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The Impacts of Current Climate Variability on Coffee Production in the Northern and Southern Highlands of Tanzania

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Abstract

Coffee is the most traded commodity in the world. In Tanzania, Coffee is the second largest traditional commodity. However, several climate change studies have predicted that coffee production will be reduced as a result of climate change. Therefore, the study aimed to assess the impact of current climate change on Tanzania's Arabica coffee production and determine the most significant climatic variables, which influence coffee production in the respective regions. Global interpolated climatic database (Worldclim dataset) and official historical coffee production data from Tanzania Coffee Board for a period of 40 years (1970-2018) were used. Climatic parameters and coffee production were compared through descriptive statistics, correlation analysis, and multiple regressions. The Mann-Kendall method was used to detect significant trends in climatic data. The minimum temperature has been increasing at a higher rate than the maximum temperature in the Northern and Southern Highlands zones. A 1 °C increase in minimum temperature (T_{min}) during short rains and annual mean temperature (T_{mean}) resulted in a significant coffee production decrease (-6,041 and -4,450 tons) in Kilimanjaro and Arusha regions respectively. In the Southern Highlands zone coffee production positively correlated with temperature. A significant reduction in coffee production due to a decline in long rains was also observed in the Kilimanjaro region. The warming and drought trends are likely to continue with significant implications on coffee production and this, calls for the development of suitable adaptation strategies to sustain production. Such strategies may include, re-adapting the coffee agronomic practices to climate change, improving water and nutrient use efficiency in coffee trees, and developing genetically improved coffee cultivars that will tolerate the impact of climate change.

Keywords: *Coffea arabica*, drought, temperature, East Africa

1. Introduction

Coffee is the second most important item in the world, in terms of trade, next to oil (Jayakumar et al., 2017). The crop is produced in about 80 tropical countries (National Coffee Association (NCA), 2017), with an estimated 125 million people depending on it for their livelihoods in Latin America, Africa, and Asia (Osario, 2002). In Tanzania, coffee is the second-largest traditional commodity (Tanzania Coffee Board (TCB), 2021). It contributes 24% to the annual agricultural foreign exchange earnings and significantly contributes to tax revenue. The industry directly supports an estimated 2.4 million individuals in Tanzania (TCB, 2017) and several million more in similar agro-ecological conditions in neighboring Uganda, Kenya, Rwanda, and Burundi. Approximately 70% of the coffee produced in Tanzania belongs to the species *Coffea arabica* and 30% is *Coffea canephora*; the former is produced mainly in Ruvuma, Mbeya, Songwe, Arusha, and Kilimanjaro regions, and the latter in the Kagera region (TCB, 2021). For the case of *Coffea arabica*, the commercial varieties grown in Tanzania are Bourbon (N39) and Kents (K 423). The main production constraints for the commercial varieties are, however, high susceptibility to major coffee diseases like Coffee Berry Disease (CBD) and Coffee Leaf Rust (CLR). Due to the above problems, Tanzania Coffee Research Institute (TaCRI) has developed coffee hybrid varieties that are resistant to CLR and CBD (TaCRI, 2011).

The production and productivity of both species largely depend on the climate to attain high yields and quality (Killeen & Harper, 2016). Arabica coffee grows well in an area with an optimum temperature range of 18-21 °C (Magrach & Ghazoul, 2015) and an optimum annual rainfall range of 1200-1800 mm (Alegre, 1959). Due to its narrow climatic requirements coffee crop, is expected to be the most affected by the increasing temperatures (Malyadri, 2016) and reduced rainfall (Wagner et al., 2021). According to IPCC (2014), the global climate has changed over the past century and is projected to continue changing throughout this century. Furthermore, global circulation models (GCMs) all point to higher mean temperatures and changes in precipitation regimes. Africa is one of the continent's most severely affected by climate change due to its geographical characteristics of having the majority of land lying across the warming tropics (Filho & Rao, 2014). In this continent, the temperature is projected to rise faster than the rest of the world, which could exceed 2 °C by mid- 21st century and 4 °C by the end of the 21st century (Niang et al., 2014). East Africa will be increasingly affected by climate change in the coming decades, with temperatures already increasing and predicted to rise further (Adhikari et al., 2015; Craparo et al., 2015). Countries within East Africa are also experiencing reduced rainfall due to the shortening of long rains (Wainwright et al., 2019). As a part of the tropical region, Tanzania has experienced sustained warming particularly since 1970 (IPCC, 2007). Based on downscaled climate models, Tanzania is projected to experience a mean temperature increase of 2-4 °C by 2100 (IPCC, 2007; Läderach et al., 2012).

The increase in temperatures and precipitation shortages has negative impacts on coffee flowering and fruiting. However, global studies indicate that precipitation factors such as annual and seasonal precipitation are of less importance compared with temperatures in determining suitability (Ovalle-Rivera et al., 2015; Rao, 2016). In Tanzania, research has shown that coffee yields are especially affected by elevated night temperatures (Craparo et al., 2015) and droughts due to a shift in seasons (Wagner et al., 2021). It is predicted that in Tanzania every 1 °C increase in minimum temperature will result in annual yield losses of nearly 140 kg ha^{-1} (Craparo et al., 2015). The severity of pests and disease spread is likely to increase with advancing climate change, a significant challenge in coffee production (Jaramillo et al., 2011). According to Ovalle-Rivera et al. (2015), generally, the influence of weather variations on coffee-producing countries is predicted to be negative. This will jeopardize coffee quantity and quality hence endangering coffee producers who occupy 90 percent of the population and their livelihoods mostly rely on coffee.

Climate change projections also suggest that some areas would lose suitability for growing coffee while others would gain from temperature increases and possibly in rainfall (Ovalle-Rivera et al., 2015). According to Killeen and Harper (2016), there would be a change in coffee production areas because suitable areas will become too warm or prone to periodic drought. Furthermore, Ovalle-Rivera et al. (2015) in their study documented future global loss of Arabica coffee area by 2050 as follows: Mesoamerica (30%), South America (16-20%), and Africa (9-25%). They have also reported that Mexico from Mesoamerica and Brazil from South America would lose about 29% of its suitable Arabica coffee growing areas respectively. Pacific countries such as India and Vietnam will also experience a loss of suitability areas and be highly affected. Davis et al. (2012) proposed a substantial reduction in the area suitable for Indigenous Arabica varieties in Eastern Africa. Land suitable for Arabica coffee in East Africa is predicted to shift from 400-2000 m above sea level to 800-2500 m above sea level. Moreover, there would be a modest change in the suitability of the areas in Ethiopia, Kenya, Rwanda, and Burundi that currently grow Arabica coffee. Tanzania and Uganda would lose suitable areas at elevations below 1400 m above sea level. For the case of the Northern Highlands of Tanzania, the optimum coffee-producing zone would need to shift upwards attitudinally by 150-200 m, to sustain coffee quality and quantity (Craparo et al., 2015). However, this pushes coffee into a higher altitudinal zone that currently hosts substantial biodiversity of (mostly protected) forest species (Hemp, 2005), thus limiting upslope coffee expansion in northern Tanzania and indeed much of the coffee regions in tropical countries.

Farmers at lower elevations will no longer be able to grow quality coffee and may have to abandon it (Läderach et al. (2017). This suggests that actors along the coffee supply chain will have to adapt to the changes that climate change will bring. According to Stafford et al. (2011), farmers can adjust by making incremental adaptations and innovations based on their experiences to deal with climate variability. Incremental adaptation occurs in a short timeframe at lower altitudes, whereas the same areas may undergo transformative adaptation in the long term. At higher altitudes incremental adaption may be needed in the long term based on two adaptation strategies to two levels of climate change (incremental adaptation for lower levels of progressive climate change and transformative adaptation for higher levels of progressive climate change). Läderach et al. (2017) has developed a two-dimensional adaptation framework in time and space for coffee production in Nicaragua.

According to the author the same principle and framework are applicable across coffee-growing regions around the world, as the patterns of decreasing exposure with higher altitudes are the same globally; only the magnitude and timeframe changes. In Vietnam, Phuong Le and Nguyen (2018), identified adaptation processes more broadly as long-term strategies and analyzes temporary coping responses to drought of coffee growers.

Generally, different studies indicate that smallholder coffee farmers have been responding to climate change impacts through a range of interventions, including agronomic practices such as planting shade trees, pruning, planting drought-tolerant varieties, and application of organic fertilizers (Kajembe et al., 2016; Wagner et al., 2018; Mbwambo et al., 2021). In the study by Pham et al. (2019), adaptation and management practices were identified by more than 70% of total studies (25 papers), of which agro forestry, either through intercropping or shading, was most common (18 papers), followed by irrigation and efficient use and management of water (12 papers), development of new cultivars that are drought and heat-stress resistant and/or pest and disease tolerant (10 papers) and diversification of cropping patterns or livelihood activities (9 papers). Other measures included the relocation of coffee plantations to more bio-climatically suitable areas (6 papers), crop insurance (3 papers), off-farm livelihoods (2 papers), and shifts from Arabica to Robusta or cocoa (2 papers). According to Mbwambo et al. (2021) the adaptation measures used by smallholders coffee farmers in the Northern and Southern Highlands of Tanzania are in the order of; use of shade tree, use of mulching, use of organic manure, planting disease resistance varieties, use of cut-off drains, use of terraces and irrigation. However, according to Craparo et al. (2015), the increase in T_{min} challenges the common notion that shade trees are always a beneficial aspect of climate change adaptation. Furthermore, responses towards adopting adaptations practices have been influenced by factors such as education level, farming experience, farm size, access to extension services, and time awareness of climate change information (Mbwambo et al., 2021).

Even though, in Tanzania, the general feeling is that the climate has been changing over the years and may be responsible for current low production and productivity (Craparo et al., 2015; Wagner et al., 2021; Mbwambo et al., 2021), this perception has largely remained anecdotal, with limited assessment covering the whole country's coffee-growing areas. Studies by Craparo et al. (2015) and Wagner et al. (2021) dealt with specific coffee-growing zones and pointed to the possible future climatic trajectories in those zones. Nevertheless, climate change studies are necessary for the formulation of climate change adaptation strategies for coffee farming in Tanzania, which does not exist yet. This study used official historical coffee production data to understand whether the general production patterns have any bearing on the historical climatic trends in major Arabica coffee growing areas in Tanzania.

2. Materials and Methods

2.1 Description of the Study Area

The study area is comprised of two major Arabica coffee growing zones. The Northern Highland zone involved the Kilimanjaro region (Hai, Moshi rural, Siha, and Rombo Districts) and Arusha Region (Arumeru, Longido, Monduli, and Karatu Districts). The Southern Highland zone included the Songwe region (Mbozi and Ileje districts), Mbeya (Mbeya and Rungwe districts), and Ruvuma (Mbinga, Songea, and Nyasa districts) (Figure 1). In these zones, Arabica coffee production is exclusively rain-fed. The Northern Highlands zone is characterized by a bimodal rainfall pattern, while the Southern Highland zone experiences a unimodal rainfall pattern.

