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Spatio-temporal Trends and Change Detection of Surface Air Temperature in Tanzania: October to April Season.

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Abstract

The paper examined the spatio-temporal variability and trends of minimum temperature (T-min), mean (T-mean), and maximum temperature (T-max) in Tanzania from October to April using the Climatic Research Unit Time Series version 4.06 from 1951-2021. The traditional Mann-Kendall (MK) test, modified MK, and Sen's slope test were used to determine the trend direction and magnitude of the T-mean, T-max, and T-min trends, respectively. Sequential MK, standard normal homogeneity, and Pettitt tests were used to detect abrupt changes, while the Hurst coefficient (H) assessed future trend behavior. Results show a statistically significant increasing trend of 0.14 °C per decade, 0.18 °C per decade, and 0.16 °C per decade in T-mean, T-max, and T-min, respectively, at a 95% confidence level. The H values of T-min, T-max, and T-mean are above 0.7, indicating their future increasing trends. The change points for T-mean and T-max were in the early 1990s, and for T-min in the late 1990s. After 1991, more locations showed significant trends (positive or negative) for T-max than T-mean, and T-min had no significant trend after 1998. The 1960s had the lowest T-max and the 2010s had the highest T-min. Therefore, this study provides valuable information for immediate planning and future climate monitoring in Tanzania.

Keywords: Tanzania; Surface air temperature; Trend analysis

Introduction

In the last century, within the period 1880-2012, substantial changes in global climate have been verified amid a rise in global air temperature of 0.85 °C. Based on the 5th report of the Intergovernmental Panel on Climate Change (IPCC 2014), the sharp rise in greenhouse gas emissions from the pre-industrial era to the present remains the main reason associated with global warming. Climate change can lead to economic, environmental, and social impacts such as loss of life, losses in agriculture and food insecurity (Sulser et al. 2021), an increase in the occurrence of diseases (Patz et al. 2005), and species extinction (Maclean and Wilson 2011), among others. Tanzania, like other countries, is also affected by climate change, whereby previous studies reported the country is experiencing extreme rainfall events more frequently and with more seasonality, which include a range of effects, such as floods and droughts (Luhunga and Songoro 2020, Mdemu 2021). One key step in identifying climate change is the analysis of changes in meteorological variables such as temperature.

Africa, as one of the continents with developing nations, has a number of hotspots related to climate change, where many vulnerable and impoverished communities are primarily affected by the environmental and physical effects of the phenomenon (Ogallo 2009, Niang 2014). Africa's climate continued to warm, according to a World Meteorological Organization report (WMO 2021) on the continent. The average rate of change between

1991 and 2021 was approximately +0.3 °C/decade, compared to +0.2 °C/decade from 1961 to 1990, −0.04 °C/decade from 1931 to 1960, and +0.08 °C/decade from 1901 to 1930. Temperature changes could considerably affect the condition of natural water resources by influencing parts of the hydrological cycle, including runoff, precipitation, and evapotranspiration (Grant 2017, Ali et al. 2018, Liu et al. 2018). Therefore, a comprehensive understanding of the spatio-temporal variability, trend, and change in the maximum temperature (T-max), minimum temperature (T-min), and mean temperature (T-mean) in Tanzania is very important for implementing effective strategies to buffer and adapt to the impacts of climate change. Previous studies (e.g., Chang'a et al. 2017, Luhunga 2022, Limbu and Makula 2023) have examined the spatio-temporal trends of extreme temperatures over Tanzania. They found that the recent change in temperature extremes has been consistent with global warming. Moreover, it was reported that there was an increase in the intensity and frequency of warm nights and days and a decrease in cold nights and days in most parts of Tanzania, indicating a significant rising trend for warm temperature indices and a declining trend for cold temperature indices. Gebrechorkos et al. (2019b) found that trends for January-February (JF) and October-December (OND) T-max were non-significantly increasing in south-western and southern parts of Tanzania, while a similar trend was observed in the majority areas of Tanzania during March-May (MAM). The trend for the T-min was significantly increasing in Tanzania during June-September (JJAS) and MAM, while during OND and JF a significant increasing trend is seen. Moreover, Limbu and Makula (2023) further reported that warm nights and days are considerably linked with the Interdecadal Pacific Oscillation, the El Nino-Southern Oscillation, the Atlantic Multidecadal Oscillation, and the Tropical Northern Atlantic Index.

The major climatic seasons in the East Africa (EA) region are accurately represented by mean monthly observations, but in Tanzania, the consensus on temperature seasons is yet to be reached. Previous studies (e.g., Ongoma and Chen 2017, Gebrechorkos et al. 2019a, 2019b) used MAM, OND, JJAS, and JF as major climatic seasons for the computation of T-mean, T-max, and T-mean. It can be assumed that the generalized climatic seasons are mainly due to the annual precipitation cycle (Yang et al. 2015), but several studies (e.g., Seregina et al. 2021) showed that Tanzania exhibits a different annual precipitation cycle. It is increasingly becoming apparent that, behind the ongoing research and debate on climatic seasons, the northern and southern parts of Tanzania are witnessing different climatic conditions (Kebacho 2022). Tanzania possesses three major climatic seasons based on rainfall distribution: October to April (ONDJFMA) in the southern region (Suleiman 2018), and OND and MAM in the northern region. Even though later seasons provide reliable climatic season information, they seem less suited to provide a more holistic view of climate changes and patterns than ONDJFMA season in Tanzania (Kebacho 2022). Understanding long-term trends and change points of the T-min, T-max, and T-mean during the ONDJFMA season offers key information that might not be evident when looking at an individual season in Tanzania. Consequently, the findings would help society especially agricultural activities take place in Tanzania during ONDJFMA season (Milheiras et al. 2022, Tups and Dannenberg 2021). In the present study, we focused on identifying the trends and change points of T-min, T-max, and T-mean, respectively.

The remainder of this paper is structured as follows: The study area, data, and methods are presented in Section 2; the results and discussion are presented in Section 3; and the study's conclusions are presented in Section 4.

Study Area, Data, and Methods

Study area

The study focuses on Tanzania, (Fig. 1) during the period 1951-2021 for the T-mean, T-max, and T-min. The country is demarcated within the geographical coordinates of longitude 29°-41°E and latitude 12°S-0°.

