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Long-term Analysis of Rainfall and Surface Air Temperature Trends and the Associated Impacts on Crop Yields in Tanzania

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Abstract

This paper analyses long-term trends in annual rainfall and surface air temperature in Tanzania (1983–2023), and assesses their impacts on crop yields. It utilised satellite data from NASA's repository, including the Geospatial Interactive Online Visualization and Analysis Infrastructure, and the Prediction of Worldwide Energy Resources. The results reveal spatial and temporal variations in both rainfall and temperature across the country. The paper identifies non-significant decreasing trends in annual rainfall in Kigoma (MK = -0.027, p = 0.82) and Kilombero (MK = -0.018, p = 0.88) over the study period. Even though the trends in areas such as Dodoma, Dar es Salaam, Geita, Same and Njombe suggest increased annual rainfall, they also exhibit many years with annual rainfall below average. Besides, the Granger causality test indicated that rainfall had a significant impact on the decrease in maize yields in Geita and Dodoma, on beans in Same, and on paddy in Dodoma. Conversely, the results revealed a significant increasing trend in annual temperature in Kilombero (MK = 0.36, p = 0.001), while Dodoma exhibited a statistically significant decreasing trend (MK = -0.23, p = 0.003). Moreover, the results revealed a total of 22 years with annual temperature above average in Njombe; with other areas such Kigoma, Geita, Same and Kilombero exhibiting 19 years with annual temperature above average. The paper emphasizes the need for climate-resilient agricultural practices, improved weather monitoring systems, and the development of drought-resistant crops to mitigate the adverse effects of climate variability. The results also raise the need for integrating climate data into agricultural planning and policy to support sustainable food production, and ensure long-term food security in Tanzania.

Keywords: *rainfall trends, temperature trends, crop yields, Tanzania, NASA data*

1. Introduction

Changes in rainfall distribution and rising average surface temperatures across regions are the main factors behind recently observed shifts in global climate patterns, which have increased the magnitude and frequency of extreme weather events (Msilu et al., 2024). These changes have affected crop productivity in regions relying heavily on rain-fed agriculture, and

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particularly sub-Saharan Africa (SSA) (Magesa et al., 2023). Rainfall and temperature are important variables in the atmospheric circulation that plays a key role in evaluating regional water balance, streamflow forecasting, floods and drought conditions (Gil-Alana et al., 2017; Hamal et al., 2020a). These variables are also important in determining the environmental conditions of a particular region that affect agricultural production (Panda & Sahu, 2019). Rainfall and surface air temperature are critical factors in rain-fed farming systems since they determine soil availability required for potential crop productivity (Muthoni et al., 2018; Panda & Sahu, 2019). Low rainfall causes agricultural drought that may reduce yields, and retard plant growth (Zampieri et al., 2017). Besides, changes in rainfall and surface air temperature may likely increase the proliferation of new crop pests and diseases (Magesa et al., 2023). Therefore, understanding the dynamic processes of these two variables and their influence on ecosystems, as well as human systems, particularly in the agricultural sector, is of great concern to climate analysts (Katunzi et al., 2016).

Observations indicate that increase in air surface temperature and rainfall variability are already evident in different parts of the world, including in Tanzania (Gebrechorkos et al., 2019). Recurring droughts are being felt in different parts of the country; and with their associated impacts on food production (Mugabe et al., 2024). The annual mean temperature has increased by 0.23℃ per decade in the country, whereas annual rainfall indicates a decreasing trend at the rate of 3.3% between the period of 1960 and 2003 (Kabote et al., 2013). Other studies (e.g., Makula & Botao, 2021) indicate more years of negative anomalies of March to May rainfalls between 1978 to 2017. Similarly, Funk et al. (2012) indicate that rainfall has decreased in the country between March, May, and June over the last three decades. Moreover, Mikova and Msafiri (2019) have shown positive trends of air temperatures in all selected weather stations in the country between 1951 to 2015.

Rainfall variability and increased surface air temperature have led to widespread adverse impacts on key economic and service sectors in the country, and predominantly on the agricultural sector, which employ more than 66% of the population (Komba & Muchapondwa, 2015). Frequent and recurrent dry spells have reduced crop yields in different parts of the country, and increased food shortages, hence leading to food insecurity (Kabote et al., 2013). For example, on average climate change reduced maize and wheat yields by 5.8% and 2.3%, respectively, in sub-Saharan Africa, including Tanzania, between 1974 and 2008 (Adhikari et al., 2015; Muthoni et al., 2018). Additionally, in Tanzania, projections indicate that by 2050, seasonal temperature increases by 2ºC will reduce crop yields for sorghum by 8.8%, maize by 13%, and rice by 7.6% (Rowhania et al., 2011). The fact that the agricultural system in the country is more concentrated in the rural areas, highly rain-fed, and contributes to about 75% of the rural household income, makes the sector more vulnerable to climate change impacts; and hence makes it an issue of national concern (NAPA, 2007). In due regard, it is increasingly becoming more important to understand changes in climatic patterns—particularly temperature and rainfall patterns—and their associated impacts on crop yields to help better management of the impacts (Makula & Botao, 2021). Considerately, it is becoming also important to understand these variables to be able to assess climate induced changes; and hence suggest feasible adaptation measures to the current observed and projected impacts of climate change on crop yields in the country (Panda & Sahu, 2019).

Some of the studies that have addressed this topic in Tanzania (i.e., Mugabe et al., 2024), have examined the impacts of rainfall and temperature trends on crop yields using household surveys and satellite observations at local scales. In contrast, Batho et al. (2019) used only meteorological data to analyse the impacts of temperature and rainfall variation on maize in Mbeya. On the other hand, Chijioke et al. (2017) present rainfall and temperature trends at a national scale using meteorological data, without showing their impacts on crop yields. Studies at the national scale (e.g., Lukali et al., 2021) have used meteorological data to show the impacts of rainfall and temperature trends on maize. Rowhani et al. (2010) examined the impacts of climate trends on three crops (maize, sorghum, and rice), while Mafie (2021) explores the impacts of these two variables (temperature and rainfall) on maize and paddy yields. Other studies (e.g., Limbu & Makula, 2023; Mwambumba et al., 2022) have used satellite observations to show spatial and temporal trends of temperature and rainfall in the country, without associating those changes with crop yields. However, it has been advanced that *ground-based meteorological observations lack adequate spatial and temporal resolution to reliably support regional climate datasets, making satellite observations a necessary alternative* (Hamal et al., 2020b; Hughes, 2006). Thus, in this regard, there are few studies that analyse rainfall and temperature trends and their impacts on crop yields at the national scale using satellite observations.

Therefore, to address the aforementioned research gaps, this paper analyses the long-term rainfall and surface air temperature trends in Tanzania using satellite observations, and assesses their associated impacts on crop yields. *The study hypothesizes a significant decline in rainfall and a rise in surface air temperature in Tanzania over the past four decades, trends that correlate with reduced crop yields.* The paper anticipates answering two questions: (i) What are the observed trends in annual rainfall and surface air temperature across Tanzania between 1983 and 2023? (ii) How have these changes impacted crop yields over time in the country?

2. Methodology

2.1 Description of the Study Area

2.1.1 Location

Tanzania is geographically found in the East African region. The country is located between longitudes 29°E to 41°E and latitudes 1°S and 12°S (NAPA, 2007). Tanzania has a land area of 885,800km^2, which extends over 1,000 km^2 inland from the Indian ocean (Luhunga et al., 2018). The country is bordered by Uganda to the northwest; Kenya to the northeast; Burundi, Rwanda and Democratic Republic of Congo to the west; Malawi to the south; Zambia to the southwest; and Mozambique to the southeast (Bourguignon & Wangwe, 2023). Tanzania also includes the islands of Pemba and Zanzibar, and other offshore islands in the Indian Ocean (FAO, 2016).