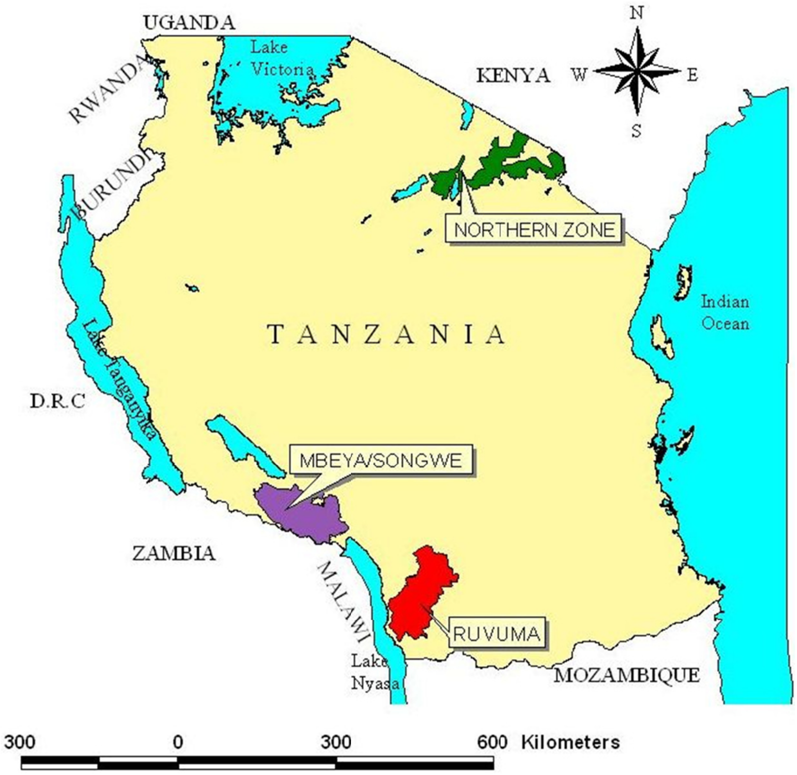


Figure 1. Map of Tanzania indicating study locations (callouts)

2.2 Data Collection

Monthly minimum temperature (T_{min}), maximum temperature (T_{max}), and precipitation for the period between 1979-2018 were collected from the global interpolated climatic database (Worldclim dataset). The Worldclim dataset was cropped using the Tanzania country boundary layer mask. Tanzania map was also masked with the boundaries from the major Arabica coffee growing areas and served into shapefiles, which were then used to clip Worldclim datasets on the Tanzania mask. The dataset is available at a spatial resolution of 2.5 minutes (equivalent to 21 km^2 at the equator). Each download is a "zip" file containing 120 GeoTiff (.tif) files, for each month of the year for 10 years (Fick & Hijmans, 2017). The observed station dataset (rainfall and temperature) were also acquired from Lyamungo and Burka Coffee estate (Northern Highland zone) and Mbimba and Mbinga (Southern Highlands Zone). Data from Lyamungo, Mbimba, and Mbinga were acquired from the offices of the Tanzania Meteorological Authority (TMA), while data from the Burka Coffee estate were acquired from a private operator. The observed station dataset was used to evaluate the performance of gridded climatic data. Coffee production (tons per region) for five regions (Ruvuma, Mbeya, Songwe, Kilimanjaro, and Arusha) for 40 years (1979-2018) was obtained from official records of the Tanzania Coffee Board.

2.3 Data Analysis

Missing values in the rainfall and temperature dataset from TMA were determined according to the "3/5" rule (WMO, 1989). The temperature data set had missing values ranging between 5 and 19%, while that of rainfall ranged between 1 and 5%. They were estimated using the multiple imputation method due to its characteristics to account for uncertainty about the imputed values. The performance of gridded datasets (Worldclim) was evaluated statistically using Mean Bias (MB). Mean Bias Error (MBE) shows bias from the mean, thus the approach to zero of this parameter indicates that the method simulates reality well and far from zero shows high deviation and inaccuracy (Hassan et al., 2020).

$$\text{Mean Bias} = 1/n \sum_{1}^{n} y_i - o_i \qquad (1)$$

Where, y and o represent observed and predicted values respectively and n is the number of targeting data used for testing. The results in Table 1 indicate that the Worldclim dataset performed well in depicting the study areas dataset.

Table 1. Comparison of observed and gridded climatic data using Mean Bias (MB)

Dataset	Northern Highlands zone		Southern Highlands zone	
	Kilimanjaro	Arusha	Mbeya and Songwe	Ruvuma
Rainfall (mm)	-0.205	2.227	0.979	2.979
T_{min}	-4.823	0.823	-1.652	1.7034
T_{max}	0.380	2.783	0.865	2.474

Note. T_{max} = Maximum temperature; T_{min} = Minimum temperature.

Descriptive statistics (frequencies and percentiles), correlation analysis, and multiple regressions were performed in STATA 13.0 (StataCorp LP, College Station, TX, USA) and SPSS 21.0 (IBM-SPSS Inc, Chicago, IL, USA) software. The rank-based nonparametric Mann-Kendall (Mann, 1945; Kendall, 1975) method was applied to the long-term climatic data to detect statistically significant trends. In this test, the null hypothesis (H_0) was that there has been no trend in rainfall and temperature over time; the alternative hypothesis (H_1) was that there has been a trend (increasing (+) or decreasing (-) over time. In the Northern Highlands zone, correlation analysis was used to examine the relationship of long rains, short rains, and annual rainfall with coffee production. T_{min} (°C), T_{max} (°C), and T_{mean} (°C), both in the long rains, short rain seasons, and annually were also correlated with coffee production. In the Southern Highlands zone the climatic parameters (rainfall, T_{min} (°C), T_{max} (°C), and T_{mean} (°C) were also correlated with coffee production in the growing season and annually. On the other hand, a multiple regression model was used to see the effect of independent variables (amount of rainfall and temperature) on the dependent variable (amount of coffee produced in tons). The model with the best statistical quality and highest adjusted R-squared was chosen. Regressors with higher p-values (smaller t-statistic values) were excluded one by one. If the exclusion of a regressor produced a positive change in the adjusted R squared value, it was left out and subsequently tried with the next regressor that had the highest p-value. Regressors with the highest p-values were excluded until the change in the adjusted R-squared was negative (Gay et al., 2006). Mbeya and Songwe were one region (Mbeya) before they split in 2015. Therefore, to have a 40-year coffee production data, these two regions (Mbeya and Songwe) were combined. The regression equation is represented as;

$$Y = B_o + B_1X_1 + B_2X_2 + \dots + B_nX_n \tag{2}$$

Where, Y = Dependent variable (Coffee (t)); B_o = Intercept; $B_{(1-n)}$ = Coefficients of regression line; $X_{(1-n)}$ Predictor variables (rainfall and temperature parameters).

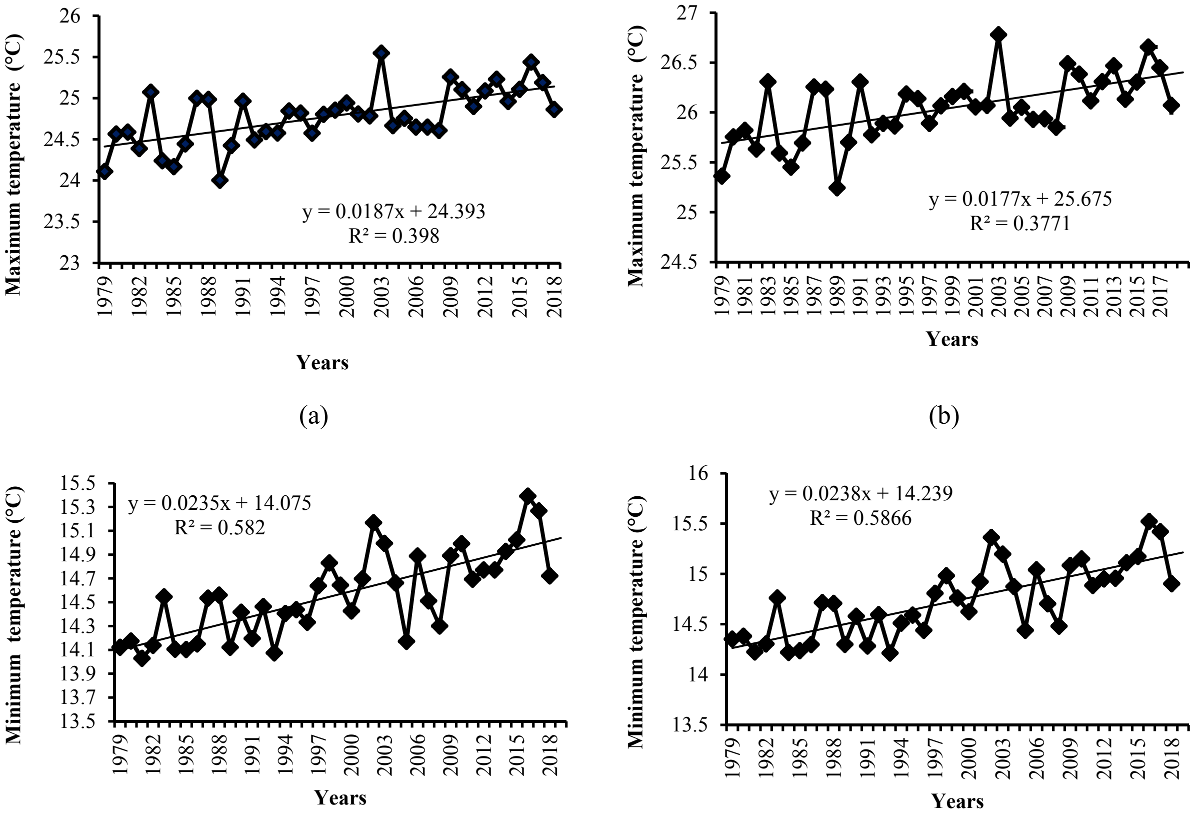
3. Results

3.1 Monthly, Seasonal and Annual Analyses of Temperature and Rainfall

3.1.1 Northern Highlands Zone

The average annual total rainfall for the past 40 years (1979-2018) in Kilimanjaro and Arusha regions was found to be 1435.77 mm and 733.4 mm respectively (Appendix A). In the Kilimanjaro region, the highest amount of rainfall was 2131.5 mm observed in 2006, which is higher than the long-term average of 1979-2018 by 695.73 mm. Nevertheless, out of 40 years, 22 years were below the average annual rainfall. In the Arusha region, the highest amount of rainfall was 1033 mm in 1988 which is higher than the long average of 1979-2018 by 299.6 mm. In addition, in the Arusha region, 23 years were below the average annual rainfall. T_{mean} in Kilimanjaro and Arusha regions were observed to be 19.67 °C and 20.3 °C respectively (Appendix A).

