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Assessment of the Spatio-Temporal Trends of Annual Extreme Temperature Indices over Tanzania during the Period of 1982-2022

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Abstract

Extreme weather and climatic phenomena, such as heatwaves, cold waves, floods and droughts, are expected to become more common and have a significant impact on ecosystems, biodiversity, and society. Devastating disasters are mostly caused by record-breaking extreme events, which are becoming more frequent throughout the world, including Tanzania. A clear global signal of an increase in warm days and nights and a decrease in cold days and nights has been observed. The present study assessed the trends of annual extreme temperature indices during the period of 1982 to 2022 from 29 meteorological stations in which the daily minimum and maximum data were obtained from NASA/POWER. The Mann-Kendall and Sen slope estimator were employed for trend analysis calculation over the study area. The analyzed data have indicated for the most parts, the country has an increase in warm days and nights, extreme warm days and nights and a decrease in cold days and nights, extreme cold days and nights. It has been disclosed that the number of warm nights and days is on the rise, with the number of warm nights trending significantly faster than the number of warm days. The percentile-based extreme temperature indices exhibited more noticeable changes than the absolute extreme temperature indices. Specifically, 66% and 97% of stations demonstrated positive increasing trends in warm days (TX90p) and nights (TN90p), respectively. Conversely, the cold indices demonstrated 41% and 97% negative decreasing trends in TX10p and TN10p, respectively. The results are seemingly consistent with the observed temperature extreme trends in various parts of the world as indicated in IPCC reports.

Keywords

Climate Extremes, Absolute Extreme Temperature, Percentile Extreme Temperature, Mann-Kendall Test, NASA

1. Introduction

The effects of extreme climate events have gained significant attention, and they are now major research subjects. Extreme weather and climatic phenomena, such as heatwaves, cold waves, floods, and droughts, are expected to become more common and have a significant impact on ecosystems, biodiversity, and society, according to projections made by Meehl and Tebaldi (2004) and Sherwood and Huber (2010). In recent years, there has been a lot of research on the analysis of climate change indicators, especially temperature, because long homogeneous records are available and temperature data can accurately depict the energy exchange process over the earth's surface (Bhutiyani et al., 2007; Ding et al., 2018). Rising greenhouse gas emissions have altered the frequency of extreme weather events worldwide (Smith & Reynolds, 2005; Alexander et al., 2006; Brohan et al., 2006). There has been a rapid and significant warming since the 1970s and 1980s, following a relative cooling phase in the 1950s and 1960s (Alexander et al., 2006; Elguindi et al., 2013).

A clear global signal of an increase in warm days and nights and a decrease in cold days and nights has been observed, according to Zhang et al. (2011). This trend is consistent with the mean temperature's warming. Despite rising mean temperatures both globally and locally, this does not always translate into more frequent extreme events (Finkel & Katz, 2018). Since regional changes in climatic extremes have an immediate influence on civilizations, it is imperative to continuously monitor any evidence of such changes.

Devastating disasters are mostly caused by record-breaking extreme events, which are becoming more frequent throughout the world, including Tanzania (Chang'a et al., 2017; Handmer et al., 2012; Seneviratne et al., 2012). Tanzania is among the majority of African countries whose socioeconomic development has been most affected by climate variability and change, especially in traditional rain-fed agriculture, pastoralism, and water resources. These factors are placing increased strain on human and natural systems.

Temperature has an effect on all kinds of climate extremes, including heat waves and cold snaps. These extremes impact human health, the environment, and the natural ecosystem in different ways. Many studies have been conducted in relation to temperature extremes, especially heatwaves. According to the IPCC (2012) in numerous regions across the globe where adequate data are available, there is a moderate level of confidence that either the duration or frequency of warm spells or heat waves has risen, although this is not applied to all regions. Different continents have varying degrees of certainty, but globally, there is a significant possibility that fewer cold days and nights and more warm days and nights have occurred since 1950 (Chen et al., 2018). Additionally, by the 2060s and 2090s, it is predicted that the average annual temperature will rise by 1.0˚C to 2.7˚C and 1.5˚C to 4.5˚C, respectively, leading to a consistent rise in the number of hot days and nights (Lal et al., 2012; Sun et al., 2017).

The attainment of numerous socio-economic development policies and plans, such as the Sustainable Development Goals (SDG), the National Strategy for Growth and Reduction of Poverty, and the National Development Vision (Vision 2025) (*THE UNITED REPUBLIC OF TANZANIA*, 2021), is thus gravely threatened by climate extremes. The first Sustainable Development Goal (SDG) is to eradicate all forms of poverty by 2030. The second SDG focuses on reducing hunger, attaining food security, enhancing nutrition, and advancing sustainable development. A further goal of Tanzania's development strategy, strategy 2025, was to move the nation from a least developed to a middle-income status and to semi-industrialize, with modernized and highly productive agricultural activities driving the economy from low productivity to high.

Ending extreme poverty by 2025 and achieving high-quality livelihoods via food security and self-sufficiency are two of Vision 2025's objectives. In light of the growing frequency and severity of climatic extremes, successful plans and strategies to improve and sustain production and productivity are necessary to meet these goals, especially for the cattle and agricultural industries. Initiatives and efforts towards eradicating poverty and reaching zero hunger are greatly impacted by the trends and patterns of climate extremes. For the majority of developing countries, including Tanzania, socio-economic development and livelihoods are strongly linked to their dependencies on natural resources and rain-fed agriculture. However, it is anticipated that extreme events will become more frequent and that their effects will only become worse. This is especially true for sectors that are vulnerable to climate change, like water, health, forestry, agriculture, and food security. Therefore, apart from the previous studies, the current study has explored 29 stations with the dual objectives to determine the significant trends in extreme temperature indices and assess spatio-temporal trends of annual extreme temperature series over Tanzania.

2. Data and Methodology

2.1. Study Area

The study area lies in East Africa, specifically in the latitude range of 1˚ to 12˚S and the longitude range of 29˚ to 41˚E (**Figure 1**). The nation is bordered to the north by Kenya and Uganda, to the west by Burundi, Rwanda, and the Democratic Republic of the Congo, to the south-west by Malawi and Zambia, to the south by Mozambique, and to the east by the Indian Ocean. The region's climatic diversity is mostly due to the nation's intricate topographical terrain. Bimodal rainfall patterns occur in the north, northeastern highlands, Pemba and Unguja on the Island of Zanzibar, the center, and the southern coast (Luhunga et al., 2016). Unimodal rainfall patterns occur in the western and southwestern highlands.