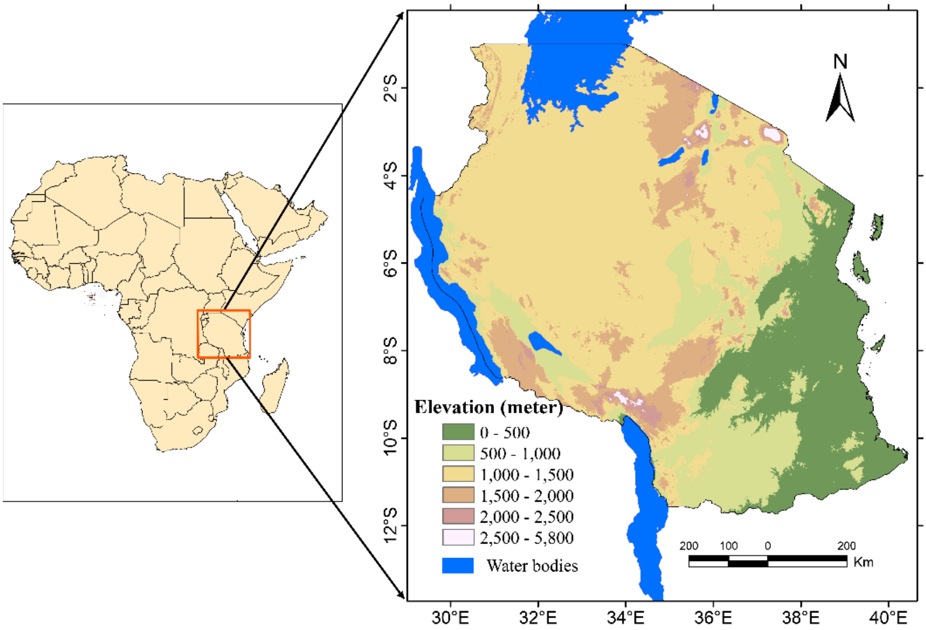

Figure 1: Location of Tanzania and its elevation in the African continent. The insert shows Tanzania's location on the African continent map.

Tanzania experiences seasonal variations in rainfall due to its equatorial position and the movement of the Inter-Tropical Convergence Zone. Coastal areas exhibit relatively lower temperature variations throughout the year in comparison to inland regions, because water heats up and cools down more slowly than land. The dry season, which usually occurs during JJAS, is distinguished by reduced humidity and milder temperatures, whereas the rainy season is marked by elevated temperatures and increased humidity (Kashaigili et al. 2014, Mwituruban 2019, Rubekie et al. 2022).

Data

The study employed an observational-based dataset of monthly T-min, T-mean, and T-max, derived from the Climatic Research Unit (CRU) Time Series (TS) version 4.06 (hereafter CRU) (https://crudata.uea.ac.uk/cru/data/hrg/, at a spatial resolution of 0.5° × 0.5° (Harris et al. 2020). The CRU dataset covers the period from 1951 to 2021. A number of temperature data products have been assessed to perform better in EA (Engdaw et al. 2022). According to Engdaw et al. (2022), the Japanese Meteorological Agency's 55-year reanalysis, CRU, Modern-Era Retrospective Analysis for Research and Applications, Version 2(MERRA2) and Medium-Range Weather Forecasts Reanalysis 5 datasets are consistent in their representation of the temperature annual cycle in EA. The current study considers CRU among the datasets to assess the robustness of T-mean, T-max, and T-min trends and variability. In addition, CRU flagged out limited coverage issues identified in MERRA2.

Methods

Analysis of trend using linear regression, traditional and modified Mann-Kendall

In the current study, the statistical analysis of linear regression was used to identify the rate of change of T-mean, T-max, and T-min in the ONDJFMA season during 1951-2021. Additionally, we examined the trend of the T-min, T-max, and T-mean during the

ONDJFMA season by using a non-parametric test, namely the traditional Mann-Kendall (MK) test (Mann 1945, Kendall 1975, Blest 2000) and Sen’s slope estimator (magnitude of change) (Sen 1968). The latter trend methods are applied to reveal the presence of a significant trend for Tanzania that might be missed by the linear regression method.

Linear regression method

The trend of T-max, T-min, and T-mean are computed by fitting a linear regression to the time series using equation 1.

$$y = mx + b \qquad (1)$$

where y is the dependent variable, m is the slope, x is the independent variable, and b is the intercept.

Traditional MK method

The traditional MK method determines whether a time series follows a positive or negative trend over time. The null hypothesis (H_o) assumes that there is no trend, while the alternative hypothesis (H_a) considers that there is a trend. The traditional MK statistic S used to estimate significance is calculated according to equation 2:

$$S = \sum_{i=1}^{m-1} \sum_{j=i+i}^{m} \operatorname{sgn}\left(x_j - x_i\right) \qquad (2)$$

where S is a statistic, x_j and x_i are sequential data values, m is the dataset size and $sgn()$ is defined by equation 3 as

$$sgn(x_j - x_i) = \{1\ 0\ -1\ if\ x_j > x_i\ if\ x_j = x_i\ if\ x_i < x_j \qquad (3)$$

The positive value of S signifies an increasing trend, while a very low negative value of S signifies a decreasing trend. The variance of S is given by equation 4 as:

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+7)}{18} \qquad (4)$$

Where n is the tied group's number taking similar value for a data group, and it is the data number in the *i*th tied group. The significance of the trend is determined by using Z value (Equation 5)

$$Z = \{\frac{S-1}{\sqrt{V(S)}}\ 0\ \frac{s-1}{\sqrt{V(S)}}\ if\ S > 0\ if\ S = 0\ if\ S > 0 \qquad (5)$$

The H_o is rejected at a significance level of $\propto$ if $|Z| \geq Z_{\frac{\propto}{2}}$, where $Z_{\frac{\propto}{2}}$ is a critical value of standard normal distribution with a probability exceeding $\frac{\propto}{2}$, and it displays the trend is significant. If $|Z| \leq Z_{\frac{\propto}{2}}$then the H_o is accepted, and the trend is not significant.

Sen’s slope

The study used Sen’s slope test to estimate the magnitude of the trend. The set of linear slopes d_k was calculated by equation 6 as:

$$d_k = \frac{x_t - x_b}{t-b} \qquad (6)$$

for *, where N is the number of data, and t, b are indices.

Sens’s slope is then computed as the median of the slopes:

$q = Median\ d_k$ (Hirsch et al. 1982).

A negative value of q displays a decreasing trend and a positive value indicates an increasing trend.

Modified MK

Unlike the traditional MK tests, the following statistical tests are applied specifically to address the problem of autocorrelation structures during the testing trend of the T-min, T-max, and T-mean. This study applied the Yue and Wang (2004), and Hamed and Rao (1998) modified MK to testing trend.