Over the 40 years, T_{max} in the Northern Highlands zone has been increasing significantly ($P < 0.001$) at the rate of 0.018 °C year^{-1} and 0.017 °C year^{-1} in Kilimanjaro and Arusha regions respectively (Figures 2a and 2b). Arusha and Kilimanjaro regions have also experienced a significant ($P < 0.01$) increase of T_{max} during the long rain season at the rate of 0.01 °C season^{-1}. The short rains season, on the other hand, has been characterized by significant ($P < 0.01$) increases of T_{max} (0.02 °C season^{-1}) in Kilimanjaro and Arusha regions. The study has also revealed a significant ($P < 0.01$) increase in T_{min} at the rate of 0.023 °C year^{-1} in the Kilimanjaro and Arusha regions (Figures 2c and 2d). Furthermore, a significant ($P < 0.01$) increase in T_{min} during the short rain season was observed at Kilimanjaro and Arusha regions at the rate of 0.03 °C season^{-1}. Significant ($P < 0.01$) increase in T_{min} during the long rain season was also observed in the Arusha region only at the rate of 0.02 °C season^{-1}. The results from the Mann-Kendall trend analysis for the Kilimanjaro region indicate statistically significant positive trends ($P < 0.05$) for T_{max} in all months while for T_{min} only two months (March and April) showed insignificant trends ($P > 0.05$). In the Arusha region, significant positive trends for T_{max} were observed in most of the months except for February. For the case of T_{min}, only two months (April and November) did not show positive significant trends. Mean warming for the Arabica growing regions of Northern Tanzania over the 40 years (1979-2018) has been + 0.819 °C (Kilimanjaro) and + 0.702 °C (Arusha).

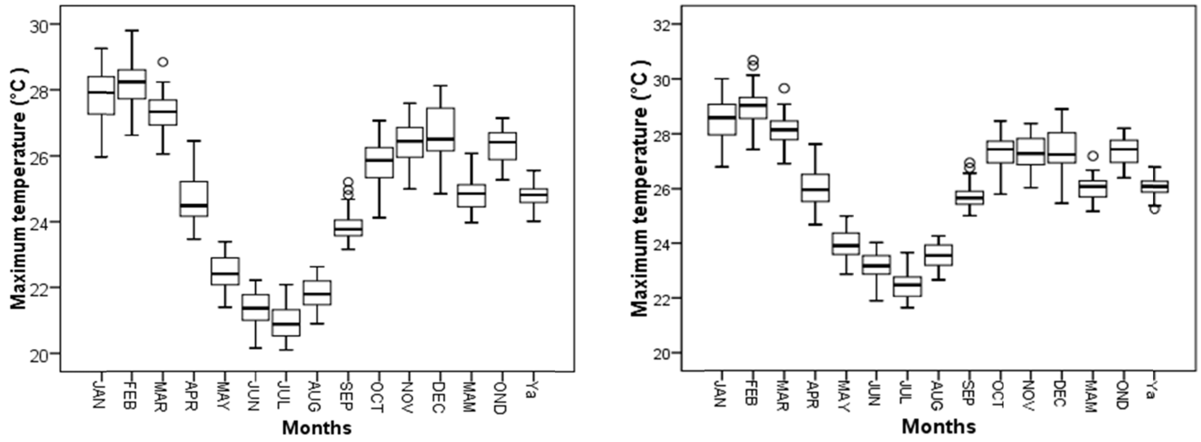


(a) (b)

(c) (d)

Figure 2. Annual temperature trends (°C) for (a) Tmax in Kilimanjaro (b) Tmax in Arusha region; (c) Tmin in Kilimanjaro and (d) Tmin in Arusha regions from 1979-2018

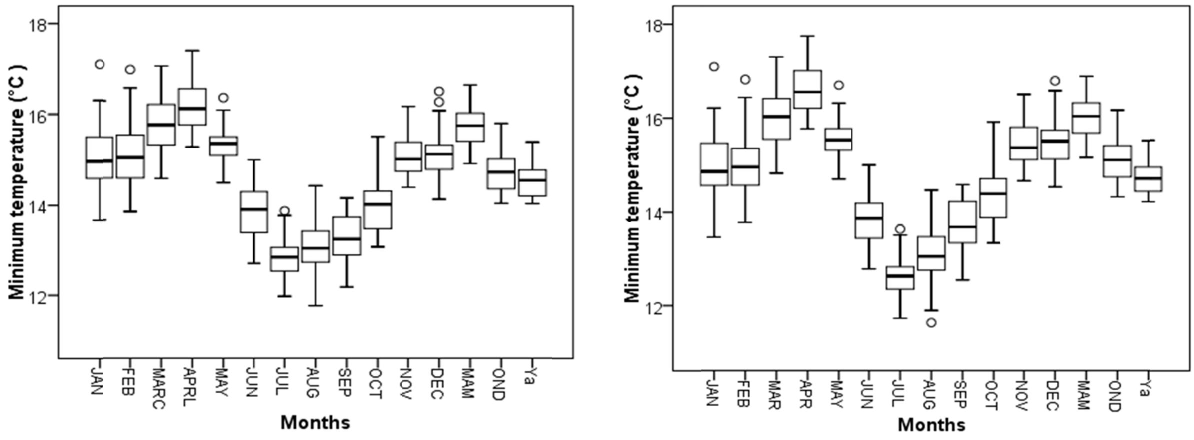
The box plots below (Figures 3 and 4) indicate that the highest T_{max} was observed in the Arusha region (30.67 °C) followed by the Kilimanjaro region (30 °C) in February. Furthermore, the months of June, July, and August had the lowest T_{max} (20-22 °C). The highest T_{min} was observed in April in Kilimanjaro (17.4 °C) and Arusha (17.7 °C) regions while the lowest T_{min} was in July and August (12 °C). The long rains season in Kilimanjaro and Arusha regions has experienced lower T_{max} (26.5 °C) as compared to T_{max} in the short rains (27.5 °C).



(a) (b)

Figure 3. Box and Whisker plot of maximum temperature (°C) in (a) Kilimanjaro (b) Arusha region from 1979-2018

Note. MAM = long rain season made up of March, April, and May; OND = Short rain season made up of October, November, and December; Ya = Annual.



(a) (b)

Figure 4. Box and Whisker plot of minimum temperature (°C) in (a) Kilimanjaro (b) Arusha region from 1979 to 2018

Note. MAM = long rain season made up of March, April, and May; OND = Short rain season made up of October, November, and December; Ya = Annually.

Annual rainfall has been decreasing at a higher rate in the Kilimanjaro region (-7.77 mm year^{-1}) than in the Arusha region (-2.14 mm year^{-1}) (Figures 5a and 5b). However, annual rainfall decrease in the Northern Highlands zone, were not statistically significant ($P > 0.05$). Nevertheless, a significant decrease in rainfall ($P < 0.05$) has been observed during the long rain season in the Kilimanjaro region (14.65 mm season^{-1}) and the Arusha region (-3.29 mm season^{-1}). Short rains, on the other hand, have been increasing significantly ($P < 0.05$) in the Arusha region only at the rate of 2.2 mm season^{-1}.

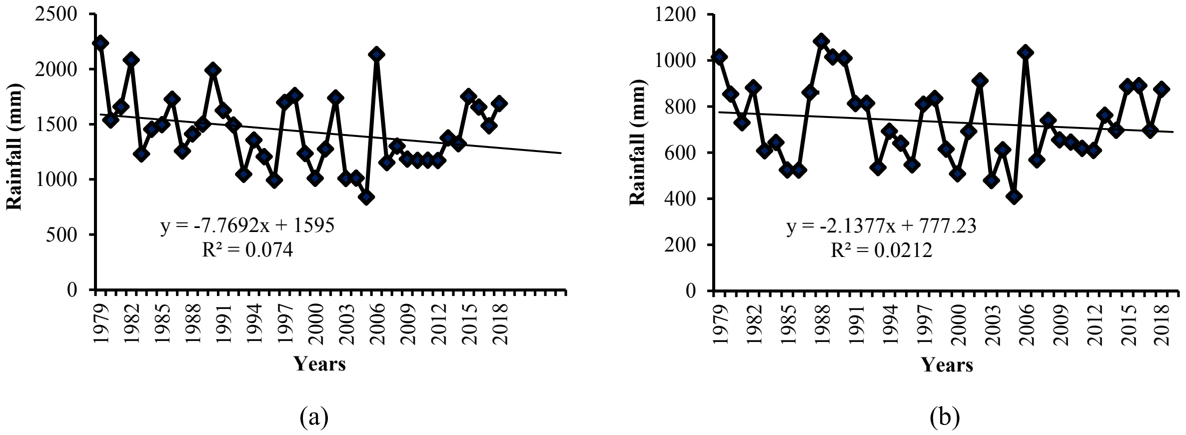
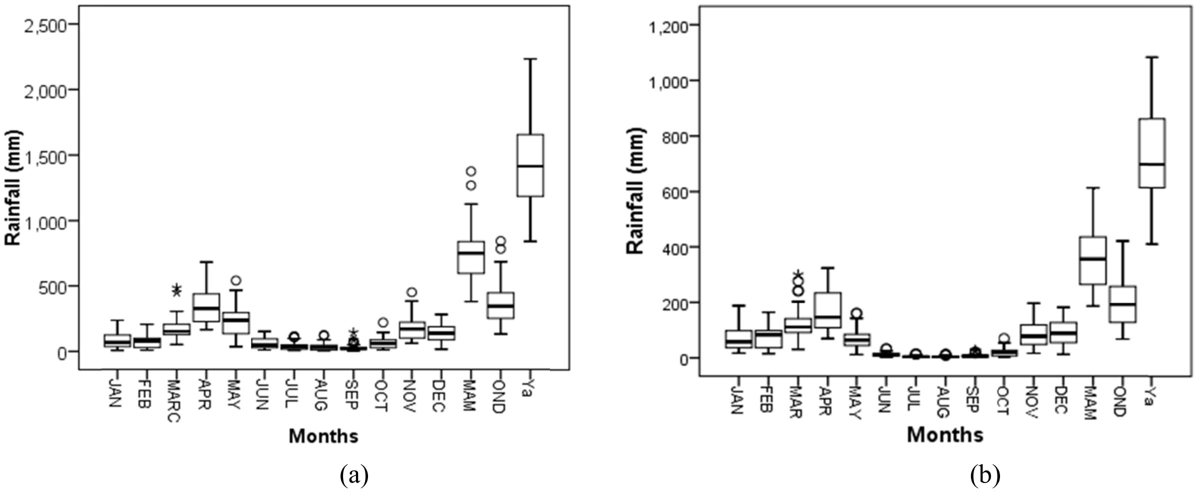


Figure 5. Yearly total rainfall (mm) in (a) Kilimanjaro (b) Arusha regions from 1979-2018

Kilimanjaro region received a higher amount of rainfall in April and May while the Arusha region received a higher amount of rainfall in March and April (Figures 6a and 6b). On the other hand, of all the months it was the month of April that had less rainfall variability in Kilimanjaro (Coefficient of variation (CV) = 39.53%) and Arusha (CV = 44.34%) regions. In the Kilimanjaro region, the monthly highest CV was in the order of September (94.9%) > August (87.6%) > July (81.2%) > October (73%) > January (72%). The highest CVs in Arusha were in the order of September (87.8%) > August (85.3%) > October (78%) > July (76%) > June (70%). On the other hand, short rains in Kilimanjaro and Arusha regions had higher CV (44.11% and 45.76%) as compared to long rains (29.36% and 31.29%) respectively. When the CV for the annual rainfall was calculated, it was the least in the Kilimanjaro region (23.26%) followed by the Arusha region (23.39%) (Figure 7).