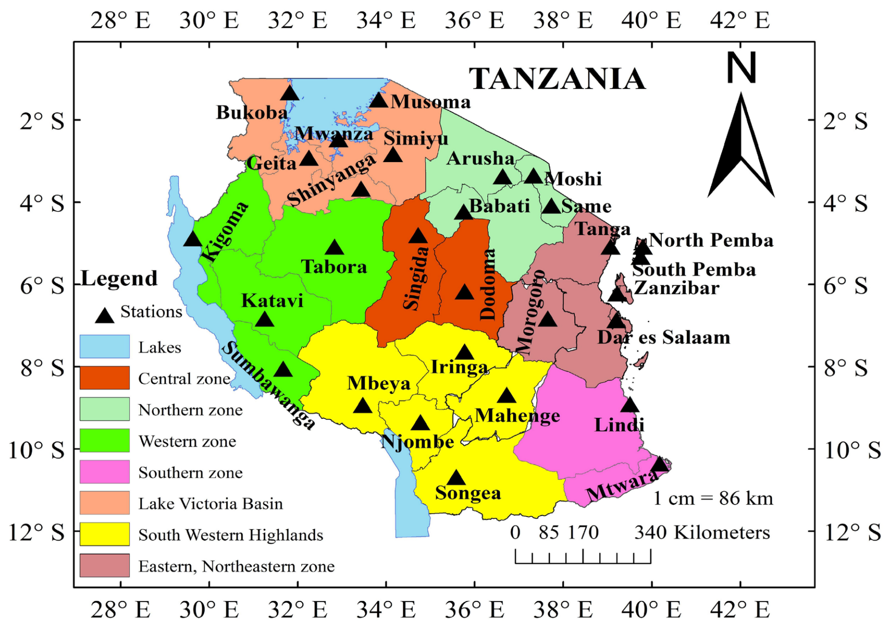

Figure 1. A map of Tanzania showing the 29 meteorological stations with the distribution of zones.

The shifting of the Inter-Tropical Convergence Zone (ITCZ) is the primary cause of various patterns of rainfall (Borhara et al., 2020). This zone runs through Tanzania from October to February, then the reverse direction from March to May. Tanzania's seasonal rainfall varies greatly by region; in the wettest months, some regions receive as much as 300 mm of rain every month. Tanzania experiences monthly rainfall ranging from 50 to 200 mm on average.

Tanzania's average yearly temperature varies by region by 14.4˚C and 1837 mm of rainfall (Luhunga et al., 2016; Borhara et al., 2020). In comparison to other locations, the western and coastal regions have milder temperatures. In contrast, May marks the start of the low-temperature season, which lasts until August or September. The season with the maximum temperatures in all of the regions starts in October and lasts until February or March. The regions' lowest and highest average annual temperatures, respectively, range from 9.6˚C - 22˚C to 19.1˚C - 30.7˚C.

2.2. Data Source

Since it was not possible to have daily observed minimum and maximum temperature data from the 29 stations (**Table 1**) from the study area, the climate data were obtained from National Aeronautical and Space Administration (NASA) retrieved from https://power.larc.nasa.gov/data-access-viewer/. For many years, the National Aeronautics and Space Administration (NASA) has funded satellite systems and studies that provide crucial data for the study of climate and climate processes through its Earth Science research program. These contain estimations of meteorological variables and surface solar energy fluxes that have been long-term averaged climatologically. The time series format further contains

Table 1. The list of 29 stations used showing geographical coordinates and altitude.

No.	Stations	Longitude (E)	Latitude (S)	Altitude (m)
1	Arusha	36.63	3.37	1372
2	Babati	35.75	4.23	1551
3	Bukoba	31.82	1.33	1144
4	Dar	39.2	6.87	53
5	Dodoma	35.77	6.17	1120
6	Geita	32.25	2.92	1224
7	Iringa	35.77	7.63	1721
8	Katavi	31.25	6.83	1116
9	Kigoma	29.63	4.88	822
10	Lindi	39.51	8.91	317
11	Mahenge	36.72	8.68	1040
12	Mbeya	33.47	8.93	1758
13	Morogoro	37.65	6.83	526
14	Moshi	37.33	3.35	813
15	Mtwara	40.18	10.35	113
16	Musoma	33.83	1.5	1147
17	Mwanza	32.92	2.47	1140
18	Njombe	34.77	9.35	1821
19	NorthPemba	39.8	5.08	46
20	Same	37.73	4.08	860
21	Shinyanga	33.43	3.67	1202
22	Simiyu	34.15	2.83	1119
23	Singida	34.72	4.8	1260
24	Songea	35.58	10.68	1036
25	SouthPemba	39.75	5.33	46
26	Sumbawanga	31.67	8.05	1829
27	Tabora	32.83	5.08	1182
28	Tanga	39.07	5.08	49
29	Zanzibar	39.22	6.22	18

the mean daily values of the underlying solar and meteorological data. In places where surface measurements are scarce or nonexistent, these satellite and model-based products have proven to be accurate enough to deliver trustworthy data on solar and meteorological resources.

An analysis of earlier research using NASA/POWER records and data from the US Cooperative Observer Program (COOP) revealed strong agreement between the two datasets (White et al., 2008). NASA/POWER climate datasets have also been verified by Van Wart et al. (2015), White et al. (2008), and Bai et al., (2010). As a result, a database containing past climatic information for every station was created. NASA climate data characteristics are accurate and agreeable with a spatial resolution of 1˚ latitude and 1˚ longitude with observed climate data which are archived in the Agro-climatology Archive (Chandler et al., 2013).

