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Trends of Temperature Extreme Indices over Arusha and Kilimanjaro Regions in Tanzania

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Abstract

The study aimed at analyzing the trends and variability of temperature extremes over the northeastern highlands in Tanzania, specifically over Arusha and Kilimanjaro regions. Quality controlled mean monthly, daily maximum and minimum temperature data for the period 1961 to 2020, obtained from Tanzania Meteorological Authority, were used in the study. Rclimdex and the National Climate Monitoring Products (NMCP) software, developed by the World Meteorological Organization (WMO), were used for computation of the indices at a monthly, seasonal and annual time scale. The computed indices were also subjected to trend analysis to determine their direction and magnitude of change. Extraction and assessment of the top five highest and lowest maximum and minimum temperatures were also done. Increasing trends of temperature anomalies for seasonal and annual timescales were observed for both Arusha and Kilimanjaro regions. Also, the increasing trends of warm and extreme warm days and nights and relatively increasing trends of cold and extreme cold days and nights were observed for both regions. The highest ever recorded temperatures since the establishment of the two stations were 36.3˚C observed on 16th February 2011 and 38.6˚C observed on 22nd February 2005 for Arusha and Kilimanjaro respectively. These results indicate that The last two decades have been characterized by enhanced warming, which is consistent with overall global temperature trend patterns as depicted in recent IPCC reports and the report of the State of Climate in Africa.

Keywords

Climate Extreme, Warm Night, Cold Night, Extreme Temperature, Indices,

NCMP

1. Introduction

Recent reports from the Intergovernmental Panel on Climate Change [1] [2] [3] [4] have highlighted the increasing threat posed by climate change and climate variability to human and natural systems across the globe. Warming of the climate system has accelerated at an unprecedented rate, with six warmest years on record happening over the last decade, between 2015 and 2020, whereby 2016, 2019 and 2020 are three warmest years on record [5]. Anthropogenic warming reached approximately 1.0˚C above pre-industrial levels (1890-1900) in 2017 [3], and 1.1˚C above pre-industrial levels in 2019 [6]. Record breaking extreme events are becoming common in different parts of the world including Tanzania, and are the major causes of devastating disasters [7] [8] [9]. Climate variability and change, and particularly increasing frequency and intensity of climate extremes are exerting more pressure on human and natural systems and significantly affecting socio-economic development of most African countries including Tanzania, particularly in traditional rain-fed agriculture, pastoralism and water resources [10].

Extreme events, such as floods and droughts, are causing major human and environmental impacts and disruptions of various socio-economic development strategies and plans of most African countries including Tanzania [11]. Furthermore, average annual temperature is projected to increase by 1.0˚C to 2.7˚C by the 2060s and by 1.5˚C to 4.5˚C by the 2090s, resulting in the regular increase in the number of hot days and nights. As well as projected increase in frequency and amplitude of extreme climate events in most parts of the country, particularly the Central and Northern Zones, and resulting in long-term impacts on the agricultural and other vulnerable sectors [12] [13] [14] [15] [16].

Unfortunately, there is still only limited knowledge and understanding about the distribution, dynamics and trends of extreme temperature in many localized parts of Tanzania including in Arusha and Kilimanjaro regions. Understanding the distribution of extreme temperature and the associated trends at a finer resolution is critical for informed decision making, in planning and implementation of various socio-economic activities, sensitive to climate variability and change, and also for development of effective climate change adaptation options. Therefore, this study aimed at analyzing and characterizing temperature extremes, and their associated trends over the northeastern Tanzania focusing on Arusha and Kilimanjaro regions.

2. Description of the Study Area

The northeastern part of Tanzania comprises three regions Arusha, Kilimanjaro and Manyara. The study focused on Arusha and Kilimanjaro regions, which lie between 2˚S and 4˚S and meridians 35˚E and 38.5˚E as depicted in **Figure 1**. The regions exhibit a mountainous terrain including Mount Meru with an altitude of 4566 m, and Arusha and Mount Kilimanjaro with an altitude of 5895 m above sea level. (Mount Kilimanjaro is the highest mountain in Africa and the world's highest, single, free standing dormant volcanic mountain, measuring 80 km by 50 km, and located on the Tanzania-Kenya border 3˚04'S, 37˚21'E). The seasonal rainfall patterns are mainly associated with the southward and northward movement of the ITCZ, which is the main cause of the bimodal rainfall regime namely "Long rainy" season, which starts in March and ends in May (MAM) and the "short rainy" season, which starts in October and ends in December (OND). Moreover, the amount of rainfall varies according to altitude and the direction of the slope in the mountainous areas. In these two regions, livestock keeping, agriculture and tourism are the main socio-economic activities, which are strongly affected by climate change including rising in temperatures.