(a) (b)

Figure 6. Box and Whisker plot of monthly rainfall (mm) in (a) Kilimanjaro (b) Arusha region from 1979 to 2018

Note. MAM = long rain season made up of March, April, and May; OND = Short rain season made up of October, November, and December; Ya = Annually.

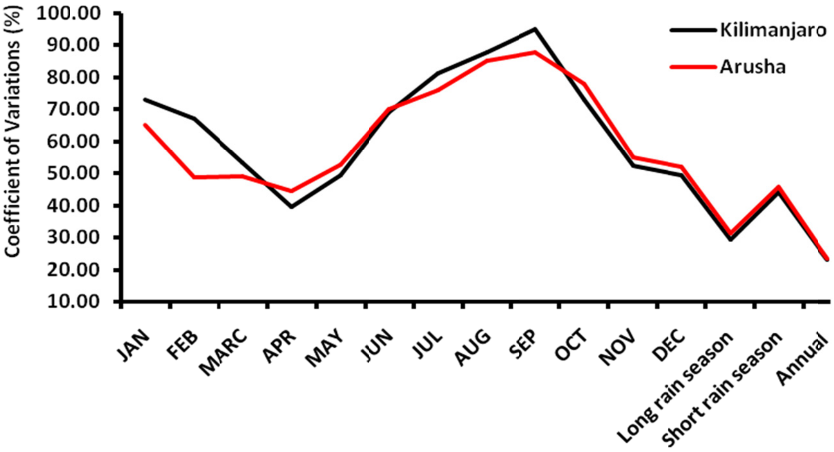
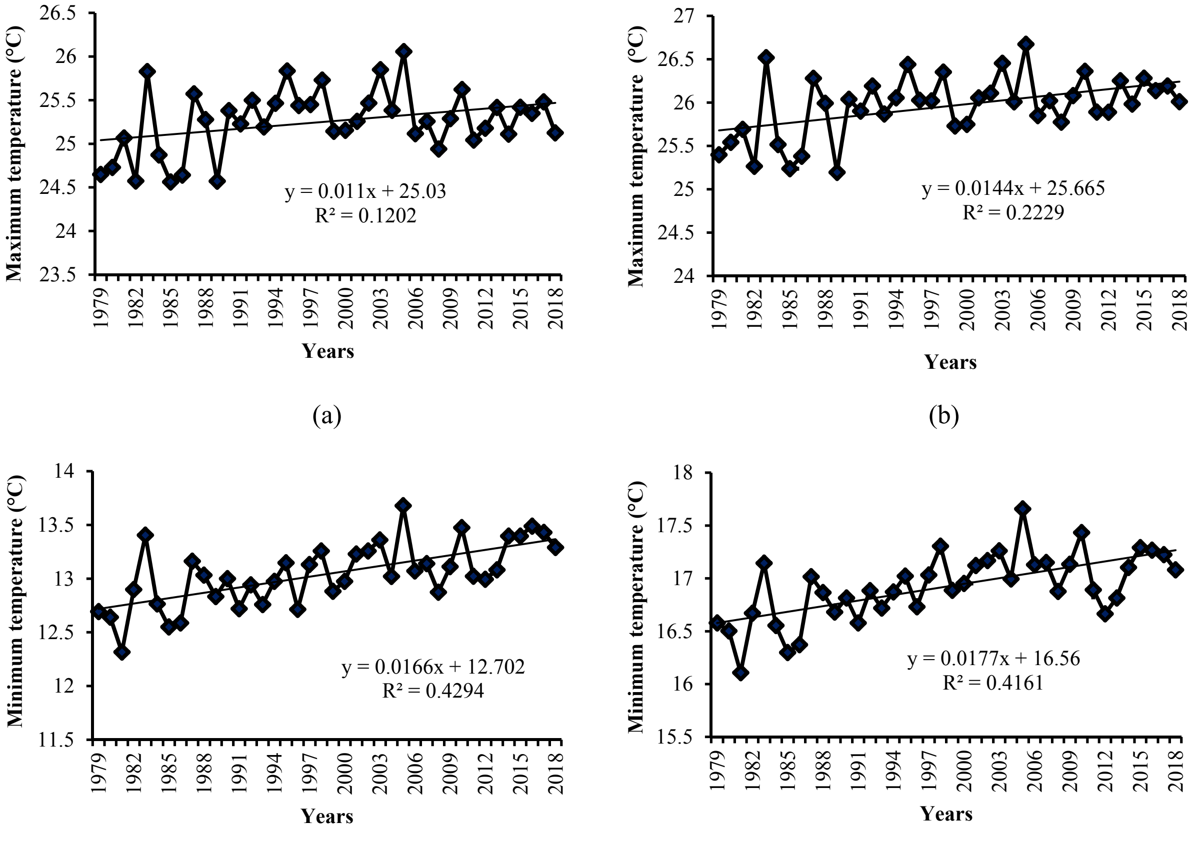


Figure 7. Coefficient of variation (CV) for the monthly rainfall in the 40 years (1979-2018) in the Northern Highlands zone

3.1.2 Southern Highlands Zone

The average annual total rainfall for the past 40 years (1979-2018) in Mbeya-Songwe and Ruvuma regions was found to be 1306.09 mm and 1203.74 mm respectively (Appendix A). In the Mbeya-Songwe region, the highest amount of rainfall was 2036.51 mm observed in 1979, which is higher than the long-term average of 1979-2018 by 730.42 mm. On the other hand in the Ruvuma region, the highest amount of rainfall was 1588.55 mm in 1979 which is higher than the long average of 1979-2018 by 384.81 mm. Furthermore, more than half of the years in the Southern Highlands zone received rainfall that was below the average annual rainfall. The T_{mean} in the Mbeya-Songwe and Ruvuma regions was 19.44 °C and 21.44 °C respectively (Appendix A).

T_{max} has been increasing significantly ($P < 0.01$) at a rate of 0.011 °C and 0.014 °C year^{-1} in Mbeya-Songwe and Ruvuma regions respectively (Figure 8a and 8b). Moreover, T_{max} significantly ($P < 0.01$) increased at the rate of 0.005 °C per rainy season in the Mbeya and Songwe regions. Ruvuma region has also experienced a significant increase ($P > 0.01$) of T_{max} at the rate of 0.008 °C season^{-1}. Significant ($P < 0.01$) increases in T_{min} at the rate of 0.016 °C and 0.017 °C year^{-1} have also been observed in Mbeya-Songwe and Ruvuma regions respectively (Figures 8c and 8d). However, T_{min} increased insignificantly ($P > 0.05$) during the growing season in the Mbeya, Songwe, and Ruvuma regions. Mean warming for the Arabica growing regions in the Southern Highlands zone over the last 40-year period (1979-2018) has been +0.507 °C (Mbeya and Songwe) and +0.624 °C (Ruvuma).

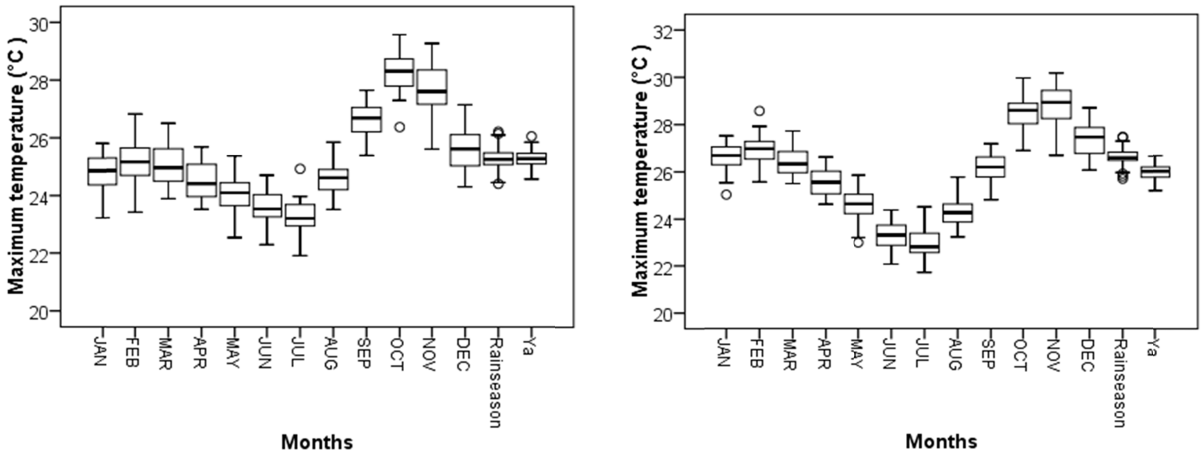


(a) (b)

(c) (d)

Figure 8. Annual temperature trend (°C) for (a) T_{max} in Songwe-Mbeya regions (b) T_{max} in Ruvuma regions (c) T_{min} in Songwe-Mbeya regions and (d) T_{min} in Ruvuma regions; from 1979-2018

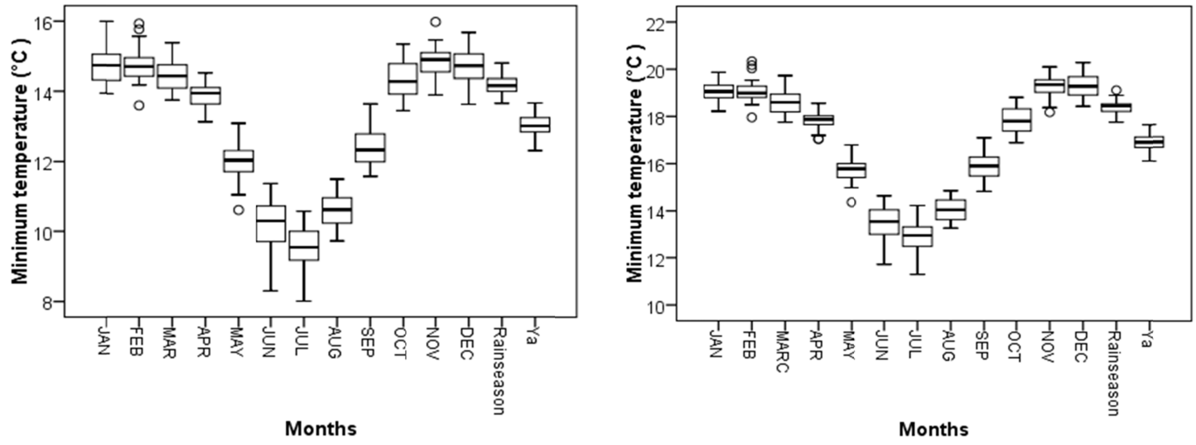
Seven months in the Mbeya and Songwe regions have shown significant positive trends in T_{max} ($P < 0.05$). However, only the months of August and October exhibited significant positive trends in T_{min} ($P < 0.05$). In the Ruvuma region, seven months exhibited a significant upward trend in T_{max} and T_{min}. In this zone, October and November have been the hottest months in terms of T_{max} (Figures 9a and 9b). The months of June and July on the other hand had the lowest T_{max} up to 22 °C. The highest T_{min} (17 °C) was also observed in January and February in Mbeya and Songwe regions while in the Ruvuma region the T_{min} of above 20 °C was also observed in the same months. On the other hand, Mbeya and Songwe regions had the lowest T_{min} (8 °C) in July followed by the Ruvuma region (11 °C) in the same month (Figures 10a and 10b).



