Decadal Trends in Seasonal Climatic Variables in Dar es Salaam, Tanzania: A Non-Parametric Approach Using the Mann-Kendall Test

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ABSTRACT

Background: Coastal urban cities like Dar es Salaam, Tanzania, are increasingly vulnerable to the adverse effects of climate variability, including urban flooding, heat stress, and changes in water availability. Understanding the evolution of key climatic variables over time is essential for supporting adaptive strategies and sustainable urban development.

Methods: This study analyzed decadal seasonal trends in rainfall, daytime and nighttime temperatures, and relative humidity using monthly data from January 2014 to October 2024 obtained from the Tanzania Meteorological Authority. The analysis utilized the non-parametric Mann-Kendall trend test and Sen's slope estimator to detect and quantify monotonic trends across five seasons.

Results: Statistically significant trends were identified across multiple seasons. Rainfall during the long dry season (JJA) showed an increasing trend with a Sen's slope of +1.95 mm/year and a p-value of 0.005, indicating a notable deviation from expected seasonal dryness. Also, daytime temperatures during JJA declined significantly with a Sen's slope of –0.038°C/year ($p = 0.001$), while nighttime temperatures during the short dry season (JF) also exhibited a significant decreasing trend (Sen's slope = –0.062°C/year; $p = 0.044$). Relative humidity exhibited only minor, statistically insignificant fluctuations across all seasons, with the highest z-value observed in OND.

Conclusion: The findings underscore shifting climatic patterns in Dar es Salaam that deviate from conventional expectations, such as increased precipitation during dry periods and cooling in some seasons. Hence highlighting the need for climate-informed urban planning and infrastructure development and the importance of continued localized climate monitoring to support evidence-based policy and resilience-building measures.

Keywords: Climate variability, Mann-Kendall trend test, Sen's slope, Urban resilience, Dar es Salaam

1. Introduction

Climate change is increasingly recognized as one of the most critical challenges of the 21st century, driving long-term shifts in global temperatures and weather patterns, primarily due to the retention of solar heat in the Earth's atmosphere [1]. It is marked by rising global temperatures and an increase in the frequency and severity of extreme weather events such as droughts, floods, and heatwaves [2]. Projections indicate that water availability and annual average runoff could decline by 10–30% by the mid-21st century, exacerbating water insecurity in many regions [1]. These changes highlight the critical importance of examining historical climate patterns to guide the development of effective adaptation strategies, particularly in vulnerable regions where socio-economic systems are highly susceptible to climatic stressors [3].

IPCC synthesis report highlights that human activities have driven rapid and widespread changes in the biosphere, cryosphere, ocean, and atmosphere. These changes have caused significant losses and damages, particularly affecting vulnerable communities that have contributed the least to climate change [2]. Tanzania is particularly vulnerable to the adverse impacts of climate change, with seasonal variations in recorded rainfall and temperature trends observed across many regions of the country [4].

Several studies in Tanzania have used the Mann-Kendall test and Sen's slope estimator to analyze climate trends [4–6]. These studies have covered various aspects, including extreme temperature changes, extreme precipitation indices ,agricultural impacts in specific districts and hydro-climatic trends in river catchments [7].

However, there remains a notable gap, as no recent studies have specifically examined the decadal seasonal trends of key climatic variables such as temperature, rainfall, and relative humidity within Dar es Salaam. Decadal trends in temperature, relative humidity, and seasonal rainfall are crucial for comprehending recent shifts in climatic patterns. This study especially examines possible changes in climate variability during the last ten years (2014-2024), in contrast to earlier research. By doing this, it highlights how adaptation strategies based on local climate data are essential for controlling climate-related risks and guaranteeing that solutions are adapted to the unique requirements and vulnerabilities of communities at the local level.

This paper contributes to the growing discourse on urban climate resilience by offering a comprehensive, decade-long analysis of climatic variability in Dar es Salaam, Tanzania's most populous coastal city. By focusing on seasonal trends in temperature, rainfall, and relative humidity from 2014 to 2024, the study provides context-specific insights that are essential for understanding emerging climate patterns and guiding adaptive planning.

2. Materials and Methods

2.1 Study Area

Dar es Salaam, Tanzania's largest city and economic hub, is located along the Indian Ocean coast between latitudes 6°36'S and 7°00'S and longitudes 39°00'E and 39°17'E. It has a humid tropical climate, characterized by bimodal rainfall patterns with peaks in March–May and October–December. The city experiences annual temperatures ranging from 18°C to 34°C and receives an average of approximately 1,100 mm of rainfall per year [8]. As a rapidly urbanizing coastal city, Dar es Salaam is highly susceptible to climate-related challenges such as flooding, heat stress, and water insecurity, making it a critical case for localized climate trend analysis. Figure 1 presents a panel map illustrating the study area, with a map of Tanzania on the left and an arrow pointing to a more detailed map of Dar es Salaam on the right.