Change point detection

We are concerned with determining how the trends have changed with time. Subsequently, the study applied sequential MK, standard normal homogeneity (SNH), and the Pettitt test to detect the abrupt change points of T-min, T-max, and T-mean in Tanzania. The multiple tests allow a more rigorous and comprehensive assessment of the abrupt change in the time series since the tests are complementary to each other. The break year for a series was selected when at least two out of three tests were detected in the same year.

Sequential MK test

The sequential MK (Mann 1945, Kendall 1975) test is a progressive and retrograde analysis of the traditional MK method, that gives sequential values of standardized variables $u(t_i)$ (Equation 7) with zero mean and unit standard deviation.

$$u(t_i) = \frac{[t_i - E(t_i)]}{\sqrt{Var(t_i)}} \qquad (7)$$

where, $E(t_i)$ and $Var(t_i)$ mean and variance of the test statistic, respectively.

The sequential MK test is used to locate change points in the T-min, T-max, and T-mean data by observing the variations during the study period. H_o was assumed that the T-min, T-max, and T-mean display no abrupt change point. When the progressive (u(t)) or retrograde (u′(t)) surpasses the threshold before and after the crossing point, the H_o of the T-mean, T-max, and T-min has no abrupt points must be rejected, and this trend turning point may be significant at a certain confidence level (i.e. say 95% confidence level)

Standard normal homogeneity test

The SNH test as developed by Alexandersson (1986) was applied to identify a change point in a time series of the T-mean, T-max, and T-min. H_o: The P variables xi follow an $N(0,1)$ distribution. H_a: Between times 1 and n, the variables follow $N(\mu_2, 1)$ distribution.

The Pettitt's test

This is a non-parametric test developed by Pettitt (1979), which is used in the current study for identifying the occurrences of abrupt changes in T-min, T-mean, and T-max. The Pettitt's test computes statistic by equation 8 as

$$U_t = \sum_{j=1}^{t} \sum_{i=j+1}^{m} sgn(X_i - X_j) \qquad (8)$$

where,

$$sgn(X_i - X_j) = \{1\ 0\ -1\ if\ \ if\ if\ sgn(X_i - X_j) > 0\ sgn(X_i - X_j) = 0\ sgn(X_i - X_j) < 0 \qquad (9)$$

Hurst coefficient

The Hurst coefficient (H) is a measure employed in the examination of time series data to quantify the extent of long-term memory or persistence in patterns. Understanding the behaviour of trends in the future is highly relevant as it offers insights into the predictability and stability of the underlying processes (Agbazo et al. 2019, Shiru et al. 2020, Ogunjo et al. 2024). The Hurst exponent quantifies the level of self-similarity or long-range dependency in a time series. The range of values is from 0 to 1. A Hurst exponent greater than 0.5 suggests a persistent trend, implying that future values are more likely to align with the existing trend. This suggests that trends exhibit greater predictability over extended periods when the value of H is higher. The value of H also indicates the stability of trends. A Hurst exponent near 0.5 indicates that the time series displays a random walk pattern without a significant long-term trend. On the other hand, values of H that deviate greatly from 0.5 reflect trends that are more stable and long-lasting. Through the examination of the Hurst coefficient, one can make accurate forecasts regarding future patterns and tendencies. For example, when the Hurst exponent is above 0.5, it shows a strong level of persistence, implying that the current trend is likely to endure in the future. In contrast, when H is low, indicates that the trend is less stable and more susceptible to reversal or mean reversion. In this study, the Hurst coefficient values were calculated by rescaled range (R/S) analysis.

Results and Discussion

General characteristics of the T-mean, T-max, and T-min in Tanzania.

Figure 2 shows the climatology of (a) T-mean, (b) T-max, and (c) T-min in Tanzania during the period of 1951-2021.

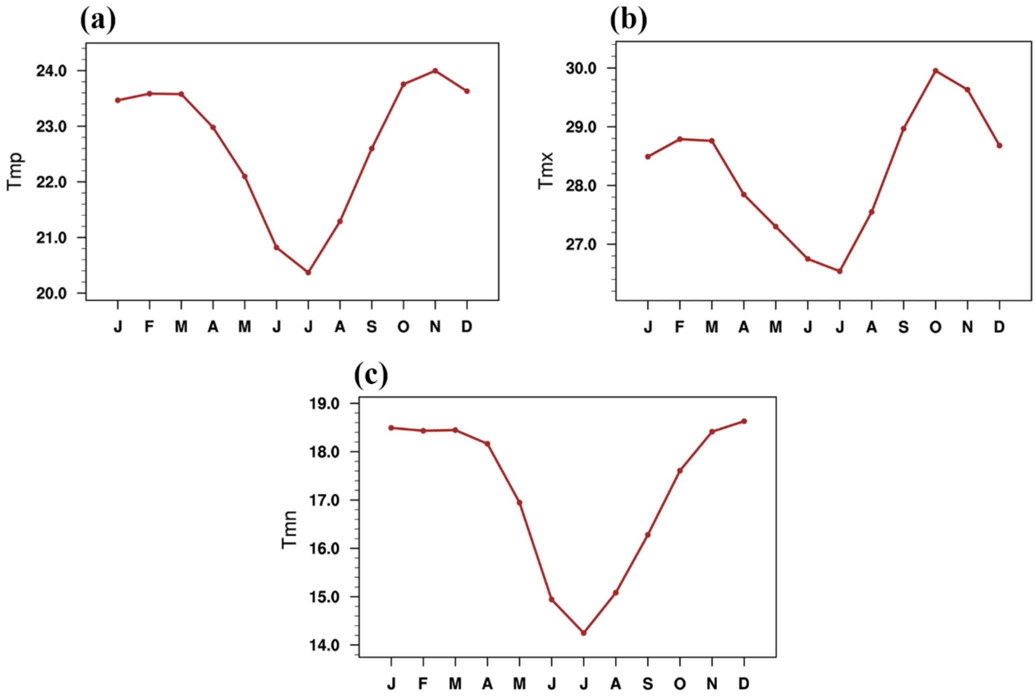

Figure 2: The annual cycle of (a) T-mean (units: °C), (b) T-max (units: °C), and (c) T-min (units: °C) averaged over Tanzania.