(a) (b)

Figure 9. Box and Whisker plot of maximum temperature (°C) in (a) Mbeya and Songwe regions (b) Ruvuma region from 1979 to 2018

Note. Ya = Annual.

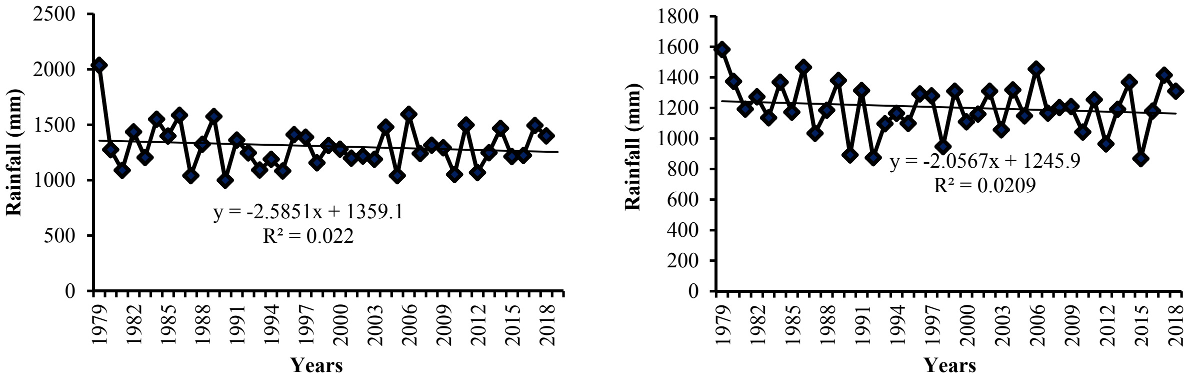


(a) (b)

Figure 10. Box and Whisker plot of minimum temperature (°C) in (a) Mbeya and Songwe regions (b) Ruvuma region from 1979 to 2018

Note. Ya = Annual.

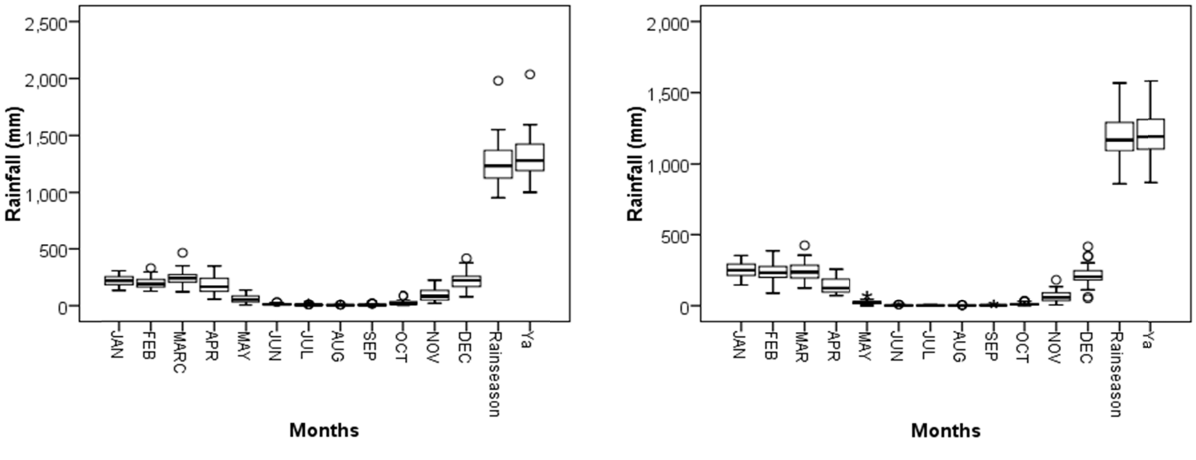
The findings from this study also revealed an insignificant decrease of rainfall by 2.59 and 2.06 mm year^{-1} in the Mbeya-Songwe and Ruvuma regions respectively ($P > 0.05$) (Figures 11 a and 11b). Significant negative trends ($P < 0.05$) in the monthly rainfall were detected in March and July in the Ruvuma region. An insignificant decrease of rainfall ($P > 0.05$) has also been observed during the rainy season at Mbeya and Songwe regions (-2.54 mm season^{-1}) and Ruvuma region (-2.14 mm season^{-1}).



(a) (b)

Figure 11. Yearly total rainfall (mm) in (a) Songwe-Mbeya (b) Ruvuma regions from 1979-2018

Figures 12a and 12b indicate that Mbeya-Songwe and Ruvuma regions received a higher amount of rainfall during December, February, and March. On the other hand, the amount of rainfall received in April and May in the Mbeya-Songwe regions was higher as compared to the amount of rain received in the Ruvuma region. Furthermore, January had less rainfall variability both in Mbeya-Songwe regions (CV = 19.4%) and Ruvuma region (CV = 21%) (Figure 13). Five months with higher CV in Mbeya and Songwe regions were in the order of October (CV = 79.6%) > September (CV = 73.2%) > May (CV = 62.7%) > November (CV = 60.2%) > June (CV = 57.9%). In Ruvuma region the five months with higher CV were in the order of June (CV = 95.3%) > July (CV = 87.1%) > October (74.4%) > September (73.5%) > May (64.7%). The findings also revealed higher rainfall variability in the rain season in Mbeya (CV = 15.6%) than in the Ruvuma region (CV = 13.8%). When the CV for the annual rainfall was calculated, it was highest in Mbeya and Songwe regions (15.8%) followed by the Ruvuma region (13.8%).



(a) (b)

Figure 12. Box and Whisker plot of monthly rainfall (mm) in (a) Mbeya and Songwe regions (b) Ruvuma region from 1979 to 2018 (indicate in terms of months the rainy season)

Note. Ya = Annually.

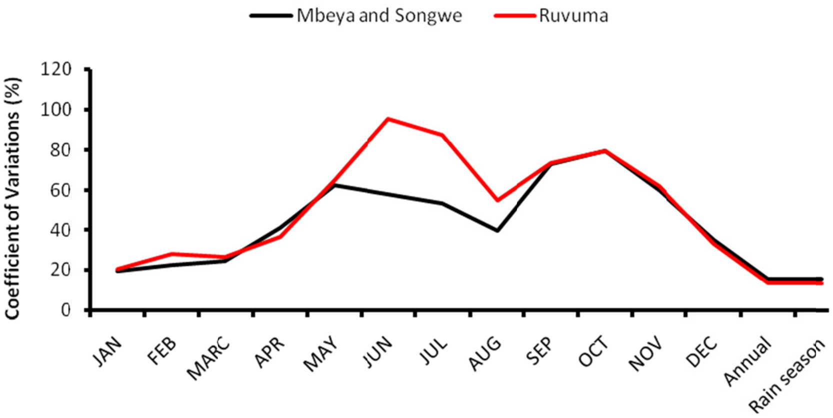
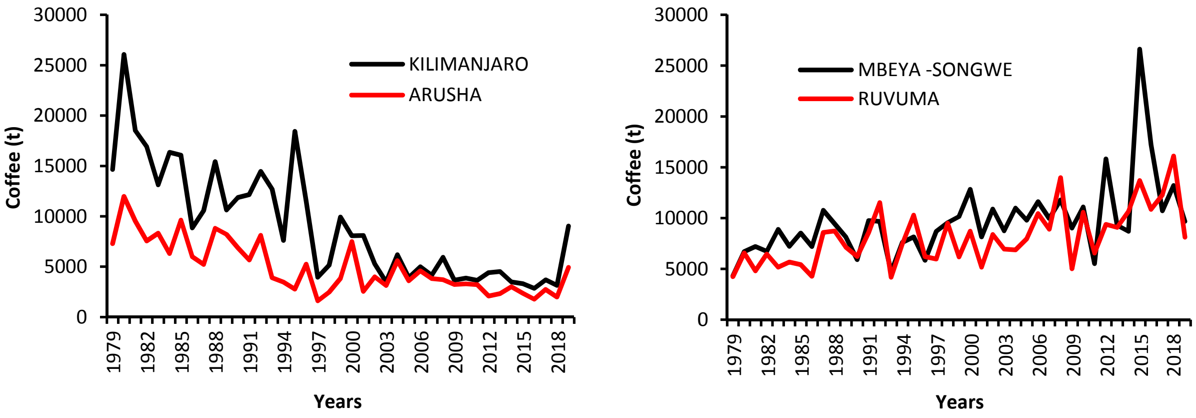


Figure 13. Coefficient of variation for the monthly rainfall in the 40 years (1979-2018) in the Southern Highlands zone

3.2 *Coffee Production Records*

Based on the 40 years (1979 to 2018), coffee production data from Tanzania Coffee Board (TCB), a decreasing trend has been observed in the Northern Highlands zone (Figure 14a and Table 2) while the Southern Highlands zone has shown an increasing trend (Figure 14b and Table 2). The maximum coffee production in the Songwe region was 15,826 t in the year 2012 while in Ruvuma the maximum production was 16,104 t, in 2017 (Figure 14b). On the other hand, maximum coffee production in Kilimanjaro and Arusha region was 27,077 to and 11,974 t respectively in 1980 and since then the production has fallen (Figure 14a).



(a) (b)

Figure 14. (a) Northern and (b) Southern Highlands zones yearly coffee production trends 1979 to 2018

Source: Tanzania Coffee Board (TCB).

Total percentage change calculated from the trends of coffee production in the Northern zone indicates that over the 40 years coffee production has been declining at about 94.52% and 82.37% in Kilimanjaro and Arusha regions, respectively. On the other hand, coffee production in Ruvuma and Mbeya-Songwe regions has been increasing at about 55% and 21% respectively (Table 2).

Table 2. Analysis of coffee production trend from 1979 to 2018 in the Northern and Southern Highlands Zones

	Northern Highlands		Southern Highlands	
	Kilimanjaro	Arusha	Mbeya/Songwe	Ruvuma
Annual Production (t)	9040.01	4933.63	8683.23	8113.26
Minimum production (t)	2847	421.5	2022	2022
Maximum production (t)	27077	11974	15826	16104
Trend (tons/ year)	-415.4	-177.2	54.21	158.9
Total change calculated from the trend (t/40 years)	16185	6910.8	6197.1	2114.19
Total change calculated from the trend (%)	94.52	82.37	55	21

Note. Total change is the difference between the trend line value of the first and last year.

