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Research Article

Spatial and temporal trend analysis of temperature extremes in Tanzania

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Abstract

This study examines the effects of extreme temperature events, defined explicitly as the 98th percentile temperature for heat, in Tanzania from 1981 to 2023. The study utilises percentile analysis, z-score calculations, and trend mapping to highlight the prevalence of extreme temperatures. The z-score analysis examines the occurrence of extreme temperatures and their distribution in terms of frequency and space. It identified Tanzania's mid-eastern and north-western regions as areas with a high concentration of extreme temperatures over the previous 43 years. The study analyses the length of extreme occurrences and reveals changing patterns. In 2020, the events were shorter, while in 2021 and 2022, they became longer-lasting, and there was a notable concentration of extended anomalies near the northern coastline. In 2023, the highest temperatures ever recorded were observed, with more than half of the regions seeing prolonged periods of extreme temperatures lasting for a week and significant deviations from the norm staying for four weeks or more. This was particularly notable in the southern regions of Lindi and Mtwara. The harmonic trend analysis of temperature shows an upward temperature trend noticeably in regions such as Arusha, Kilimanjaro, Kagera, Morogoro, Simiyu, and Shinyanga and is somewhat inconspicuous in most areas.

Key words: Climate change, East Africa, ERA5-Land, heatwaves, multidimensional, percentile, z-score

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1. Introduction

Climate change, particularly extreme weather events, has profound impacts on ecosystems (Ummenhofer and Meehl 2017), infrastructure (Pregnolato et al. 2016), and human populations (Curtis et al. 2017). These impacts are often more significant than those caused by changes in average climate conditions. One of the most pressing concerns is the increasing frequency and intensity of heatwaves, which pose severe risks worldwide. This highlights the urgent need for targeted adaptation and mitigation measures, informed by localised analyses of extreme temperature patterns.

In climate-sensitive sectors, decision-makers require information on extreme events, especially as events once considered extreme become more common in a changing climate (Walsh et al. 2020). Developing countries, in particular, must implement adaptation and mitigation measures and integrate them into all development programs to minimise the effects of catastrophic climatic events. However, before formulating these policies, it is crucial to thoroughly characterise and understand extreme climatic occurrences at various timeframes and geographical extents. This understanding will provide the essential evidence to guide the policy formation process. Climate change poses a critical global threat, with Africa being particularly vulnerable. Despite contributing minimally to greenhouse gas emissions, Africa experiences a disproportionate burden of climate change impacts (Muggambiwa 2021). This manifests in increasing temperatures, shifting rainfall patterns, and a rise in the frequency and intensity of extreme weather events such as heatwaves, droughts, and floods (Mbawala et al. 2024). These events seriously challenge the continent's food security, water availability, and human health.

This study focuses on Tanzania and the critical issue of extreme temperatures. By exploring the spatial and temporal dynamics of temperature extremes in Tanzania, this research contributes to a broader understanding of climate change impacts in the East African region. The findings will offer valuable insights for policymakers and stakeholders working on climate change adaptation and resilience strategies in Tanzania and similar contexts. Several studies conducted in Tanzania, such as those by Kijazi and Reason (2009), Tumbo et al. (2010), Chang’a et al. (2017), and Luhunga (2022), have examined and described the extreme climatic occurrences that have occurred in the past. While this body of research provides valuable insights, there is a need for more comprehensive analyses that leverage high-resolution gridded data and robust statistical methods to capture the spatial and temporal dynamics of extreme temperatures accurately. Chang’a et al. (2017) analysed extreme meteorological indices in Tanzania from 1961 to 2015. They utilised observed daily rainfall and minimum and maximum temperatures. The study revealed that the average temperature anomaly in the country has risen by 0.69°C. This study expands upon the research conducted by Chang’a et al. (2017) by utilising multidimensional gridded data. The 18 meteorological stations Chang’a et al. (2017) use offer sufficient data, albeit at a localised level. A substantial number of weather stations is necessary to effectively capture the intricate geographic variations in temperature extremes. A comprehensive understanding of climatic occurrences requires a deep understanding of this spatial distribution. Nevertheless, the historical data derived from station observations are insufficient in most regions worldwide, including Tanzania, primarily due to the scarcity (and, in some instances, diminishing) or complete absence of station networks (Dinku et al. 2018). By utilising gridded data obtained from radars and weather models, it is possible to get meteorological information in areas not covered by gauges. This approach enables a more fine-grained understanding of extreme temperature patterns, facilitating the identification of the region’s most vulnerable to heat-related impacts. This allows a more comprehensive comprehension of weather phenomena. Nevertheless, estimates obtained from satellite-gridded data yield are prone to biases caused by intricate topography, resulting in a tendency to underestimate the severity of extreme weather events. Additionally, these estimates are less reliable in rural areas with fewer rain-gauge stations (Gebremichael et al. 2014). The Climate Hazards center InfraRed Temperature (CHIRTS)-daily maximum temperature and the ERA5-Land are satellite-based temperature products that have been recently developed and offer high spatial and temporal resolutions and cover a large part of the globe (Kimani et al. 2017). Both datasets leverage remotely sensed and in situ observations. The European Centre for Medium-Range Weather Forecasts (ECMWF) developed the ECMWF Reanalysis v5 (ERA5) dataset. Research conducted by Dinku et al. (2018), Parsons et al. (2022), and Kimani et al. (2017) have evaluated the accuracy of satellite-derived gridded products compared to ground observations in East Africa. These studies consistently demonstrate excellent performance and indicate that these satellite products have a significant role in future climatic research.

This study complements existing research by employing a percentile-based approach (98th percentile for heat) to define extreme temperatures and analyse them across the entire country over 43 years (1981–2023). This comprehensive approach allows a more holistic understanding of Tanzania's spatial and temporal distribution of extreme temperature events. Furthermore, this study goes beyond simply identifying extreme temperatures. It delves into their duration, revealing a dynamic pattern with variations across the years. This nuanced analysis provides valuable information for stakeholders who must prepare for and mitigate the effects of heat waves. An extensive array of percentile-based indexes is available in the literature. Temperature extremes are typically identified by utilising percentiles within the range of the 90th to the 99th, as demonstrated in studies such as Ban et al. (2015), Camuffo et al. (2020), and Barry et al. (2018). The work conducted by Abatan et al. (2016) analysed trends in extreme temperature over Nigeria from percentile-based threshold indices. The 90th and 10th percentile indices were calculated from daily minimum and maximum temperature data for 1971–2012 for 21 stations in Nigeria. The spatial and temporal trends in the index indicate that Nigeria had experienced a statistically significant increase in the frequency of hot extremes and a decrease in cold extreme events. A strict threshold, such as the 99th percentile, enhances the likelihood of detecting potentially significant societal and environmental events (Sulikowska and Wypych 2020). Conversely, examining the fluctuations in the occurrence rate of these events is challenging due to their infrequency, resulting in a significant level of uncertainty (Zhang et al. 2011). Opting for a moderately forgiving standard, such as the 90th percentile, guarantees the selection of a suitably large sample for analysing temporal changes. However, the research sample may include many “non-extreme” occurrences. Hence, selecting a percentile is frequently a trade-off between ensuring an adequate sample size and accurately capturing the degree of extremity in the cases (Perkins and Alexander 2013). This study utilises the 98th percentile temperature in the analyses. By examining temperature data through the lens of the 98th percentile, researchers can better understand the health risks associated with heat stress, dehydration, and other heat-related illnesses (Schoetter et al. 2015; Rennie et al. 2019).