The minimum, mean and maximum temperatures reveal a consistent annual cycle over Tanzania with a warm season spanning from October to April and a cold season from May to September. This is in line with Sigalla et al. (2023) who also indicated T-min warm season ranging from October to March over the Kilombero River Catchment (southern Tanzania). Nevertheless, Engdaw et al. (2022) found that the EA annual temperature cycle exhibits two warm peaks, September to October and March to April. Toward this end, selecting ONDJFMA as the temperature season in Tanzania is objective and reasonable. Figure 3 shows the spatial patterns of the long-term seasonal ONDJFMA average of the T-min, T-mean, and T-max in Tanzania during the period from 1951 to 2021.

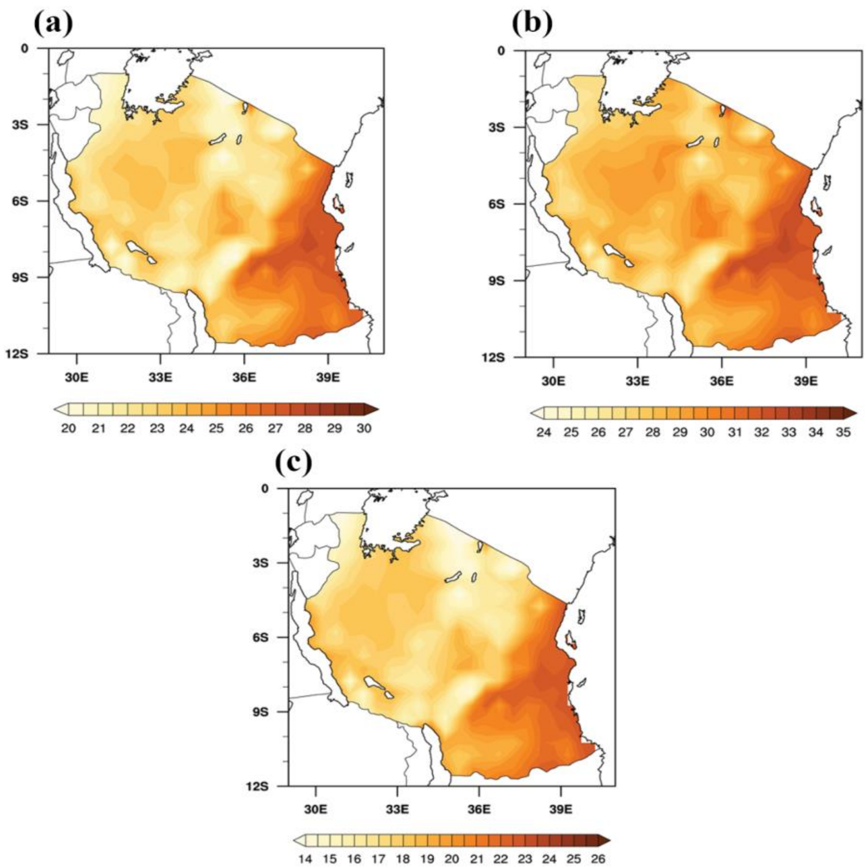

Figure 3: Long-term seasonal ONDJFMA averages of (a) T-mean (units: °C), (b) T-max (units: °C), and (c) T-min (units: °C) in Tanzania during the period of 1951-2021.

The observed pattern of T-mean is higher in the eastern region and lower in the highland region. The similar pattern holds T-max and T-min. The high temperature values in the eastern region is associated with low-lying areas proximity to Indian Ocean as shown in Figure 1. Further, the long-term values for the T-mean vary from 22.7 to 24.2 °C, for T-max ranges from 27.7 to 29.7 °C, and for the T-min extends from 17.4 to 19.3 °C.

Trend analysis of the T-mean, T-max, and T-min during the ONDJFMA season

The trend analysis of the T-mean, T-max, and T-min time series during the ONDJFMA season over Tanzania was done for the period of 1951-2021.

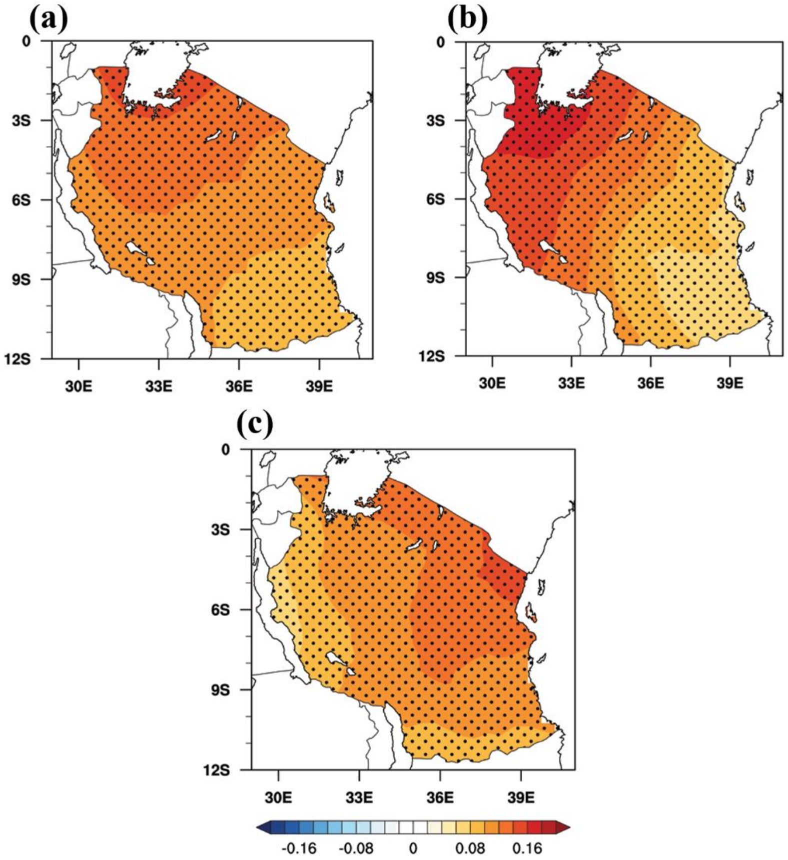

Figure 4: Trend of seasonal ONDJFMA averages of (a) T-mean, (b) T-max, and (c) T-min in Tanzania during the period of 1951-2021 using Sen's slope estimator. The dots indicate areas where trends are statistically significant at the 95% confidence level.