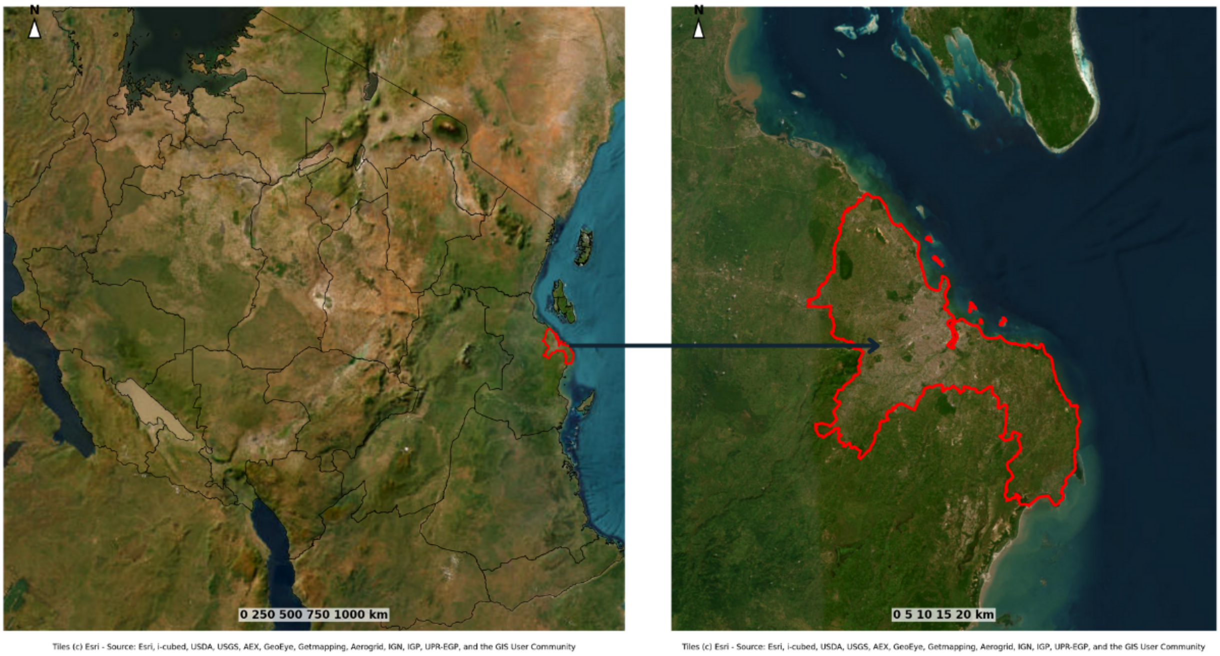


Figure 1: Map of Study Area (Author's own contribution)

2.2 Study design and data source

A retrospective, ecological time-series design was used to examine ten-year trends in climatic variables across five seasons. Monthly climate data for Dar es Salaam, spanning January 2014 to October 2024, were sourced from the TMA. This dataset included rainfall (mm), daytime and nighttime temperatures (°C), and relative humidity (%). The TMA pre-validated the complete data, which required no imputation or correction, thus ensuring consistent and reliable trend analysis.

2.3 Data Analysis

2.3.1 Classification of seasons

Analysis was conducted for the five climatological seasons recognized for Dar es Salaam: JF (Short Dry Season), MAM (Long Rainy Season), JJA (Long Dry Season), S (Transitional Period), and OND (Short Rainy Season)

Table: Classification of seasons

Season ID	Months within the Season	Season Name
JF	January and February	Short Dry Season
MAM	March, April, and May	Long Rainy Season
JJA	June, July and August	Long Dry Season
S	September	Transition Period
OND	October, November and December	Short Rainy Season

2.3.2 Mann Kendall test and Sen's slope estimator

The non-parametric Mann-Kendall (MK) trend test was employed to detect the presence of monotonic trends in the time series data without requiring the data to follow any specific distribution. This method is particularly suitable for environmental and climatological data where non-normality and missing values may be present. The corresponding magnitude and direction of the trends were estimated using Sen's slope estimator. All statistical analyses were conducted at a 5% significance level ($\alpha = 0.05$), and trends were interpreted using the computed S-statistics, variance, Z-scores, p-values, and slope estimates.

In the MK test, the S-statistic was calculated as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i)$$

where $sgn(x_j - x_i)$ is the sign function, returning +1, 0, or –1 depending on whether the difference is positive, zero, or negative, respectively.

For large sample sizes (n > 10), the variance of S was computed using:

$$Var(S) = \frac{n(n-1)\,(2n+5) - \sum t_p(p-1)(2p+5)}{18}$$

where t_p denotes the number of ties of extent *p*.

The standardized test statistic Z was then derived as:

$$Z = \{ \frac{S-1}{\sqrt{Var(S)}} \; 0, \; \frac{S+1}{\sqrt{Var(S)}} \qquad if\ S > 0\ if\ S = 0\ if S < 0$$

The null hypothesis of no trend was rejected if the absolute value of Z exceeded the critical value at the 5% significance level (i.e., |Z| > 1.96).

Sen's slope estimator was used to quantify the magnitude of the trend. For each pair of time-ordered observations, the slope (*Qi*) was calculated as:

$$Q_i = \frac{x_j - x_i}{j - i}, \quad for\ all\ 1 \le i < j \le n$$

Where x_i and x_j are data values at time points *i* and *j* respectively. The Sen's slope was then determined as the median of all Q_i values:

$$Sen's\ slope = Qn_{/2} \;\; (if\ n\ is\ odd)$$

$$Sen's\ slope = \frac{Qn_{/2} + Qn/_{2+1}}{2} \quad (if\ n\ is\ even)$$

This approach provides a robust and unbiased estimate of the linear trend over time, even in the presence of outliers or non-normal data distributions [9,10].

3. Results

3.1 Description of the climatic variables

Monthly variations in climatic variables revealed distinct seasonal patterns and interannual dynamics over the decade. Warmer months consistently occurred from January to March and November to December, while cooler months with lower nighttime temperatures were observed from June to September. Rainfall exhibited significant fluctuations, with higher amounts predominantly in April and May. Notably, heavy rainfall was recorded in November 2023 (557 mm), deviating from typical patterns, and a consistent rainfall shortage occurred from June to September. Relative humidity levels correlated with rainfall, being higher in

April, May, and November, and lower from July to September, highlighting the interconnected influence of rainfall and humidity on the regional climate (See Figure 1-4).