The 98th percentile is often used to define extreme temperature events due to its robust statistical foundation and ability to capture rare and severe occurrences. By selecting the 98th percentile, only the top 2% of temperature readings are considered, effectively isolating extreme outliers and providing a reliable benchmark for extreme weather events. Numerous studies have employed this percentile in their analyses of extreme temperatures. For instance, a study by Sillmann et al. (2013) used the 98th percentile to analyse changes in extreme temperature events under different climate scenarios. Similarly, Perkins and Alexander (2013) utilised the 98th percentile to define extreme heat events in their research on heat waves. The consistent adoption of the 98th percentile across various studies underscores its efficacy as a metric for characterising extreme temperature events, providing a standardised approach for assessing climatic extremes. The 98th percentile threshold is a robust measure for defining extreme heat events, particularly when considering their impact on public health. Recent studies (Schoetter et al. 2015; Rennie et al. 2019) have demonstrated a strong association between temperatures at the 98th percentile and increased risks of heat stress, dehydration, and other heat-related illnesses. Furthermore, this threshold aligns with the definition of heatwaves used by the World Meteorological Organization (WMO), facilitating comparison with other regions globally (Rennie et al. 2019). Focusing on the 98th percentile, this study aims to provide actionable insights for policymakers and healthcare providers in Tanzania to understand better and prepare for the health risks associated with extreme heat events.

An essential requirement for effectively creating and executing coping and adaptation measures to the impacts of climate change is to comprehend the geographical and temporal patterns of extreme weather events. This study offers a contemporary comprehension of the nationwide patterns of extreme temperature indices. This research aims to analyse extreme temperatures in Tanzania based on a 98th percentile threshold. The spatial distribution of extreme temperature zones is mapped to provide a comprehensive overview of where extreme heat events are most prevalent in Tanzania. This study offers a contemporary and nuanced comprehension of Tanzania’s nationwide patterns of extreme temperature indices. It aims to fill knowledge gaps by providing in-depth analyses of high-resolution gridded data, explicitly focusing on most extreme temperature events’ spatial and temporal variability. The results will contribute to a better understanding of Tanzania's climate dynamics and inform the development of targeted adaptation and mitigation measures to address the escalating challenges of extreme heat events.

The paper’s novelty lies in focusing on the 98th percentile temperature, and using z-scores allows for a robust definition of “extreme” temperature, capturing infrequent but highly impactful events. The paper also analyses the frequency and duration of extreme temperature occurrences across Tanzania over a substantial period (1981–2023). This provides a long-term view of trends and pinpoints regions vulnerable to these extremes. The study also uses a higher-resolution temperature dataset to represent finer-scale details and variations in climate data. Given Tanzania's reliance on agriculture and susceptibility to droughts, these extreme temperature patterns pose risks to crop yields and food security. This study’s findings can inform targeted irrigation development, the adoption of heat-resistant crop varieties, and early warning systems for farmers. Additionally, urban planning must consider these trends to mitigate the impact of heat stress on vulnerable populations.

2. Materials and methods

2.1. Study area

This study is conducted in Tanzania (Fig. 1), a country in East Africa along the geographical coordinates of longitudes 29–41°E and latitudes 1–12°S. The nation encompasses an area of 945,100 km^2. Most of Tanzania is situated above 200 m, except for the coastal areas. Additionally, a significant portion of the country is located at an altitude exceeding 1000 m a.s.l. Tanzania's climate is mainly categorised as Tropical Savannah (Aw) according to the Köppen climate classification (Spinoni et al. 2015), characterised by alternating dry and wet seasons. Nevertheless, the climate is primarily affected by variations in altitude. Hence, there are four distinct subregional zones: 1. Lowland Coastal Zone—refers to a region situated at an altitude of 0 to 1000 m a.s.l., characterised by high levels of moisture and annual rainfall ranging from 1000 mm to 1800 mm. 2) The Highlands Zone consists of the north-eastern highlands and the southern highlands. These places typically receive substantial rainfall, up to 2000 mm per year. 3) Plateau Zone—regions situated adjacent to Lake Victoria and extending westward, characterised by predominantly arid conditions with an average annual precipitation of approximately 600 mm. 4) The Semi-Arid Zone encompasses the middle portions of the country and typically receives annual precipitation of less than 600 mm (John 2023). The extended arid season spans from May to October, whereas precipitation occurs from November to April. The rainy season in the coastal regions and the vicinity of Mount Kilimanjaro occurs from March to May, with intermittent rainfall between October and December. Precipitation in the country's western region, specifically near Lake Victoria, is evenly spread throughout the year, with the highest occurring between March and May (John 2023). According to the National Bureau of Statistics (2017), the highest average temperature ranges from 26.6°C in the southwestern region to 33.1°C in the north-eastern region between September and March. On the other hand, the lowest average temperature occurs in July, with a range of 5.3°C in the southern portions and 18.3°C in the coastal areas.

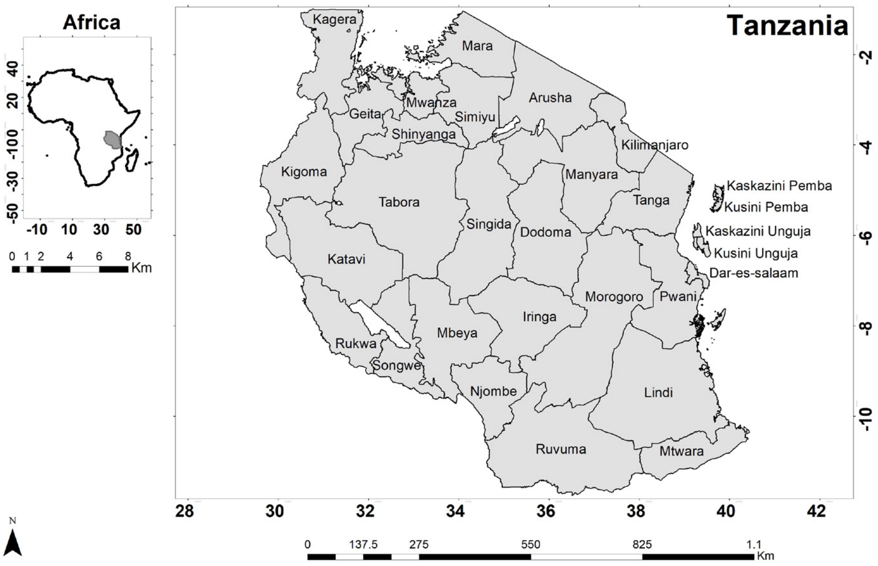

Figure 1. Map of Tanzania and its regions.

2.2. Materials

The study utilises a gridded ERA5-Land reanalysis dataset, providing high-resolution information on surface variables. Specifically, the study focuses on the daily maximum temperature (Tmax) variable at the near-surface level from January 1981 to December 2023. ERA5-Land is a cutting-edge global data collection designed for land applications (Muñoz-Sabater et al. 2021). Its spatial resolution is 0.1° × 0.1°, and its horizontal resolution is 10 km.

The chosen criterion for extreme temperature in this investigation is the 98th percentile temperature for heat, as determined by Schoetter et al. (2015) and Rennie et al. (2019). Using a percentile-based threshold, such as temperature, offers the advantage of defining extreme heat based on the varying absolute values of extremely high temperatures in different regions.

2.3. Methods

2.3.1. Creating multidimensional raster data

Multidimensional raster data allows for trend analysis, prediction, aggregation, and change detection better to comprehend a geographical phenomenon (ESRI 2022). In ArcGIS Pro, the following are the steps in the process of making a multidimensional raster: a) creating an empty mosaic dataset to add the raster files to; b) adding daily temperature data (1981–2023) to the mosaic dataset; c) adding two fields to the footprint attribute table, one for the variable (Tmax) and one for the timestamp (daily data); d) create multidimensional info; e) and create a multidimensional raster layer. A multidimensional raster can be viewed as many vertical 1D dimension arrays, and the dimension is time.