A considerable rising trend in the T-mean (up to 0.14 °C per decade) is observed in Tanzania (Fig. 4a). T-mean increased meridionally from the southern to the northern region, with the largest increase occurring in Lake Victoria Basin. The higher rate of increase in the T-mean in the Lake Victoria Basin may impact the precipitation patterns in the area. Warmer temperatures can result in modified precipitation patterns, impacting the amount and distribution of rainfall in the vicinity of Lake Victoria. This could have substantial consequences for agriculture, water supplies, and human livelihoods in the nearby regions. Tanzania witnessed the largest and most significant increase in T-max (Fig. 4b). The significant increase was observed as a belt stretching from the southeastern region of Tanzania to the northwestern region of Tanzania. The result displays a significant increasing trend up to 0.18 °C per decade. An increase in T-max in the northwestern part of Tanzania can increase soil and plant evapotranspiration rates, and thus rise water demands by crops (Osbahr et al., 2011; Tahmasebi et al., 2020). T-min significantly increased zonally from the western regions of Tanzania to the extreme northeastern region of Tanzania (Fig. 4c). The long-term analysis depicts a significant rising trend up to 0.16 °C per decade. The increasing trend of T-max is much larger than T-min, suggesting that significant seasonal mean warming mainly occurs during the day. The increase in T-min in the extreme northeastern part of Tanzania might lead to the drying up of some natural water resources, hence creating problems like a shortage of drinking water. The temperatures all depicted increasing trends, nevertheless, the warming rates were different.

Further, trends of the T-min, T-max, and T-mean during the ONDJFMA season estimated using Sen's slope, and traditional and modified MK's tests are presented in Table 1.

Table 1. A summary of Sen and Mann-Kendell tests (one-tailed with 5% significance interval) with and without autocorrelation of seasonal ONDJFMA T-mean, T-max, and T-min based on the period of 1951-2021.

Tests' outcomes	**SS (°C /year)**	**P-value (α = 5%)**			**Significance**
		MK Trd[1]	**MK Y&W**[2]	**MK H&R**[3]	
T-mean	0.011	0.000	0.000	0.000	Significant
T-max	0.011	0.000	0.000	0.000	Significant
T-min	0.011	0.000	0.000	0.000	Significant

SS: Sen's slope; negative and positive signs of slope indicate a decreasing trend and an increasing trend, respectively.

[1] p value calculated using the traditional Mann-Kendal test.

[2] p value was calculated using Monte Carlo Simulation taking autocorrelation into account by the method of Yue and Wang (2004).

[3] p value was calculated using Monte Carlo Simulation taking autocorrelation into account by the method of Hamed and Rao (1998).

Over the past 71 years, the results revealed a significantly increasing trend (~ 0.011°C per year) at 5% significance level. The increasing rate may be associated with anthropogenic climate forcing (Tokarska *et al.* 2020). Table 2 shows the results of H values for the T-max, T-min, and T-mean during the ONDJFMA season for the period of 1951-2021.

Table 2. The Hurst coefficient test results and future trends of seasonal ONDJFMA T-mean, T-max and T-min for the period of 1951-2021.

Tests' outcomes	**H**	**Historical trends**	**Future trends**
T-mean	0.7471	Increasing (extremely significant)	Increasing
T-max	0.7190	Increasing (extremely significant)	Increasing
T-min	0.7326	Increasing (extremely significant)	Increasing

There is little difference in the values of H, although they are all greater than 0.5. This indicates no difference in overall trends of the T-min, T-max, and T-mean between the future and past. The H and the MK trend test revealed a warming trend of the T-mean, T-max, and T-min time series.

Change point analysis of the T-mean, T-max, and T-min during the ONDJFMA season

The change point analysis is vital to detect the abrupt point of change in the T-mean, T-max, and T-min. Figures S1-S3 show the change point year derived using sequential MK, SNH, and Pettitt tests. The results showed that the change point year for the T-mean and T-max time series is 1990. This result is generally consistent with the results of the SNH and Pettitt test that indicate the changing point around the early 1990s, except for the sequential MK test. The change point year for the T-min is found in the late 1990s. All tests except the sequential MK test showed the changing point in the year 1997. Generally, there was an abrupt change point year in temperature around 1990 and 1997. Next, we analyze the spatial patterns corresponding to abrupt change points of the T-mean, T-max, and T-min series to better understand their features. As described above, the study divides the whole period into two sub-periods of 1951-1990 and 1991-2021 to discuss the T-mean and T-max trends. Consistently, the T-min trend was also analyzed after being divided into 1951-1997 and 1998-2021 periods.

T-mean in western Tanzania experienced a significant increasing trend during the period of 1951-1990 (Fig. 5a). The eastern parts of Tanzania show a significant increasing trend of the T-mean from 1991 to 2021 (Fig. 5b). The western parts of Tanzania show a significant increasing trend of T-max during the period of 1951-1990 (Fig. 5c). But the same areas show a significant decreasing trend in T-max during the period of 1991-2021 (Fig. 5d). A significant increasing trend was observed for T-min in the southwestern part of Tanzania during the period of 1951-1997 (Fig. 5e). After 1997, non-significant increasing trends were observed for T-min in the central and northeastern parts of Tanzania (Fig. 5f).

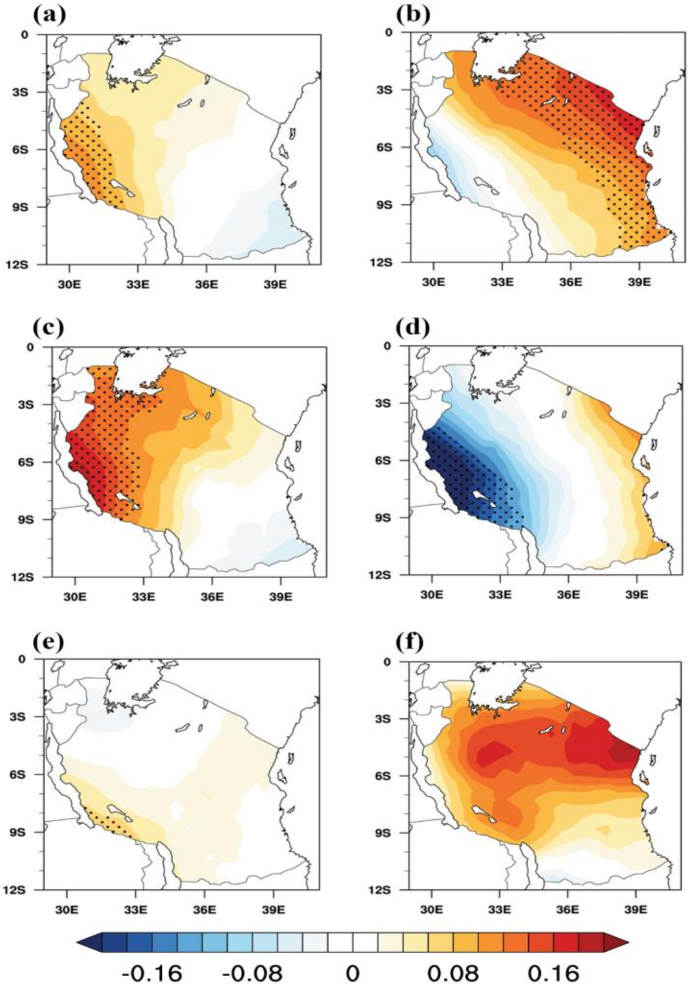

Figure 5: Trend of seasonal ONDJFMA averages of (a) T-mean, (c) T-max in Tanzania before 1991 using Sen's slope estimator. (b) and (d) are the same as (a) and (c), respectively but after 1991. The trend of seasonal averages of (e) T-min in Tanzania before 1998. (f) the same as (e), but after 1998 using Sen's slope estimator. The dots indicate areas where trends are statistically significant at the 95% confidence level.