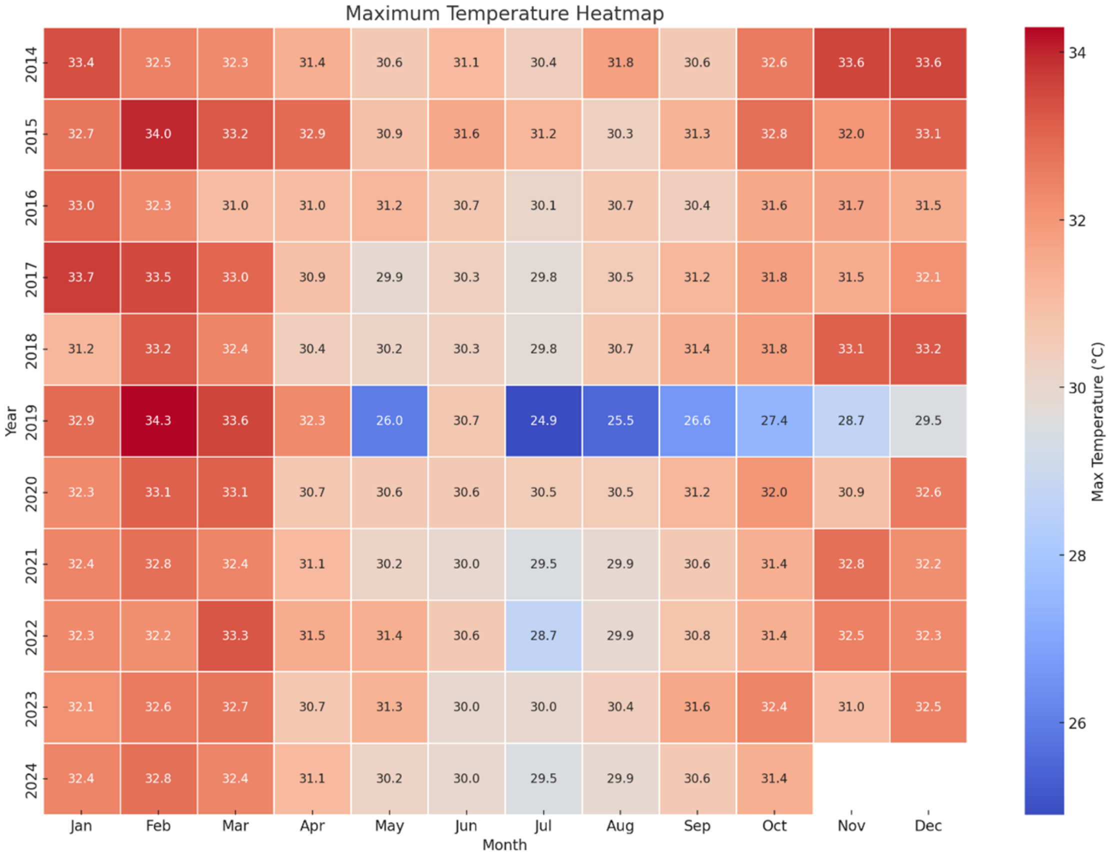


Figure 2: A heatmap of Monthly and Interannual Variations in Daytime Temperature

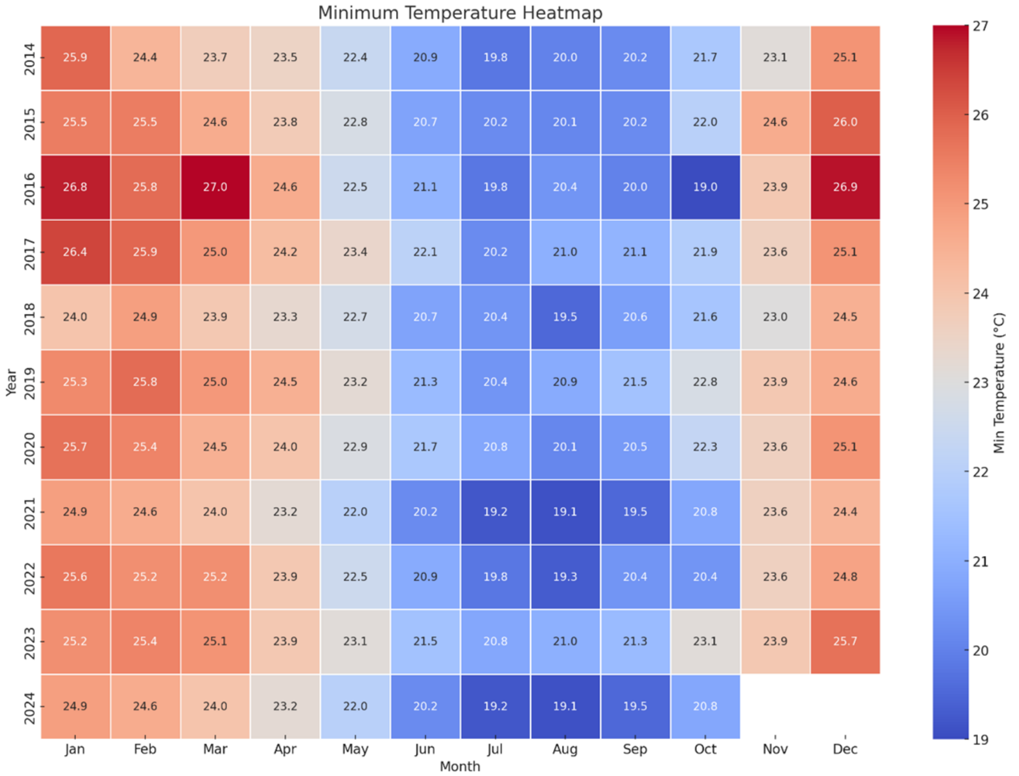


Figure 3: A heatmap of Monthly and Interannual Variations in Nighttime Temperature