2.3.2. Determining extreme temperature thresholds using percentiles

The Aggregate Multidimensional Raster tool in ArcGIS Pro combines pixel time series within a specified time interval after creating the multidimensional raster. This study primarily employs the statistical measures of mean and percentile to consolidate data daily, weekly, or monthly. To account for the variation in temperature values throughout the year, the study computes the 98th percentile temperature for each month. This includes gathering data from January yearly and determining the 98th percentile temperature spanning 43 years. The result is a multidimensional raster consisting of 12 slices, each representing the 98th percentile temperature for a particular month. The study employs the “percentile” aggregation approach and the “recurring monthly” interval. The study also computes the 50th percentile of temperature to assess the disparity between the extreme values and their median values. October is chosen as the period to showcase the findings because it is considered one of the warmest months in Tanzania (Mongi et al. 2010).

2.3.3. The frequency of occurrence of extreme weather events

The Compute Multidimensional Anomaly tool calculates the difference between each dimension and the overall mean, median, or z-score. Anomaly can serve as a descriptor for extreme weather. The z-score-based anomaly measure quantifies the standard deviations by which a particular observation deviates from the mean. It is more effective for detecting extremes and convenient for comparing temperature than using anomalies based on absolute difference. The study employs a z-score of 2.32 to characterise the extreme temperature, as the temperature at the 98th percentile corresponds to a z-score of 2.32 in the context of normally distributed data. Below is the z-score equation:

$$Z = \frac{x - \bar{x}}{s} \tag{1}$$

Where:
x = original data value
$\bar{x}$ = mean of the original distribution
s = standard deviation of the original distribution

The study used daily maximum temperature (Tmax) data and then consolidated it into weekly data using the Aggregate Multidimensional Raster Geoprocessing tool. The aggregation method is “mean”, and the period used is “weekly.” Furthermore, the study employs the Compute Multidimensional Anomaly using the z-score method and a “recurring weekly” calculation period to determine the anomalies. Unlike the weekly interval, the “recurring weekly” interval calculates the average of the same week throughout all years rather than calculating the average for each year every week. Furthermore, the analysis identifies the data points with a z-score greater than or less than the mean by 2.32. Lastly, the study uses the Aggregate Multidimensional Raster tool to tally the number of weeks surpassing the established criterion and determine the frequency.

The choice to analyse weekly mean temperatures over daily maximum temperatures in the context of Tanzania is strongly supported by the specific vulnerabilities and impacts associated with prolonged heat waves in the region. At the same time, daily maximum temperatures offer insights into peak heat levels, and weekly mean temperatures provide a more comprehensive understanding of the duration and intensity of heat events, critical factors influencing various sectors and livelihoods in Tanzania. Prolonged heatwaves, captured by weekly mean temperatures, have significantly impacted agricultural productivity in Tanzania. Studies such as Mongi et al. (2010) and Chang’a et al. (2017) have highlighted the vulnerability of crops to extended periods of high temperatures, leading to reduced yields, crop failures, and subsequent food insecurity. By capturing the duration and intensity of heat events, weekly mean temperatures offer critical insights into the agricultural, health, water resources, and ecological consequences of prolonged heat exposure.

2.3.4. Quantifying the duration of extreme temperature events

Awareness of the specific timing and location of prolonged episodes of severe weather is crucial. The Find Argument Statistics tool is utilised to analyse temperature data and determine the duration of protracted extreme weather. This feature identifies the dates for each pixel position at which the time series reaches its maximum or minimum values. In this study, the focus is on the years 2023, 2022, 2021 and 2020. Using the “subset” function, we utilised the weekly anomaly result obtained in the previous step and extracted the weeks from the years above. Subsequently, we employed the Argument Statistics tool to determine the duration, measured in weeks, during which the anomaly consistently exceeded the 2.32 z-score. 2023 Tanzania experienced its highest recorded temperatures, as documented in the Nachilongo report (2023). Globally, the average temperature was 1.43°C higher than the preindustrial average, as stated in the study by Ripple et al. (2023). Therefore, this study evaluated the duration of severe weather occurrences throughout the past four years, starting from 2023.

2.3.5. Examining spatial and temporal temperature trends

The study employs the Generate Trend Raster tool to visually represent and chart the temperature pattern over the past 43 years. The Generate Trend Raster tool analyses each pixel's time series by fitting it with a linear model (ESRI 2022). The result is a raster with many bands that include the model's coefficients. The initial band represents the gradient characterising a linear pattern, offering a straightforward means to depict and comprehend the trend in the climatic data. Additional coefficients inside the model can describe the harmonic trend. Due to the seasonal nature of temperature, a harmonic model is employed with a frequency of one year. By accounting for seasonal variations, harmonic trends provide a more accurate representation of the underlying long-term trend in temperature data (Li et al. 2022). This is crucial for understanding how temperatures are changing over time in Tanzania. Below is the harmonic trend equation:

$$y = \beta 0 + \ \beta 1t + \sum_{i=1}^{f} ai\ cos\left(\frac{2\pi}{365.25}\mathrm{w}it\right) + yi\,\sin\left(\frac{2\pi}{365.25}\mathrm{w}it\right) \tag{2}$$

Where:

y = the pixels variable value; t = the Julian date; β_0 = the y-intercept; β_1 = the rate of change;

a , y = coefficients of inter-annual or intra-annual changes; ω = 1 / i ; f = harmonic frequency

The choice of ArcGIS Pro for this study was motivated by its robust capabilities and specific advantages in spatial and temporal climate data analysis. Unlike other software primarily focused on statistical and graphical representations, ArcGIS Pro excels in handling geographically referenced data, enabling intricate spatial visualisations crucial for climate research. The software's built-in tools for creating and working with multidimensional raster datasets (ESRI 2022) were instrumental in handling large volumes of time-series temperature data, allowing for efficient trend analysis, aggregation, anomaly calculation, and the identification of extreme events. Furthermore, the Argument Statistics tool seamlessly determines the duration of extreme weather events. The study benefits from its rich statistical and computational functionalities. This synergy empowers calculating complex statistics, trend analysis, and manipulating time-series data, yielding valuable insights.

3. Results

3.1. Determining extreme temperature values

Extreme weather is described as the 98th percentile temperature for heat (Ragettli et al. 2017). Percentiles express the relative standing of a value within a dataset, where the 50th percentile is the median, representing a typical temperature, while the 98th percentile represents an extremely high temperature occurring only 2% of the time. Fig. 2 shows the differences between mean temperatures for the 50th and 98th percentiles in October, displaying more significant differences for the 98th percentile. These differences appear in all years. For October, it is observed that the 98th percentile temperature ranges from 14.9 to 37.1°C, which is higher than the median (50th), ranging from 12.3 to 34.9°C.