2.3. Methodology

2.3.1. Data Quality Control

In order to guarantee the robustness of the results for trend assessments, it was imperative to conduct a data quality evaluation prior to computing the extreme indices. This is because the presence of any false outliers has the potential to upset the trends. The R-based tool RClimDex 1.10 was utilized by the study to identify any missing data, verify mistakes, and handle outliers in the daily temperature datasets (Alexander et al., 2006). RClimDex utilizes the R statistical computing environment and offers an accessible interface for computing climate extreme indices. Its primary function is to facilitate the monitoring and identification of climate change through these calculations and for more information the software can be accessible through https://etccdi.pacificclimate.org/indices.shtml. The mean plus or minus n times the daily value's standard deviation, (mean − n*std, or mean + n*std) is what defines an outlier. Values that fall outside of this range are those that the user declares. The mean is the value that was calculated from the day's climate data, the standard deviation is the day's standard deviation, and n is an input value defined by user. Because the program finds values outside of the selected standard deviations of the time series mean, the number of standard deviations in this study was set at four. If there was a difference between the daily minimum and maximum temperatures, the daily minimum and maximum temperatures were set to a missing value. The values outside of four standard deviations of the daily value's climatological mean were likewise considered outliers in the assessment of maximum and lowest temperatures (Alexander et al., 2006).

2.3.2. Extreme Indices

Out of the 27 temperature and precipitation indices recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI) to characterize climate severe events throughout Tanzania, only 8 indices related to extreme temperature were used for this study (**Table 2**). RClimDex produced the yearly mean of these indices. Based on their indicators, the indices are divided into two groups: absolute indicators, such as minimum Tmin (TNn), maximum Tmin (TNx), minimum Tmax (TXn), and maximum Tmax (TXx). According to Feng et al. (2018), the frequency of cold nights (TN10p), warm nights (TN90p), cold days (TX10p), and warm days (TX90p) are the percentile-based indicators used in this study. These indices' insights are detailed and accessible at http://etccdi.pacificclimate.org/list_27_indices.shtml (Zhang et al., 2005).

Table 2. Description of 8 extreme temperature indices used in the study.

Indices	Indicator name	Index definition	UNITS
TXx	Max T_{max}	The maximum value of daily maximum temperature per year.	˚C
TXn	Min T_{max}	The minimum value of daily maximum temperature per year.	˚C
TNx	Max T_{min}	The maximum value of daily minimum temperature per year.	˚C
TNn	Min T_{min}	The minimum value of daily minimum temperature per year.	˚C
TN10p	Cold nights	Percentage of days when daily minimum temperature < 10th percentile in a year.	Days
TN90p	Warm nights	Percentage of days when daily minimum temperature > 90th percentile in a year.	Days
TX10p	Cold days	Percentage of days when daily maximum temperature < 10th percentile in a year.	Days
TX90p	Warm days	Percentage of days when daily maximum temperature > 90th percentile in a year.	Days

2.3.3. Trend Analysis

The Mann-Kendall (MK) test (Mann, 1945; Kendall, 1975) was used in the study to determine whether or not extreme climatic indices show a trend. According to Rodrigo and Trigo (2007), this test is one of the most used non-parametric methods for identifying trends in meteorological time series. The process is rank-based and resistant to the impact of extreme values and outliers. Using the non-parametric Kendall's tau based on slope estimator (Sen, 1968), the linear trends were computed, and their statistical significance was tested at a 5% (Luhunga et al., 2014) confidence level. If the trend was less than or equal to a threshold of 5%, it was deemed statistically significant. Equation (1) was used to determine the difference between the later measured value and all earlier measured values in order to get the Mann-Kendal test statistic (S) (Yue & Wang, 2004).

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sign}\left(Y_j - Y_i\right) \quad (1)$$

where sign ($Y_j - Y_i$) is equal to +1, 0 or −1. When the magnitude of the S is large positive number, the later measured values tend to be larger than earlier one, and an increasing trend is indicated, whereas when S is large negative number, the later measured values tend to be smaller than the earlier ones and the trend will be a decreasing one.

$$\operatorname{sign}\left(X_j - X_i\right)\left\{\begin{array}{l} 1 \text{ if } X_j - X_i > 0 \\ 0 \text{ if } X_j - X_i = 0 \\ -1 \text{ if } X_j - X_i < 0 \end{array}\right\} \quad (2)$$

($X_j - X_i$), where $j > 1$, and assign the integer 1, 0 or −1 to positive difference, no difference, and negative differences, respectively. The S test statistic is computed as the sum of the integers (Equation (1)). The magnitude of the slope of the trends from temperature extremes was computed using the Sen's slope estimator (ß) (Sen, 1968); which is the median of set of slopes using Equation (3) that $j > 1$.

$$\beta = \frac{y_j - y_i}{t_j - t_i} \quad (3)$$

The variance of *S*, for the situation where there may be ties (i.e., equal values) in the *x* values, is given by;

$$\mathrm{var}(s)=\frac{1}{18}\left[N(N-1)(2N+5)-\sum_{i=1}^{m}t_i(t_i-1)(2t_i+5)\right] \tag{4}$$

where, m is the number of tied groups in the data set and t_i is the number of data points in the i^{th} tied group.

3. Results and Discussion

3.1. Annual Changes in Extremes Temperature Indices

The results of the trend analysis from 29 stations time series of annual averages of extreme temperature indices during 1982-2022 are being summarized in Table 4. The frequency of the percentages of eight temperature indices at 29 analyzed stations are grouped based on the type of trend employed as; significant positive trend 29.3%, non-significant positive trend 37.9%, significant negative trend 13.4%, non-significant negative trend 19.4% and no trend 0% as summarized in Table 3.

3.2. Annual Changes of Absolute Extreme Temperature

The maximum value of daily maximum temperature (TXx) and the minimum value of maximum temperature (TXn) present positive average trend (increasing) but the trends are not statistically significant as in Figure 3(a), Figure 3(b) respectively. The maximum value of daily minimum temperature (TNx) and the minimum value of daily minimum temperature (TNn) indicate positive average trend (increasing) and they are statistically significant (Figure 3(c), Figure 3(d)).

During the period of analysis the annual TXx had an increasing rate of 0.005˚C/year in Tanzania. From Table 3, only 18.79% of the series had a statistical significant trend in which 10.34% were positive and 3.45% negative. Generally, the

Table 3. Positive and negative trends for the annual extreme temperature indices in Tanzania by percentages of stations from 1982 to 2022.