3.3 Relationship Between Climatic Data and Coffee Production

3.3.1 Correlation Analysis

The relationship between the amounts of coffee (t) produced and the amount of rainfall (mm) was positively significant ($P < 0.05$) during the long rain season at Kilimanjaro and Arusha region. Results also showed a significant negative relationship ($P < 0.05$) between the amount of coffee produced and average T_{min} long and short rain season and average T_{min} in Kilimanjaro and Arusha regions. Furthermore, the analysis indicates a significant negative relationship ($P < 0.05$) between the annual average T_{max} and the amount of coffee produced in both regions. Average T_{max} had also a significant relationship ($P < 0.05$) with coffee production during short rain in the Kilimanjaro region and during long rain in the Arusha region. Pearson correlation analysis also resulted in the negative correlation between Annual mean temperature and coffee production in Arusha and Kilimanjaro regions (Table 3).

Table 3. Pearson correlation values for the amount of coffee (t) and climatic data in the Northern Highlands zone

		Coffee production in Kilimanjaro	Coffee production in Arusha
T_{min} short rain	Pearson correlation	-0.694**	-0.558**
T_{min} long rain		-0.472**	-0.427**
Average T_{min}		-0.700**	-0.628**
T_{max} short rain		-0.321**	-0.440**
Average T_{max}		-0.518****	-0.553**
T_{mean}		-0.654**	-0.708**
Long rains		0.347*	0.320*

Note. *: Significant at 0.05 level; **: Significant at 0.01 level; T_{min} = Minimum temperature, T_{max} = Maximum temperature, T_{mean} = Average temperature.

Table 4 indicated a significant positive relationship ($P < 0.05$) between average T_{min} rain season, annual average T_{min}, T_{mean}, and the amount of coffee produced at Songwe-Mbeya and Ruvuma regions. The analysis also shows the positive relationship between the annual averages T_{max} and the amount of coffee produced in the Ruvuma region. No significant correlation between coffee production and rainfall ($P > 0.05$).

Table 4. Pearson correlation values for the amount of coffee (t) and climatic data in the Southern Highlands zone

		Coffee production in Mbeya -Songwe	Coffee production in Ruvuma
T_{min} rain season	Pearson correlation	0.316*	0.334*
Average T_{min}		0.457**	0.464**
Average T_{max}		0.216	0.360*
T_{mean}		0.351*	0.434**
Annual rainfall		-0.228	-0.231
Rain season		-0.216	-0.235

Note. T_{min} = Minimum temperature, T_{max} = Maximum temperature, T_{mean} = Average temperature. *: Significant at 0.05 level; **: Significant at 0.01 level.

3.3.2 Regression Analysis

(1) Northern Highlands Zone

In the Kilimanjaro region, three independent variables were significantly predictive of coffee production according to ANOVA statistics [F (3, 37) = 21.04, *P* < 0.01]. The model's percent of explaining the variance in coffee production in the Kilimanjaro region was found to be 63% ($R^2 = 0.63$). In the regression analysis results, the absolute value of Beta indicates the order of importance of the independent variables. The variable with the highest beta value is the relatively most important independent variable. Therefore, analyzing the contributions made by the independent variables in the model, it was found that T_{min} short rain season made the biggest contribution with the value of (Beta = 0.473). It was followed by the average Tmin and long rains respectively (Table 5).

Table 5. The relationship between coffee production (t) and temperature range (°C) in the Kilimanjaro region

	Un standardized Coefficients		Stand. Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	162367.523	24283.425		6.686	0.000
Long rains	6.794	2.716	0.263	2.502	0.017
T_{min} short rain	-6040.778	1853.899	-0.473	-3.258	0.002
Average T_{min}	-4761.400	2356.505	-0.302	-2.021	0.051

Note. B = Un standardized Beta; t = Statistical T; T_{min}: Minimum temperature.

Based on the regression analysis results, the regression equation is represented as,

$$\text{Coffee (t) in Kilimanjaro region} = 162367.5 + 6.79\ (\text{long rains}) - 6040.78\ (T_{min}\ \text{short rain}) - 4761.4\ (\text{Average}\ T_{min}) \quad (3)$$

The regression relationship between climatic data and coffee production in the Arusha region was also highly significant and the model a good fit for the data [F (5, 32) = 9.454, *P* < 0.01]. Five independent variables were found to predict coffee production significantly in the region. Analyzing the relationship it was found that the model's degree of explaining the variance in the dependent variable was 58% ($R^2 = 0.57.5$). The contribution of the independent variables to the model was in the order of T_{mean} > average T_{min} > T_{min} long rains > T_{max} short rain > long rains. Although the contribution made by T_{mean} was the only one significant, the contribution made by other independent variables entered the model due to the property of regression analysis, and they were found to make the smallest contributions to the model (Table 6).

Table 6. The relationship between coffee production (tons) and temperature range (°C) in the Arusha region

	Un standardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	124095.221	27647.361		4.489	0.000
T_{min} long rain	2326.180	1320.826	.374	1.761	0.087
Average T_{min}	-3160.907	2082.941	-.440	-1.518	0.138
T_{max} short rain	-757.535	581.811	-.159	-1.302	0.201
T_{mean}	-4450.107	2035.176	-.486	-2.187	0.036
Long rains	3.090	2.807	.136	1.101	0.279

Note. B = Un standardized Beta; T = Statistical T; T_{min}: Minimum temperature; T_{max} = Maximum temperature; T_{mean} = Average temperature.

Based on the regression analysis results, the regression equation is represented as,

$$\text{Coffee (t) in Arusha region} = 124095.221 + 2326.180\ (T_{min}\ \text{long rain}) - 3160.907\ (\text{Average}\ _{Tmin}) - 757.535\ (T_{max}\ \text{short rain}) - 4450.107\ (T_{mean}) + 3.090\ (\text{long rains}) \quad (4)$$

(2) Southern Highlands Zone

The regression relationship for Mbeya-Songwe regions was highly significant and a good fit of the data [F (2, 38) = 6.05, *P* < 0.01]. The regression model showed that 24% ($R^2 = 0.241$) of the changes in the coffee production in the Mbeya-Songwe regions are explained by the combined effect of T_{min} rain season and average T_{min}, Among the two independent variables, average T_{min} made the biggest contribution to the model as compared to T_{min} during the rainy season (Table 7).

Table 7. The relationship between coffee production (t) and temperature range (°C) in Mbeya and Songwe regions

	Un standardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	-47650.738	28393.560		-1.678	0.102
T_{min} rain season	-5324.462	4177.780	-.377	-1.274	0.210
Average T_{min}	10191.939	3825.841	.789	2.664	0.011

Note. B = Un standardized Beta; t = Statistical T; T_{min}: Minimum temperature.

Based on the regression analysis results, the regression equation is represented as;

$$\text{Coffee (t) in Mbeya-Songwe regions} = \\ -47650.738 - 5324.462\ (T_{min}\ \text{rain season}) - 10191.939\ (\text{Average } T_{min}) \quad (5)$$

The regression model for Ruvuma region was also highly significant and a good fit for the data [F (2, 38) = 7.52, $P < 0.01$]. The model showed that 28% ($R^2 = 0.284$) of the changes in the coffee production are explained by the combined effect of T_{min} rain season and average T_{min}. As observed in the Mbeya-Songwe regions, the average T_{min} resulted in the biggest contribution as compared to T_{min} long rains in Ruvuma region (Table 8).

Table 8. The relationship between coffee production (tons) and temperature range (°C) in the Ruvuma region

	Un standardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	-33352.587	25688.607		-1.298	0.202
T_{min} rain season	-6891.895	3627.193	-.700	-1.900	0.065
Average T_{min}	9949.119	3289.968	1.113	3.024	0.004

Note. B = Un standardized Beta; t = Statistical T; T_{min}: Minimum temperature.

Based on the regression analysis results, the regression equation is represented as,

$$\text{Coffee (t) in Ruvuma region} = \\ -33352.587 - 6891.895\ (T_{min}\ \text{rain season}) - 9949.119\ (\text{Average } T_{min}) \quad (6)$$

4. Discussion

4.1 Climate Variability

The decline in long rain in the Northern Highlands zone of Tanzania is characterized by the shortening of the rainy season which is caused by earlier cessation as the result of a decline of rainfall in April and May. Other studies also show a decline in the March-to-May seasonal rainfall over eastern Africa (Rowell and Booth 2015; Maidment et al., 2015; Wainwright et al., 2019), however, with drying in March, April, and May (Niang et al., 2014). Contrary to our findings, the study by Wagner et al. (2021) indicated a significant increase in the amount of rainfall during May and a reduction of rainfall in April around Mt. Kilimanjaro over the last 19 years (2001-2019). On the other hand, according to Wainwright et al. (2019), the observed decline in Eastern African long rains is characterized by shortening of the rainy season (with late-onset and earlier cessation) rather than by a decrease in the peak daily rainfall. Different observations observed in different studies can be explained by large regional and local variability in precipitation (Dai, 2018; Macleod & Caminade, 2019), and therefore changes observed in other parts of Tanzania or East Africa do not necessarily contest with what is experienced in Arusha and Kilimanjaro regions.

The suggested link to the decrease in rainfall is the rapid warming of the Indian Ocean which causes an increase in convection and precipitation over the tropical Indian Ocean, contributing to the decrease in rainfall over the continental land surface (Lemma & Megersa, 2021). Over the last three decades rainfall has decreased by around 15% over eastern Africa, in the main growing season (March and May/June) (Williams et al., 2012). On the other hand, the increase in short rain observed in the Arusha region (Northern Highlands zone) could be the result of extreme Indian Ocean Dipole (IOD) events which affect the short rainy season from October to December (Shelleph Limbu et al., 2019). With increasing global mean temperature, the frequency of extreme positive IOD is expected to significantly increase (Cai et al., 2018). The increase in short rains in the Arusha region (Northern Highlands zone) conform with projections from different General Circulation Models (GCMs) which are broadly indicating increases in annual rainfall in Ethiopia (Niang et al., 2014), but these increases are largely due to increased rainfall in the October-December period in southern Ethiopia (McSweeney et al., 2010).