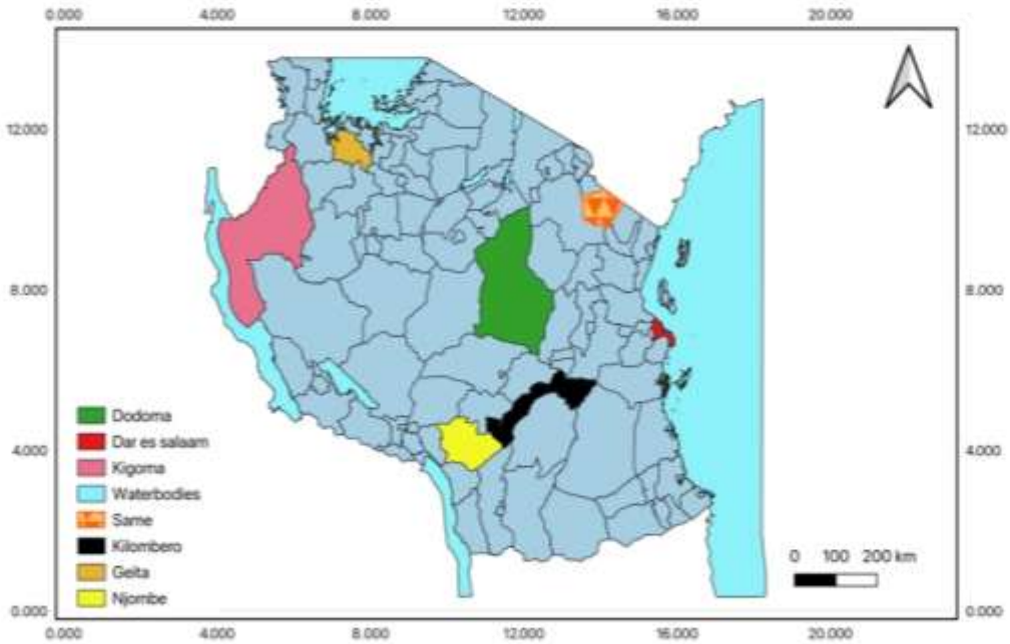


Figure 1: Map of Tanzania Showing Study Sites

2.1.2 Climate

Tanzania experiences both unimodal and bimodal rainfall patterns which are influenced by the movement of the ITCZ (Luhunga et al., 2014 & 2018). The ITCZ influences the unimodal rainfall pattern in the southwestern, central, southern and western parts of the country in October; and continues to April or May (ibid.). On the contrary, other regions in the northern coast, north, north eastern, Island of Zanzibar and Lake Victoria basin receive two distinct rainfall patterns; with the short season starting from October to December, and the long one from

March to May (ibid.). The total annual rainfall ranges from 200 to 2000mm over most part of the country; with the northeastern and southeastern regions recording higher amount of rainfall annually (McSweeney et al., 2010). Contrarywise, the central part of the country receives 400mm of rainfall annually. The annual average temperature ranges from 25 to 32°C (ibid.).

2.1.3 Agro-ecological Zones

Tanzania is divided into seven agro-ecological zones: semi-arid, coastal, southern and western highlands, arid, plateau, northern highlands, and alluvial plains (Mkonda, 2021) (Table 1). This classification is based on the precipitation patterns, altitude, average water holding capacity of the soils, dependable growing seasons, and physiographic features (NAPA, 2007).

Table 1: Sampled Study Sites from the Agro-ecological Zones of Tanzania

SN	Zones	Study sites	Longitude	Latitude	Time Period Used
1	Semi-arid	Dodoma	35° 78′E	6° 15′S	1983–2023
2	Coast	Dar es Salaam	39° 29′E	6° 80′S	1983–2023
3	Plateau	Geita	32° 20′E	2° 88′S	1983–2023
4	Arid	Same	37° 73′E	4° 07′S	1983–2023
5	Southern Highlands	Njombe	34° 78′E	9° 32′S	1983–2023
6	Western highlands	Kigoma	29° 65′E	4° 83′S	1983–2023
7	Alluvial plains	Kilombero	36° 97′E	7° 97′S	1983–2023

The coastal agro-ecological zone encompasses Dar es Salaam and the Coastal regions; extends northward to cover the Tanga region (excluding Lushoto); and stretches southward to include Mtwara and the eastern part of Lindi. The coastal zone also covers the islands of Zanzibar (Mkonda, 2021). These regions receive unimodal rainfall, ranging from 800 to 1200mm per annum in the south; and bimodal rainfall, ranging from 750 to 1200mm in the north**.** The arid and semi-arid zones include the central and southern regions of Tanzania. The central region includes Singida, Dodoma, parts of Arusha and Shinyanga, and northern Iringa (NAPA, 2007). The southern part includes the region of Morogoro excluding Kilombero, Wami Basin, and Uluguru Mountains. It also includes southwest of Mtwara and Lindi. The plateau zone covers the regions of Rukwa, Tabora and western part of Mbeya. It also covers a part of Mara region to the north, Kigoma, Ruvuma, and the southern part of Morogoro to the south. These regions receive unimodal rainfall, ranging from 500 to 800mm per annum.

On the other hand, the southern and western highlands zone covers a broad ridge from the northern part of Morogoro to Lake Nyasa. It also covers parts of Iringa, Ufipa plateau in Sumbawanga, Mbeya, and the shore of Lake Tanganyika in Kigoma and Kagera regions (Mkonda, 2020). With the exception of Kigoma and Kagera, which have bimodal rainfall (1000 to 2000mm), the remaining regions receive unimodal rainfall ranging from 800 to 1400mm per annum. Moreover, the northern highlands zone covers the foot of Mt. Meru and Mt. Kilimanjaro, Mt. Uluguru in Morogoro, eastern Rift valley to Eyasi, Tarime highlands in Mara, Pare Mountains in Kilimanjaro, and Usambara Mountains in Tanga (NAPA, 2007). These regions receive bimodal rainfall ranging from 1000 to 2000mm per annum. On the other hand, the alluvial plain zone covers Kilombero in Morogoro, Usangu (Mbeya), Rufiji (Coast) and Wami (Morogoro) (Mkonda, 2021). These regions receive unimodal rainfall ranging from 600 to 1800mm per annum.

2.1.4 Economic Activities

The economy of Tanzania is heavily reliant on natural resources, agriculture, and a growing service sector (NAPA, 2007). Agriculture is the backbone of the country's economy; contributing about 25% of its GDP (Magesa et al., 2023), and employing nearly 65% of the population (ibid.). Key food crops grown in the country include maize, cassava, beans and sorghum; whereas cash crops include coffee, tea, tobacco, cotton, cashew nuts, and sisal. Tanzania has a significant livestock population that include goats, cattle, and sheep (NAPA, 2007; Bourguignon & Wangwe, 2023). Other sectors include manufacturing that accounts for approximately 23.2% of the GDP; tourism (10%), and mining (5%).

2.2 Data Collection Procedures and Analysis

This paper used satellite data products covering 41 years (1983–2023) to analyse spatial-temporal trends of temperature and rainfall in Tanzania. The datasets (for temperature and rainfall) were obtained using the web-based Geospatial Interactive Online Visualization and Analysis Infrastructure (GIOVANNI); and the NASA Prediction of Worldwide Energy Resources (POWER) database. The GIOVANNI is an online data source maintained and developed by the National Aeronautics and Space Administration, and Goddard Earth Sciences Data and Information Services Center (NASA_GESDISC). Using the GEOVANNI web-based application, the study used the Combined Precipitation Data set (GPCPMON), which includes AIRS (Atmospheric Infrared Sounder), and SSMI (Special Sensor Microwave Imager), at a resolution of $0.5° \times 0.5°$, to understand rainfall trends in the country. Additionally, the Global Land Data Assimilation System (FLDAS) model, at a resolution of $0.1° \times 0.1°$; and the Modern-Era Retrospective analysis for Research and Application Version 2 (MERRA-2), at resolution of 0.5° x 0.625°, were used to understand the temperature trends over the country. All extracted datasets (both GPCP, FLDAS and MERRA-2) were re-gridded and resampled to a 200 meters resolution, using bilinear interpolation (for temperature), and inverse distance weighting (IDW) (for rainfall) in QGIS. These methods align with established practices in climate and environmental studies, where resolution standardization is required for multi-source data integration (Chen & Liu, 2012; Muthoni et al., 2018 & Dinku et al., 2019).

These satellite datasets were chosen because of their long-time coverage. For example, GPCPMON spans from 1979 to the present, FLDAS spans from 1982 to the present, and MERRA-2 covers from 1980 to the present. Other datasets recommended for the East African region (i.e., TRMM, MODIS and GPM) have short-time coverage spanning 9 to 23 years. Additionally, GPCPMON and MERRA-2 provide global precipitation estimates, making it suitable for analysing rainfall patterns across East Africa and beyond. Moreover, these datasets have widely been used by different researchers (i.e., Liebmann et al., 2014; Kimani et al., 2017 & Keys et al., 2022) to understand temperature and rainfall patterns in the East African region, including in Tanzania.

Besides, the NASA POWER was used to extract the maximum surface air temperature and rainfall datasets for MERRA-2 in seven different zones of Tanzania (Table 1). The selection of the study sites was based on the seven agro-ecological zones of Tanzania (Figure 1). Agro-ecological zones were delineated based on the classification system of Tanzania's Ministry of Agriculture (2016), which accounts for climate, soil and land use variability. Within each zone, one study site was selected using a simple random sampling technique, making a total of seven study sites (see Table 1). Also, the Mann-Kendall test and the Sen's slope were used to analyse MERRA-2 data (temperature and rainfall) using the XLSTAT software (see Tables 2 & 3). The Mann-Kendall test is used to indicate statistically significant increasing or decreasing trends in long-term temporal data (Mallick et al., 2021). On the other hand, the Sen's slope is used to calculate the magnitude of trends in a long-term temporal data (Agarwal et al., 2021). Hence, the Sen's slope was applied in this study to calculate the magnitude of the trend for rainfall and temperature data.