3. Data and Methodology

3.1. Data Source and Type

This study used quality-controlled mean monthly, daily maximum and minimum temperature data from Arusha and Kilimanjaro meteorological stations, for the period 1961-2019 and 1972-2019 respectively. The temperature data was obtained from Tanzania Meteorological Authority (TMA). The description of

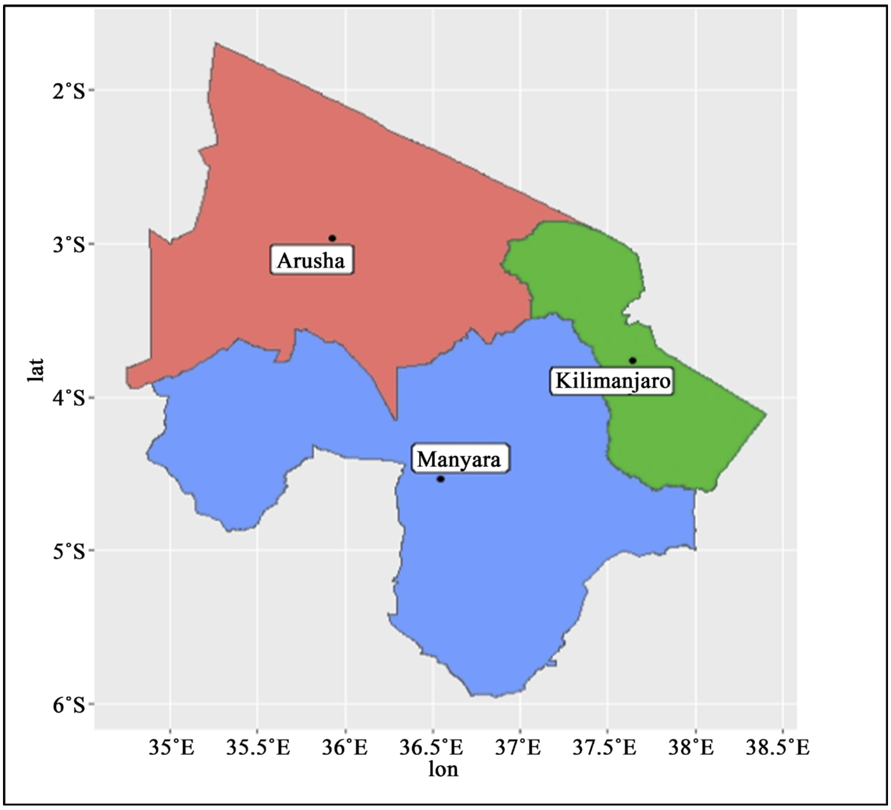

Figure 1. A geographical map of northeastern Tanzania.

the data used included the geographical coordinates and altitude of the respective stations as provided in **Table 1**. The use of quality controlled data is a necessary prerequisite in the analysis of climate Indices [17] [18]. It provides an opportunity to identify suspicious data and any erroneous outlier that might influence the analysis, including daily values outside the user-predefined threshold. It helps to verify whether the reported data value is representative of what was intended to be measured, and has not been contaminated by unrelated factors. RClimdex and National Climate Monitoring Products (NCMP) software used in this study for quality control of the data, are often used to examine the data and identify those that fail pre-defined tests [7] [19].

Table 1. Geographical coordinates of the stations used in the study.

Stations	Latitude	Longitude	Altitude (m)	Period of data used
Arusha airport	3˚22'	36˚38'	1372	1961-2019
Kilimanjaro airport (KIA)	3˚25'	37˚4'	1144	1972-2019

3.2. Methodology

RClimdex and NMCP softwares were used for the computation of the climate extreme Indices, adopting a similar approach as used by Expert Team on Climate Change Detection Indices (ETCCDI) and Expert Team on National Climate Monitoring Products (NCMPs) [18].

Detailed description of the methods and approach used in the computation of the climate indices using Rclimdex and NCMP software is shown in [7] [14] [16] and can also be accessed from [11] [20] [21]. The linear trends presented in this study (**Figure 2** to **Figure 7**) are computed from the indices series using a Kendall's tau based slope estimator [22]. This estimator is robust enough to detect of outliers in the series. It has been widely used to compute trends in hydro-meteorological series, as seen, for example, in [23] [24] [25] [26]. The significance of the trend was determined using the Mann-Kendall test and was estimated at a 5% significance level [27]. The trend was considered to be statistically significant if it was less than or equal to a level of 5% [28] [29] [27] [30].

Daily maximum and minimum temperature data are analyzed for the estimation of warm and cold day/night trends, and extreme warm and extreme cold day/night trends using eight (8) extreme temperature indices provided in **Table 2**. Moreover, the computation of the top five extreme temperatures that occurred during the period 1961-2019 and 1972-2019 for Arusha and Kilimanjaro respectively is carried out; and finally analysis of mean monthly temperature data for temperature anomalies on seasonal and annual timescales is implemented.

4. Results and Discussion

The findings in this study are presented in four sections that includes description of the trends of warm and cold days and nights (Section 4.1); description of the trends of the extreme warm and cold days and nights (Section 4.2); trends of

Table 2. Definition of extreme temperature indices used in this study.