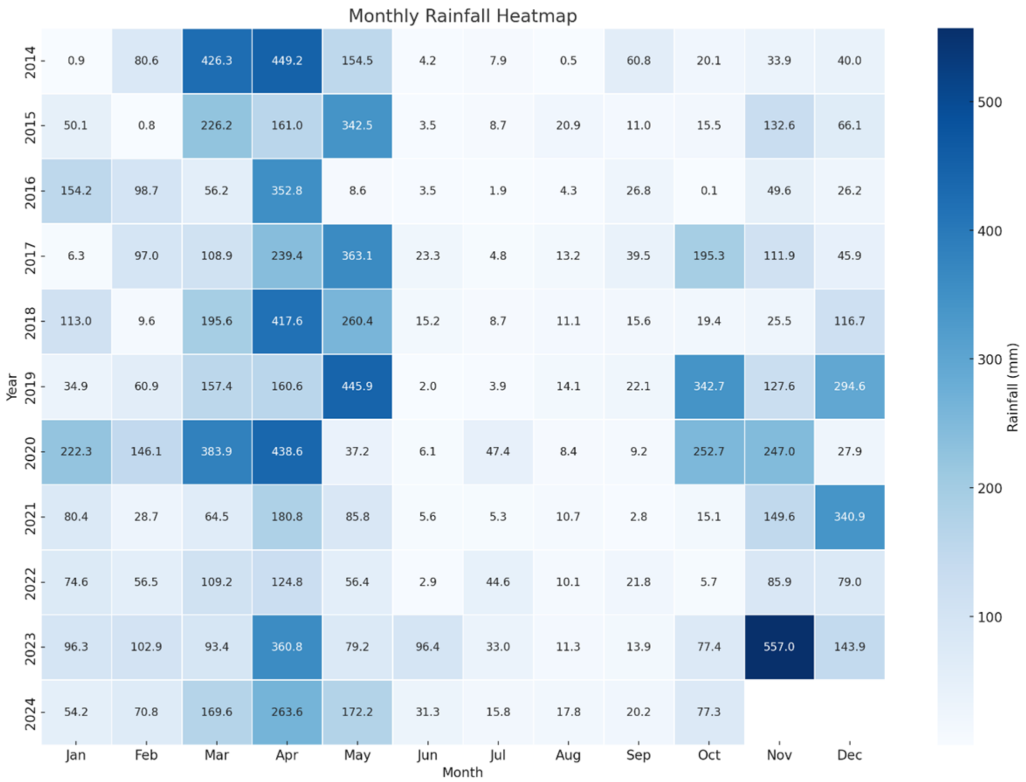


Figure 4: Heatmap of monthly rainfall in Dar es Salaam from Jan 2014 - Oct 2024

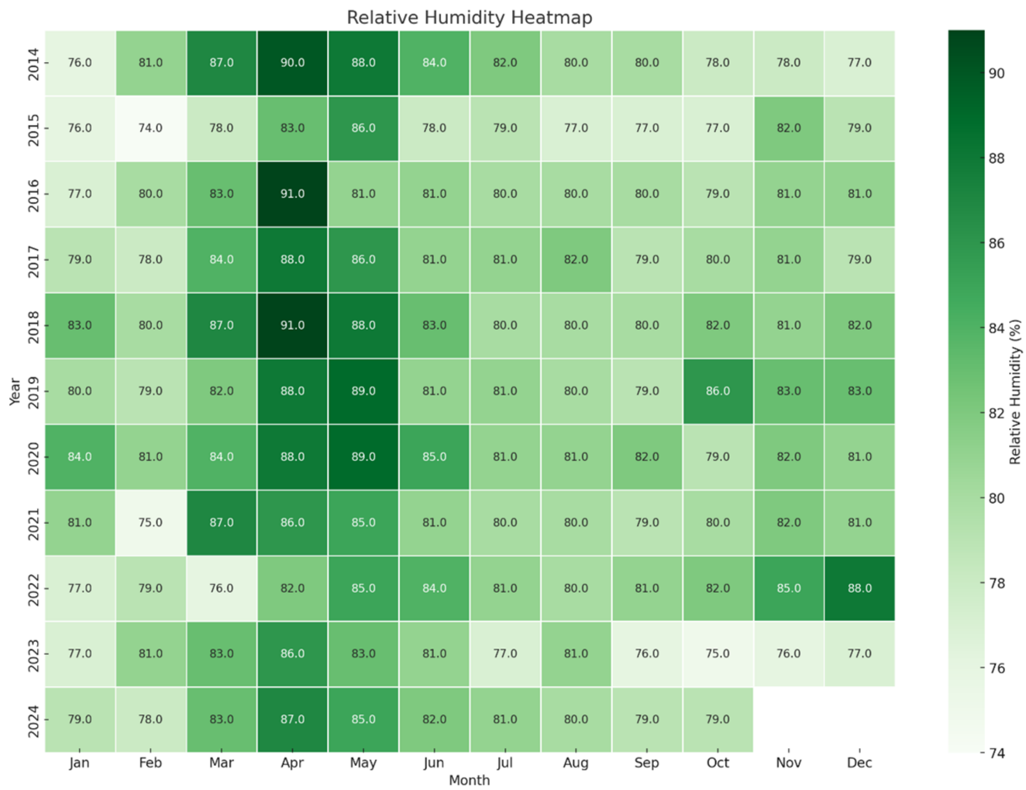


Figure 5: Heatmap of Monthly Relative Humidity in Dar es Salaam from Jan 2014 - Oct 2024

3.2 Decadal Trend Analysis with Mann Kendall test and Sen's slope estimator

Seasonal trends in rainfall, daytime and nighttime temperatures, and relative humidity across Dar es Salaam. A statistically significant increasing trend in rainfall was observed during the Long Dry season, a period traditionally characterized by minimal precipitation. The Mann-Kendall test yielded a z-statistic of 0.349 with a corresponding p-value of 0.005, indicating a robust trend. The Sen's slope estimator quantified this increase at 1.95 mm/year, suggesting a consistent year-over-year rise in rainfall during this typically dry period.

Conversely, a significant decreasing trend in daytime temperatures was identified during the same Long Dry season. The Mann-Kendall test resulted in a z-statistic of -0.406 and a p-value of 0.001, signifying a strong downward trend. This was further corroborated by the Sen's slope of -0.038°C/year, suggesting a gradual cooling in daytime temperatures during this period. In contrast, nighttime temperatures exhibited a significant decrease during the Short Dry season, with a z-statistic of -0.318 and a p-value of 0.044. The Sen's slope for this trend was -0.062°C/year, revealing a noticeable decline in nighttime temperatures during these months.