Furthermore, data sets for MERRA-2 were used to calculate the Standardized Anomaly Index (SAI) for rainfall and temperature over 13 years (2005–2017) to assess the wet and dry years. The SAI is used to show temperature or rainfall variability, and the number of standard deviations that events deviate from the long-term mean considered (Siddharam et al., 2020). This index has widely been used to monitor drought, and determine wet and dry years in the record (Eshetu et al., 2015). On the other hand, the crop yields data covering 13 years (2005–2017) were collected from the Tanzanian National Sample Census of Agriculture.

This paper employed data from a study which used the fourth (2007/08) and fifth (2019/20) National Sample Censuses of Agriculture, which provides consistent crop yields data district- and region-wise, compared to the first (1971/72), second (1993/94) and third (2002/03) censuses that have more missing data in some years (URT, 2021). Additionally, the first and second censuses focused more on household characteristics and livestock count without collecting crop area and production data (URT, 2021). In due regard, the computation of the Pearson correlation coefficient between crop yields and climate data (temperature and rainfall) were reduced to 13 years (2005–2017). Crop yields were converted into Z-scores to determine how far each crop yield value is from the mean of the dataset measured in terms of standard deviations (Omoyo et al., 2015). A negative score shows that the data is below the mean, while a positive score shows that the data is above the mean (Omoyo et al., 2015).

3. Results

3.1 Long-term Spatial-temporal Analysis of Rainfall Trends

A long-term analysis of the combined precipitation datasets using AIRS and SSMI instruments (GPCP), based on monthly data for 41 years, indicates highest rainfall values ranging between 40.34 to 73.57mm/day within the Lake Victoria Basin and its adjacent areas of Musoma, Mwanza and Bukoba (Figure 2). Contrarywise, the northern part of the country, around Tarime, exhibits a rainfall range of 33.7mm/day; whereas the western part along Lake Tanganyika shows a value of 27.05mm/day. Besides, the results show the lowest rainfall value of 7.1mm/day in the central part around Dodoma; and in the northern eastern part around Same, Mwanga and Tanga. The southern and eastern parts of the country—around Dar es Salaam, Lindi and Mtwara—exhibit a value of 13.76mm/day. Furthermore, the results indicate a rainfall value of 20.4mm/day in the western part around Tabora and Mbeya; and in the southern part around Ruvuma and Njombe.

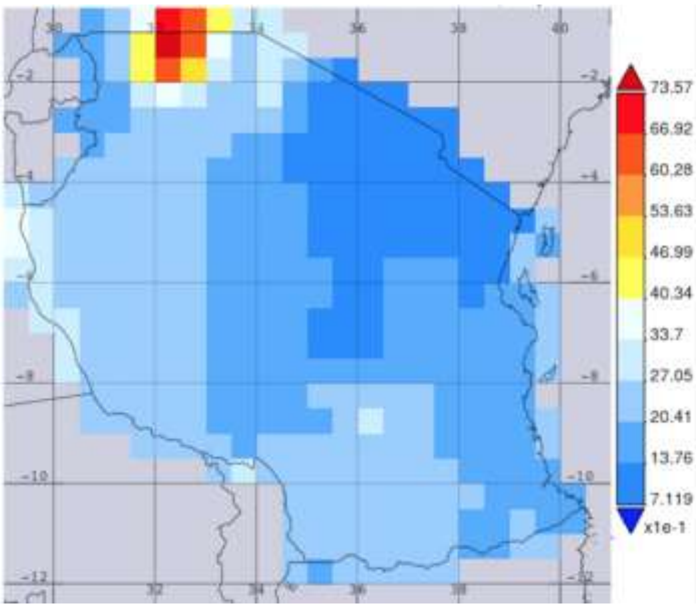


Figure 2: Mean Monthly Rainfall Trends (AIRS, SSMI)

in Tanzania: 1983–2023 (mm/day)

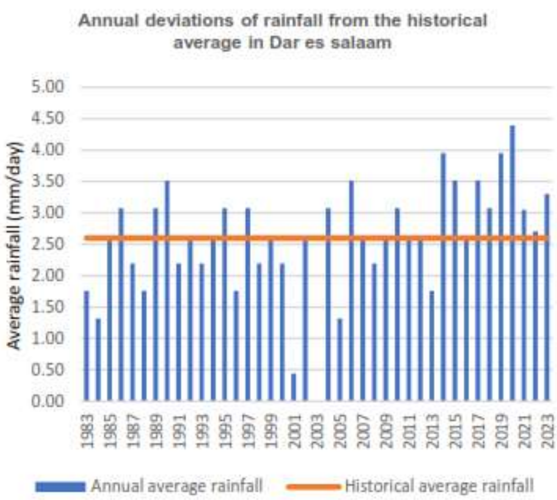
The Mann-Kendall test was further applied to analyse rainfall trends in seven selected study sites using MERRA-2 annual rainfall data for 41 years (1983–2023) (Table 2). The results revealed a significant increase in rainfall trends in Dodoma, with a Kendall's Tau value of 0.418 (p = 0.000); while in Dar es Salaam it was 0.27 (p = 0.014); and in Njombe it was 0.24 (p = 0.03).

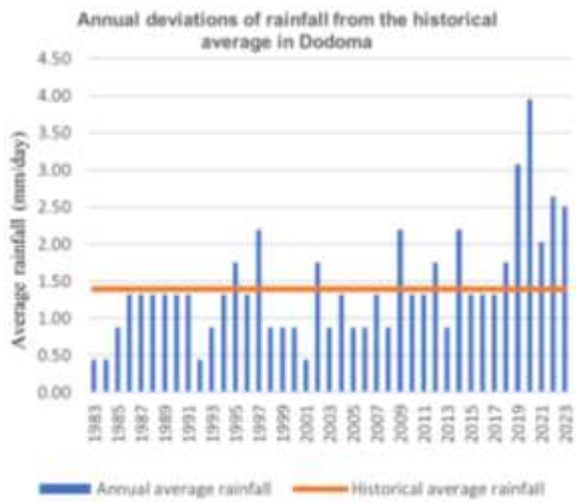
Table 2: Mann-Kendall and Sen's slope Trend Analysis of Rainfall (1983–2023)

Regions	Mean (mm)	Mini (mm)	Maxim (mm)	St. Dev.	Coef. Var.	Mann-Kendall trend	Sign.	Sen's slope
Dodoma	587	268.9	1297.3	217.5	7361.7	0.418	0.000*	10.5
Dar es Salaam	998.7	353.3	1645.3	273.8	7364.7	0.27	0.014**	8.7
Geita	966.9	427.2	1560.9	272.5	7362.7	0.05	0.64	1.45
Same	559.5	247.9	991.4	192.1	7353	0.14	0.18	3.25
Njombe	1640.6	717.2	3670.3	655.5	7364.7	0.24	0.03**	21.3
Kigoma	1058.4	643.4	1766.6	256.9	7363.7	-0.027	0.82	-1.41
Kilombero	1256	723.3	2000.2	283.6	7366.7	-0.018	0.88	-0.22

Key: *Significant at 0.001 level; ** Significant at 0.05 level; *** Significant at 0.01 level

The other selected study areas exhibit non-statistically significant increasing of rainfall trends. These include Geita, with a Kendall's Tau value of 0.05 (p = 0.64); and Same with a value of 0.14 (p = 0.18). Njombe exhibits the highest magnitude of an increasing trend, approximately of 21.3mm per year on average (Table 2). Contrarywise, the results indicate a non-statistically significant decreasing trend in Kigoma (-0.027, p = 0.82) and Kilombero (-0.018, p = 0.88) (Table 2). Furthermore, an analysis of annual rainfall deviations from the historical average in the selected study sites reveals notable variations over the years (Figure 3).