Index	Indicator name	Definition	Unit
TXx	Warmest day-Max T_{max}	Annual highest TX-Monthly maximum value of daily maximum temperature	˚C
TNx	Warmest night-Max T_{min}	Annual highest TN-Monthly maximum value of daily minimum temperature	˚C
TXn	Coldest day-Min T_{max}	Annual lowest TX-Monthly minimum value of daily maximum temperature	˚C
TNn	Coldest night-Min T_{min}	Annual lowest TN-Monthly minimum value of daily minimum temperature	˚C
TN10p	Cold night frequency	Percentage of days when TN < 10^{th} percentile of 1961-1990	%
TX10p	Cold day frequency	Percentage of days when TX < 10^{th} percentile of 1961-1990	%
TN90p	Warm night frequency	Percentage of days when TN > 90^{th} percentile of 1961-1990	%
TX90p	Warm day frequency	Percentage of days when TX > 90^{th} percentile of 1961-1990	%

seasonal and annual temperature anomalies (Section 4.3); and the top five extreme temperatures and the lowest five extreme temperatures for Arusha and Kilimanjaro since the establishment of the stations (Section 4.4).

4.1. Trends of Warm and Cold Days/Nights

It has been observed that, for both Arusha and Kilimanjaro regions, the percentage of warm days and warm nights exhibit an increasing trend; while the percentage numbers of cold days and cold nights show a decreasing trend. Figure 2 and Figure 3 depict a trend of the percentage of number of warm and cold days/nights at Arusha airport and KIA station respectively. In both regions, it is observed that, the trend of cold days (TX10p) and nights (TN10p) is decreasing fast. The sharp and fast decrease in the number of cold days and cold nights may be translated into a warming of the minimum temperature across the region, which is consistent with national and regional temperature patterns [7]. Time series analysis of the number of cold days and cold nights over Arusha and Kilimanjaro stations indicates that the percentage number of both days and nights exhibits a decreasing trend, and is characterized by stronger inter-annual variability (Figure 2 and Figure 3). Comparatively, the percentage number of warm nights and warm days has been increasing, and the trend is more pronounced in the percentage number of warm nights, particularly in Arusha, indicating that the nights are warming faster (Figure 2). These findings are consistent with other nation wide analyses [7], and also compliant with the observed temperature extreme trends in different parts of the world as depicted in the IPCC Assessment Reports [1] [31] [4] and [7], which indicates that the number of cold days and nights have been decreasing, while the number of warm days and nights are increasing.

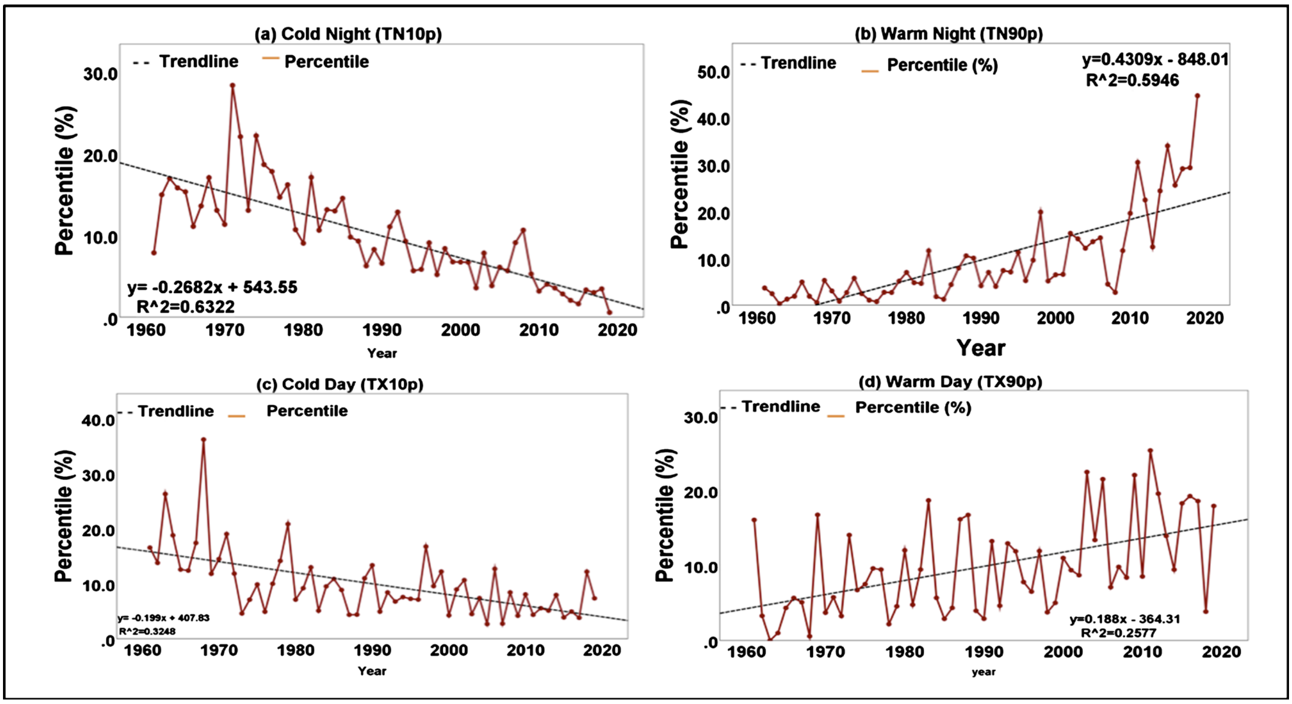

Figure 2. Trends in warm and cold days and nights 1961-2019 in Arusha airport station in Arusha region.

