, N.A.B., Adukpo, D.C., Owusu, K. and Nkrumah, F. (2018) Assessment of Trends and Variability of Temperature in Ghana over the 20th Century. *Weather and Climate Extremes*, **19**, 27-35.

[31] Nyatuame, M., Kasei, R.A. and Martey, E. (2014) Trend Analysis of Temperature and Rainfall in Selected Communities of Vea Catchment of Upper East Region of Ghana. *Environment and Pollution*, **3**, Article 52.

[32] Adiku, S.G.K., MacCarthy, D.S., Kumaga, F.K. and Osei, R.D. (2015) Climate Change and Cereal Crop Production in Ghana: Implications for Food Security. *Ghana Policy Journal*, **9**, 39-57.

[33] Kasei, R.A., Afuakwa, J.J. and Abdul-Razak, M. (2010) Rainfall Variability and Its Impact on Maize Yield in Ghana. *Proceedings of the Environmental Management Conference*, Abeokuta, 3-7 October 2010, 1-11.

[34] Laube, W., Schraven, B. and Awo, M. (2011) Smallholder Adaptation to Climate Change: Dynamics and Limits in Northern Ghana. *Climatic Change*, **111**, 753-774. https://doi.org/10.1007/s10584-011-0199-1

[35] Apata, T.G., Samuel, K.D. and Adeola, A.O. (2016) Analysis of Climate Change Perception and Adaptation among Arable Food Crop Farmers in South Western Nigeria. *International Journal of Climate Change Strategies and Management*, **8**, 403-418.

[36] Kasei, R., Diekkrüger, B. and Leemhuis, C. (2009) Drought Frequency in the Volta Basin of West Africa. *Sustainability Science*, **5**, 89-97. https://doi.org/10.1007/s11625-009-0101-5

[37] Nyadzi, F., Ofori, B.D. and Ampadu, B. (2015) Trend Analysis of Rainfall and Temperature in the Upper West Region of Ghana. *Weather and Climate Extremes*, **8**, 26-34.

[38] Dietz, T., Millar, D., Dittoh, S., Obeng, F. and Ofori-Sarpong, E. (2004) Climate Change and Rural Livelihoods in Northern Ghana: A Risk Scenarios Approach. In: Dietz, A.J., Ruben, R. and Verhagen, A., Eds., *The Impact of Climate Change on Drylands, with a Focus on West Africa*, Springer, 149-172.

[39] Gbetibouo, G.A. and Hassan, R.M. (2005) Measuring the Economic Impact of Climate Change on Major South African Field Crops: A Ricardian Approach. *Global and Planetary Change*, **47**, 143-152. https://doi.org/10.1016/j.gloplacha.2004.10.009

[40] Adjei, K.A., Boamah, D. and Nketia, S. (2020) Assessing the Effects of Rainfall Variability on Water Resources in Northern Ghana. *Ghana Journal of Geography*, **12**, 72-88.

[41] Ntiamoa-Baidu, Y. (2008) Biodiversity Conservation and Sustainable Development in Ghana: The Case of the Wechiau Community Hippo Sanctuary. In: Roe, A.R., Ed., *Conservation and Sustainable Development in Ghana*, Ghana Wildlife Society, 43-58.

[42] Tschakert, P., Sagoe, R., Ofori-Darko, G. and Codjoe, S.N. (2010) Floods in the Sahel: An Analysis of Anomalies, Memory, and Anticipatory Learning. *Climatic Change*,

**103**, 471-502. https://doi.org/10.1007/s10584-009-9776-y

[43] Ampadu, B., Codjoe, S.N.A. and Owusu, G. (2021) Community-Based Adaptation to Climate Variability and Change in Ghana: Practices and Lessons. *Climate and Development*, **13**, 41-53.

[44] Mertz, O., Mbow, C., Reenberg, A. and Diouf, A. (2008) Farmers' Perceptions of Climate Change and Agricultural Adaptation Strategies in Rural Sahel. *Environmental Management*, **43**, 804-816. https://doi.org/10.1007/s00267-008-9197-0

[45] Nkrumah, F., Quagraine, K., Kabo-Bah, A.T. and Codjoe, S.N.A. (2020) Assessing the Observed Variability and Trends in Rainfall and Temperature in Northern Ghana. *Heliyon*, **6**, e04026.

[46] Anyadike, R.N.C. (2009) Climate Change and Sustainable Development in Nigeria: Conceptual and Empirical Issues. In: Ayoade, J.A. and Akintola, M.O., Eds., *Climate Change and Sustainable Development in Nigeria*, Nigerian Meteorological Society, 23-38.

[47] Mensah, C., Agyeman, V.K. and Owusu, K. (2015) Climatic Trends in Southern Ghana and the Potential Implications for Forest Ecosystem Services. *Climate*, **3**, 833–849.

[48] Sarr, B. (2012) Present and Future Climate Change in the Semi-arid Region of West Africa: A Crucial Input for Practical Adaptation in Agriculture. *Atmospheric Science Letters*, **13**, 108-112. https://doi.org/10.1002/asl.368

[49] Akinbode, O.M. (2010) Climate Change and Food Security in Nigeria: Implications for Sustainable Rural Development. *Ozean Journal of Social Sciences*, **3**, 57-66.

[50] Tambo, J.A., Kansiime, M.K. and Wainaina, P. (2021) Farmer Risk Preferences and Uptake of Climate-Smart Agricultural Technologies in Ghana. *Climate and Development*, **13**, 388-398.

[51] Waha, K., Müller, C., Bondeau, A., Dietrich, J.P., Kurukulasuriya, P., Heinke, J., *et al*. (2013) Adaptation to Climate Change through the Choice of Cropping System and Sowing Date in Sub-Saharan Africa. *Global Environmental Change*, **23**, 130-143. https://doi.org/10.1016/j.gloenvcha.2012.11.001

[52] Acheampong, E.N., Ozor, N. and Owusu, K. (2014) Vulnerability and Adaptation to Climate Change: A Review of Local Actions and National Policy Response in Ghana. *African Journal of Agricultural Research*, **9**, 2375–2384.

[53] Badu-Apraku, B., Oikeh, S.O. and Lum, A.F. (2010) Strategies for Drought Tolerance and Water Use Efficiency in Maize in Sub-Saharan Africa. *West African Journal of Applied Ecology*, **17**, 1-13.

[54] Partey, S.T., Zougmoré, R.B., Ouédraogo, M. and Campbell, B.M. (2018) Developing Climate-Smart Agriculture to Face Climate Variability in West Africa: Challenges and Lessons Learnt. *Journal of Cleaner Production*, **187**, 285-295. https://doi.org/10.1016/j.jclepro.2018.03.199

[55] Codjoe, S.N.A. and Owusu, G. (2011) Climate Change/Variability and Food Systems: Evidence from the Afram Plains, Ghana. *Regional Environmental Change*, **11**, 753-765. https://doi.org/10.1007/s10113-011-0211-3