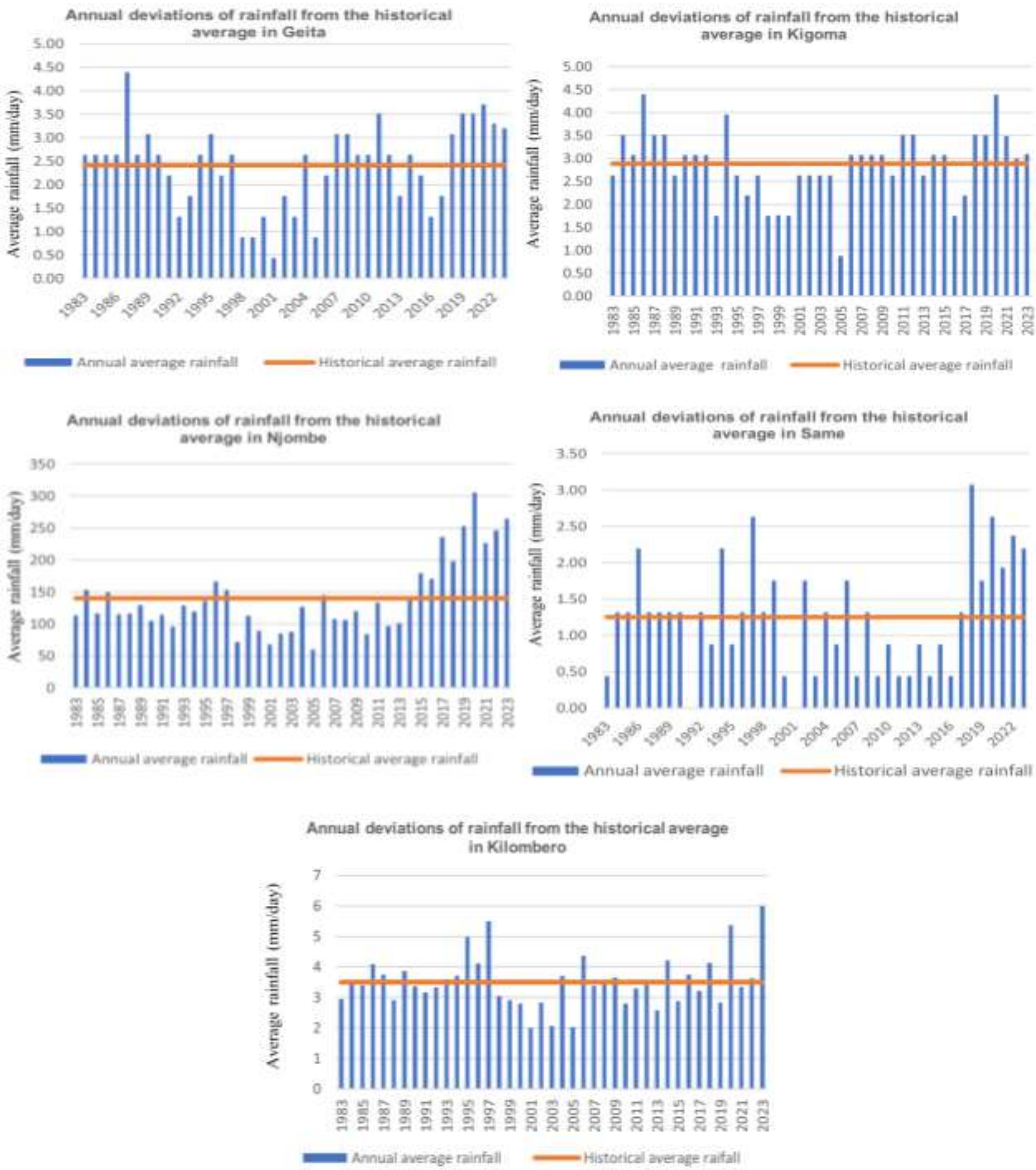


Figure 3: Deviations of Annual Rainfall from the Historical Average

For example, over the study period, the annual rainfall in Dodoma exhibited only 12 years of rainfall above average, while others recorded deficits. Njombe exhibited 14 years with rainfall above average; and Kilombero recorded only 15 years with the same (Figure 3). This indicates that these areas recorded many years with rainfall below average.

3.2 Long-term Spatial-temporal Analysis of Temperature Trends

A long-term analysis of surface air temperature using the FLADAS model indicates the highest record of above 2.96°C in the coastal areas, and within the Lake Victoria Basin (Figure 4). Similarly, a temperature record of 2.96°C is observed in the western part, along Lake Tanganyika. Similarly, the results also indicate a temperature record of 2.89°C in the central part around Dodoma and Singida; and in the northern part around Manyara. The lowest recorded temperatures over time are observed in the areas surrounding Mount Kilimanjaro. Besides, the results show a temperature record of 2.86°C in the southern part, around Njombe and Mafinga. The remaining parts of the country exhibit a temperature record of 2.92°C.

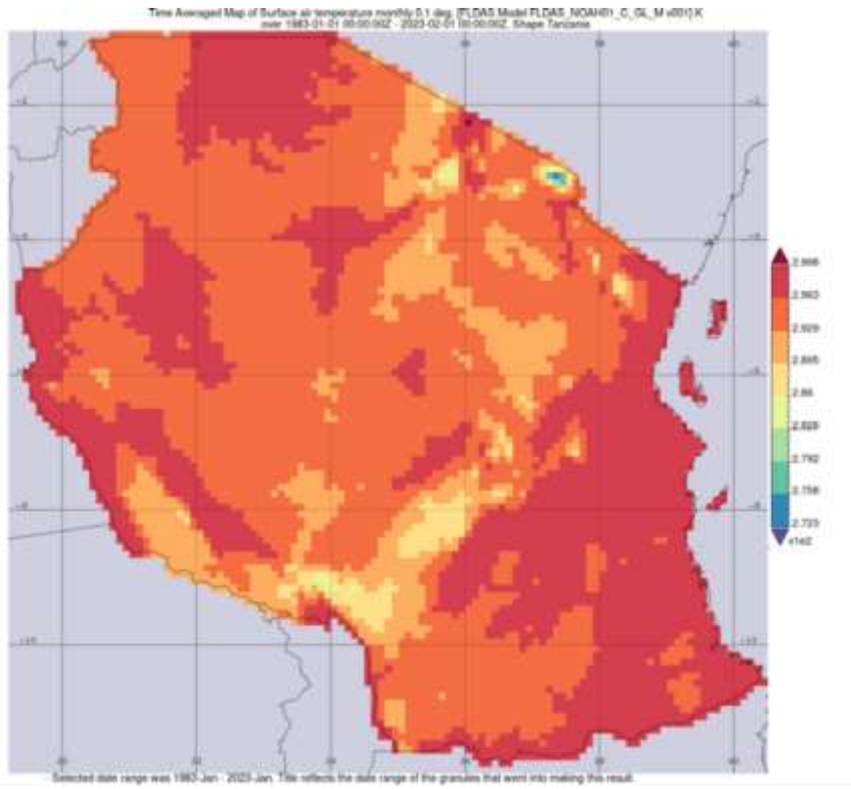


Figure 4: Mean Monthly Surface Air Temperature (FLDAS Model) in Tanzania

The Mann-Kendall test results (Table 3) revealed a significant increase in temperature trends in Kilombero, with a Kendall's Tau value of 0.36 ($p = 0.001$). Dodoma exhibits a statistically significant decrease in temperature, with a Kendall's Tau value of -0.23 ($p = 0.003$). The remaining selected study sites exhibit non-statistically significant increasing in temperature trends. Moreover, an analysis of annual temperature deviations from the historical average in the selected study sites reveals a total of 22 years with temperature above average in Njombe. Other areas—including Kigoma, Geita, Same and Kilombero—each exhibit 19 years with annual temperatures above average.

Table 3: Mann-Kendall and Sen's slope Trend Analysis of Temperature (1983–2022)

Regions	Mean (mm)	Mini (mm)	Maxim (mm)	St. Dev	Coef. Var.	Man-Kendall Trend	Sign.	Sen's Slope
Dodoma	32.01	29.4	34	0.84	7366.7	-0.23	0.03*	-0.025
Dar es Salaam	32.2	31.2	33.9	0.6	7361.7	0.09	0.41	0.008
Geita	34.5	32.9	37.6	0.94	7363.7	0.048	0.67	0.007
Same	36.4	35.08	38.8	0.86	7362.7	0.067	0.55	0.005
Njombe	30.1	27.6	31.7	0.8	7363.7	0.148	0.184	0.015
Kigoma	35.7	33	37.3	0.74	7361.7	0.089	0.43	0.009
Kilombero					7365.7	0.36	0.001**	0.067

Note: * Significant at 0.05 level; ** Significant at 0.001

3.3 Observed Impacts of Rainfall Trends on Crop Yields in Tanzania

The Pearson correlation analysis results (Table 4) showed a very strong positive correlation between rainfall and beans yields in Dar es Salaam ($r = 0.96$, $p < 0.001$); indicating that increased rainfall is strongly associated with higher beans production. This relationship is highly statistically significant. The results also indicate a weak to very weak positive relationship for cassava and sweet potato; and a weak to very weak negative relationship for maize and paddy. On the other hand, a moderate to strong positive correlation was observed for paddy in Njombe ($r = 0.64$, $p = 0.018$). This suggest that rainfall trends have significantly enhanced paddy yields in Njombe. Additionally, a moderate negative correlation was found between rainfall and maize yields in Geita ($r = -0.54$, $p = 0.57$), and in Dodoma ($r = -0.47$); implying that rainfall trends in the regions have reduced maize production. A moderate negative correlation was also observed in Geita for sweet potato ($r = -0.43$) and beans ($r = -0.41$). Moreover, the results indicate a moderate positive correlation for maize in Kilombero ($r = 0.44$), and in Same ($r = 0.40$). Also, the results indicate a weak negative correlation between rainfall and four different types of crops in Dodoma (maize, paddy, cassava, and beans) and Geita (maize, paddy, sweet potato, and beans). This implies that rainfall trends are associated with decreasing crop yields in these regions (Table 4).