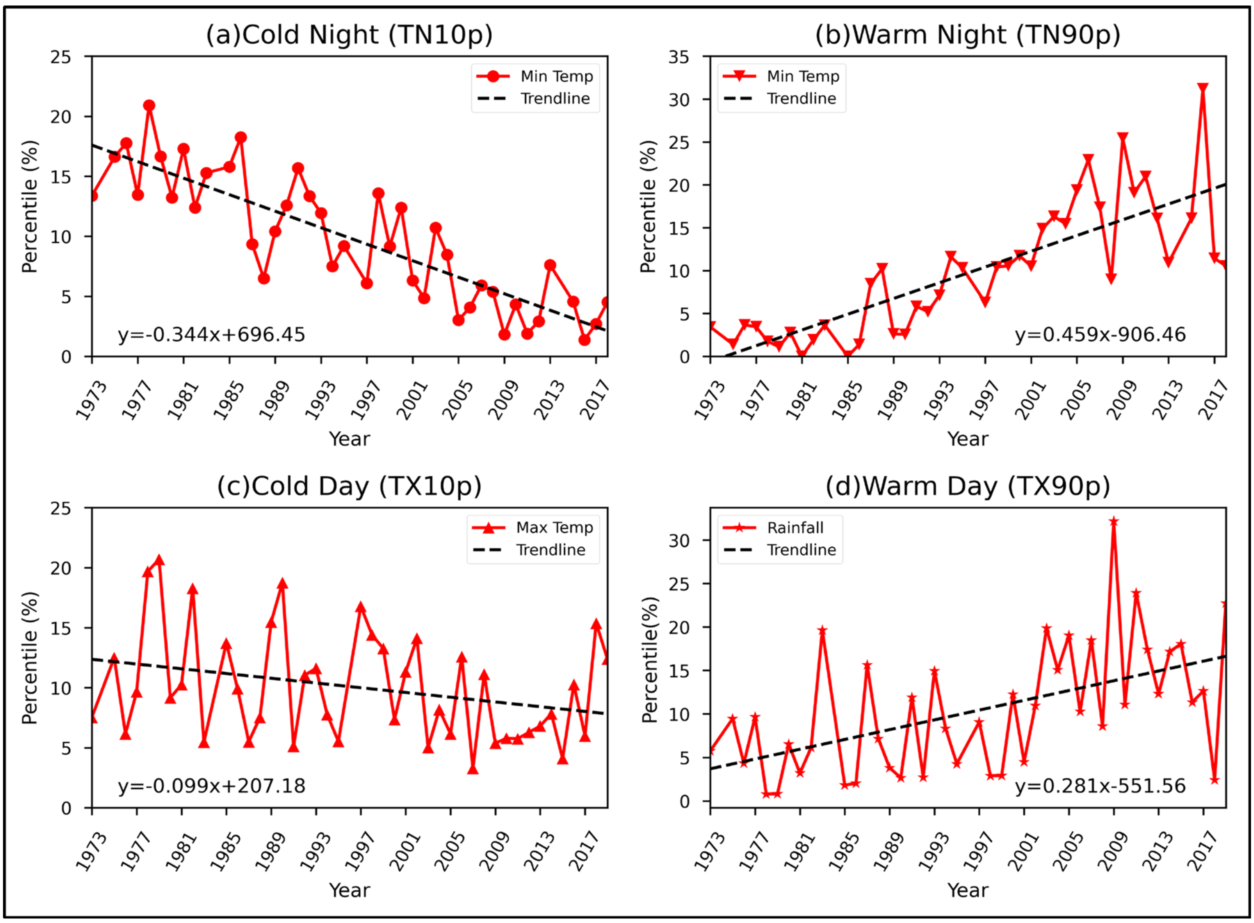

Figure 3. Trends of warm and cold days and nights 1972-2019 in Kilimanjaro Airport station (KIA) in Kilimanjaro region.

4.2. Trends of Extreme Warm and Cold Days/Nights

The trends of extreme warm days (TXx) and extreme warm nights (TNx) are observed to increase at both Arusha and Kilimanjaro meteorological stations (Figure 4 and Figure 5). Similar trend pattern is observed for extreme cold days and extreme cold nights, whereby warming of the extreme cold nights is more pronounced than warming of extreme cold days. This implies that the nights are getting warmer faster than the days.

4.3. Trends of Seasonal and Annual Temperature Anomalies

The analysis of trends in seasonal and annual temperature anomalies is done for four seasons; January-February (JF), March to May (MAM), June to September (JJAS) and October to December (OND). It is well known that, during March to May (MAM) and October–December (OND) the study domains experience "long rainy" and "short rainy" seasons respectively. During January-February (JF), the regions experience a transition period which is relatively dry, while during June to September (JJAS) both regions experience relatively dry and cold weather conditions respectively.