Relative humidity did not show any statistically significant trends across all seasons, indicating relative stability in atmospheric moisture content over the analyzed period. While minor fluctuations were observed, none met the threshold for statistical significance ($p > 0.05$). For instance, the highest z-value observed for relative humidity was during the Short Rainy season with a z-statistic of 0.193 and a p-value of 0.149, further highlighting the lack of significant trends in humidity (See Table 1)

Table 1: Mann-Kendall Test for Seasonal Climatic Trends (January 2014–October 2024)

Variable	Season	z	p-value	Sen's Slope
Rainfall (mm)	*JF (Short Dry Season)*	0.126	0.430	6.60
	MAM (Long Rainy Season)	-0.148	0.233	23.10
	JJA (Long Dry Season)	0.349	**0.005**	1.95
	S (Transitional Period)	-0.345	0.161	-0.0500
	OND (Short Rainy Season)	0.239	0.0615	-6.30
Daytime temperature (℃)	*JF (Short Dry Season)*	-0.280	0.075	-0.029
	MAM (Long Rainy Season)	-0.052	0.687	-0.066
	JJA (Long Dry Season)	-0.406	**0.001**	-0.038
	S (Transitional Period)	0.057	0.874	0.000
	OND (Short Rainy Season)	-0.183	0.158	-0.040
Nighttime temperature (℃)	*JF (Short Dry Season)*	-0.318	**0.044**	-0.062
	MAM (Long Rainy Season)	-0.104	0.411	-0.053
	JJA (Long Dry Season)	-0.114	0.367	-0.056
	S (Transitional Period)	-0.019	1.000	-0.070
	OND (Short Rainy Season)	-0.004	0.986	-0.030
Relative Humidity (%)	*JF (Short Dry Season)*	0.113	0.494	0.095
	MAM (Long Rainy Season)	-0.144	0.261	-0.063
	JJA (Long Dry Season)	0.064	0.639	-0.125
	S (Transitional Period)	-0.080	0.808	-0.100
	OND (Short Rainy Season)	0.193	0.149	0.033

The time series plots, derived from the Mann-Kendall analysis, illustrate statistically significant trends identified in the rainfall data, revealing a notable pattern of increasing rainfall during the long dry season (see Figure 6). Also, significant trends identified in the daytime temperature reveal a notable pattern of decreasing temperature during the daytime of the long dry season (see Figure 7). Furthermore, significant trends were identified in the nighttime temperature, revealing a notable pattern of decreasing nighttime temperature during the short dry season (see Figure 8).