Table 4: Correlation Result of Rainfall and Crop Yields in the Selected Study Areas

	Dar es Salaam	Dodoma	Geita	Kigoma	Njombe	Same	Kilombero
Maize	-0.18	-0.47	-0.54	0.29	0.54	0.40	0.44
Paddy	-0.07	-0.35	-0.08	-0.38	0.64**	-0.39	-0.36
Sweet potato	0.16	0.06	-0.43	-0.39	-0.10	0.18	-0.08
Cassava	0.12	-0.04	0.05	0.17	0.29	-0.39	-0.02
Beans	0.96*	-0.27	-0.41	-0.14	0.21	-0.17	0.09

Note: *Significant at 0.01 level; ** Significant at 0.05 level

The results for the Granger causality test between rainfall and crop yields are presented in Table 5. The null hypothesis that rainfall do not Granger cause crop yields is rejected for maize production in Geita (p-value = 0.050), Dodoma (p-value = 0.004), Kigoma (p-value = 0.034), and Kilombero (p-value = 0.010). Additionally, the null hypothesis that rainfall does not Granger cause paddy yields in Dodoma (p-value = 0.042), cassava in Geita (p-value = 0.106), and beans in Njombe (p-value = 0.160) is rejected. Similarly, the null hypothesis for beans production in Same is also rejected. This indicates that past rainfalls in the studied areas have had a significant predictive impact on these crop yields.

Table 5: Granger Causality Test Result Between Rainfall and Crop Yields

Null Hypothesis	F-statistic and Probability level						
	Dar es Salaam	Dodoma	Geita	Kigoma	Njombe	Same	Kilombero
Rainfall does not Granger	0.196	2.425	5.586**	8.892**	0.325	6.498	0.149
cause Maize yields	(0.674)	(0.004)*	(0.050)	(0.034)	(0.586)	(0.994)	(0.010)*
Rainfall does not Granger	0.437	0.916	0.123	1.038	1.672	0.125	0.001
cause Paddy yields	(0.533)	(0.042)**	(0.736)	(0.433)	(0.237)	(0.735)	(0.974)
Rainfall does not Granger	0.0002	0.236	0.371	1.208	0.714	0.032	0.133
cause sweet potato yields	(0.990)	(0.798)	(0.561)	(0.362)	(0.426)	(0.862)	(0.726)
Rainfall does not Granger	0.712	0.418	2.912***	0.018	0.337	1.305	0.248
cause Cassava yields	(0.420)	(0.692)	(0.106)	(0.982)	(0.578)	(0.290)	(0.632)
Rainfall does not Granger	0.293	0.176	0.003	0.799	2.399 ***	7.067**	0.009
cause Beans yields	(0.602)	(0.845)	(0.961)	(0.492)	(0.160)	(0.032)	(0.925)

Note: *Significant at 0.01 level; **Significant at 0.05 level; *** Significant at 0.1 level

3.4 Observed Impacts of Temperature Trends on Crop Yields in Tanzania

The Pearson correlation analysis results for temperature and crop yields indicate a moderate to strong correlation for maize in Geita (r = 0.65) and sweet potato (r = 0.65) in Same; implying that rainfall trends have increased yields of these two crops (Table 6). The results also indicate a moderate positive correlation between higher temperatures and maize yields in Dodoma (r = 0.43), and Same (r = 0.51). Additionally, a moderate positive correlation was observed in sweet potato (r =

0.43) and beans (r = 0.44) in Geita; and paddy in Kigoma (r = 0.45) and Kilombero (r = 0.44). Moreover, a weak negative correlation was observed in four different crops (maize, paddy, cassava, and bens) in Njombe, and three crops in Kigoma; implying that higher temperatures are slightly associated with decreasing crop yields (Table 6).

Table 6: Correlation Result of Temperature and Crop Yields in the Selected Study Areas

	Dar es Salaam	Dodoma	Geita	Kigoma	Njombe	Same	Kilombero
Maize	-0.22	0.43	0.65*	-0.01	-0.29	0.51	-0.23
Paddy	0.28	0.36	0.28	0.45	-0.33	-0.13	0.44
Sweet potato	0.13	0.15	0.43	-0.01	0.11	0.65*	0.39
Cassava	0.24	0.00	-0.10	-0.26	-0.10	-0.33	0.27
Beans	0.35	0.28	0.44	0.15	-0.25	0.06	0.11

Note: *Significant at 0.05 level

Conversely, the Granger causality test results between temperature and crop yields are presented in Table 7. The null hypothesis that temperature do not Granger cause crop yields is rejected for sweet potato in Dar es Salaam (p-value = 0.061), Same (p-value = 0.047), and Kilombero (p-value = 0.032). Similarly, the null hypothesis for maize production is rejected in Geita (p-value = 0.042), and Same (p-value = 0.103). Additionally, the null hypothesis for cassava in Geita (p-value = 0.089) and paddy in Kigoma (p-value = 0.036) are all rejected. This indicates that past temperatures in the studied areas have had a significant predictive impact on these crop yields.

Table 7: Granger Causality Test Result Between Temperature and Crop Yields

Null Hypothesis	F-statistic and Probability Level						
	Dar es Salaam	Dodoma	Geita	Kigoma	Njombe	Same	Kilombero
Temp does not Granger cause Maize yields	0.018 (0.896)	0.462 (0.521)	6.136 **(0.042)	1.030 (0.343)	1.933 (0.206)	3.678 (0.103)**	1.550 (0.253)
Temp does not Granger cause Paddy yields	1.828 (0.225)	0.030 (0.867)	0.363 (0.567)	6.654** (0.036)	0.0002 (0.987)	0.764 (0.415)	0.873 (0.381)
Temp does not Granger cause Sweet potato yields	5.272*** (0.061)	0.001 (0.966)	0.073 (0.794)	1.455 (0.266)	0.636 (0.451)	6.584** (0.042)	7.120** (0.032)
Temp does not Granger cause Cassava yields	1.630 (0.281)	0.690 (0.430)	3.722*** (0.089)	0.216 (0.654)	0.001 (0.967)	0.004 (0.947)	0.417 (0.537)
Temp does not Granger cause Beans yields	0.705 (0.423)	0.109 (0.748)	0.549 (0.479)	0.012 (0.914)	1.471 (0.259)	0.857 (0.385)	0.429 (0.531)

Note: *Significant at 0.01 level; **Significant at 0.05 level; *** Significant at 0.1 level

4. Discussion

4.1 Observed Rainfall Trends and Associated Impacts on Crop Yields

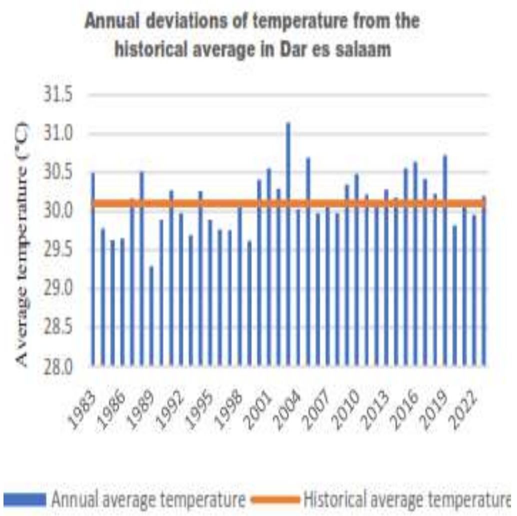
The results reveal notable spatial variations in rainfall patterns across the country over the past 41 years (1983–2023), with the Lake Victoria Basin and the adjacent areas of Bukoba, Musoma, and Mwanza recording the highest cumulative rainfall. The next high rainfall centres are localized in the southern highlands over Iringa, and north of Lake Malawi around Tukuyu, which matches the findings of Borhara et al. (2020) that were based on the same observations using GPCC datasets. Other high rainfall centres are observed in the northern part around Tarime, and in the western part along the Lake Tanganyika. The lowest rainfall was recorded in the central part of the country: around Dodoma, northern eastern part around Mwanga, Same and Tanga. This concurs with other studies (i.e., NAPA, 2007; Yanda et al., 2015), which included these regions in the semi-arid and arid agro-ecological zones. Additionally, Dar es Salaam, and the southern eastern part of the country—including Lindi and Mtwara—ranked among areas with the second-lowest recorded rainfall.