It has been observed that in all seasons (JF, MAM, JJAS and OND) for both Arusha and Kilimanjaro, mean seasonal temperature anomalies are characterized by stronger inter-annual variability, and exhibits a well pronounced increase in the trend (Figures 6(a)-(e) to Figures 7(a)-(e)). For JF and JJAS seasonal temperature anomalies in both Arusha and Kilimanjaro, earlier decades

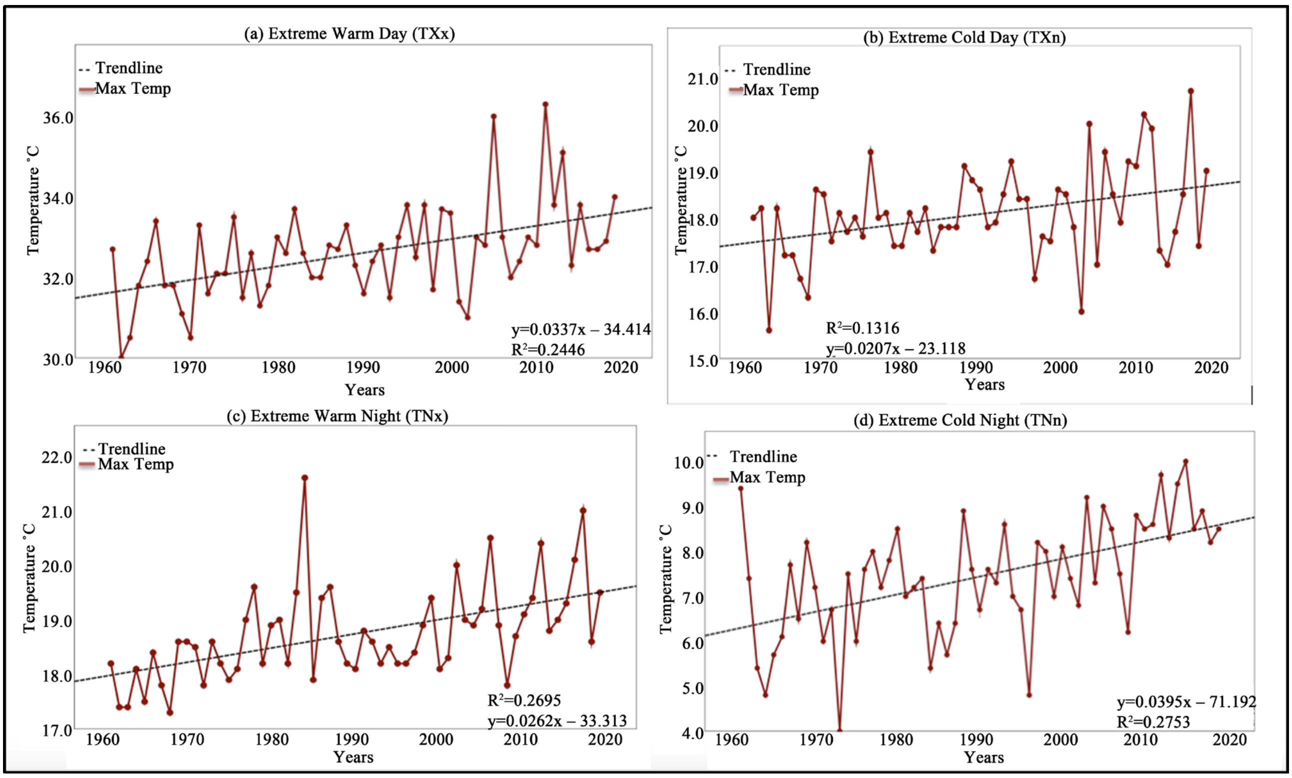

Figure 4. Trends in extreme cold and extreme warm days and nights 1961-2019 in Arusha Airport station in Arusha region.