Moreover, despite the prediction that annual precipitation will increase in East Africa (Wainwright et al., 2019; Adhikari et al., 2015), our findings indicate a decrease (not significant) in annual rainfall in the coffee-growing areas of the Northern Highlands zone for the four past decades (1979-2018). The decrease of long rains in the Northern Highlands zone has a direct link with the decline in annual rainfall over the area. According to Liebmann et al. (2014) “long rains” season [March-May (MAM)] is a manifestation of a long-term decline in rainfall totals. In addition, there has been no such downward trend in the “short rains” [October-December (OND)], but this season has continued to exhibit large year-to-year variability, which at times has exacerbated the impact of the long rains decline. This explains why coffee farmers in the Northern Highlands zone perceived drought increase (Mbwambo et al., 2021) despite the short rain increase. This is where successful adaptation measures are critical (Wagner et al., 2019). Furthermore, coffee-growing farmers, in the Southern Highlands zone are also confronted with reduced rainfall which occurs during the growing season and annually. As in Craparo et al. (2015), the decrease in rainfall in the Southern Highlands zone was not statistically significant. Moreover, the study revealed that half of the study period has been experiencing low rainfall (rainfall below long-term annual average). However, even though there has been low rainfall in the coffee-growing area, irrigation has been used at a low scale. The study conducted by Mbwambo et al., 2021 found that over 40 years (1979-2018), only about 17% of coffee farmers in the Northern and 5% in the Southern Highlands zone used irrigation practices in their coffee fields. Other adaptation practices used by coffee farmers in the Northern Highlands zone were in the order of shade trees (96%) > Mulching (94%) > cut-off drains (28%) and Terraces (14%). In the southern Highlands zone, adaptation practices were in the order of shade trees (70%) > Mulching 70%) > Terraces (46%) and cut-off drains (37%) (Mbwambo et al., 2021).

The study revealed further that, there have been increasing trends in monthly, seasonal, and annual temperature in the two zones with T_{min} increasing at a higher rate than T_{max}. These findings are in agreement with those from the Northern part of Tanzania (Craparo et al., 2015), Ethiopia (Mekasha et al., 2014), Kenya (Omondi et al., 2014), and Uganda (Nsubuga et al., 2014) which reported that mean warming is primarily driven by substantial increases in the daily minima composition compared with daily maxima. According to Niang et al. (2014), this is an indicator of continued warming. Additionally, according to the observed results, the T_{mean} in the Northern and Southern Highlands zone of Tanzania seems to have reached the upper limit of the mean temperature bracket (18-21 °C) suitable for coffee cultivation (Alègre, 1959).

4.2 Effect of Climate Change on Coffee Production

The decline of coffee production in the Northern Highlands zone is linked to the decrease in long rains and the increase of T_{min}. Generally, both, long and short rains are very important in the reproductive phase of the coffee plant. On one hand, the short rains in October trigger flowering in coffee plants after the dry spell period (Jassogne et al., 2013), and on the other hand, long rainy season (March to May) if delayed and inadequate will negatively affect the expansion stage, during which rainfall is required to sustain berry development. Normally, in the Northern Highlands zone coffee crop enters the reproductive phase during the short rain season (October-December) and so the crop becomes more sensitive to temperature during this period. Generally, high night temperatures increase the rate of respiration so the assimilates which could be used for growth and yield are reduced (Nagarajan et al., 2010; Bapuji Rao et al., 2014). Drought and high temperatures during this period in the Kilimanjaro region will cause fruit abortions, increased bean defects, reduced berry growth, and acceleration of ripening, leading to a reduction in coffee yield and quality (Craparo et al., 2020; Wagner et al., 2021). The study of Craparo et al. (2015), reported similar findings that yield in the Northern Highlands zone is decreasing as the results of the increase in T_{min}, however, in their study, there was no relationship between yield decrease and decrease in long rains as observed in this study.

Additionally, although T_{mean} affected coffee production in the Arusha region, it was T_{min} that accelerated the increase of T_{mean} Therefore, the decrease in coffee production observed in the Northern Highlands zone which is experiencing reduced rainfall is aggravated by higher T_{min} in the area. The inclusion of more shade trees might help to reduce heat stress (Kajembe et al., 2016), however, conservation of heat during the night challenges the common notion that shade trees are always a beneficial aspect of climate change adaptation (Craparo et al., 2015). Other strategies may include, re-adapting the coffee agronomic practices to climate change, use of technologies that will improve water and nutrient use efficiency in coffee trees, and developing genetically improved coffee varieties that will tolerate the impact of climate change.

On the other hand, coffee production in the Southern Highlands zone positively correlated with temperature even though T_{mean} is already out of the optimum range. The observed positive correlation could be explained by the fact that there was no significant decrease in rainfall during the growing season (November to May) and annually. Moreover, the Southern Highlands zone is also characterized by very low T_{min} and T_{max} in June, July, and August. The low temperature in these months can reduce the negative impact of high temperature during the growing seasons. However, from all climatic parameters, it was only the average T_{min} that resulted in a significant increase in coffee production in the Southern Highlands zone. Nevertheless, the findings from this study revealed further that, if T_{min} during the growing season will continue to increase in the Southern Highlands zone, coffee production will also be affected, as the inclusion of this parameter improved the model in both regions of the Southern Highlands zone. Generally, the findings from this study conform to the perceptions of farmers in the Northern and Southern Highlands zone reported by Mbwambo et al. (2021), that reduced rainfall and/or increase in temperature have resulted in coffee production decline. Other non-climatic factors may have contributed to the increase in coffee production in the Southern Highlands zone as discussed below.

4.3 Other Factors Affecting Production

Despite the positive relationship between low coffee productions with weather-related problems, the sharp decrease in coffee production noted in the Northern Highlands zone is likely to have been magnified by factors other than climate change per se. Bureau for Agricultural Consultancy and Advisory Service (BACAS) (2005) noted that the nationalization of estate farms in the Northern Highlands zone contributed to the decline in coffee production in the zone, which used to produce 50% of total coffee in 1972/73 due to the dismal performance under primary cooperatives. Another possible factor is the farmers' disincentive to invest in coffee due to the historic price slump of 1980-2002. The slump, from an average of 5 USD lb^{-1} in 1980 to 0.77 USD lb^{-1} in 2002 (Drip Beans, 2020) caused a lot of problems to those who depend on coffee for their livelihoods, including farmers. They could barely meet the cost of production and as a result, production fell steadily, with the area under coffee also declining.

Another area for consideration is land holding per small holder family. BACAS (2005) reported that households owning less than 2 ha in the Northern zone were almost 70% of the sampled households while in the Southern zone they were only 32%, implying that land is scarcer in the northern zone, particularly so in Kilimanjaro. Mbwambo et al. (2021) also reported that the majority of the smallholder coffee farmers from the Northern Highlands zone possess farm sizes between 0.5 and 1ha, while those from the Southern Highlands zone had farm sizes between 1 and 2 ha. Due to land scarcity, coffee farmers may opt to intercrop coffee with other crops and this can reduce the number of coffee trees per area, hence low production. Also, the rate of planting new trees in the Northern Highlands zone is reported to be less than that of the Southern Highlands zone, because the aging coffee trees are owned by the elderly who are naturally risk-averse. These indicate that may be the increase in coffee production observed in the Southern Highlands zone, apart from being favored by climatic factors, has been further boosted by the replanting of new coffee trees and adoption of new, high-yielding varieties.

5. Conclusion and Recommendations

There has been a decline in long rains and a rise in T_{min} which ultimately affected coffee production in the Northern Highlands zone. The Southern Highlands zone, on the other hand, has not yet suffered from the impact of climate change. Nevertheless, T_{min} is increasing at a higher rate in the area and it may affect the production of coffee shortly. Therefore, without sufficient adaptation measures, coffee production in the Northern Highlands zone will be reduced and the famous brand of Kilimanjaro Coffee will disappear from the Market. This calls for public and private sectors to invest in climate change adaptation strategies that will better sustain this important industry and the livelihoods of millions of smallholder farmers who depend on it. The emphasize should also be given by the Arabica coffee growing region which may have already suffered yield losses due to climate change. Such strategies may include, re-adapting the coffee agronomic practices to climate change, improving water and nutrient use efficiency in coffee trees, and developing genetically improved coffee cultivars that will tolerate the impact of climate change.

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Reference

Adhikari, U., Nejadhashemi, A. P., & Woznicki, S. A. (2015). Climate change and eastern Africa: A review of the impact on major crops. *Food and Energy Security, 4*(2), 110-132. https://doi.org/10.1002/fes3.61

Alègre, C. (1959). Climates et caféiers d'Arabie. *Agron. Trop., 14*, 23-58.

BACAS (Bureau for Agricultural Consultancy and Advisory Service). (2005). *Final report on Coffee Base-line*. BACAS, Sokoine University of Agriculture for Tanzania Coffee Research Institute.

Bapuji Rao, B., Santhibhushan Chowdary, P., Sandeep, V. M., Rao, V. U. M., & Venkateswarlu, B. (2014). Rising minimum temperature trends over India in recent decades: Implications for agricultural production. *Global and Planetary Change, 117*, 1-8. https://doi.org/10.1016/j.gloplacha.2014.03.001

Cai, W., Wang, G., Gan, B., Wu, L., Santoso, A., Lin, X., … Yamagata, T. (2018). Stabilised frequency of extreme positive Indian Ocean Dipole under 1.5 °C warming. *Nat. Commun., 9*, 1419. https://doi.org/10.1038/s41467-018-03789-6

Craparo, A. C. W., Van Asten, P. J. A., Läderach, P., Jassogne, L. T. P., & Grab, S. W. (2015). Coffea arabica yields decline in Tanzania due to climate change: Global implications. *Agricultural and Forest Meteorology, 207*, 1-10. https://doi.org/10.1016/j.agrformet.2015.03.005

Craparo, A. C. W., van Asten, P. J. A., Läderach, P., Jassogne, L. T. P., & Grab, S. W. (2020). Warm nights drive Coffea arabica ripening in Tanzania. *Int. J. Biometeorol., 65*, 181-192. https://doi.org/10.1007/s00484-020-02016-6

Dai, A., Zhao, T., & Chen, J. (2018). Climate change and drought: A precipitation and evaporation perspective. *Curr. Clim. Chang. Rep., 4*, 301-312. https://doi.org/10.1007/s40641-018-0101-6

Drip Beans. (2020). *How coffee prices have changed over the years, 1975-2020*. Retrieved from http://www.dripbeans.com/coffee-price-history

Fick, S. E., & Hijmans R. J. (2017). WorldClim 2: New 1 km spatial resolution climate surfaces for global land areas. *International Journal of Climatology, 37*(12), 4302-4315. https://doi.org/10.1002/joc.5086

Filho, W. L., & Rao, K. P. C. (2014). *Adapting African Agriculture to Climate Change Transforming Rural Livelihoods*. Springer, Berlin. https://doi.org/10.1007/978-3319-13000-2

Gay, L., Mills, G., & Airasian, P. (2006). *Educational research competencies for analysis and applications* (8th ed.). New Jersey, Pearson.

Hassan, I., Kalin, R. M., White, C. J., & Aladejana, J. A. (2020). Evaluation of Daily Gridded Meteorological Datasets over the Niger Delta Region of Nigeria and Implication to Water Resources Management. *Atmospheric and Climate Sciences, 10*, 21-39. https://doi.org/10.4236/acs.2020.101002

Hemp, A. (2005). Climate change-driven forest fires marginalize the impact of ice cap wasting on Kilimanjaro. *Global Change Biol., 11*, 1013-1023. https://doi.org/10.1111/j.1365-2486.2005.00968.x

IPCC (Intergovernmental Panel on Climate Change). (2007). The physical science basis. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, … H. L. Miller (Eds.), *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom/New York, NY.

IPCC (Intergovernmental Panel on Climate Change). (2014). *Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects* (p. 1132). Cambridge University Press: Cambridge, UK.