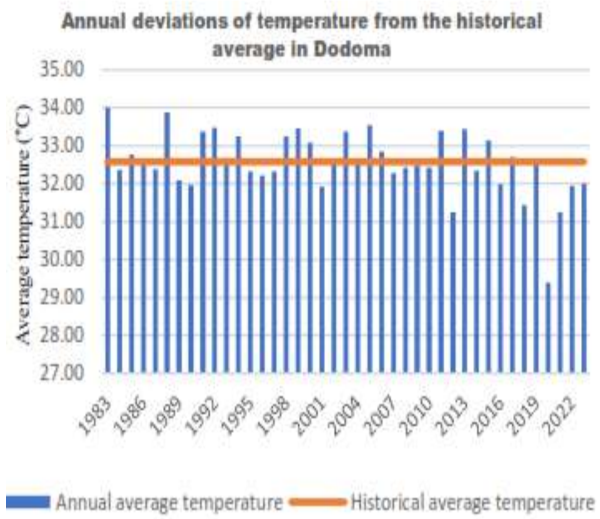
The results also depict decreasing annual rainfall trends in Kigoma (MK = -0.027) and Kilombero (MK = -0.018) over the study period. These trends, though not significant, suggest potential long-term changes in rainfall patterns. While these observed decreasing trends are weak, there is a need for a continued monitoring to determine if these trends become more pronounced over time, and how they can potentially lead to agricultural challenges and water shortages. Even though the trends in the remaining areas (Dodoma, Dar es Salaam, Geita, Same and Njombe) suggest an increased annual rainfall, interannual variability remains a key concern for agricultural water management and planning in these regions (Biswas et al., 2024; Knight et al., 2024). The results further reveal 29 years in which annual average rainfall was below the long-term average rainfall in Dodoma. Njombe exhibited 25 years with rainfall below the long-term average; and for Kilombero it was 20 years. Other regions—namely Kigoma and Geita—exhibited 18 and 16 years, respectively, with rainfall below the long-term average (Figure 4). This means that the total amount of rainfall received over these years was less than the historical average, indicating drier-than-normal conditions; which can have several implications on crops production. This corresponds with the results of this study, which indicated a negative correlation between annual rainfall and the production of maize, paddy, cassava, and beans in Dodoma. Additionally, a weak negative correlation is also observed in four different crops involved in the analysis in Geita (Table 4). Conversely, a weak negative correlation is observed for three different types of crops in Same, Kigoma and Kilombero.

Moreover, the null hypothesis that rainfall do not Granger cause crop yields is rejected for maize production in Dodoma, Geita, Kigoma and Kilombero. The null hypothesis is also rejected for paddy yields in Dodoma, cassava in Geita, and beans in Njombe and Same; indicating that past rainfall has a significant predictive impact on these crop yields in the studied areas. These results also indicate that rainfall has a significant impact on the decreasing maize yields in Geita and Dodoma, beans in Same, and paddy in Dodoma. Previous studies (e.g., Mkonda & He, 2018) have also indicated a decline in crop yields due to inter-annual variations in rainfall in the semi-arid regions of Tanzania, leading to food shortages and poverty. For example, Lukali et al. (2021) found that between 1988 and 2017, years of decline in maize yield in Tanzania were characterized by a decrease in rainfall throughout the year. This indicates that rainfall is a key determinant of agricultural productivity in the country, where the majority of farming is rain-fed. Since about 75% of the rural households in the country rely on agriculture for their income and livelihoods, a decline in crop yields will leave many people, particularly smallholder farmers, into hunger and poverty (Magesa et al., 2023).

4.2 Temperature Trends and Associated Impacts on Crop Yields

The analysis of surface air temperature trends in Tanzania revealed notable patterns of temperature across the country with regional variations in warming rates over study period (Figure 5). The highest recorded surface air temperature is observed within the Lake Victoria Basin and coastal areas. Similarly, the same trend is observed in the western part along Lake Tanganyika, western Tabora, and northern Singida. The lowest recorded temperatures are observed in the areas surrounding Mount Kilimanjaro. On the other hand, Njombe and Mafinga, in the southern part, ranked as the second-lowest areas in recorded surface air temperature.





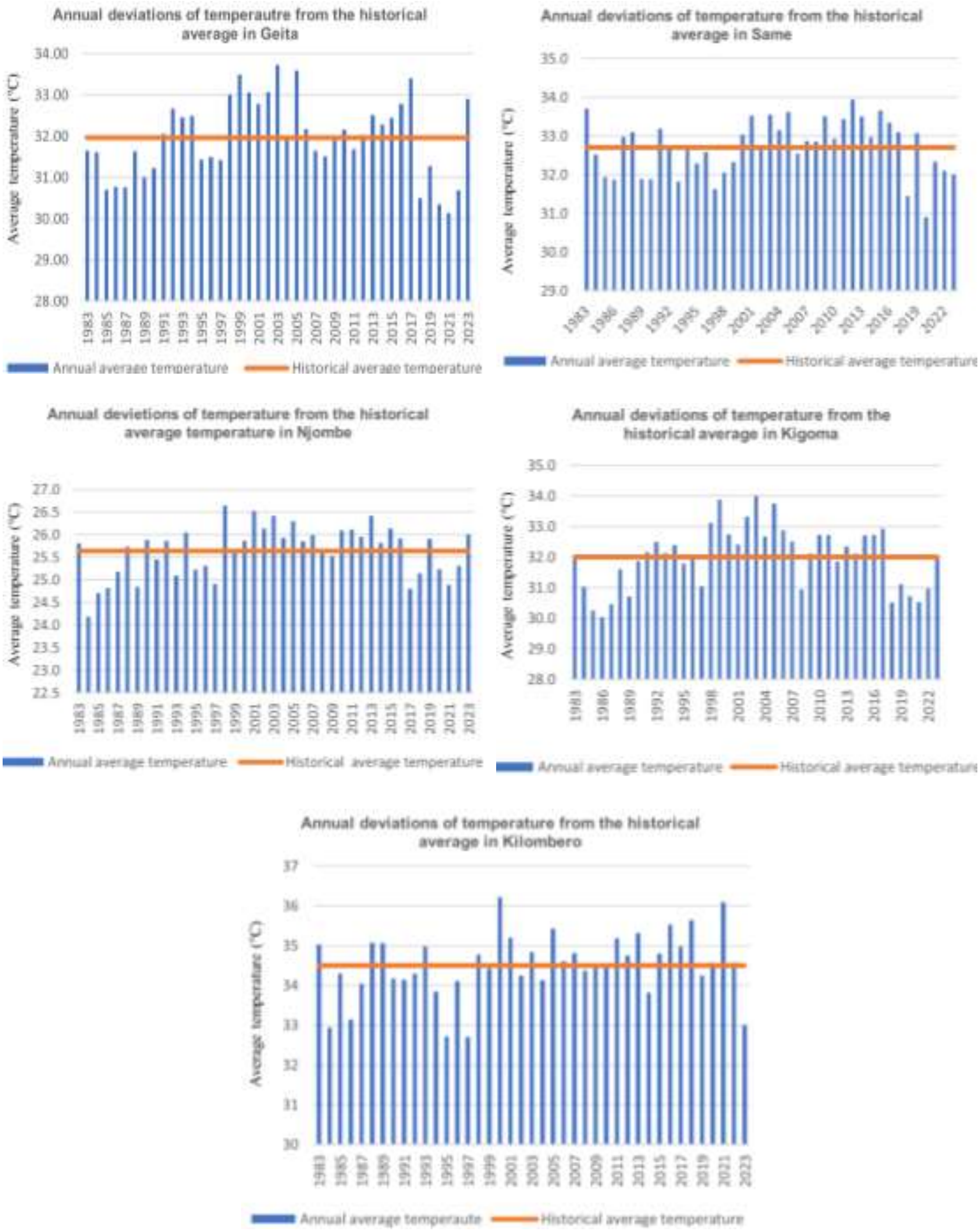


Figure 5: Deviations of Annual Temperature from the Historical Average

The Mann-Kendall test (see Table 3) revealed a significant increase in temperature trends in Kilombero, with a Kendall's Tau value of 0.36 ($p = 0.001$). Dodoma exhibits a statistically significant decrease in temperature with a Kendall's Tau value of -0.23 ($p = 0.003$). This trend contrasts with the global warming patterns. This can be related to the cold bias of MERRA-2 datasets in semi-arid zones (Molod et al., 2015). This bias has been observed in various studies comparing in-situ observations with MERRA-2 data. Other studies in Dodoma (Mayaya et al., 2015; Mikova & Msafiri, 2019) found a positive trend using ground-based observations. The remaining selected study sites exhibit non-statistically significant increasing temperature trends. Moreover, the analysis of annual temperature deviations from the historical average (Figure 5) in the study sites reveals a total of 22 years with temperature above average in Njombe. Other areas—including Kigoma, Geita, Same and Kilombero—each exhibit 19 years with annual temperature above average. This indicates that, the study areas recorded annual temperatures above the historical average for several years, suggesting a significant warming trend. These findings align with Kabote et al. (2013), who indicated that between 1960 and 2003, annual temperatures increased by 0.23°C per decade in the country.