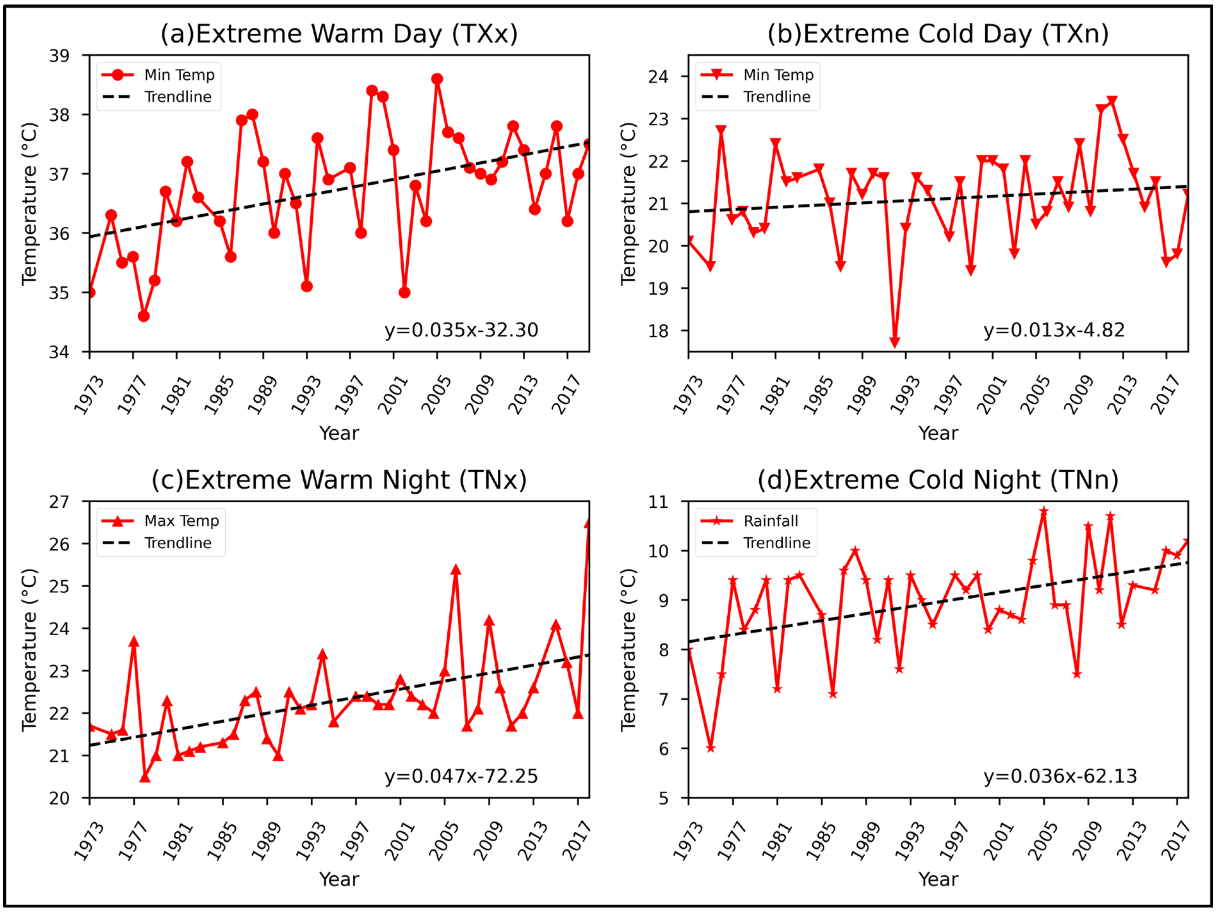

Figure 5. Trends in extreme cold and extreme warm days and nights 1972-2019 in KIA station in Kilimanjaro region.

(1961-1981) have been characterized by negative temperature anomalies, while recent decades (1989-2019) have been characterized by positive temperature anomalies (Figure 6(a) and Figure 6(c)). However, MAM and OND seasons have been dominated by positive temperature anomalies (Figure 6(b) and Figure 6(d)). Mean annual temperature anomalies exhibit stronger inter-annual variability, whereby the earlier decades (1961-1981) have been dominated by negative temperature anomalies, while the last two decades have been dominated by positive temperature anomalies (Figure 6(e)).

For Kilimanjaro region, the JF, MAM, JJAS and OND have been dominated by positive temperature anomalies especially in the last two decades (2000-2020), while earlier decades (1971-1990) have been largely dominated by negative temperature anomalies. These results indicate the accelerated warming over the last two decades.

4.4. Top Five Extreme Temperature Occurrences

Monitoring and characterization of extreme temperature indices is very important and useful for climate change detection and for effective planning and designing of various infrastructures related development activities. The result indicates that, for both Arusha and Kilimanjaro regions, the top five highest daily