Jaramillo, J., Muchugu, E., Vega, F. E., Davis, A., Borgemeister, C., & Chabi-Olaye, A. (2011). Some like it hot: The influence and implications of climate change on coffee berry borer (hypothenemus hampei) and coffee production in East Africa. *PLoS ONE, 6*, e24528. https://doi.org/10.1371/journal.pone.0024528

Jassogne, L., Läderach, P., & Van Asten, P. (2013). *The impact of climate change on coffee in Uganda: Lessons from a case study in the Rwenzori Mountains*. Oxfam GB, Oxford, UK.

Jayakumar, M., Rajavel, M., Surendran, U., Gopinath, G., & Ramamoorthy, K. (2017). Impact of climate variability on coffee yield in India—with a micro-level case study using long-term coffee yield data of humid tropical Kerala. *Clim Chang, 145*, 335-349. https://doi.org/10.1007/s10584-017-2101-2

Kajembe, J., Lupala, I., Kajembe, G., Wilson, M., & Faraji, N. (2016). The role of selected agro forestry trees in temperature adaptation on *Coffea arabica*: A case study of the Moshi district, Tanzania. *Climate change and multi-dimensional sustainability in African agriculture* (pp. 553-566). Springer, Cham. https://doi.org/

10.1007/978-3-319-41238-2_29

Killeen, T. J., & Harper, G. (2016). *Coffee in the 21st century: Will climate change and increased demand lead to new deforestation?* Conservation International.

Läderach, P., Eitzinger, A., Ovalle, O., & Carmona Rahn, S. E. (2012). *Brief: Future Climate Scenarios for Tanzania's Arabica Coffee Growing Areas*. Centro Internacional de Agricultura Tropical, Cali, Colombia.

Laderach, P., Ramirez-Villegas, J., Navarro-Racines, C., Zelaya, C., Martinez-Valle, A., & Jarvis, A. (2017). Climate change adaptation of coffee production in space and time. *Clim Chang, 141*, 47-62. https://doi.org/10.1007/s10584-016-1788-9

Lemma, D. T., & Megersa, H. G. (2021). Impact of Climate Change on East African Coffee Production and Its Mitigation. *World Journal of Agricultural Sciences, 17*(2), 81-89.

Liebmann, B., Bladé, I., Kiladis, G. N., Carvalho, L. M. V., Senay, G. B., Allured, D., … Funk, C. (.2012). Seasonality of African precipitation from 1996 to 2009. *J. Climate, 25*, 4304-4322, https://doi.org/10.1175/JCLI-D-11-00157.1

Macleod, D., & Caminade, C. (2019). The moderate impact of the 2015 El Niño over East Africa and its representation in seasonal reforecasts. *J. Clim., 32*, 7989-8001. https://doi.org/10.1175/JCLI-D-19-0201.1

Magrach, A., & Ghazoul, J. (2015). Climate and Pest-Driven Geographic Shifts in Global Coffee Production: Implications for Forest Cover, Biodiversity and Carbon Storage. *PLoS ONE, 10*(7), e0133071. https://doi.org/10.1371/journal.pone.0133071

Maidment, R. I., Allan, R. P., & Black, E. (2015). Recent observed and simulated changes in precipitation over Africa. *Geophys. Res. Lett., 42*, 8155-8164. https://doi.org/10.1002/2015GL065765

Malyadri, P. (2016). Status of coffee plantation in India: A high time for innovation and sustainability towards make in India. *VSRD Int J Bus Manag Res, 6*(2), 47-50.

Mbwambo, S. G., Mourice, S. K., & Tarimo, A. J. P. (2021). Climate Change Perceptions by Smallholder Coffee Farmers in the Northern and Southern Highlands of Tanzania. *Climate, 9*, 90. https://doi.org/10.3390/cli9060090

McSweeney, C., Lizcano, G, New, M., & Lu, X. (2010). The UNDP Climate Change Country Profiles: Improving the accessibility of observed and projected climate information for studies of climate change in developing countries. *Bulletin of the American Meteorological Society, 91*(2), 157-166. https://doi.org/10.1175/2009BAMS2826.1

Mekasha, A., Tesfaye, K., & Duncan, A. J. (2014). Trends in daily observed temperature and precipitation extremes over three Ethiopian eco-environments. *International Journal of Climatology*, *34*(6), 1990-1999. https://doi.org/10.1002/joc.3816

Nagarajan, R., Rajmohan, N., Mahendran, U., & Senthamilkumar, S. (2010). Evaluation of groundwater quality and its suitability for drinking and agricultural use in Thanjavur city, Tamil Nadu, India. *Environmental Monitoring and Assessment, 171*(1-4), 289-308. https://doi.org/10.1007/s10661-009-1279-9

NCA (National Coffee Association). (2017). *Coffee around the world.*

New, M., Hewitson, B., Stephenson, D. B., Tsiga, A., Kruger, A., Manhique, A., … Lajoie, R. (2006). Evidence of trends in daily climate extremes over southern and West Africa. *J. Geophys. Res., 111*, 1-11. https://doi.org/10.1029/2005JD006289

Niang, I., Ruppel, O. C., Abdrabo, M. A., Essel, A., Lennard, C., & Padgham, J. (2014). Africa. In V. R. Barros, C. B. Field, D, J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, … L. L. White (Eds.), *Climate change 2014: Impacts, adaptation, and vulnerability. Part B: regional Aspects* (pp. 1199-1265). Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, Cambridge, United Kingdom and New York, NY.

Nsubuga, F. W., Olwoch, J. M., & Rautenbach, H. (2014). Variability properties of daily and monthly observed near-surface temperatures in Uganda: 1960-2008. *Int.J. Climatol., 34*, 303-314. https://doi.org/10.1002/joc.3686

Omondi, P. A., Awange, J. L., Forootan, E., Ogallo, L. A., Barakiza, R., Girmaw, G. B., … Komutunga, E. (2014). Changes in temperature and precipitation extremes over the Greater Horn of Africa region from 1961 to 2010. *International Journal of Climatology, 34*(4), 1262-1277. https://doi.org/10.1002/joc.3763

Osorio, N. (2002). *The global coffee crisis: A threat to sustainable development*. London: International Coffee Organization.

Otte, I., Detsch, F., Mwangomo, E., Hemp, A., Appelhans, T., & Nauss, T. (2017). Multidecadal trends and interannual variability of rainfall as observed from five lowland stations at Mt. Kilimanjaro, Tanzania. *J. Hydrometeorol., 18*, 349-361. https://doi.org/10.1175/JHM-D-16-0062.1

Ovalle-Rivera, O., Läderach, P., Bunn, C., Obersteiner, M., & Schroth, G. (2015). Projected shifts in Coffea arabica suitability among major global producing regions due to climate change. *PLoS One, 10*(4), e0124155. https://doi.org/10.1371/journal.pone.0124155

Pham, Y., Reardon-Smith, K., Mushtaq, S., & Cockfield, G. (2019). The impact of climate change and variability on coffee production: A systematic review. *Climatic Change, 156*(4), 609-630. https://doi.org/10.1007/s10584-019-02538-y

Phuong Le, N., & Nguyen, M. D. (2018). Drought Adaptation and Coping Strategies among Coffee Farmers in the Central Highlands of Vietnam. *Preprints, 2018*, 2018120337. https://doi.org/10.20944/preprints201812.0337.v1

Rao, G. (2016). Weather extremes and plantation crops the tropics. *Mausam, 67*(1), 251-258. https://doi.org/10.54302/mausam.v67i1.1189

Rowell, P. D., & Booth, B. B. (2015). Benreconciling past and future rainfall trends over East Africa. *J. Clim., 28*, 9768-9788. https://doi.org/10.1175/JCLI-D-15-0140.1

Shelleph Limbu, P. T., & Guirong, T. (2019). Relationship between the October-December rainfall in Tanzania and the Walker circulation cell over the Indian Ocean. *Meteorol. Z., 28*, 453-469. https://doi.org/10.1127/metz/2019/0939

Stafford, S. M., Lisa, H., Alex, H., & Clive, H. (2011). Rethinking adaptation for a 4 °C world. *Phil. Trans. R. Soc. A., 369*(1934), 196-216. http://doi.org/10.1098/rsta.2010.0277

TaCRI (Tanzania Coffee Research Institute). (2011). *Agricultural Practices of Arabica. Coffee Productivity and Quality Improvement Programme* (p. 78). Tanzania Coffee Research Institute, Moshi.

Tavares, P. D., Giarolla, A., Chou, S. C., Silva, A. J. D., & Lyra, A. D. (2018). Climate change impact on the potential yield of Arabica coffee in Southeast Brazil. *Reg Environ Chang, 18*, 873-883.https://doi.org/10.1007/s10113-017-1236-z

TCB (Tanzanian Coffee Board). (2017). *Tanzanian Coffee Industry Development Strategy* (p. 53). Tanzanian Coffee Board: Dar es Salaam, Tanzania.

TCB (Tanzanian Coffee Board). (2021). *Tanzanian Coffee Industry Development Strategy* (p. 47). Tanzanian Coffee Board: Dar es Salaam, Tanzania.

Wagner, S., Jassogne, L., Price, E., Jones, M., & Preziosi, R. (2021). Impact of climate change on the production of Coffea arabica at Mt. Kilimanjaro, Tanzania. *Agriculture (Switzerland), 11*(1), 1-15. https://doi.org/10.3390/agriculture11010053

Wainwright, C. M., Marsham, J. H., Keane, R. J., Rowell, D. P., Finney, D. L., Black, E., & Allan, R. P. (2019). 'Eastern African Paradox' rainfall decline due to shorter not less intense Long Rains. *Npj Climate and Atmospheric Science, 2*(1), 1-9. https://doi.org/10.1038/s41612-019-0091-7

Williams, A. P., Funk., C., Michaelsen, J., Rauscher, S. A., Robertson, I., Wils, T. H. G., … Loader, N. J. (2012). Recent summer precipitation trends in the Greater Horn of Africa and the emerging role of Indian Ocean sea surface temperature. *Climate Dynamics, 39*, 2307-2328. https://doi.org/10.1007/s00382-011-1222-y

WMO (WorldMeteorological Organization). (1989). *Calculation of Monthly and Annual 30-Year Standard Normals* (WMO/TD-No. 341). WMO: Geneva, Switzerland.

Appendix A

Summary of seasonal and annual rainfall and temperature statistics for study regions

		Regions			
		Kilimanjaro	Arusha	Mbeya and Songwe	Ruvuma
Rainfall (mm)	Mean	1435.77	733.4	1306.09	1203.74
	STD	333.93	171.55	203.79	166.2
Temperature (°C)	Mean	19.67	20.3	19.44	21.44
	STD	0.329	0.285	0.301	0.319
	T_{max}	24.78	26.04	25.25	26.62
	STD	0.346	0.442	0.442	0.414
	T_{min}	14.56	14.73	13.04	16.00
	STD	0.36	0.362	0.292	0.32

Note. STD = Standard deviation, T_{min} = Minimum temperature, T_{max} = Maximum temperature.

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