Additionally, Mikova and Msafiri (2019) indicated a positive trend of air temperatures at all weather stations in the country between 1951 and 2015; with the exception of Arusha, Songea, and Mtwara stations. Higher temperatures can lead to increased evaporation, reduced soil moisture, and greater stress on agricultural systems (Muthoni et al., 2018). This concurs with the findings of this study, which indicated a negative weak correlation between annual temperatures and maize production in Dar es Salaam, Njombe, and Kilombero (Table 6). A weak negative correlation is also observed for cassava in Kigoma and Same; and for paddy in Njombe. These findings match those of Mkonda and He (2018), which found a negative correlation between temperatures and agro-ecological zone of Tanzania. Besides, a moderate positive correlation is observed for maize in Geita, and sweet potato in Same.

The null hypothesis that temperature do not Granger cause crop yields is rejected for maize yields in Geita and Same, paddy in Kigoma, and cassava in Geita (Table 7). Similarly, the null hypothesis is rejected for sweet potato in Dar es Salaam, Same and Kilombero. The Pearson correlation analysis results between temperature and crop yields in these areas indicated a positive correlation, with the exception of cassava in Geita. These results indicate that temperatures have a significant impact on the decreasing trend of cassava in Geita.

5. Conclusions and Policy Implications

This paper analysed the long-term rainfall and air surface temperature trends in Tanzania, and assessed their associated impacts on crop yields. The results reveal spatial and temporal variations in rainfall and temperature trends across Tanzania over the past four decades, and highlight their impacts on agricultural productivity, particularly crop yields. The results confirm that regions—such as Lake Victoria Basin, Iringa, Tukuyu, and areas along major lakes like Lake Tanganyika and Lake Malawi—experience high rainfall; while central and northeastern regions—including Dodoma, Mwanga, and Same—consistently record lower rainfall levels. Despite certain areas showing increasing rainfall trends, the overall interannual variability—particularly the frequency of below-average rainfall years in regions like Dodoma and Njombe—suggests an increasing vulnerability of rain-fed agriculture to climate variability.

Rainfall and temperature trends have shown to significantly influence the yields of key staple food crops such as maize, paddy, cassava, and beans. The Granger causality tests results indicate that historical rainfall and temperature patterns can predict yields for these crops in several regions, reinforcing the importance of taking into account weather patterns in agricultural planning. Notably, declining yields in Dodoma, Geita, Same, and Kilombero correlate with unfavourable changes in climate variables, highlighting the urgent need for adaptive strategies. While some crops like sweet potato exhibit resilience—or even benefit—from moderate warming in certain areas, most staple crops show a weak to moderate negative correlation with increasing temperatures.

Based on these findings, the following policy interventions are recommended:

- Promotion of practices that enhance resilience to rainfall variability and temperature extremes, including the adoption of drought-resistant crop varieties, agroforestry, and improved irrigation systems, especially in vulnerable areas like Dodoma, Geita, and Kilombero.
- Investments in localized and real-time weather monitoring infrastructure to support early warning systems to better inform farmers of impending weather-related risks.
- Developing and implementing water harvesting and conservation strategies, particularly in semi-arid and arid zones, to ensure water availability during dry spells.
- Expanding research into climate-resilient crop varieties, and strengthening agricultural extension services to disseminate this knowledge and technology to smallholder farmers effectively.
- Encouraging the diversification of income sources beyond agriculture, particularly in the most climate-sensitive regions, to reduce vulnerability to crop failures.

References

Agarwal, S., Suchithra, A. & Singh, S. P. (2021). Analysis and Interpretation of Rainfall Trend Using Mann-Kendall's and Sen's slope Method. *Indian Journal of Ecology*, 48(2): 453–457.

Batho, P., Shaban, N. & Mwakaje, A. (2019). Impacts of Rainfall and Temperature Variation on Maize (Zea Mays L.) Yields: A Case Study of Mbeya Region, Tanzania. *Archives of Agriculture and Environmental Science*, 4(2): 177–184 (2019). https://doi.org/10.26832/24566632.2019.040208.

Biswas, J.C., Islam, T.H. & Hossain, Z. A. (2024). Interannual Climate Variability and Its Impacts on Major Crop Productivity. In: Rahman, M. M. (Eds): *Climate Change and Soil- Water Plant Nexus*. Singapore: Springer Nature.

Borhara, K., Pokharel, B., Bean, B., Deng, L. & Wang, S. (2020). On Tanzania's Precipitation Climatology, Variability and Future Projection. *Climate*, 8(2), 34. doi:10.3390/cli8020034.

Bourguignon, F. & Wangwe, S. M. (2023). *Tanzania in Geographic, Demographic, and Historical Perspective*. Cambridge University Press. https://doi.org/10.1017/9781009285803.003.

Chen, W. F. and Liu, C.W. (2012). Estimation of the Spatial Rainfall Distribution Using Inverse Distance Weighting (IDW) in the Middle of Taiwan. *Paddy and Water Environment*, 10: 209–222). DOI 10.1007/s10333–012–0319–1.

Chijioke, L.B., Kijazi, A.L., Luhunga, P.M., Ng'ongolo, H.K. & Mtongori, H.I. (2017). Spatial and Temporal Analysis of Rainfall and Temperature Extreme Indices in Tanzania. *Atmospheric and Climate Sciences*, 7: 525–539. https://doi.org/10.4236/acs.2017.74038.

Dinku, T. (2019). Challenges With Availability and Quality of Climate Data in Africa. In: *Extreme Hydrology and Climate Variability* (pp. 71–80). Elsevier. https://doi.org/10.1016/B978–0–12–815998–9.00007–5.

Eshetu, G., Johansson, T. & Garedew, W. (2015). Rainfall Trend and Variability Analysis in Setema-Gatira Area of Jimma, Southwestern, Ethiopia. *African Journal of Agricultural Research*, 11(32): 3037–3045. DOI: 10.5897/AJAR2015.10160.

FAO. (2016). *AQUASTAT Country Profile-United Republic of Tanzania*. Food and Agriculture Organization of the United Nations (FAO). Rome, Italy.

Funk, C., Michaelsen, J. & Marshall, M. (2012). Mapping Recent Decadal Climate Variations in Precipitation and Temperature Across Eastern Africa and the Sahel. In: *Remote Sensing of Drought: Innovative Monitoring Approaches* [Wardlow, B.D., Anderson, M.C. & Verdin, J.P. (eds.)]. CRC Press, Boca Raton, FL, USA, pp. 331–358.

Gebrechorkos, S. H., Hülsmann, S. & Bernhofer, C. (2019). Long-term Trends in Rainfall and Temperature Using High-Resolution Climate Datasets in East Africa. *Scientific Reports*, *9*(1): 11376. https://doi.org/10.1038/s41598–019–47933–8.

Gil-Alana, L.A., Yaya, O.S. & Fagbamigbe, A. (2017). Time Series Analysis of Quarterly Rainfall and Temperature (1900–2012) in Sub-Saharan African countries. *Theoretical and Applied Climatology*. https://doi.org/10.1007/s00704–018–2583–5.

Hamal, K., Sharma, S., Khadka, N., Baniya, B., Ali, M., Shrestha, M. S., Xu, T., Shrestha, D. & Dawadi, B. (2020a). Evaluation of MERRA-2 Precipitation Products Using Gauge Observation in Nepal. *Hydrology*, 7(3): 40. https://doi.org/10.3390/hydrology7030040.

Hughes, D. A. (2006). Comparison of Satellite Rainfall Data With Observations from Gauging Station Networks. *Journal of Hydrology*, *327*(3–4): 399–410. https://doi.org/10.1016/j.jhydrol.2005.11.041.

Intergovernmental Panel on Climate Change. (2012). *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M., Mach, K., Plattner, G., Allen, S.K., Tignor, M. and Midgley, P.M. (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.

Intergovernmental Panel on Climate Change. (2014). Climate Change 2014: Impacts, Adaptation and Vulnerability. In Field, C. B., Barros, V.R., Mastrandrea, M. D & Mach, K. J. (Eds.): *Summary for policymakers. Cambridge*, UK: Cambridge University Press.

Intergovernmental Panel on Climate Change. (2021). Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, c., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R. and Zhou, B (eds.)]. Cambridge University Press. In Press.

Kabote, S.J., Mamiro, D., Synnevg, G., Urassa, J.K., Mattee, A.Z., Mbwambo, J.S., Nombo, C., Masolwa, L.W. & Chingonikaya, E. (2013). Inter-annual Anomaly and Seasonal Variability of Rainfall and Temperature in Selected Semi-arid Areas of Tanzania. *Journal of Continuing Education and Extension,* 4(2): 295–317. https://www.suaire.sua.ac.tz/handle/123456789/1351.

Katunzi, Bushesha, & Mwakalila (2016). Examining Rainfall and Temperature Pattern Change over Time: A Case of Kishapu District, Shinyanga Region in Tanzania. *Climate Change*, 2(8): 557–572.