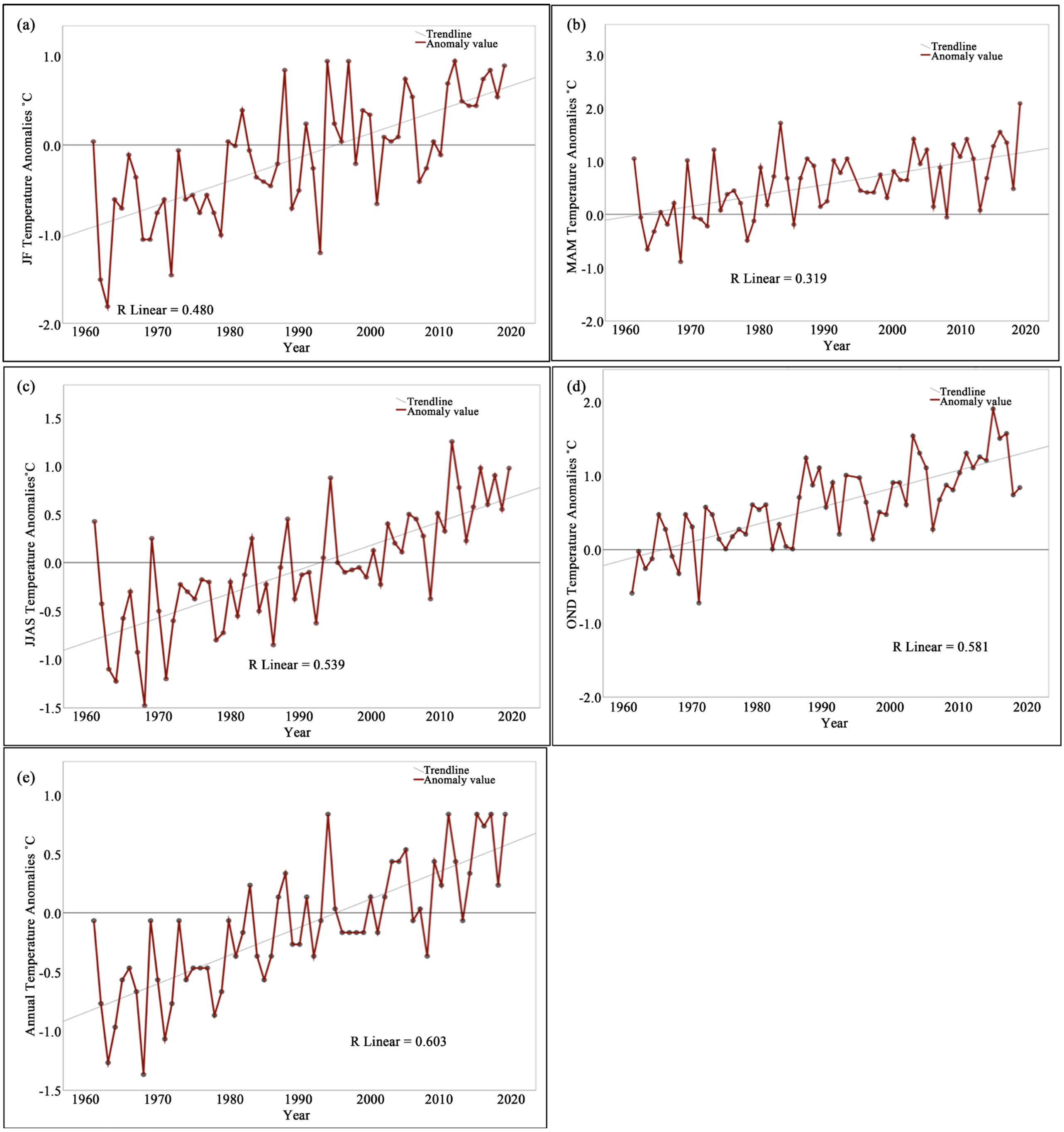

Figure 6. (a) Average temperature anomalies for JF from 1961-2019 over Arusha region. (b) Average temperature anomalies for MAM from 1961-2019 over Arusha region. (c) Average temperature anomalies for JJAS from 1961-2019 over Arusha region. (d) Average temperature anomalies for OND from 1961-2019 over Arusha region. (e) Annual mean temperature anomalies from 1961-2019 over Arusha region.

maximum temperatures have been observed in the last two decades, that is between 2000 and 2020 (Table 4 and Table 6). The highest ever-recorded daily maximum temperatures for Arusha region is 36.3˚C observed on 16th February 2011, and for Kilimanjaro it is 38.6˚C observed on 22nd February 2005. Table 3 and Table 5 present the lowest five daily minimum temperatures for Arusha