To better distinguish the features of the two decadal variations, the anomalies of variables for the decadal variation around 1990 were computed using the mean of the period 1991-2021 minus that of the period 1951-1990; for the decadal variation around 1997, the mean of the period 1951-1997 minus that of the period 1998-2021 was used. Figure 6 shows the composite anomalies of T-mean, T-max, and T-min for two decadal variations during the ONDJFMA season. It can be seen that significant positive anomalies occur in Tanzania for the T-mean, T-max, and T-min but present distinct spatial distributions. For the T-mean, the positive anomalies are concentrated more northward and over the Lake Victoria basin. The composite T-max anomaly exhibits a positive anomaly extended toward the northwest of Tanzania. The positive anomaly intensity of the T-min is somehow weaker compared to the T-mean and T-max, located more northeastward.

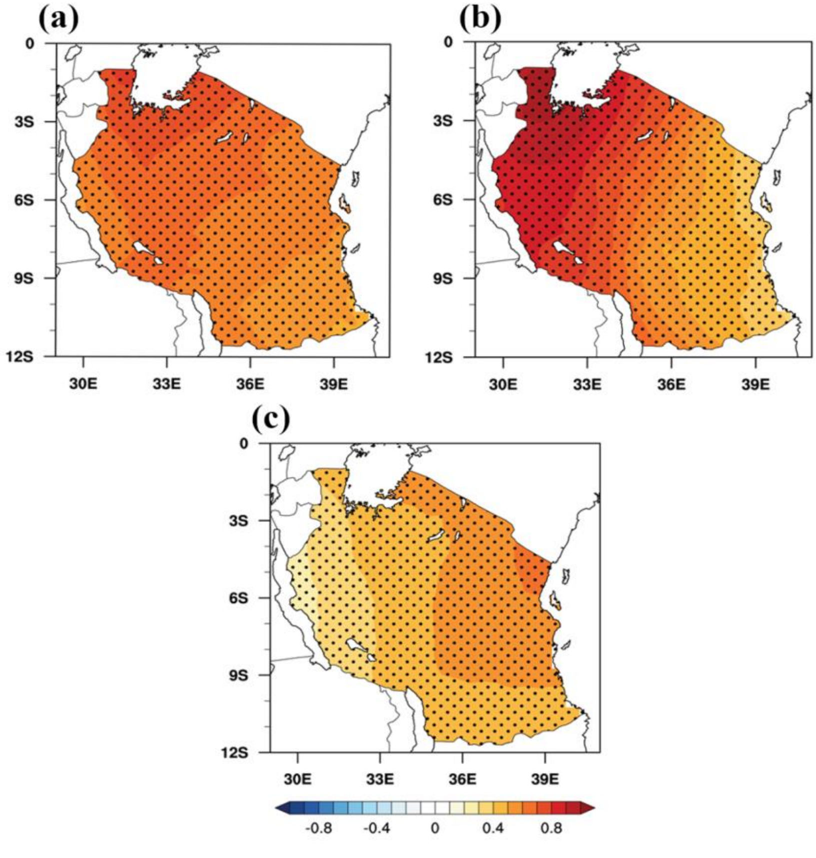

Figure 6: Composite of seasonal ONDJFMA averages of (a) T-mean (units: °C), (b) T-max (units: °C) anomalies in Tanzania for 1991-2021 minus the 1951-1990 period, and (c) T-min (units: °C) anomalies in Tanzania for 1998-2021 minus the 1951-1997 period.

Interannual and decadal variability of the T-mean, T-max, and T-min during the ONDJFMA season

Figure 7 shows the interannual variations in T-mean, T-max, and T-min anomalies during the ONDJFMA season from 1951 to 2021. The warmest season was in 2006, with a 1.40°C anomaly, while the coldest was in 1981, with a -1.15°C anomaly. The lowest seasonal T-mean occurred in 1968, with a -

0.80°C anomaly, and the highest in 2019, with a 0.73°C anomaly. In 1968, the seasonal T-max also hit its lowest at -1.14°C, peaking in 2003. The highest seasonal T-min, 1.01°C above normal, was in 2016, while the lowest was in 1965, with an anomaly of -0.85°C. Notably, the seasonal T-min began rising in the late 1990s, later than the T-mean and T-max, which saw significant warming in the early 1990s. Throughout the study period (1951-2021), T-mean, T-max, and T-min increased annually by 0.010°C, 0.011°C, and 0.011°C, respectively. The trends estimated by parametric linear regression (shown in Fig. 7) and three nonparametric methods (outlined in Table 1) were similar for T-min, T-max, and T-mean.

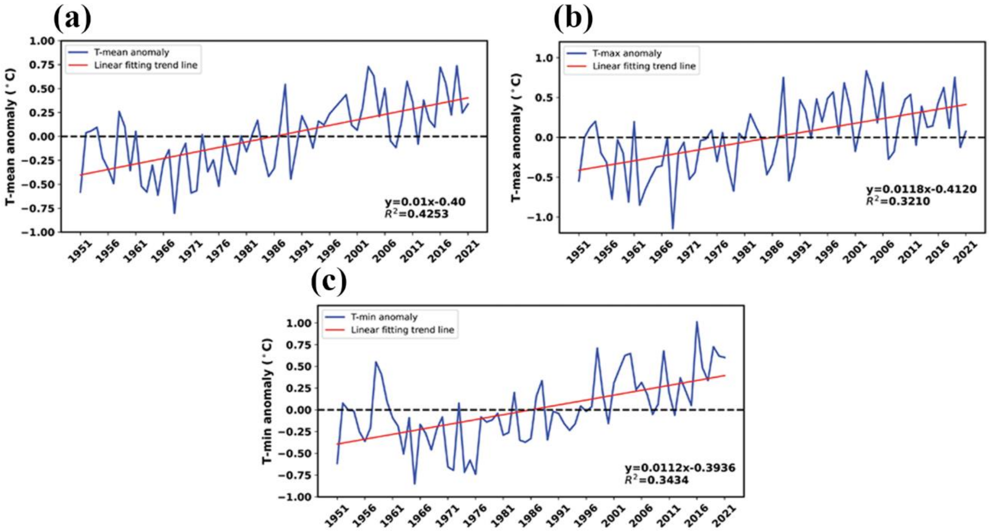

Figure 7: Seasonal ONDJFMA averages of (a) T-mean, (b) T-max, and (c) T-min anomalies averaged over Tanzania during the period of 1951-2021.