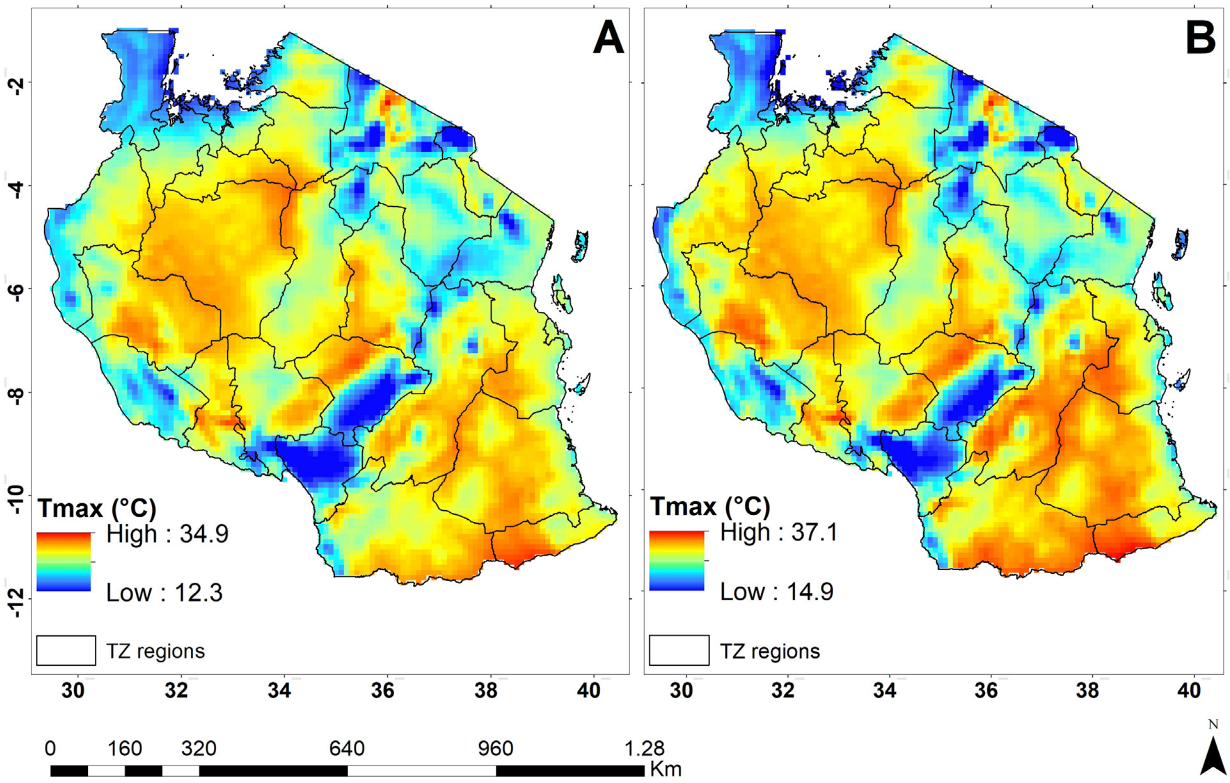

Figure 2. 50th (A) and 98th (B) percentile temperature ranges of October (1981–2023).

3.2. Frequency of extreme temperature occurrence

Utilizing a z-score enables the description of an observation concerning the overall distribution of all observations. Using a z-score of 2.32, we characterized the severe temperature and subsequently determined the frequency by tallying the number of weeks that surpassed this threshold (Fig. 3). The frequency map indicates that the mid-eastern, mid-southern, and north-western regions saw numerous extreme temperatures over the previous 43 years, while the other areas exhibited more moderate temperature fluctuations. Significant spatial patterns of trends were observed in Iringa, Kagera, Lindi, Morogoro, and

Njombe. The map shows a value of 0.215 for the weekly temperature extreme frequency because it represents the proportion of weeks from 1981–2023 where the temperature was at an extreme, as defined by being more than 2.32 standard deviations away from the mean. This is calculated using z-score-based anomaly, effectively detecting extremes in data like temperature. The value of 0.215 indicates that approximately 21.5% of the weeks in those years experienced extreme temperatures.

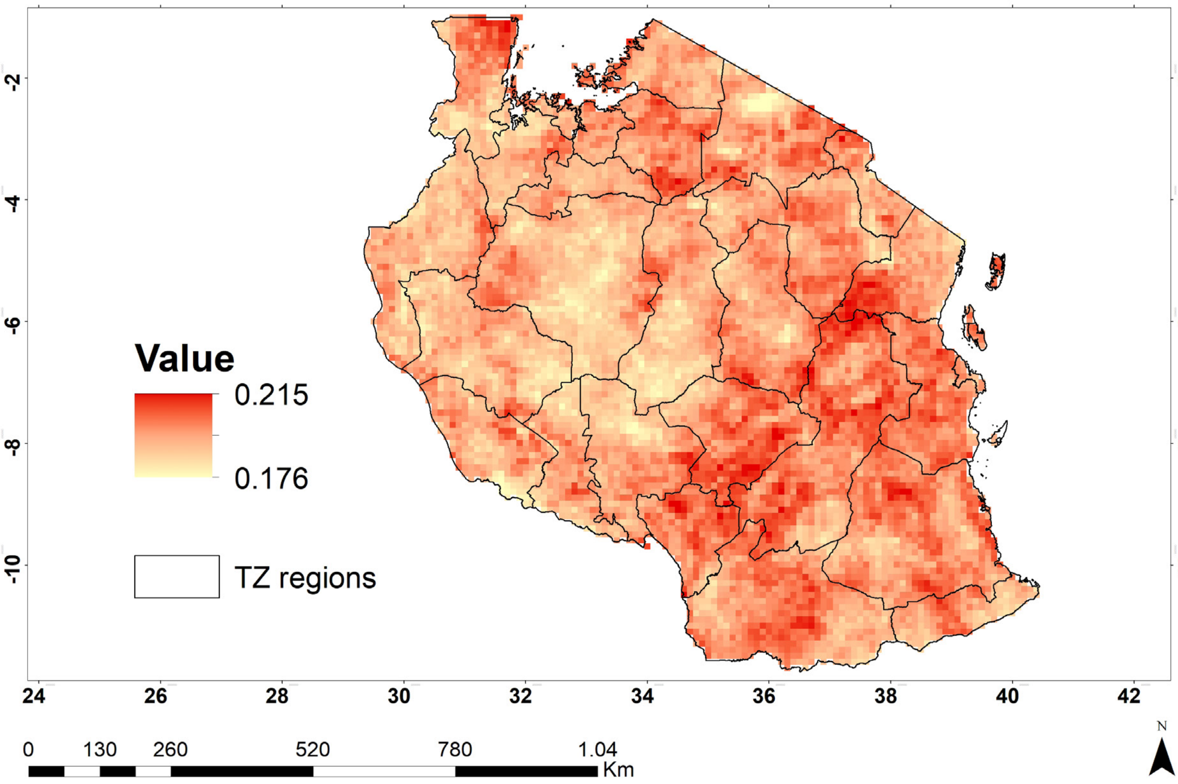

Figure 3. Weekly temperature extreme frequency (1981–2023).

3.3. Length of extreme weather events

The study employed the Argument Statistics tool to determine the consecutive weeks the anomaly consistently surpassed the 2.32 z-score for each year between 2020 and 2023. The years coincided with specific large-scale climate drivers such as La Niña and exceptional heatwaves (TMA 2022) and offered an opportunity to analyse the length of extreme weather events. La Niña is associated with cooler-than-average sea surface temperatures in the central and eastern Pacific Ocean, which can lead to reduced rainfall and extended periods of drought in East Africa. The data provided fascinating insights into the pattern of severe temperature episodes over several years. In 2020 (Fig. 5), a substantial amount of the examined region saw brief periods of excessive temperatures, lasting less than a week, covering 65% of the country's central and western areas, while those lasting for one week accounted for 29%.

Daily maximum temperature (Tmax) events beyond 35°C were limited due to persistent heavy rains experienced across various regions of the country throughout the hot months of January, February, and March (TMA 2020). The graph in Fig. 4 shows extreme temperature anomalies in 2020. Overall, the graph illustrates a clear pattern of variation in z-score anomalies over the year, with a notable peak in September followed by a decline towards the end. In Fig. 5, the spatial distribution of extreme temperature zones lasting three or more weeks was limited to the southern regions. Maximum monthly temperature anomalies of approximately 2.0°C were recorded in the southwestern highlands, specifically over Mbeya.