Index	Positive Trend			Negative Trend			No Trend (%)
	Total (%)	Sig (%)	Non-Sig (%)	Total (%)	Sig (%)	Non-Sig (%)	
Absolute							
TXx	68.96	10.34	58.62	31.04	3.45	27.59	0.0
TXn	72.41	17.24	55.17	27.59	0.0	27.59	0.0
TNx	86.21	48.28	37.93	13.79	0.0	13.79	0.0
TNn	86.21	34.48	51.73	13.79	3.45	10.34	0.0
Percentile							
TX90p	65.52	24.14	41.38	34.48	0.0	34.48	0.0
TX10p	58.62	20.69	37.93	41.38	17.24	24.14	0.0
TN90p	96.55	79.31	17.24	3.45	0.0	3.45	0.0
TN10p	3.45	0.0	3.45	96.55	82.76	13.79	0.0

increasing trends were predominant in 68.96% of the series. The increasing pattern was noticed clearly in the years from 1997-2006. The increase of TXx index was concentrated mainly in 17 regions in Eastern, Northeastern, south highlands, western and Lake Victoria areas. The statistical significant trends were observed in the regions of Mahenge, Mtwara and Same (Table 4, Figure 2(a)). Only one station in the Northern part, which is Arusha, had a significant decrease spatial pattern (Table 4, Figure 2(a)). The regions of Mwanza, Geita, Shinyanga, Tabora, Singida, Dodoma, Moshi and Mbeya had shown decreasing trends but not statistically significant as shown in Figure 2(a).

In the analysis it had been revealed that the annual TXn had an increasing rate of 0.009˚C/year. In Table 3, only 17.24% of the series had a positive statistical significant trend. In general, the increasing trends were predominant in 72.41% of the series. The increasing pattern had been seen in the years between 1998 and 2017 as shown in Figure 3(b). The increasing spatial pattern dominance was

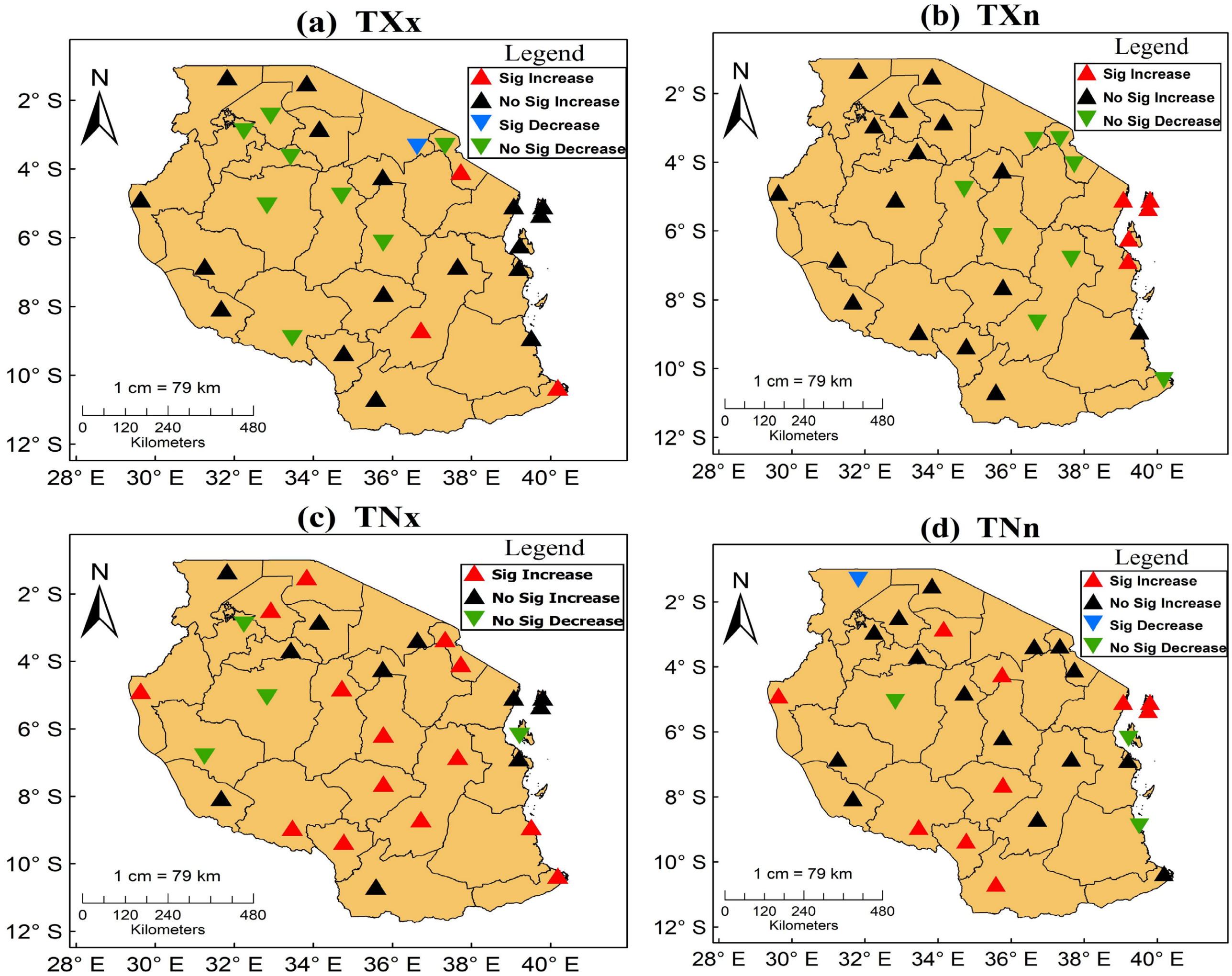

Figure 2. Spatial pattern of the annual average trends of absolute extreme temperature indices during 1982-2022 over Tanzania: (a) extreme warm days (TXx), (b) extreme cold days (TXn), (c) extreme warm nights (TNx) and (d) extreme cold nights (TNn). The Sig and No Sig represent the significant and No significant in the legends respectively.

Table 4. Annual trends of extreme temperature for 29 stations.