Decadal variability of the T-min, T-max, and T-mean during the ONDJFMA season are shown in Figs. 8-10 for spatial distributions during the period of 1951-2021. The T-mean shows negative values before the 1990s, with the lowest values in northern Tanzania during the 1960s (Fig. 8). The positive values are observed over Tanzania from the 1990s onward. The largest increase in T-max occurred in Tanzania after the 1980s, with the largest values occurring in western, northwestern, and northern Tanzania, respectively (Fig. 9). The same areas experienced the lowest values during the 1950s and 1960s, respectively. The magnitude of T-min decreased to its lowest point in eastern Tanzania during the 1970s (Fig. 10). T-min attained significantly large values in northern and northeast Tanzania during the 2000s and 2010s, respectively. It is worth noting that during the 2000s, warming of T-mean, T-max, and T-min occurred at a higher rate over the Lake Victoria basin as compared to the rest areas.

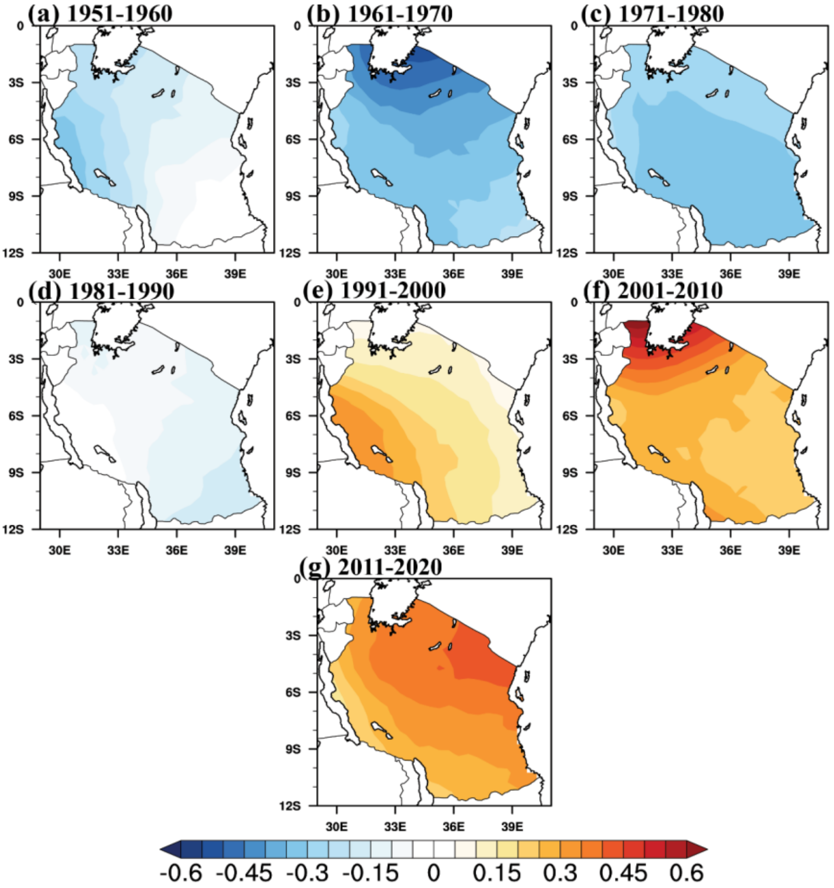

Figure 8: Decade seasonal ONDJFMA averages of T-mean (units: °C) anomalies in Tanzania during the period of 1951-2021.

Figure S4 depicts the decade-to-decade variability of T-mean, T-max, and T-min averages over Tanzania during the ONDJFMA season. The T-mean showed a decline before the 1960s, followed by a gradual increase starting from the 1980s. T-max experienced a slight decline before the 1960s and then rose post-1960s. T-min decreased before the 1960s, continued to drop during the 1970s, and then began increasing from the 1980s. All three measures T-mean, T-max, and T-min exhibited warming trends both before and after the start of the twenty-first century, with their lowest temperatures recorded in the 1960s (T-mean and T-max) and 1970s (T-min) at -0.34°C, -0.39°C, and -0.36°C, respectively. 1991-2000 decade exhibited a low warming rate for T-min, which then accelerated during the core period of the global warming hiatus (Medhaug et al. 2017).