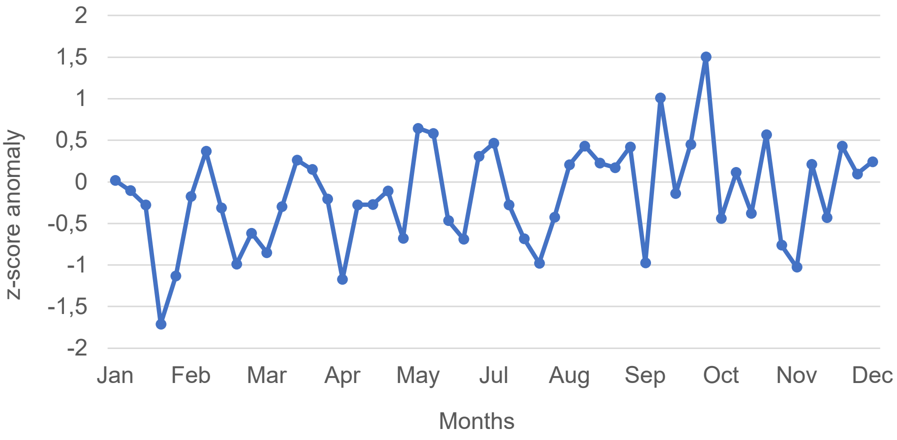

Figure 4. 2020 weekly z-score anomaly in Tanzania.

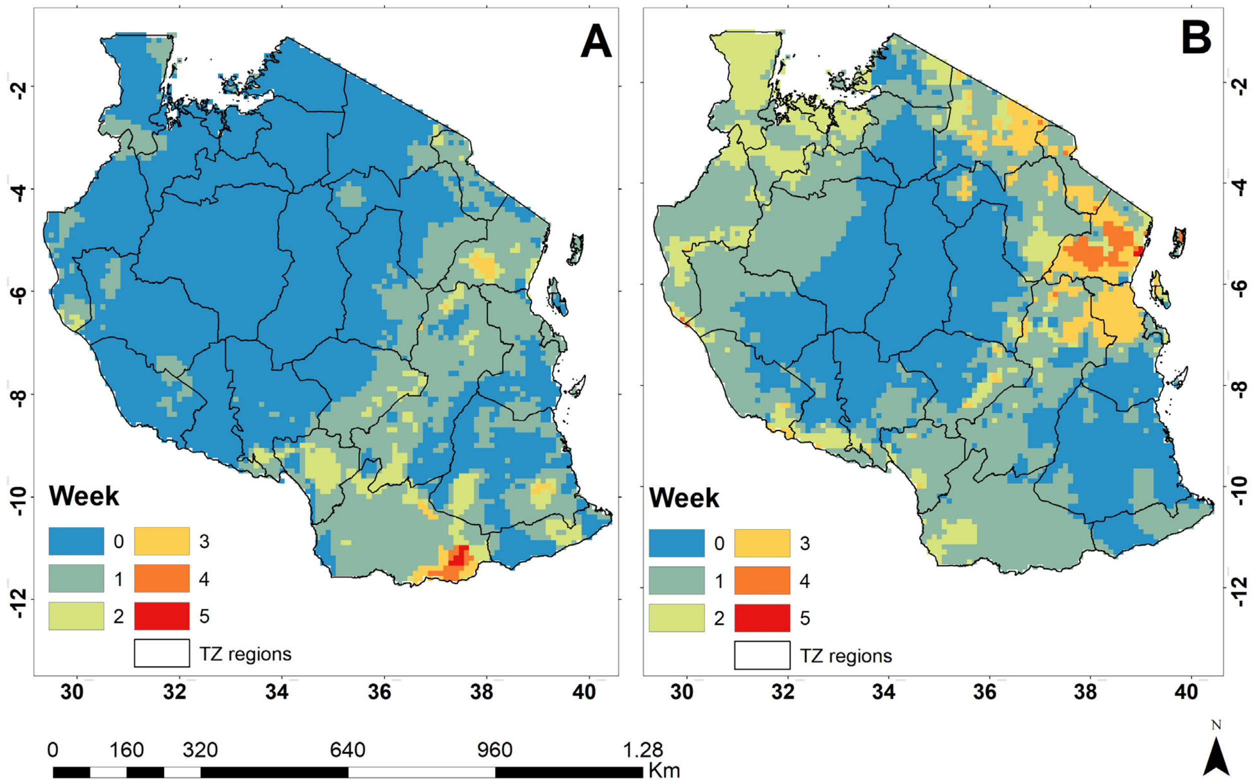

Figure 5. Extreme temperature zones by weeks for 2020 (A) and 2021 (B).

Weather patterns changed significantly in 2021. The share of locations experiencing extreme weather for less than a week decreased to 39%, while those experiencing extremes over a week grew to 44%. Longer durations also experienced an increase, as illustrated in Fig. 5. Throughout the year, temperatures were slightly above average (varying from 0°C to 1°C) in March and from May to October. However, November and December saw significant warming, with several regions experiencing temperature anomalies ranging from 1°C to 2°C, and some surpassing 2°C, particularly along the northern coast, in the northeastern highlands, and in the south. In contrast, the southern highlands were cooler from May to August, with July being especially cold, with numerous nights below 5°C (TMA 2021). A variety of local, regional, and worldwide variables impacted temperature patterns in 2021. The TMA (2021) indicated that the Indian Ocean basin had a neutral Indian Ocean Dipole (IOD) until May 2021, after which it moved to a negative phase for the remainder of the year. Sea surface temperature anomalies over the Indian Ocean were rather weak, resulting in increased convection over the eastern Indian Ocean, which coincided with the negative IOD. This was aided by persistent westerly anomalous winds at low levels over the tropical Indian Ocean that extended to the country's eastern regions throughout the majority of the year, with the exception of December. As a result, less moisture was delivered into the country, resulting in lower rainfall in several locations, particularly the eastern parts, with substantial monthly rainfall anomalies noted in March, April, May, October, and November (Ame et al. 2021).

The year 2022 showcased a distinctive pattern, where temperature extremes lasting two and three weeks covered substantial proportions of 36.3% and