Stations	TXx	TXn	TNx	TNn	TX90p	TX10p	TN90p	TN10p
Arusha	**−0.040***	−0.011	0.016	0.020	0.062	0.134	**0.391***	**−0.219***
Babati	0.005	0.009	0.015	**0.027***	0.173	0.084	**0.383***	**−0.287***
Bukoba	0.006	0.007	0.001	**−0.017***	−0.108	−0.020	0.062	0.016
Dar es Salaam	0.008	**0.022***	0.003	0.008	**0.253***	**−0.193***	**0.275***	**−0.324***
Dodoma	−0.006	−0.008	**0.027***	0.012	−0.010	0.131	**0.218***	**−0.271***
Geita	−0.002	0.001	−0.003	0.019	0.087	0.076	0.084	−0.117
Iringa	0.013	0.006	**0.019***	**0.052***	0.065	−0.101	**0.367***	**−0.353***
Katavi	0.003	0.001	−0.001	0.017	−0.053	0.106	−0.025	−0.077
Kigoma	0.016	0.011	**0.013***	**0.033***	0.133	−0.114	**0.239***	**−0.296***
Lindi	0.006	0.007	**0.011***	−0.002	0.159	−0.094	**0.197***	**−0.200***
Mahenge	**0.018***	−0.002	**0.018***	0.001	0.036	0.101	**0.212***	**−0.197***
Mbeya	−0.003	0.023	**0.016***	**0.048***	0.044	−0.019	**0.337***	**−0.369***
Morogoro	0.010	−0.023	**0.024***	0.008	−0.002	**0.185***	**0.310***	**−0.244***
Moshi	−0.006	−0.011	**0.022***	0.022	**0.202***	0.086	**0.431***	**−0.315***
Mtwara	**0.036***	−0.016	**0.018***	0.008	0.152	0.018	**0.289***	**−0.206***
Musoma	0.006	0.003	**0.020***	0.015	−0.028	**0.156***	**0.275***	**−0.277***
Mwanza	−0.006	0.013	**0.018***	0.023	−0.001	0.121	**0.136***	**−0.176***
Njombe	0.015	0.028	**0.016***	**0.047***	0.140	−0.023	**0.317***	**−0.305***
NorthPemba	0.015	**0.033***	0.006	**0.029***	0.469	**−0.512***	**0.403***	**−0.451***
Same	**0.019***	−0.010	**0.021***	0.009	**0.200***	0.087	0.396	**−0.273***
Shinyanga	0.000	0.005	0.003	0.011	0.007	**0.142***	0.116	−0.127
Simiyu	0.001	0.007	0.014	**0.021***	−0.066	**0.223***	**0.265***	**−0.308***
Singida	−0.011	−0.017	**0.021***	0.011	−0.146	**0.175***	**0.233***	**−0.257***
Songea	0.013	0.002	0.014	**0.024***	−0.004	0.056	**0.194***	**−0.225***
SouthPemba	0.012	**0.031***	0.007	**0.029***	**0.406***	**−0.472***	**0.380***	**−0.481***
Sumbawanga	0.014	0.006	0.007	0.016	**0.109***	−0.023	0.114	**−0.176***
Tabora	−0.001	0.010	−0.012	−0.013	−0.144	**0.160***	0.032	−0.044
Tanga	0.006	**0.021***	0.005	**0.023***	**0.270***	**−0.264***	**0.311***	**−0.323***
Zanzibar	0.004	**0.027***	−0.001	−0.001	**0.022***	**−0.270***	**0.286***	**−0.400***

Note: *Statistical Significant at confidence level of 0.05.

seen in all areas of Lake Victoria, Western area and southern highlands as in Figure 2(b). Only regions of Tanga, South Pemba, North Pemba, Zanzibar and Dar es salaam had a significant increase (Table 4, Figure 2(b)). The decrease was seen in Arusha, Moshi, Same, Morogoro, Mahenge, Singida, Dodoma and Mtwara but not statistically significant (Figure 2(b)).

The annual maximum value of daily minimum temperature (TNx) had an increase rate of 0.01˚C/year. In Table 3, only 48.28% of the series had a positive