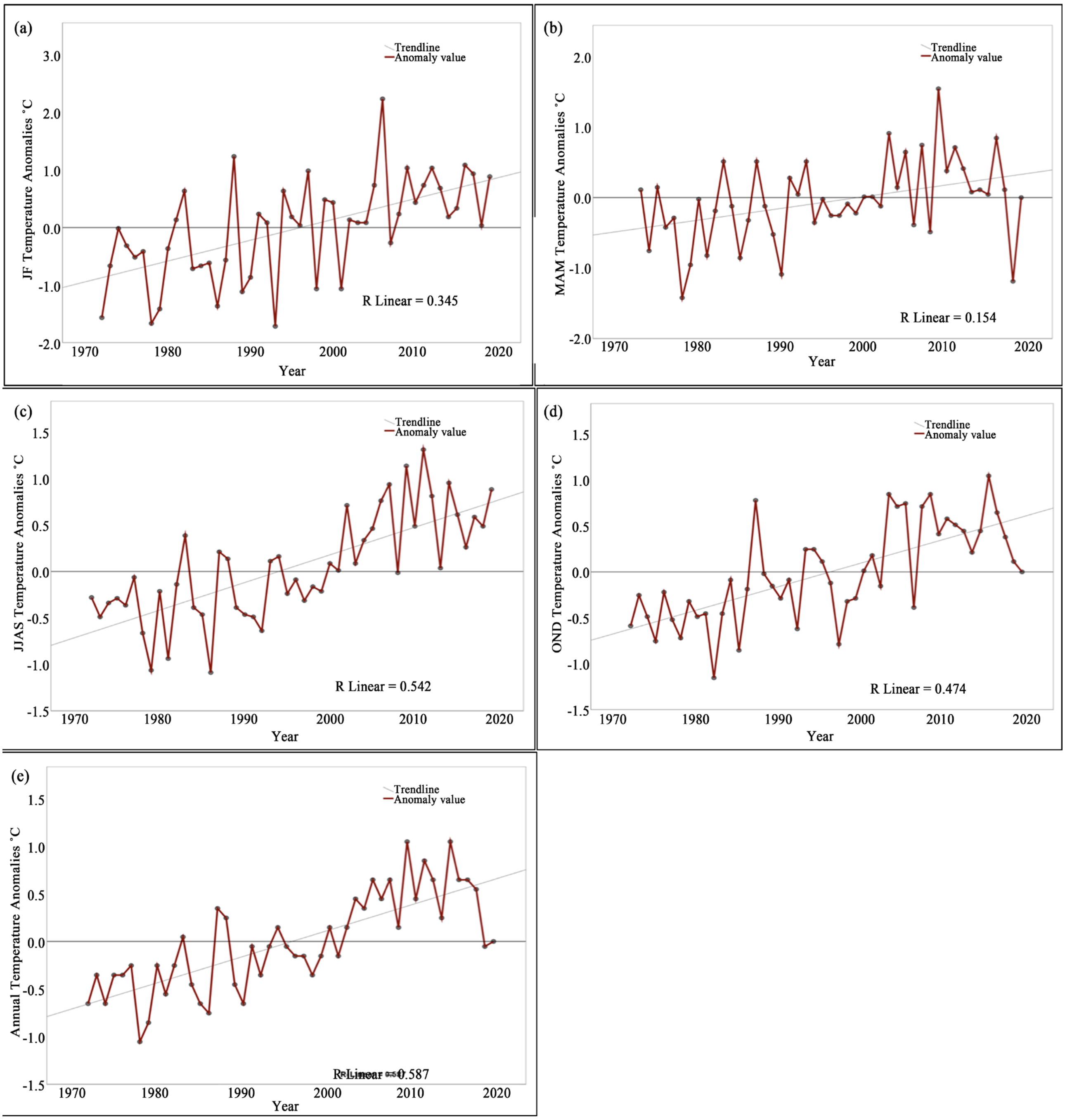

Figure 7. (a) Average temperature anomalies for JF from 1972-2019 over Kilimanjaro region. (b) Average temperature anomalies for MAM from 1972-2019 over Kilimanjaro region. (c) Average temperature anomalies for JJAS from 1972-2019 over Kilimanjaro region. (d) Average temperature anomalies for OND from 1972-2019 over Kilimanjaro region. (e) Annual mean temperature anomalies from 1972-2019 over Kilimanjaro region.

and Kilimanjaro respectively. Most of the lowest recorded minimum temperatures were observed before 2000 (Table 3 and Table 5). These results are consistent with global warming patterns as depicted in IPCC and WMO reports indicating that the last three decades have been successively warmer than any preceding decades since 1850.

Table 3. The five lowest observed daily minimum temperatures (T_{min}) at Arusha meteorological station (1961-2020).

	Month	Day	T_{min} (˚C)
2009	7	17	1.3
1973	10	8	4.0
1964	7	10	4.8
1996	8	4	4.8
1964	8	12	5.0

Table 4. The five highest observed daily maximum temperatures (T_{max}) at Arusha meteorological station (1961-2020).

Year	Month	Day	T_{max} (˚C)
2011	2	16	36.3
2005	2	22	36.0
2005	2	23	35.1
2013	2	01	35.1
2005	2	24	34.9

Table 5. The five lowest observed daily minimum temperatures (T_{min}) at Kilimanjaro meteorological station (1972-2020).

Year	Month	Day	T_{min} (˚C)
1975	7	28	6.0
1986	8	13	7.1
1981	8	1	7.2
1984	9	8	7.4
1996	7	1	7.4

Table 6. The five highest observed daily maximum temperatures (T_{max}) at Kilimanjaro meteorological station (1972-2020).

Year	Month	Day	T_{max} (˚C)
2005	2	22	38.6
2005	2	25	38.6
1999	2	10	38.4
2000	2	22	38.5
2005	2	24	38.2

5. Summary and Conclusion

In this study, the observed quality-controlled temperature data on daily, seasonal and annual timescales were analyzed to depict the trends of extreme temperature indices, the temporal distribution of the highest recorded maximum temperature and lowest recorded minimum temperature in Arusha and Kilimanjaro regions. It has been found that, for both Arusha and Kilimanjaro regions across all the seasons (JF, MAM, JJAS, OND), temporal distribution of the mean seasonal temperature anomalies is characterized by stronger inter-annual variability and exhibits a well pronounced increasing trend. It has also been found that the last two decades have been dominated by positive temperature anomalies. The number of warm days and warm nights are characterized by an increasing trend, whereby the trend in the number of warm nights is much faster than the trend in the number of warm days. However, the number of cold days and cold nights exhibits a decreasing trend, signifying that the nights are getting warmer. For both Arusha and Kilimanjaro regions, it has been observed that all of the top five highest recorded maximum temperatures occurred in the last two decades, that is between 2000 and 2020, which is consistent with global warming patterns. The observed warming trends have consequential implications to various socio-economic sectors and livelihood activities. It might also be contributing to accelerated melting of glaciers over Mt. Kilimanjaro, and leads to further investigation including projection of the warming and temperature dynamics in the near, medium and long-term future.

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Conflicts of Interest

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

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