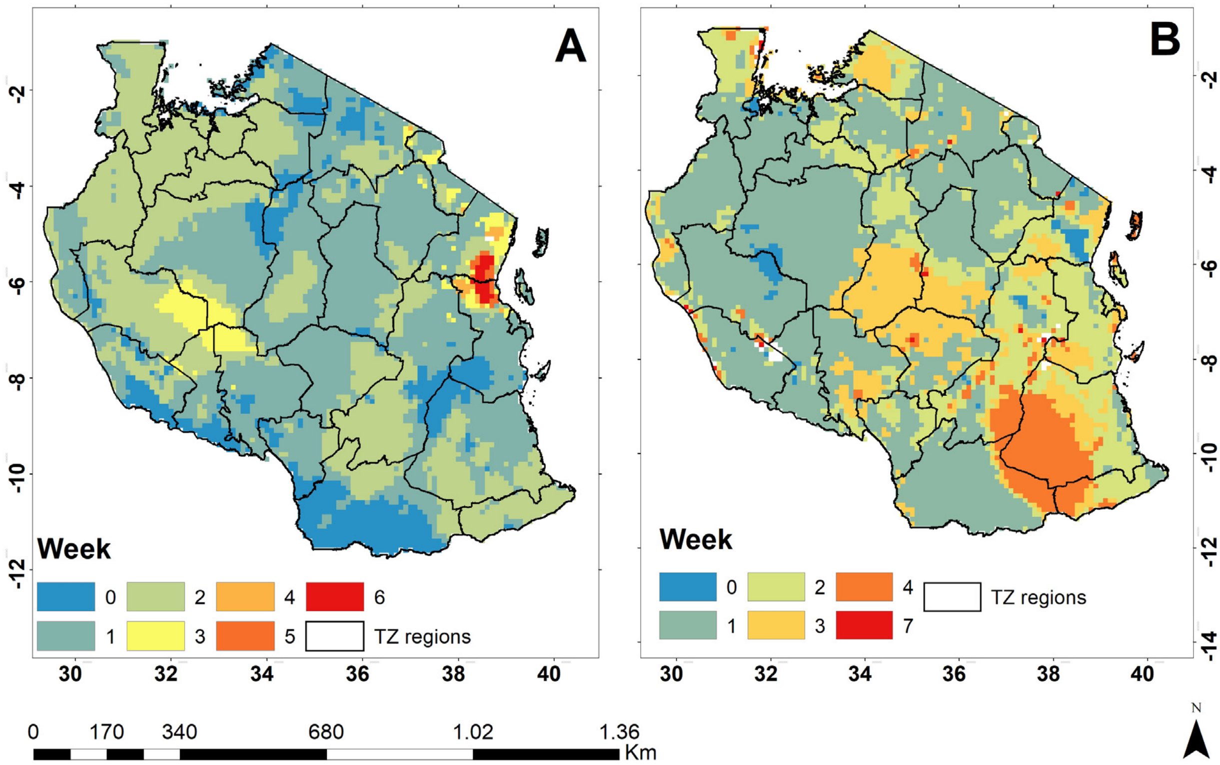

Figure 6. Extreme temperature zones by weeks for 2022 (A) and 2023 (B).

29.5% of the areas, respectively. The research pinpointed a noteworthy anomaly in 2022: temperatures exceeding four weeks were concentrated in 0.76% of Tanzania, primarily along the northern coastline (Fig. 6). According to TMA (2022), the eastern and central Pacific Oceans had lower temperatures in 2022, while the western Pacific Ocean maintained warm temperatures consistently throughout the year. Throughout the year, the La Niña phenomenon remained in the Pacific Ocean, significantly reducing rainfall across Tanzania. This mainly affected regions that typically see two rainy seasons: one from March to May (MAM) and another from October to December (OND). The northern coast and northeastern highlands experienced below-average precipitation throughout the MAM and OND rainy seasons, leading to extended periods of drought.

The monthly maximum temperature anomalies in the country during 2022 were elevated in certain months, with values of 0.6°C and 1.9°C recorded in January, April, and May. These anomalies were primarily noted in the northeastern highlands and northern shore. There were also below-normal values, with a −1.3 °C observed in February and July (Fig. 7). February experienced significantly lower than usual maximum temperatures, with anomalies ranging from −2°C to −1°C in various country regions. Nevertheless, temperatures below −1°C were documented in the central and western areas of the country.

In 2023, the study uncovered a dynamic scenario, with 54.7% of regions experiencing temperature extremes lasting a week, 22% enduring two weeks, and 14.3% persisting for three weeks, as shown in Fig. 6. Moreover, areas subject to temperature extremes surpassing four weeks and more accounted for 7.2%. These areas were found in the southern region of Lindi and Mtwara. According to Nachilongo (2023), 2023 was the hottest recorded in Tanzania. The warmer-than-average Tmax anomalies of 0.5°C (Fig. 8) and above occurred frequently, coupled with rainfall deficits and the sun's direct overhead position (Nachilongo 2023). The overheard sun is associated with extreme temperatures because the sun's radiation is drawn closer to the earth's surface. In December, the spatial distribution of temperature was that Morogoro was 1.3 degrees hotter than usual at 33.9°C, Dar es Salaam at 33.2°C (1.2°C hotter), Dodoma at 33.5°C (2.9°C hotter), and Zanzibar 33.4°C (1.6°C above average).

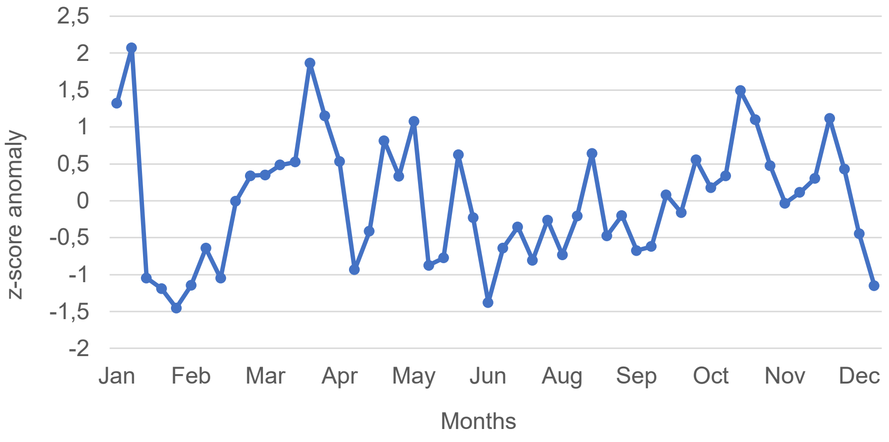

Figure 7. 2022 weekly z-score anomaly in Tanzania.

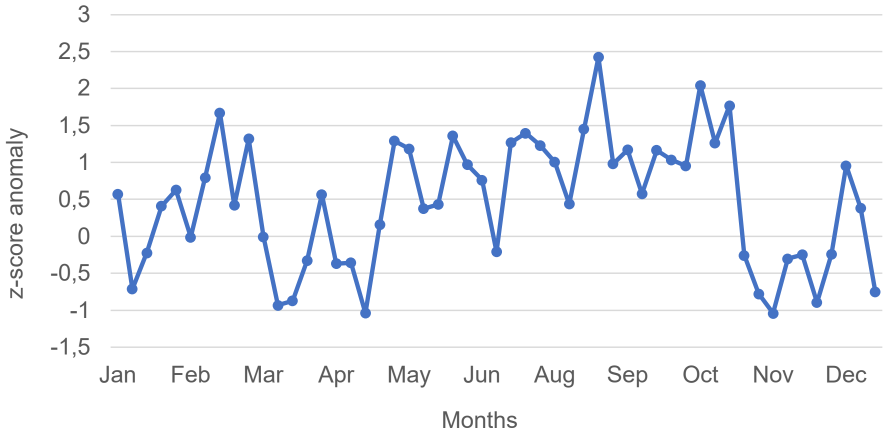

Figure 8. 2023 weekly z-score anomaly in Tanzania.

While 2020–2023 have been selected to analyse the length of extreme weather events as they stand out with prolonged periods of extreme heat in recent years, they exemplify a pattern that emerged decades earlier. Temperature records from Tumbo et al. (2010) and Chang'a et al. (2017) provide evidence of previously known extremes, suggesting that the recent events represent a continuation and intensification of an established trend. The observed escalation in temperature extremes in Tanzania aligns with the well-documented phenomenon of global warming. However, other climate cycles can also modulate regional temperature patterns. Investigating the influence of large-scale atmospheric and oceanic oscillations, such as the El Niño-Southern Oscillation (ENSO), Atlantic Multidecadal Oscillation (AMO), Interdecadal Pacific Oscillation (IPO), and Tropical Northern Atlantic Index (TNA), on Tanzanian temperatures could be a valuable area for future research. Studies by Limbu and Makula (2023) suggest significant correlations between these oscillations and temperature extremes in the country. For instance, El Niño events are often linked to increased warmth in eastern Africa, potentially influencing the extended hot periods observed in some years. A deeper understanding of how these global climate patterns interact with local factors like topography and proximity to water bodies can provide valuable insights for climate change projections and inform the development of targeted adaptation strategies.