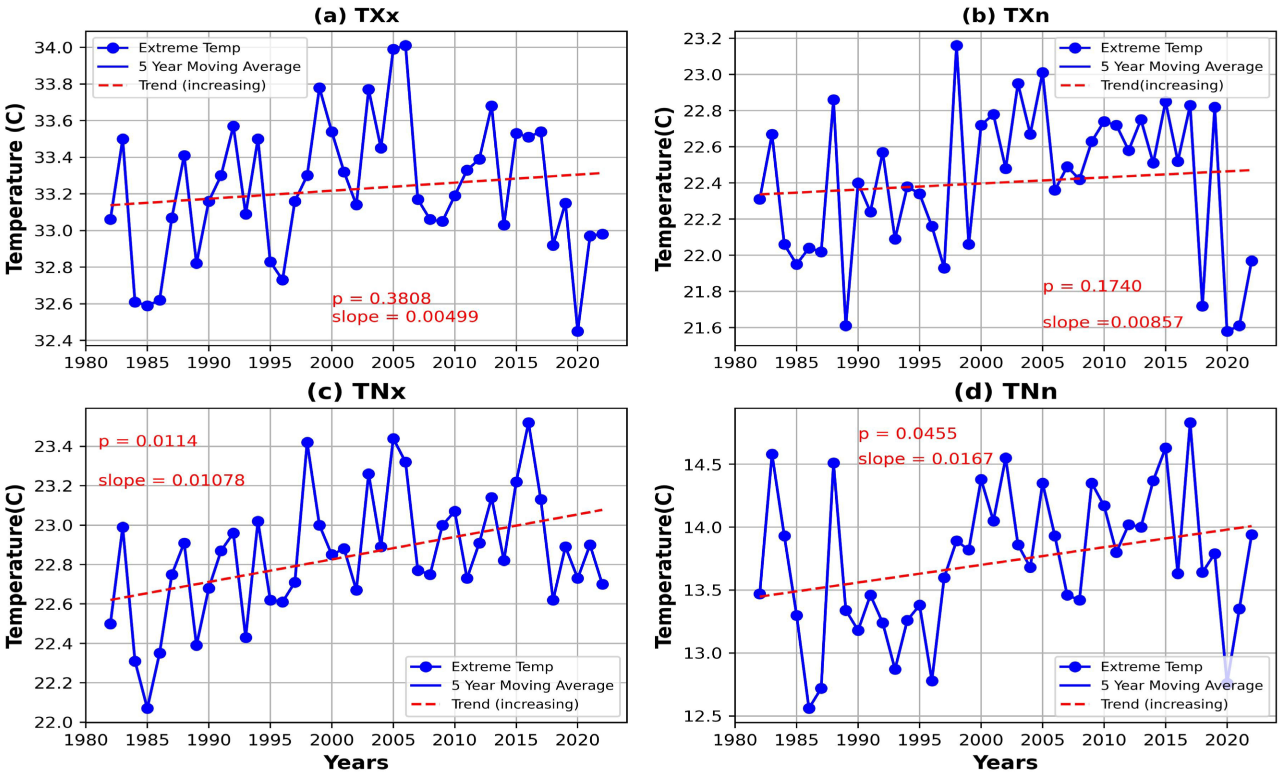

Figure 3. Annual averages of absolute extreme temperature distribution during the period of 1982-2022 in Tanzania.

statistical significant trend. In general, the increasing trends were predominant in 86.21% of the series. The increasing pattern had been seen in the years between 1998 to 2017 as in Figure 3(c). The spatial pattern significant increase had been seen in 14 regions among the 29 stations which include Musoma, Kigoma, Mwanza, Moshi, Same, Singida, Dodoma, Morogoro, Mahenge, Iringa, Njombe, Mbeya, Lindi and Mtwara (Table 4, Figure 2(c)). The increasing pattern but not statistically significant were observed in the regions of Bukoba, Simiyu, Shinyanga, Manyara, Arusha, Tanga, South Pemba, North Pemba, Sumbawanga, Songea and Dar es salaam. In the Figure 2(c) the decrease had been noticed in the regions of Geita, Tabora, Katavi and Zanzibar with no statistical significant.

The annual minimum value of daily minimum temperature (TNn) had an increase rate of 0.02˚C/year. In Table 3, only 37.93% of the series had a statistical significant trend in which positive statistical trend was 34.48% and 3.45% was for negative statistical trend. In general, the increasing trends were predominant in 86.21% of the series. The temporal increasing pattern was seen in the years of 1982 to 1984, 1997 to 2003, 2005 to 2006 and 2009 to 2015 in Figure 3(d). The spatial pattern significant increase had been seen in the regions of Kigoma, Simiyu, Babati, Tanga, South Pemba, North Pemba, Iringa, Mbeya, Njombe and Songea (Table 4, Figure 2(d)). The significant decrease was only observed in Bukoba area (Table 4, Figure 2(d)). The increasing pattern but not statistically significant was seen in the regions of Musoma, Mwanza, Geita, Shinyanga, Dodoma, Arusha, Moshi, Same, Singida, Morogoro, Mahenge, Katavi, Sumbawanga, Mtwara and Dar es salaam. The decrease was seen in Tabora, Zanzibar and Lindi regions with no statistical significant.

3.3. Annual Changes of Percentile Extreme Temperature Indices

The percentage of days when daily maximum temperature > 90th percentile in a year (TX90p) and the percentage of days when daily maximum temperature < 10th percentile in a year (TX10p) show positive (increasing) and negative (decreasing) trends but they are not statistically significant respectively. The percentage of days when daily minimum temperature > 90 percentile in a year (TN90p) and the percentage of days when daily minimum temperature < 10th percentile in a year (TN10p) show positive (increasing) and negative (decreasing) trends and they are statistically significant as indicated in **Figures 5(a)-(d)** respectively.

During the period of analysis the annual TX90p had an increase of 0.103 days/year in Tanzania. From **Table 3**, only 41.38% had significant positive trends in which there was no any negative significant trend. Generally, the increasing trends were predominant in 65.52% of the series. The temporal increasing trends pattern was seen in the years of 1983, 1988, 1991, 1998 to 2003, 2005 to 2006, 2009 to 2011, 2013, 2015 to 2017 and 2019 as seen in **Figure 5(a)**. The spatial pattern of the significant increasing had been seen in the regions of Moshi, Same, Tanga, South Pemba, North Pemba, Zanzibar and Dar es salaam (**Table 4**, **Figure 4(e)**). The increasing trend but not statistically significant was observed in the regions of Geita, Shinyanga, Manyara, Arusha, Sumbawanga, Mbeya, Iringa, Njombe, Mahenge, Lindi and Mtwara. The decreasing trend was seen in Bukoba, Musoma, Mwanza, Simiyu, Tabora, Katavi, Singida, Dodoma, Morogoro and Songea with no statistical significant as shown in **Figure 4(e)**.

In the analysis the annual TX10p had a decrease rate of 0.007 days/year in Tanzania. From the **Table 3**, only 37.93% had significant trends in which 20.69% had positive and 17.24% had negative significant trends. In general the increasing trends were predominant in 58.62% of the series. The temporal increasing trends pattern was observed in the years of 1984 to 1986, 1989 to 1990, 1990, 1996 to 1997, 1999, 2006, 2008, 2018, 2020 to 2022 as depicted in **Figure 5(b)**. The spatial pattern of the significant increasing had been seen in the regions of Musoma, Simiyu, Shinyanga, Tabora, Singida and Morogoro (**Table 4**, **Figure 4(f)**). In the meantime, the significant decreasing trends were seen in the regions of Tanga, South Pemba, North Pemba, Zanzibar and Dar es salaam (**Table 4**, **Figure 4(f)**). The increasing trends were observed in the regions of Geita, Mwanza, Arusha, Moshi, Same, Manyara, Dodoma, Mahenge, Songea and Mtwara but were not statistically significant. The decreasing trend which is not statistically significant was observed in the regions of Bukoba, Kigoma, Sumbawanga, Mbeya, Njombe, Iringa and Lindi as referred to **Figure 4(f)**.

During the analysis the annual TN90p had an increasing rate of 0.309 days/year in Tanzania. Only 79.31% had positive significant trends as shown in **Table 3**.