Keys, P., Warrier, R., Ruud, J., Galvin, K. & Boone, R. (2022). Analysis of Kenya's Atmospheric Moisture Sources and Sinks. *Earth Interactions*, 26. DOI: 10.1175/EI-D-21–0016.1.

Kimani, M.W., Hoedjes, J.C. & Su, Z. (2017). An Assessment of Satellite-Derived Rainfall Products Relative to Ground Observations Over East Africa. *Remote Sensing*, 9(5), 430. doi:10.3390/rs9050430.

Knight, C., Khouakhi, A. & Waine, T. W. (2024). The Impact of Weather Patterns on Inter-Annual Crop Yield Variability. *Science of the Total Environment*, 955. https://doi.org/ 10.1016/j.scitotenv.2024.177181.

Komba, C. & Muchapondwa, E. (2015). Adaptation To Climate Change by Smallholder Farmers in Tanzania, Discussion paper series, *Environment for Development*.

Liebmann, B., Hoerling, M., Funk, C., Blade, I., Dole, R., Allured, X., Pegion, P. & Eischeid, J. (2014). Understanding Recent Eastern Horn of Africa Rainfall Variability and Change. *Journal of Climate*, 27. DOI: 10.1175/JCLI-D-13–00714.1.

Limbu, P.T. & Makula, E.K. (2023). Investigation of Temporal Trends and Spatial Patterns of Extreme Temperatures and Their Relationship to Climate Circulation Indices in Tanzania. *Journal of the Geographical Association of Tanzania*, 43(2): 67–85. https://doi.org/10.56279/jgat.v43i2.261.

Luhunga, P. M., Mutayoba, E. & Ng'ongolo, H. (2014). Homogeneity of Monthly Mean Air Temperature of the United Republic of Tanzania with HOMER. *Atmos. Clim. Sci.* 4, 70–77. doi: 10.4236/acs.2014.41010.

Luhunga, P.M., Kijazi, A.L., Chijioke, L., Kondowe, A., Ng'ongolo, H. & Mtongori, H. (2018). Climate Change Projections for Tanzania Based on High-Resolution Regional Climate Models from the Coordinated Regional Climate Downscaling Experiment (CORDEX)-Africa. *Front. Environ. Sci.* 6:122. doi: 10.3389/ fenvs.2018.00122.

Lukali, A., Osima, S. E., Lou, Y. & Kai. (2021). Assessing the Impacts of Climate Change and Variability on Maize (Zea mays) Yields Over Tanzania. *Atmospheric and Climate Sciences*, 11(3). DOI: 10.4236/acs.2021.113035.

Mafie, G. K. (2021). The Impact of Climate Change on Agricultural Productivity in Tanzania. *International Economic Journal,* 36 (10). DOI:10.1080/10168737. 2021.2010229.

Magesa, B. A., Mohan, G., Matsuda, H., Melts, I., Kefi, M. & Fukushi, K. (2023). Understanding the Farmers' Choices and Adoption of Adaptation Strategies, and Plans To Climate Change Impact in Africa: A Systematic Review. *Climate Services*, 30: 100362. https://doi.org/10.1016/j.cliser.2023.100362.

Makula, E. K. & Botao, Z. (2021). Changes in March to May Rainfall over Tanzania During 1978–2017. *International Journal of Climatology*, 2021(1–13). DOI: 10.1002/joc.7146.

Mallick, J., Talukdar, S., Alsubih, M., Salam, R., Ahmed, M., Kahla, N. B. & Shamimuzzaman, M. (2021). Analysing the Trend of Rainfall in Asir Region of Saudi Arabia Using the Family of Mann-Kendall Tests, Innovative Trend Analysis, and Detrended Fluctuation Analysis. *Theoretical and Applied Climatology*, 143: 823–841.

Mayaya, H.K., Opata, G. & Kipkorir, E.C. (2015). Understanding Climate Change and Manifestation of Its Driven Impacts in the Semi-Arid Areas of Dodoma Region, Tanzania. *Ethiopian Journal of Environmental Studies & Management*, 8(4): 364–376. doi: http://dx.doi.org/10.4314/ejesm.v8i4.2.

McSweeney, C., New, M. & Lizcano, G. (2010). *UNDP Climate Change Country Profiles, Tanzania*. https://digital.library.unt.edu/ ark:/67531/metadc226754/.

Mikova, K.D. & Msafiri, L.C. (2019). *Trends of Climate Parameters Over Tanzania*. IOP Conference Series: Earth and Environmental Science, 321 (1), 012035. doi:10.1088/1755–1315/321/1/012035.

Mkonda, M.Y. & He, X.H. (2018). Climate Variability, Crop Yields and Ecosystems Synergies in Tanzania's Semi-Arid Agro-Ecological Zone. *Ecosyst Health Sustain,* 1:1. https://doi.org/10.108 0/20964129.2018.1459868.

Mkonda, M. Y. (2020). *Climate Change Implications to High and Low Potential Zones of Tanzania.* In Environmental Issues and Sustainable Development. IntechOpen. DOI: 10.5772/intechopen.93384.

Mkonda, M.Y. (2021). *Agricultural Sustainability and Food Security in Agro-Ecological Zones of Tanzania.* In E. Lichtfouse (Ed.), *Sustainable Agriculture Reviews, 52, 309-334.* Springer. https://doi.org/10.1007/978–3–030–73245–5_9.

Molod, A., Takacs, L., Suarez, M. & Bacmeister, J. (2015). Development of the GEOS-5 Atmospheric General Circulation Model: Evolution from MERRA to MERRA2, *Geosci. Model Dev.*, 8: 1339–1356, doi:10.5194/gmd-8–1339–2015.

Mugabe, P., Kipkulei, H., Sieber, S., Mhache, E. & Lohr, K. (2024). Examining Climate Trends and Patterns and Their Implications for Agricultural Productivity in Bagamoyo District, Tanzania. *Front. Clim.* 6:1346677. doi: 10.3389/ fclim.2024.1346677.

Msilu, S., Majule, A.E. & Perfect, J. (2024). Analysis of Rainfall and Temperature Dynamics (1981 to 2021) in Semi-arid Central Tanzania. *Ghana Journal of Geography,* 16(2). http://dx.doi.org/10.4314/gjg.v16i2.9.

Muthoni, F.K., Odongo, V.O., Ochieng, J., Mugalavai, E.M., Mourice, S.K., Zeledon, I.H., Mwila, M. & Bekunda, M. (2018). Long-term Spatial-temporal Trends and Variability of Rainfall Over Eastern and Southern Africa. *Theoretical and Applied Climatology*, 137: 1882–1882. https://doi.org/10.1007/s00704–018–2712–1.

Mwambumba, M., Yadav, B., Rwiza, M., Larbi, I., Dotse, S., Limantol, M., Sarpong, S. and Kwawuvi, D. (2022). Rainfall and Temperature Changes Under Different Climate Scenarios at the Watersheds Surrounding the Ngorongoro Conservation Area in Tanzania. *Environmental Challenges*, 7(2022): 100446. https://doi.org/ 10.1016/j.envc.2022.100446.

National Adaptation Programme of Action (NAPA). (2007). *United Republic of Tanzania National Adaptation Program of Action.* Vice President's Office (VOP): Division of Environment: Dar es Salaam.

Omoyo, N.N., Wakhungu, J. & Oteng`I, S. (2015). Effects of Climate Variability on Maize Yield in the Arid and Semi-Arid Lands of Lower Eastern Kenya. *Agriculture and Food Security,* 4 (8). DOI 10.1186/s40066–015–0028–2.

Panda, A. & Sahu, N. (2019). Trend Analysis of Seasonal Rainfall and Temperature Pattern in Kalahandi, Bolangir and Koraput Districts of Odisha, India. *Atmospheric Science Letters*, 20(10). https://doi.org/10.1002/asl.932.

Rowhani, P., Lobell, D. B., Linderman, M. & Ramankutty. (2010). Climate Variability and Crop Production in Tanzania. *Agricultural and Forest Meteorology*, 151(2011): 449–460. doi:10.1016/j.agrformet.2010.12.002.

Siddharam, Kambale, J.B., Basavaraja, D., Nemichandrappa, M. & Dandekar, A.T. (2020). Assessment of Long Term Spatio-temporal Variability and Standardized Anomaly Index of Rainfall of Northeastern Region, Karnataka, India. *Climate Change*, 6(21): 1–11.

United Republic of Tanzania (URT). (2021). *National Sample Census of Agriculture 2019/20*: National Report.

Yanda, P., Liwenga, E., Mabhuye, E., Kateka, A. & Maganga, F. (2015). Tanzania: Country Situation Assessment, Working paper.

Zampieri, M., Ceglar, A., Dentener, F. & Toreti A. (2017). Wheat Yield Loss Attributable To Heat Waves, Drought and Water Excess at the Global, National and Subnational Scales. *Environ Res Lett*, 12: 1–11. https:// doi.org/10.1088/1748–9326/aa723b.