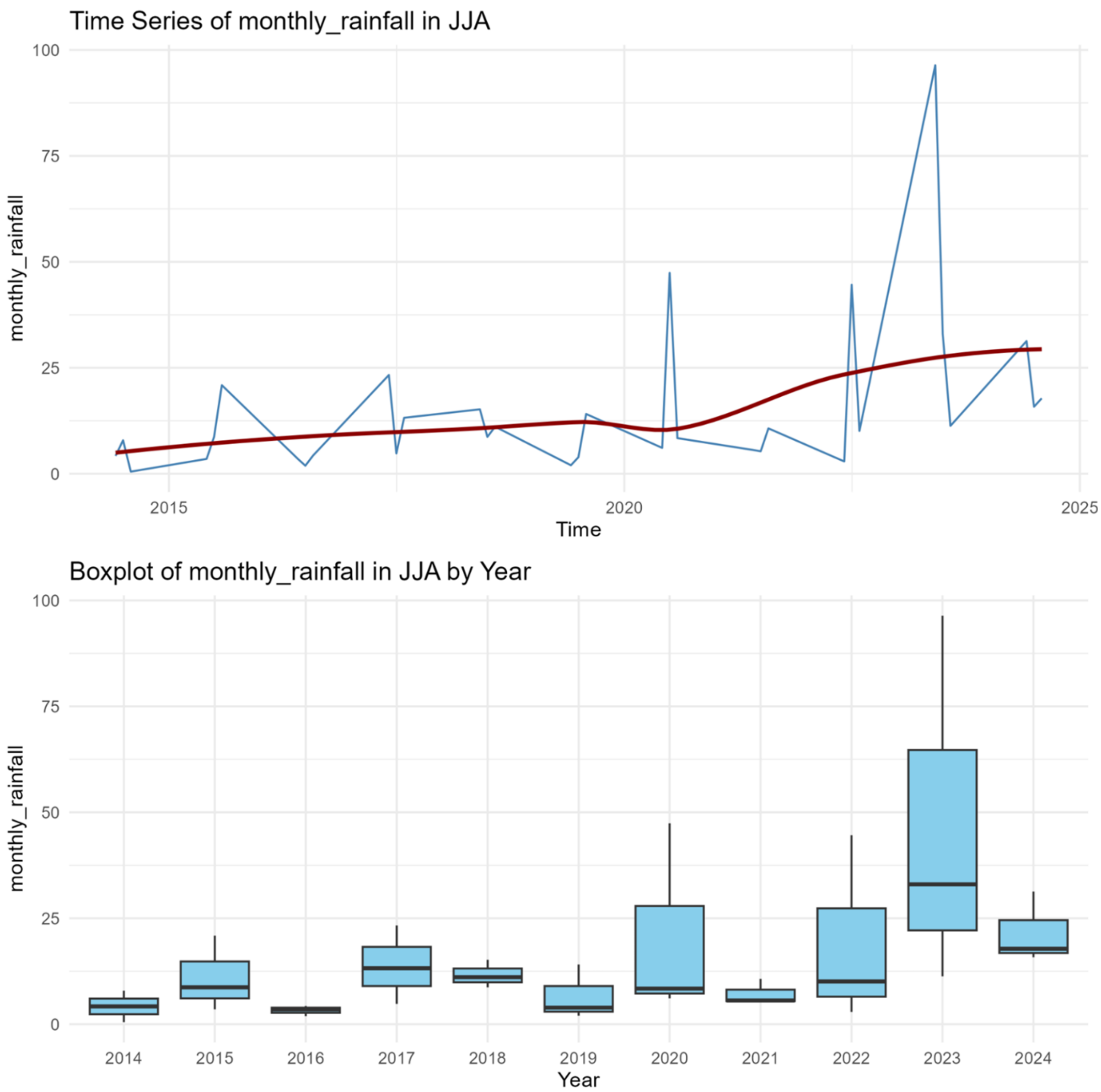
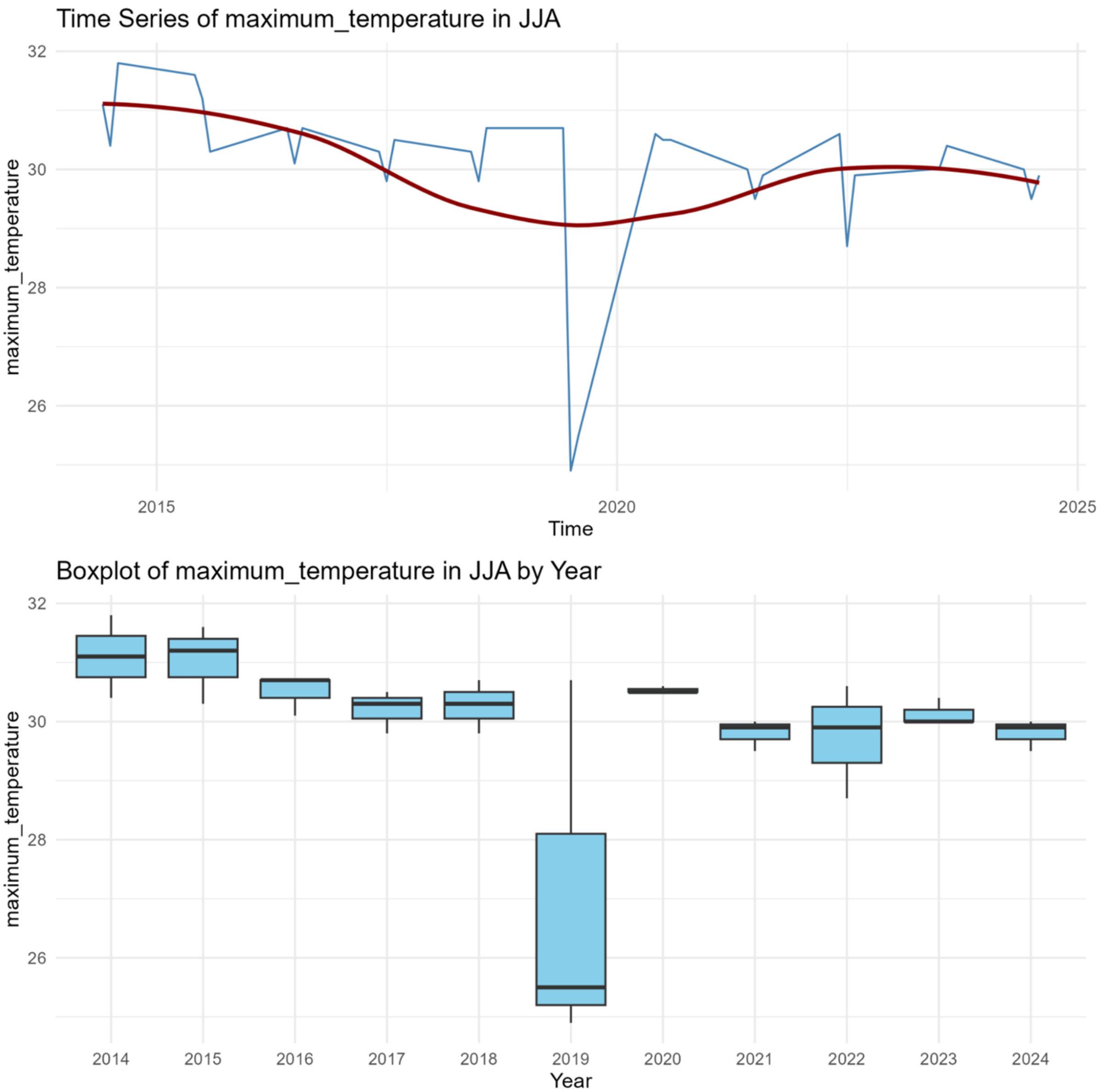


Figure 6: Time series plots of rainfall in the long dry season.



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191 *Figure 7: Time series plot of daytime temperature in the long dry season*