3.4. Examining temperature patterns

Multiple studies (Tumbo et al. 2010; Barry et al. 2018; Ame et al. 2021) indicate that climate change raises the average temperature. This study employed the Generate Trend Raster tool to visually represent and map the temperature trend over the past 43 years. Fig. 9 displays a trend map, where each pixel corresponds to the slope of the fitting curve. The colour scale ranges from −0.00000785 to 0.00012, indicating the degree of change in temperature per year. The average global warming rate is currently around 0.02°C per year (Leemans and Eickhout 2004). However, this is an average, and certain regions may experience higher or lower rates. Pixels shown in purple have a positive slope, indicating a temperature rise, whereas pixels displayed in green exhibit a negative slope, indicating a fall in temperature. This map illustrates that most re-

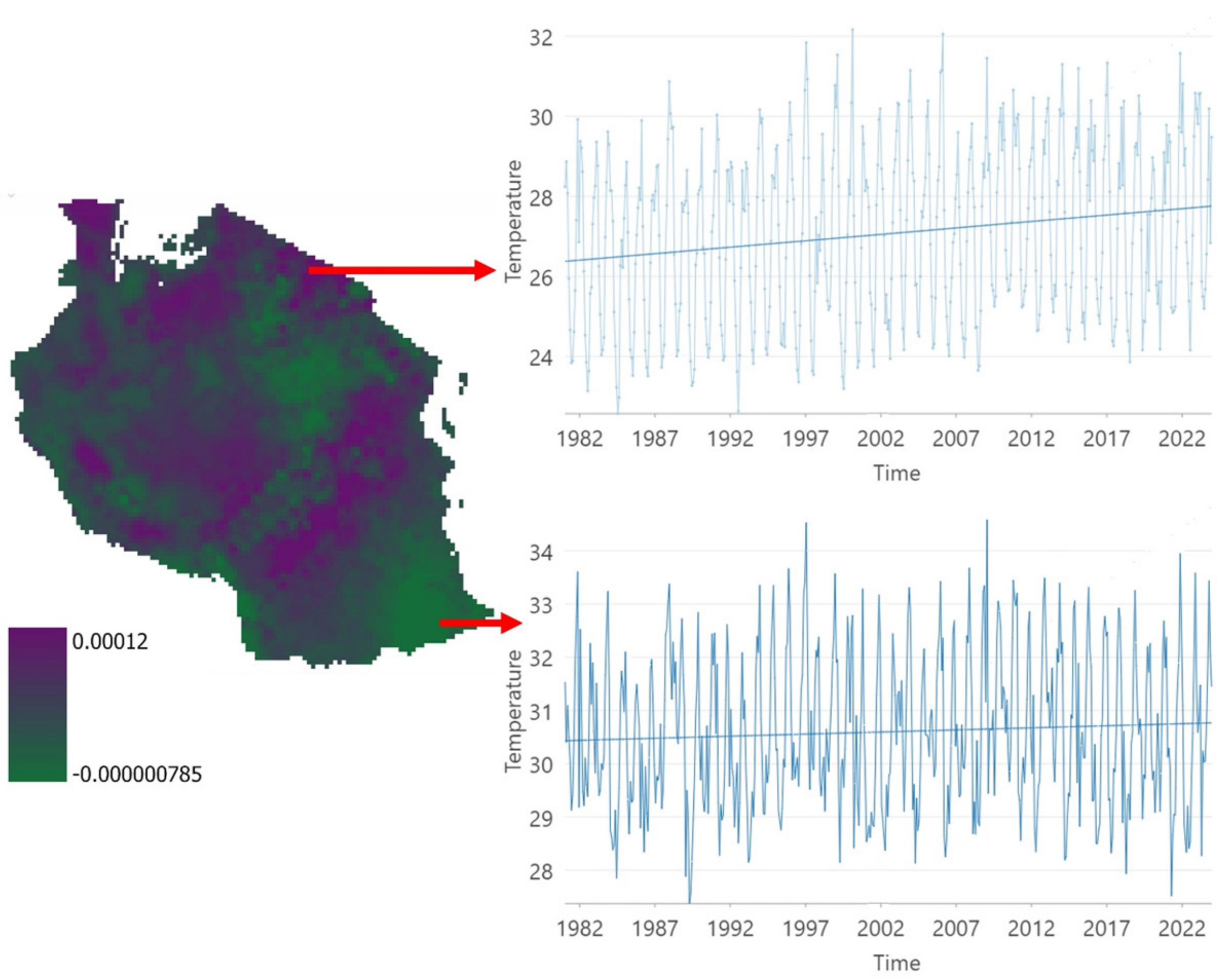

Figure 9. Monthly temperature trend using harmonic model (1981–2023).

gions in Tanzania demonstrate an upward trend; however, the rate of increase varies across different places. The trend rate can be discerned from the temporal profile chart at the two locations (shown with the red arrows). The pace of rise is somewhat inconspicuous in most areas but more noticeable in specific regions such as Arusha, Kilimanjaro, Kagera, Morogoro, Simiyu, and Shinyanga, which are depicted as dark purple.

Chang'a et al. (2017) discovered that in both the Arusha and Kilimanjaro regions, the average seasonal temperature anomalies show a significant increase over time and have a higher level of variation between years. This trend is consistent across all seasons (JF (January and February), MAM, JJAS (June, July, August, and September), and OND). Most of the highest recorded maximum temperatures, ranking among the top five, have happened over the past twenty years, specifically between 2000 and 2020. This trend aligns with the established patterns of global warming. The reported increase in temperature has significant ramifications for a wide range of socio-economic sectors and livelihood activities. Additionally, it could be exacerbating the rapid melting of glaciers on Mt. Kilimanjaro, prompting further research into the prediction of warming and temperature changes in the near, medium, and long-term future. Several regions, including Dodoma, Lindi, and Mtwara, show more variability and a less pronounced trend decline. The overall trend is relatively stable with a slight increase. Mbawala et al. (2024) similarly discovered a regional pattern with significant stable and declining trends in similar regions.

Analysis of maximum temperature trends in Tanzania over the past four decades, using a p-value image (Fig. 10) derived from trend analysis, reveals a clear pattern of statistically significant warming across most of the country. This finding is consistent with global warming patterns attributed to climate change, as documented in the Intergovernmental Panel on Climate Change (IPCC) reports (IPCC 2021). Areas shaded in green on the p-value image exhibit low p-values (< 0.05), indicating a high degree of statistical confidence that the observed warming trends in these regions are not due to chance alone. In contrast, regions shaded in purple (e.g., Mtwara and parts of Dodoma) display high p-values (> 0.05), suggesting that the observed temperature trends in these areas are not statistically significant.

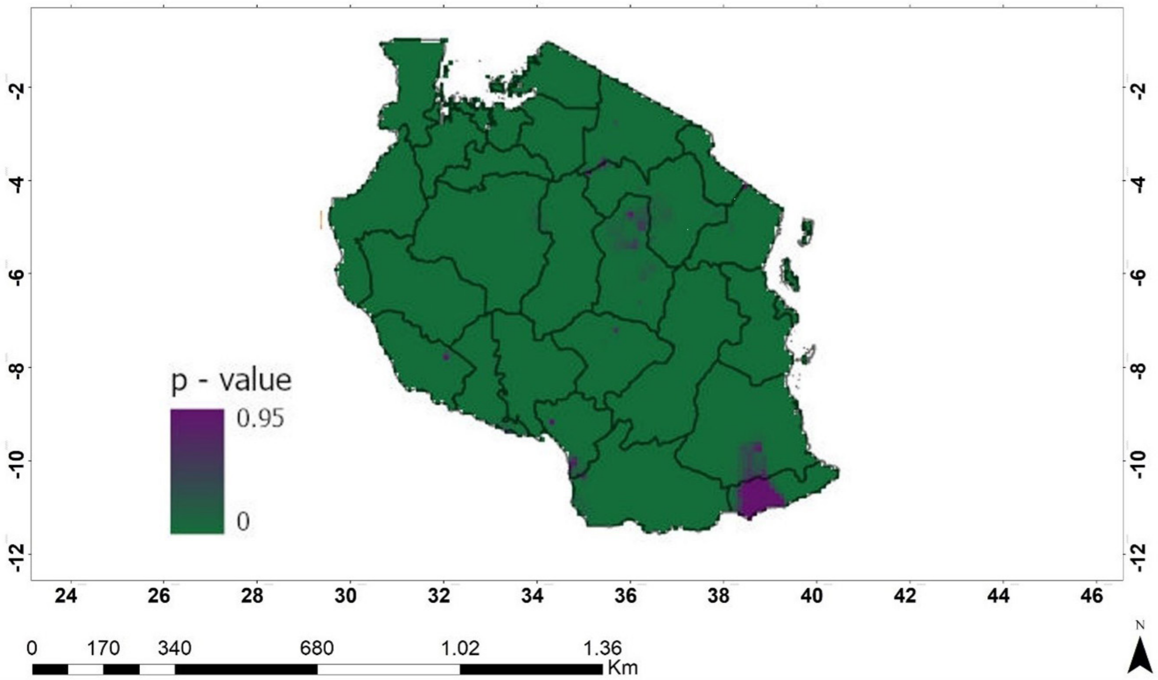

Figure 10. Spatial distribution of p-values from trend analysis of maximum temperatures.