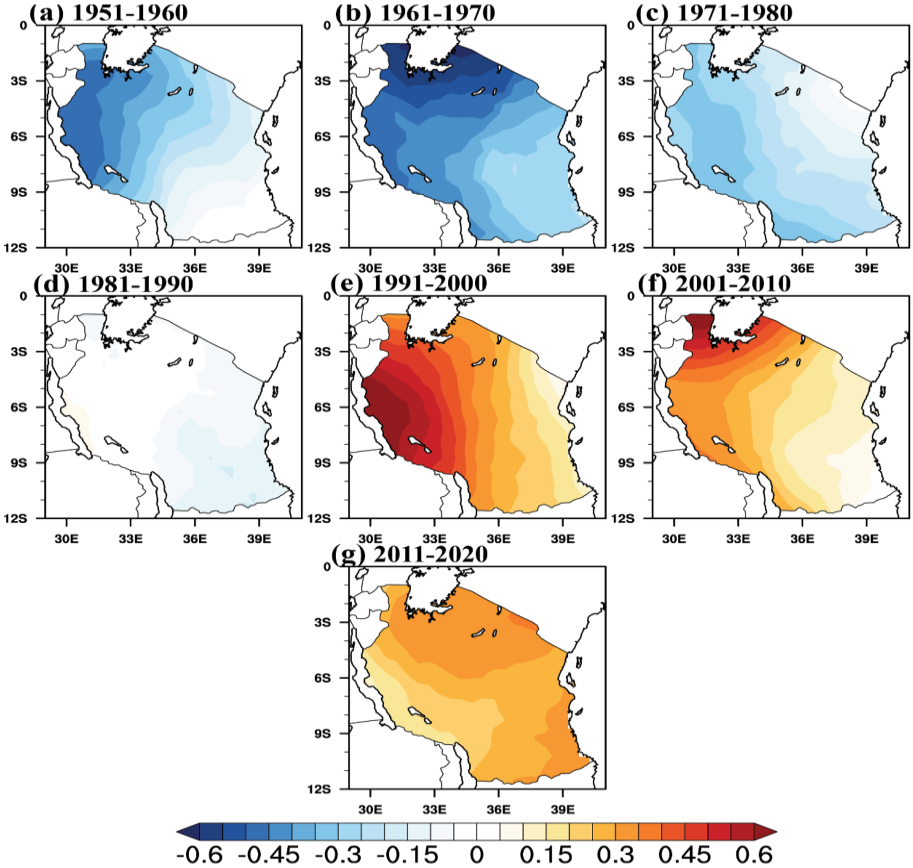

Figure 9: The same as Fig. 8 but for T-max (units: °C) anomalies.

The most recent decade (2011-2020) experienced warming significantly above the multi-decadal average from 1951 to 2020. After the 1980s, the increase in T-max was larger than that in T-min and T-mean, but after a decade (1981-1990), warming of the T-mean and T-min became more and more important. The Generally, observed increase in T-mean, T-max, and T-min anomaly from negative values during the period the 1950s-1980s to positive values during the period 1990s-2010s is in line with global warming (Camberlin 2017). Additionally, higher warming after the 1980s is observed in the T-mean and T-max as compared to the T-min.

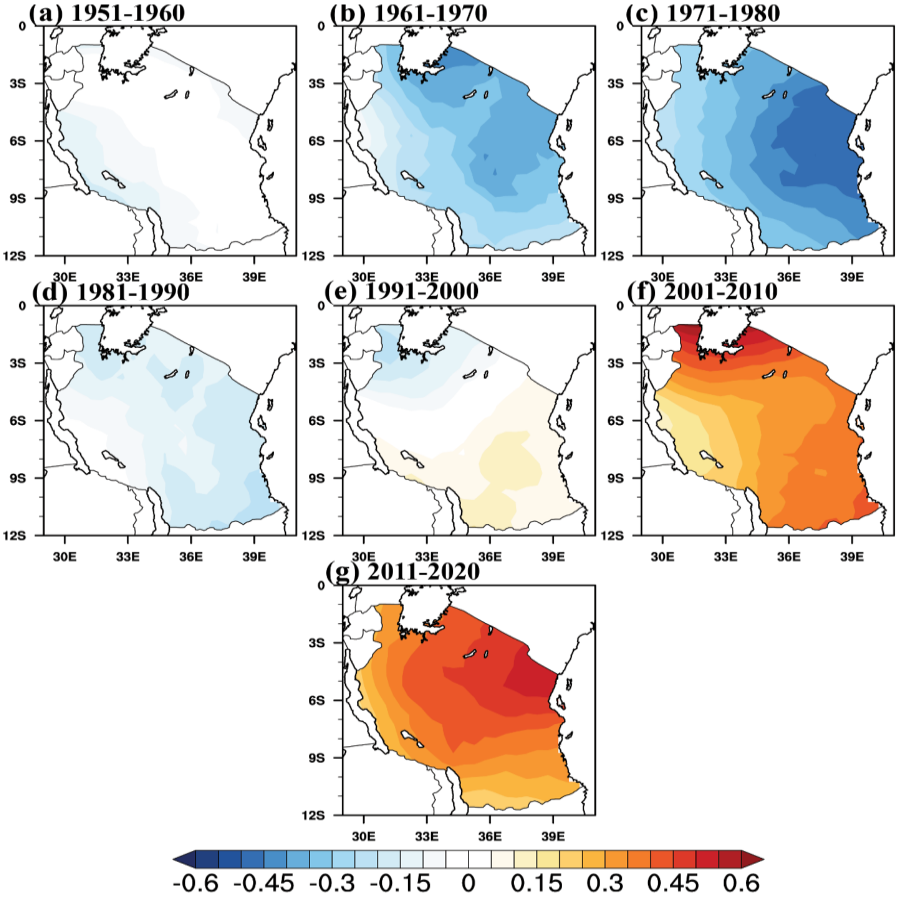

Figure 10: Same as Fig. 8 but for T-min (units: °C) anomalies.

Conclusions

In this study, the long-term variability of T-mean, T-max, and T-min during the ONDJFMA season was investigated using linear regression, Sens's slope, and traditional and modified MK tests during the period of 1951-2021. In addition to this, change point analysis for the T-mean, T-max, and T-min time series during the same period were analyzed using sequential MK, SNH, and Pettitt's test. The present study revealed the following findings:

- T-mean, T-max, and T-min significantly increased over the past 71 years, and there is the possibility of their trends to increase in the future as indicated by the H coefficients.
- A considerable rising trend in the T-mean is 0.14 °C per decade, T-max is 0.18 °C per decade, and T-min is 0.16 °C per decade.
- Both T-mean and T-max show abrupt change during the early 1990s, while T-min exhibits change during the late 1990s. After 1991, more locations were showing significant trends (positive or negative) for T-max than T-mean. T-min shows no significant trend after 1998.
- The spatial decadal variability shows that T-mean and T-max increased faster than T-min after the 1980s. A generalized warming was observed in T-mean and T-max in Tanzania during the 1990s, 2000s, and 2010s. In contrast, T-min increased significantly in Tanzania during the 2000s and 2010s.
- The temporal distribution showed that the 1960s is the decade with the lowest T-max and the 2010s is the highest one for T-min.

Previous studies have predominantly focused on using JF, MAM, JJAS, and OND seasons as major climatic seasons in Tanzania. For example, Gebrechorkos et al. (2019b) found that trends for JF and OND T-max were non-significantly increasing in southern and south-western regions of Tanzania, similar non-significant trend was observed in large parts of Tanzania during the MAM season. Our results identified a significant increasing trend in T-max over the same regions during the ONDJFMA season, hence helping in understanding long-term trends that might not be evident when looking at an individual season. The consequences of these changes to the growing ONDJFMA season in Tanzania is a fact that cannot be easily underrated. The results of the present findings would offer flexible planning and considering these possible changes in T-mean, T-max, and T-min as key elements particularly for decision makers when they are planning for agricultural activities.

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Conflicts of interest

The authors declare no conflict of interest in this research work.

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