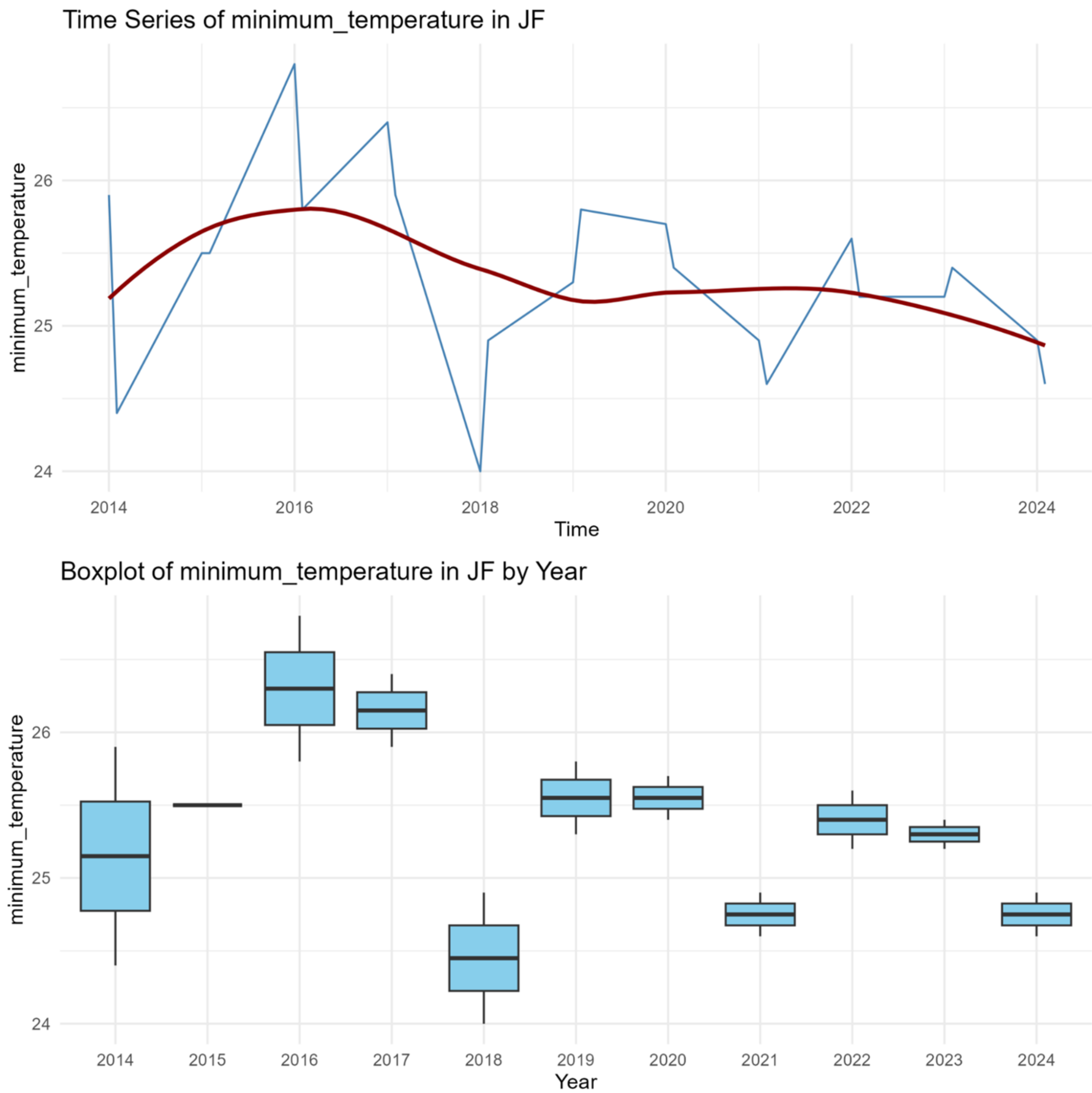

Figure 8: Time series plot of nighttime temperature in the short dry season

4. Discussions

This study found a statistically significant increase in rainfall during the long dry season (JJA), which is typically a period of low precipitation. This unexpected trend indicates a notable shift in the city's climate with important consequences. [11] also documented similar unusual increases in rainfall during dry seasons in Tanzania, attributing them to both local land use changes and broader climate change patterns.

This unexpected increase could be driven by a number of factors. The Indian Ocean Dipole (IOD) and El Niño–Southern Oscillation (ENSO) phenomena have increasingly been associated with altered rainfall patterns in East Africa [12]. Positive IOD phases, characterized by warmer sea surface temperatures near East Africa, often enhance rainfall, even in historically dry months [13]. Climate model simulations suggest that the frequency of positive IOD events is increasing under global warming scenarios [14]. Recent studies in East Africa have reported increasingly erratic precipitation, driven by warming ocean temperatures [12]. Similar results were also reported by [15], who found out that while the short rains have become wetter since the mid-1980s, the long rains in East Africa have tended toward a drier state from the mid-1980s to 2010, with some recovery thereafter. The intensity and frequency of extreme flooding and droughts, the stability of energy systems and food, the vulnerability to vector- and waterborne diseases, and the resilience of ecosystems are all impacted by these trends, which are layered on top of significant year-to-year variations.

In addition, the findings by [16] from South Sudan revealed that the rainfall shift is of particular concern as it disrupts traditional agricultural practices and increases vulnerability to climate extremes. Nevertheless, [17] documented a similar increase in dry-season rainfall in coastal Kenya, linking it to intensified regional moisture convergence.

Furthermore, local climate conditions can be altered by locally induced land-use changes, especially rapid urbanization. The conversion of vegetated land to impervious surfaces such as roads and buildings affect surface-atmosphere interactions, potentially enhancing convective activity and localized rainfall [18].

Increased dry-season rainfall could alleviate water scarcity but may also heighten flood risks in poorly drained urban neighborhoods. Urban flooding becomes a significant risk when rainfall patterns deviate from infrastructure design assumptions based on historical climatic data. In Dar es Salaam, much of the drainage infrastructure was not designed to handle substantial precipitation during dry months, heightening the risk of localized flooding. This is because much of the city's drainage system was built to manage normal rainfall patterns, not heavy storms that can occur even during the dry season [19]. The combination of inadequate infrastructure, rapid urbanization, low coverage of solid waste collection, and climate change exacerbates the problem in Dar es Salaam [20]. Furthermore, altered rainfall regimes may impact sanitation systems, especially in informal settlements where resilience is low. Additionally, this trend offers prospects for water harvesting projects and initiatives. As long as it is properly collected and stored, dry-season rainfall can help to supplement dwindling water reserves [21].

Therefore, in order to accommodate this changing trend, urban planners and policymakers must update water management strategies to include storage technology like rainwater harvesting systems. But also, Dar es Salaam's vulnerability to flash flooding underscores the importance of integrating updated rainfall patterns into city planning and resilient infrastructure development (drainage design).

In this study, it was also found that daytime temperatures in Dar es Salaam during the long dry season (JJA) displayed a substantial decline, in contrast to the dominant global trends. The short dry season (JF) also saw a decrease in nighttime temperatures. Although urban temperatures are rising globally, there have been localized cooling tendencies in areas that are implementing greening programs or where sea breezes exacerbate cooling [22].