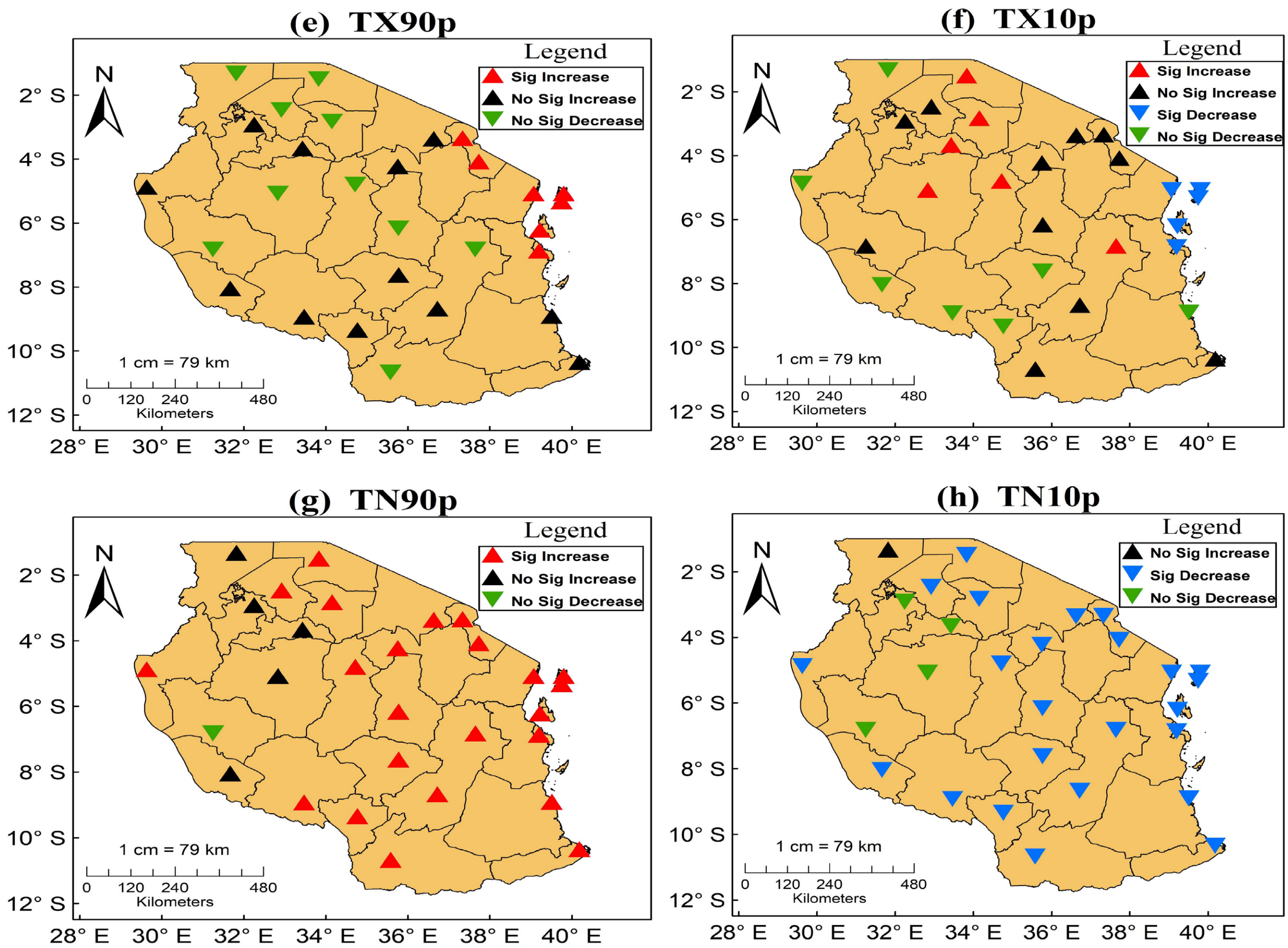

Figure 4. Spatial pattern of the annual average trends of percentile extreme temperature indices during 1982-2022 over Tanzania: the numbers of (e) warm days (TX90p), (f) cold days (TX10p), (g) warm nights (TN90p) and (h) cold nights (TN10p). The Sig and No Sig represent the significant and No significant in the legends respectively.

Generally, the increasing trends were predominant in 96.55% of the series. The fluctuations were also seen in the time series in which the temporal pattern trends were observed in the years of 1982 to 1983, 1987 to 1988, 1991, 1998, 2003, 2005 to 2007, 2009 to 2011, 2015 to 2017 and 2019 as depicted in Figure 5(c). The spatial pattern significant increasing trends were seen in the regions of Kigoma, Mwanza, Musoma, Simiyu, Arusha, Moshi, Same, Babati, Singida, Dodoma, Morogoro, Mahenge, Iringa, Mbeya, Njombe, Songea, Mtwara, Lindi, Zanzibar, South Pemba, North Pemba, Tanga and Dar es salaam (Table 4, Figure 4(g)). The decreasing trends but not statistically significant was seen only in Katavi region. The increasing trends with no statistical significant were observed in the regions of Bukoba, Geita, Shinyanga, Tabora and Sumbawanga as referred in Figure 4(g).

The analysis of annual TN10p had a decreasing rate of 0.256 days/year. Only 82.76% had negative significant trends. Generally, the decreasing trends were predominant in 96.55% of the series. The fluctuations were also seen in the time series in which the temporal pattern trends were observed in the years of 1982 to