4. Discussion

The definition of “extreme temperature” in this study, specifically the 98th percentile temperature for heat, provides a benchmark for understanding extreme temperature events in Tanzania. By calculating and presenting the 50th (median) and 98th percentile temperature ranges for October across different years, we establish a clear context for evaluating the frequency, duration, and spatial patterns of extreme temperatures. The frequency map (Fig. 3) reveals significant spatial patterns in extreme temperature trends, particularly in regions like

Iringa, Kagera, Lindi, Morogoro, and Njombe. Approximately 21.5% of the weeks in the study period experienced extreme temperatures. This high frequency of extreme temperatures is likely linked to large-scale atmospheric and oceanic indices such as the ENSO, AMO, and IPO (Limbu and Makula 2023).

The detailed analysis of extreme temperature episodes from 2020 to 2023 highlights the variability in the length and intensity of these events. For instance, the persistent extreme temperature anomalies in 2020 (Fig. 4) and the fluctuating patterns in subsequent years underscore the influence of large-scale climate drivers like La Niña and heatwaves (TMA 2022). The southern regions experienced extended periods of extreme temperatures, reflecting the complex interplay between local climatic conditions and broader climatic phenomena. The trend map (Fig. 9) and findings from Chang'a et al. (2017) show a significant increase in temperature anomalies over time in regions like Arusha and Kilimanjaro. This consistent rise in temperatures across various seasons aligns with global warming patterns, emphasizing the need for targeted adaptation strategies in agriculture, water resource management, and public health to mitigate the impacts of increasing temperatures.

The observed increase in temperature extremes poses significant threats to various sectors in Tanzania. Increased heat stress in agricultural communities could decrease productivity and lead to crop failures, exacerbating food insecurity (Tripathi et al. 2016). Rising temperatures also magnify water scarcity by increasing evaporation rates, which diminishes surface water resources essential for domestic use, irrigation, and livestock (Gebremichael et al. 2014). This water stress has severe public health implications, particularly in expanding waterborne disease vectors (Tirado et al. 2010). Additionally, the warming trend is likely to accelerate glacial melt atop Mt. Kilimanjaro, threatening water resources and the tourism industry dependent on its iconic landscape (Thompson et al. 2009).

Local factors such as topography and land cover significantly influence regional climate characteristics. For instance, the altitudinal effects in mountainous regions like Kilimanjaro and Arusha can moderate extreme heat events (Limbu and Makula 2023). However, these areas have shown significant warming trends, suggesting the influence of factors beyond local topography. Urban areas like Dar es Salaam may experience the urban heat island effect, exacerbating heat extremes (Kabanda and Kabanda 2019). Large-scale climate patterns like ENSO also modulate regional temperature patterns. El Niño events are often associated with increased temperatures in eastern Africa, contributing to observed heat extremes (Limbu and Makula 2023). Future research should investigate the relative contributions of local factors and large-scale climate patterns to regional temperature extremes in Tanzania, providing valuable insights for climate change projections and informing the development of targeted adaptation strategies.

The examination of extreme temperature patterns within Tanzania offers a nuanced understanding of regional variations. This localized knowledge is crucial for developing targeted adaptation and mitigation measures. Areas with greater magnitudes of increased temperatures, such as Lindi, Arusha, and Kilimanjaro, demand urgent adaptation strategies in agriculture and water resource management to ensure sustainable livelihoods. Regions with slightly declining temperature trends necessitate further investigation into potential underlying factors and associated vulnerabilities. These detailed findings provide valuable information for understanding the temporal evolution of temperature anomalies in Tanzania, facilitating informed discussions on climate patterns, and aiding in formulating targeted mitigation and adaptation strategies.

5. Conclusion

This research highlights the substantial impact of extreme heat events, defined as the 98th percentile temperature, on Tanzania's climate from 1981 to 2023. By employing percentiles, z-scores, and trend analysis, the study provides a comprehensive understanding of these events' frequency, duration, and spatial distribution. The consistent disparities noted between mean temperatures for the 50th and 98th percentiles (Fig. 2) emphasise the prevalence of extreme temperatures. Z-score analysis identifies the mid-eastern and north-western regions as experiencing frequent extreme temperatures over the past four decades, while further analysis reveals varying durations of these events from 2020 to 2023. 2023 stands out as the hottest on record, underscoring the urgency for climate resilience measures. Moreover, the trend analysis indicates a predominantly increasing temperature trend across most of Tanzania, particularly pronounced in areas such as Arusha, Kagera, Morogoro, Lindi, Simiyu, and Shinyanga. The findings of the research and the study by Chang'a et al. (2017) are mainly complementary, reinforcing the evidence of increasing temperature extremes in Tanzania. While some differences exist due to methodological choices and timeframes, the overall conclusions align and underscore the urgency of addressing the impacts of climate change in the region.

This study offers several key contributions. It validates previous findings of increasing temperatures with more recent, high-resolution data and provides a localised perspective within the East African climate research context. The detailed maps pinpoint areas of high extreme temperature frequency and duration. These maps are powerful tools for policymakers, guiding targeted adaptation and resilience planning to protect the most vulnerable communities. Recognising the impact of extreme heat, this work stresses the need for policies addressing heat stress mitigation in sectors like agriculture and public health. Additionally, it encourages further research into the relationship between extreme temperatures and large-scale climate drivers like ENSO and AMO to improve early warning systems and preparedness.

The research findings highlight the critical need for proactive adaptation and mitigation strategies in Tanzania. Policymakers should focus on investing in climate-resilient infrastructure, like drought-resistant crops and early warning systems for extreme weather events. The agricultural sector, which is particularly vulnerable to temperature extremes, can benefit from promoting heat-resistant crop varieties and implementing sustainable land management practices. In urban areas, measures to mitigate heat stress, such as creating green spaces and installing cool roofs, should be part of urban planning to protect vulnerable populations. Moreover, developing comprehensive climate risk assessments and adaptation plans at both national and local levels is essential for building long-term resilience against the increasing challenges posed by extreme temperatures in Tanzania.

While this study focuses on a percentile-based definition of extremely hot days, the concept remains debatable. Exploring alternative definitions, such as consecutive days exceeding a specific temperature threshold, could provide additional insights into its characterisation and impacts. This highlights the value of comparative analyses for developing tailored adaptation strategies. Ultimately, this research significantly advances the understanding of climate extremes in East Africa. The methodology, emphasising percentile-based thresholds and z-score analysis, has potential applications in other regions. By examining trends and the duration of extreme events, the study contributes to informed decision-making and a broader understanding of global climate change patterns.

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Data availability

The dataset on the daily maximum temperature (Tmax) variable at the near-surface level is available at https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land?tab=overview.