Maritime influences are advantageous for coastal cities such as Dar es Salaam, whereby sea breezes can help reduce daytime heat extremes because of the area's closeness to the Indian Ocean. Over the course of the study, increased oceanic wind patterns may have increased the frequency and intensity of these cooling breezes. Similar findings were obtained by [23], reported that, with an impact that stretches about 7.94 kilometers inland, the ocean is essential to cooling Xiamen's urban thermal climate. The ocean's moderating influence keeps land surface temperatures in coastal and adjacent interior areas considerably moderate (18–20 °C) despite dense populations and buildings. The degree of this cooling effect varied according to urban geography and wind intensity.

In addition, similar findings were also obtained from the study conducted by [24], reported that the cooling influence of Lake Ontario can lower local metropolitan areas' peak summer temperatures by as much as 3°C. But also, in a similar vein, Vancouver's many water features, including its long coastline, are essential for controlling the city's temperature. [25] reported that the existence of water features like Burrard Inlet and False Creek is reported to influence the urban microclimate by lowering local temperatures by about 2 to 4 °C.

Furthermore, localized surface cooling in Dar es Salaam can be explained in relation to atmospheric aerosols, whereby an increased particulate matter from vehicular traffic, industrial activity, and biomass burning can increase atmospheric albedo, reflecting solar radiation and leading to surface cooling. A study by [26] reported surface temperatures to be directly lowered by scattering aerosols, such as sulfates, which reflect incoming solar energy back into space. But also, through their indirect role as cloud condensation nuclei (CCN), aerosols form clouds with more numerous, smaller droplets, increasing cloud albedo and improving solar energy reflection [27]. Aerosols also increase cloud lifetimes by preventing precipitation, which prolongs cloud cover and increases cooling [28]. Therefore, areas with significant aerosol emissions are more likely to experience these combined impacts of localized surface cooling [26].

Nevertheless, lower nighttime temperatures during the dry months may be a result of a change in cloud cover mechanisms. According to studies, shifts in cloud cover patterns have been causing more nighttime cooling in East African coastal zones, with fewer nocturnal clouds enabling more infrared radiation to escape [12,15].

Cooling trends in Dar es Salaam need to be regarded with caution. While localized cooling suggests that regional causes might influence climate signals differently, it does not imply a reversal of broader global warming. Additionally, it calls into doubt the representativeness of the data, indicating that in order to distinguish between peri-urban and urban core cooling patterns, fine-scale geographical analyses are necessary.

Unlike rainfall and temperature, fluctuations in relative humidity in Dar es Salaam were negligible and not statistically significant across all seasons during the study period. Findings in other coastal areas where air moisture levels are moderated by proximity to major bodies of water are consistent with this relative stability [24].

Stable relative humidity levels in a coastal city like Dar es Salaam can be significantly moderated by the neighboring Indian Ocean, which can function as a humidity buffer and provide constant atmospheric moisture even during times of temperature and precipitation fluctuations. Dar es Salaam seems to have been protected from the more pronounced changes in humidity that are seen in inland African cities by this marine stability [29].

However, even in the absence of statistically significant trends, subtle changes in humidity can interact with temperature to drastically alter human thermal comfort levels; for example, slightly elevated humidity at higher temperatures exponentially increases heat stress risks [30]. Humidity stability lessens the unpredictability of heat indices, protecting populations from severe swings between humid and dry heat waves. Even in areas that are now stable, global warming is predicted to exacerbate the hydrological cycle, increasing evaporation and possibly increasing the frequency of extreme humidity episodes [2]. Therefore, proactive management and monitoring are still required to be ready for possible future volatility, even though the study found relative humidity to have been reasonably steady over the last ten years in Dar es Salaam.

5. Conclusion

In coastal areas like Dar es Salaam that are fast becoming more urbanized, it is essential to comprehend localized climate changes. Urban flooding, water supply, thermal comfort, and public health are all impacted by climate variability. Global and regional patterns have received a lot of attention, but city-specific, seasonal-scale evaluations are still rare despite being crucial for climate-resilient urban development.

The climate of Dar es Salaam seems to be changing seasonally in subtle but noticeable ways. Contrary to predictions, higher rainfall during the dry season and falling temperatures challenge traditional urban calendars, water management strategies, and disaster risk reduction frameworks. In order to effectively prepare for adaptation and future-proof public health systems, urban infrastructure, and economic activity in the face of climate unpredictability, localized and seasonal evaluations are essential. As explained above, this local-level seasonal study offers vital information that can help close the gap between the realities of urban planning and national climate policies. Therefore, for Dar es Salaam to become more resilient, its city master plan has to undergo regular revision and incorporate updated climatic baselines.

6. Limitation of the study

The study has some limitations. It relied on data from a single meteorological station and a relatively short temporal window (2014–2024), which may not fully capture microclimatic variations across the broader Dar es Salaam area, as there is only one local station. Additionally, the study did not investigate potential underlying drivers of the observed trends, such as the effects of urbanization or larger regional climate dynamics. To further understand urban microclimatic variability, future studies should combine lengthier datasets, remote sensing data, and localized ground-truthing.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Grammarly in order to improve readability and clarity of the paper. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Ethics statement

This study did not involve human participants or the use of personal data. All data used were publicly available meteorological records obtained from the Tanzania Meteorological Authority. Therefore, ethical approval was not required.

Author Contributions

IM: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Writing - original draft, Writing - review & editing. **JGM**: Conceptualization, Formal analysis, Methodology, Software, Validation, Visualization, Writing - review & editing. **IHR**: Conceptualization, Data curation, Methodology, Validation, Writing - review & editing. **OP**: Conceptualization, Data curation, Methodology, Validation, Writing - review & editing. **HM**: Conceptualization, Methodology, Project administration, Validation, Writing - review & editing. All authors have read and approved the final manuscript and agree to be accountable for all aspects of the work.

Data Availability Statement

The dataset used in this study has been submitted as supplementary material alongside the manuscript. All relevant materials are available to readers without restriction. For further inquiries, please contact the corresponding author.

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Declaration of competing interests

The authors declare no conflicting interests related to this study.

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