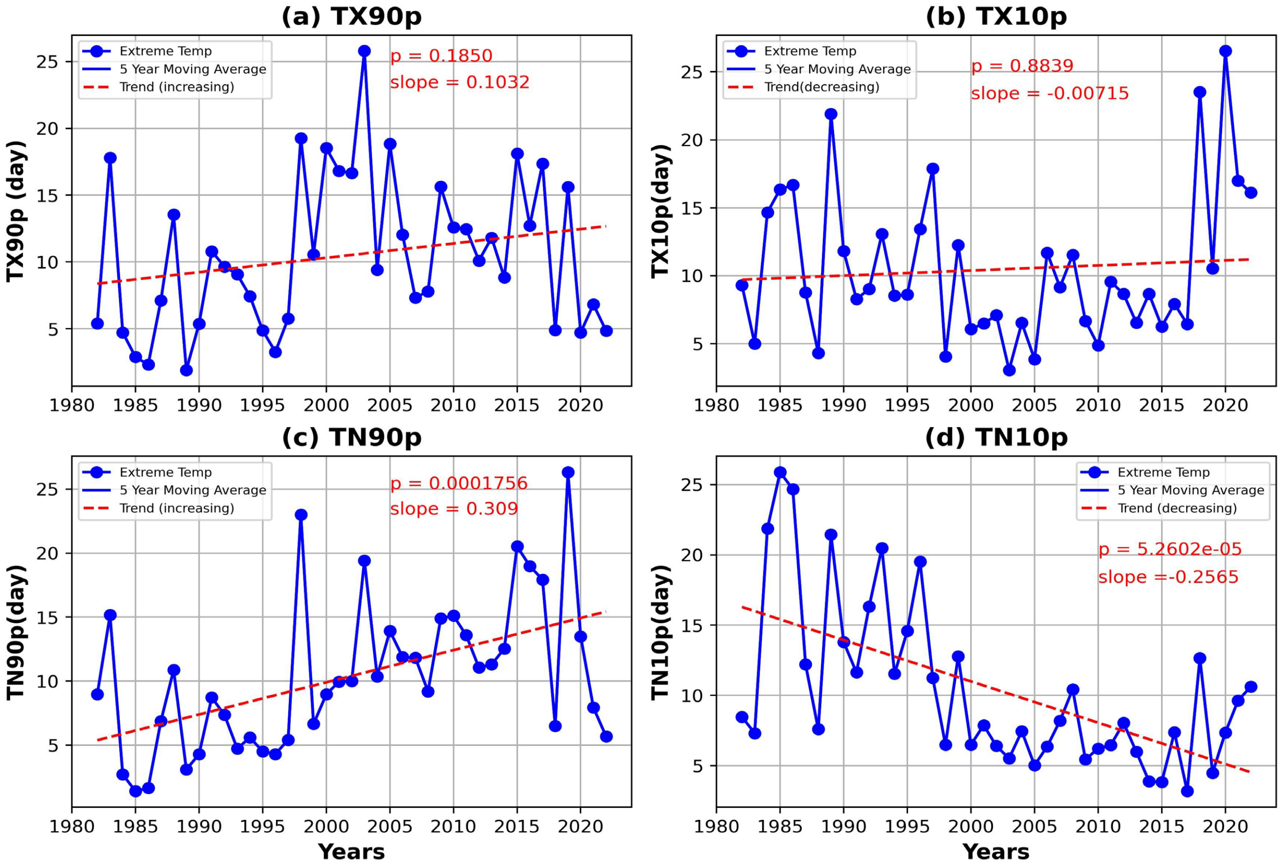

Figure 5. Annual averages of percentile extreme temperature distribution during the period of 1982-2022 in Tanzania.

1983, 1987 to 1988, 1990 to 1991, 1994, 1997 to 1998, 2000 to 2007, 2009 to 2011, 2013 to 2015 and 2017 to 2019 as shown in the Figure 5(d). The spatial pattern significant decreasing trends were observed in the regions of Musoma, Mwanza, Simiyu, Kigoma, Singida, Dodoma, Babati, Arusha, Moshi, Same, Tanga, South Pemba, North Pemba, Zanzibar, Dar es salaam, Morogoro, Mahenge, Iringa, Njombe, Mbeya, Sumbawanga, Songea, Lindi and Mtwara (Table 4, Figure 4(h)). The decreasing pattern with no statistical significant was seen in Geita, Shinyanga, Tabora and Katavi. The only increasing spatial pattern with no statistical significant was observed in Bukoba as shown in the Figure 4(h).

In comparison, there has been an increase in the percentage of warm nights (TN90p) and warm days (TX90p). The trend in the percentage of TN90p is more prominent in larger regions of the country, suggesting that the nights are warming more quickly, as illustrated in Figure 4(g). In the meantime, the results obtained are in line with other research findings in the study area (Chang'a et al., 2017; Chang'a et al., 2021). They are also in line with the observed temperature extreme trends in various parts of the world as shown in the IPCC Reports (IPCC, 2007; Chang'a et al., 2017; Wang et al., 2018), which show that the number of warm days (TX90p) and nights (TN90p) are increasing. Seemingly, the number of cold days (TX10p) and nights (TN10p) has been decreasing. On the extreme absolute temperature indices, the findings show that the warming nights have increased and the coldness have decreased comparing with the warm days and cold days. Similar phenomena agree with various obtained results from different parts of the world.

4. Conclusion

Daily climate datasets of the minimum and maximum temperatures for all 29 meteorological stations from 1982 to 2022 were retrieved from NASA and used in the analysis. Based on the study, the data match and yield comparable findings to those of previous studies that made use of observable datasets. This leads to the conclusion that the datasets are trustworthy, as confirmed by several studies that used NASA/POWER data.

Overall, the country has witnessed a rise in both warm days and nights, coupled with a decline in cold days and nights. There is an upward trend in the count of warm nights and days, particularly notable in the increasing number of warm nights. This evolving pattern indicates a general increase. Conversely, there is a tendency towards fewer cold days and nights, indicating a warming trend during the nights. The annual averages of extreme temperatures exhibit temporal variations with notable year-to-year fluctuations and evident upward and downward trends.

Similar to this, a spatial study of the extreme temperature trend has shown a statistically significant and consistent warming of the country throughout the night over a substantial portion of it, as well as a decrease in the number of cold nights in most regions.

The observed trends in warming have significant effects on several socio-economic domains and means of subsistence. However, warming over the study region may also increase the pace at which water evaporates from bodies of water and transpires through plant stomata, resulting in a decrease in the amount of water used for residential, agricultural, and livestock needs. However, from the results obtained, which looked onto annual timescale, thus, the study based on seasonal timescale shall be analyzed and the concentration on large atmospheric circulations on how they affect the extreme temperature changes shall be studied.

Data Availability

The data that support the findings of this study are openly available at the following link https://power.larc.nasa.gov/data-access-viewer/.

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Conflicts of Interest

The authors declare no any conflict of interest to the publication of this research.

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