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Research Article

Spatio-temporal Dynamics of Rainfall and Temperature in Addis Ababa: Variability, Trends, and Extremes

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Abstract

Understanding the temporal and spatial variability of rainfall and temperature is essential for climate adaptation and urban planning in rapidly growing cities. This study examines the monthly, seasonal, and annual patterns of rainfall and temperature in Addis Ababa, Ethiopia, over the period 1981-2022, using high-resolution 4 km gridded climate datasets. Trends were assessed using Modified Mann-Kendall (MMK) and Sen's slope estimators, while inter-annual variability was quantified using the Standardized Anomaly Index (SAI) and coefficient of variation (CV). Extreme temperature events were evaluated based on the 90th percentile for heat stress and the 10th percentile for cold stress. The analysis shows that Addis Ababa experiences its highest rainfall during the Kiremt season, particularly in the northern and northeastern parts, while the Belg season contributes moderate rainfall, and Bega remains the driest season. Mean monthly temperatures peak between March and May, whereas cooler conditions prevail from July through January. Spatially, southern, central, and eastern areas are consistently warmer, while northern and northwestern sectors are cooler. Trend analyses indicate no statistically significant changes in rainfall, although a slight decline in Belg and a modest increase in Kiremt are observed. Conversely, both maximum (Tmax) and minimum (Tmin) temperatures show significant increasing trends across all seasons and annually, with Tmax rising most rapidly during Belg (0.085 ℃ yr^{-1}) and Tmin increasing sharply in Bega (0.065 ℃ yr^{-1}). SAI and CV analyses highlight high inter-annual and seasonal variability in rainfall, whereas temperature variability remains relatively low, underscoring rainfall as the dominant driver of climate variability. Extreme temperature assessment reveals that heat stress events are concentrated in Belg, while cold stress is most pronounced during Bega. These findings provide a comprehensive overview of rainfall and temperature dynamics, trends, and extremes in Addis Ababa, offering essential insights for climate adaptation, urban planning, and resource management. The observed warming trends, combined with spatial and seasonal variability, emphasize the need for targeted monitoring and adaptive strategies to mitigate climate-related risks in the city.

Keywords

Addis Ababa, Rainfall, Temperature, Trend, Variability

1. Introduction

Climate variability and change are among the 21st century's most important concerns, having far-reaching consequences for environmental sustainability, socioeconomic development, and human well-being [11]. In particular, rainfall and temperature are two critical climatic variables that directly shape the availability of water resources, agricultural productivity,

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energy demand, and ecosystem functioning [28].

Across Sub-Saharan Africa, where livelihoods remain highly dependent on climate-sensitive sectors, the variability of these parameters often translates into vulnerability to droughts, floods, and other hydro-meteorological extremes [15, 20]. Understanding the patterns, variability, and trends of rainfall and temperature is therefore central to designing effective adaptation and mitigation strategies [22].

Ethiopia, located in the Horn of Africa, is among the countries most influenced by climate variability [33]. Its rainfall is highly influenced by the Intertropical Convergence Zone (ITCZ), Indian Ocean Dipole (IOD), and El Niño-Southern Oscillation (ENSO), along with regional topography and land atmosphere feedbacks [3, 34]. As a result, rainfall exhibits strong spatial and temporal variability, with marked wet and dry periods that influence food security, hydropower generation, and water supply [1, 11, 12].

Within this broader Ethiopian context, Addis Ababa, the capital city. Urban population is growing quickly. Many people have been moving from rural to urban areas in recent decades in search of better possibilities, such as employment, education, and a higher standard of living. Cities are at risk of numerous environmental issues as a result of this urban expansion [35]. Rapid urbanization has therefore been associated with a number of negative consequences, such as environmental degradation and possible urban climate hazards and extremes in the past 10 years [31].

Understanding the climate risks in Addis Ababa requires an understanding of temperature dynamics as well. Over the past 40 years, Ethiopian observational records show a steady increase in mean and extreme temperatures, which is consistent with broader patterns of global warming [26]. The urban heat island effect, which exacerbates heat stress, raises the need for cooling, and has an impact on human health, exacerbates these changes in urban areas [9]. Understanding temperature variability and extremes is crucial for public health preparedness, energy planning, and infrastructure design in Addis Ababa, a city experiencing rapid urbanization and expansion.

Relatively few studies have specifically examined the rainfall and temperature dynamics of Addis Ababa, even though research on Ethiopia's climate is steadily expanding. Most existing work has focused on regional or national scales, overlooking city-level processes that are essential for effective urban planning and climate resilience. Extremes such as heatwaves, prolonged dry spells, and heavy rainfall events remain especially underexplored, despite their disproportionate role in driving socioeconomic disruptions in urban areas. While seasonal variability and long-term trends have received some attention, the lack of detailed city-level analysis leaves a critical knowledge gap that must be addressed to inform targeted adaptation strategies.

In this context, climate characterization takes on special importance given Addis Ababa's distinct geography and topography. As the nation's political, economic, and cultural hub, the city faces heightened exposure to climate hazards due to rapid population growth and expanding infrastructure [10, 30]. A thorough understanding of rainfall and temperature dynamics, including variability, extremes, and long-term trends is therefore indispensable for climate risk management, infrastructure design, and sustainable urban planning.

This study responds to that gap by analyzing multi-decadal meteorological records to describe the rainfall and temperature dynamics of Addis Ababa. Specifically, it examines long-term patterns, seasonal variations, and the frequency and severity of extreme events, while also accounting for spatial differences across the city. The findings are intended to strengthen climate adaptation planning, enhance environmental sustainability, and improve the resilience of Ethiopia's capital.

The general objective of this study is to analyze the spatio-temporal dynamics of rainfall and temperature in Addis Ababa, focusing on variability, extremes, and long-term trends. Specifically the study aims to i) Analyze the historical variability of rainfall and temperature in Addis Ababa, ii) To assess rainfall and temperature extremes in Addis Ababa and iii) To evaluate long-term trends in rainfall and temperature.

2. Materials and Method

2.1. Study Area Description

Addis Ababa Figure 1, the capital of Ethiopia, is located in the central highlands at about 9°02′ N and 38°44′ E, with elevations ranging from 2,300 to 3,000 meters above sea level [16]. Covering valleys and undulating slopes at the base of Mount Entoto, the city's topography contributes to notable microclimatic variations. Addis Ababa is the country's political, economic, and cultural hub, and also serves as Africa's diplomatic center, hosting the headquarters of the African Union (AU) and the United Nations Economic Commission for Africa (UNECA) [36].

Climatically, Addis Ababa falls under the subtropical highland (Cwb) category of the Köppen system, with an annual mean temperature of about 16°C. Rainfall is strongly seasonal, with the main rainy season (Kiremt) from June to September, short rains (Belg) from March to May, and a dry season from October to February.

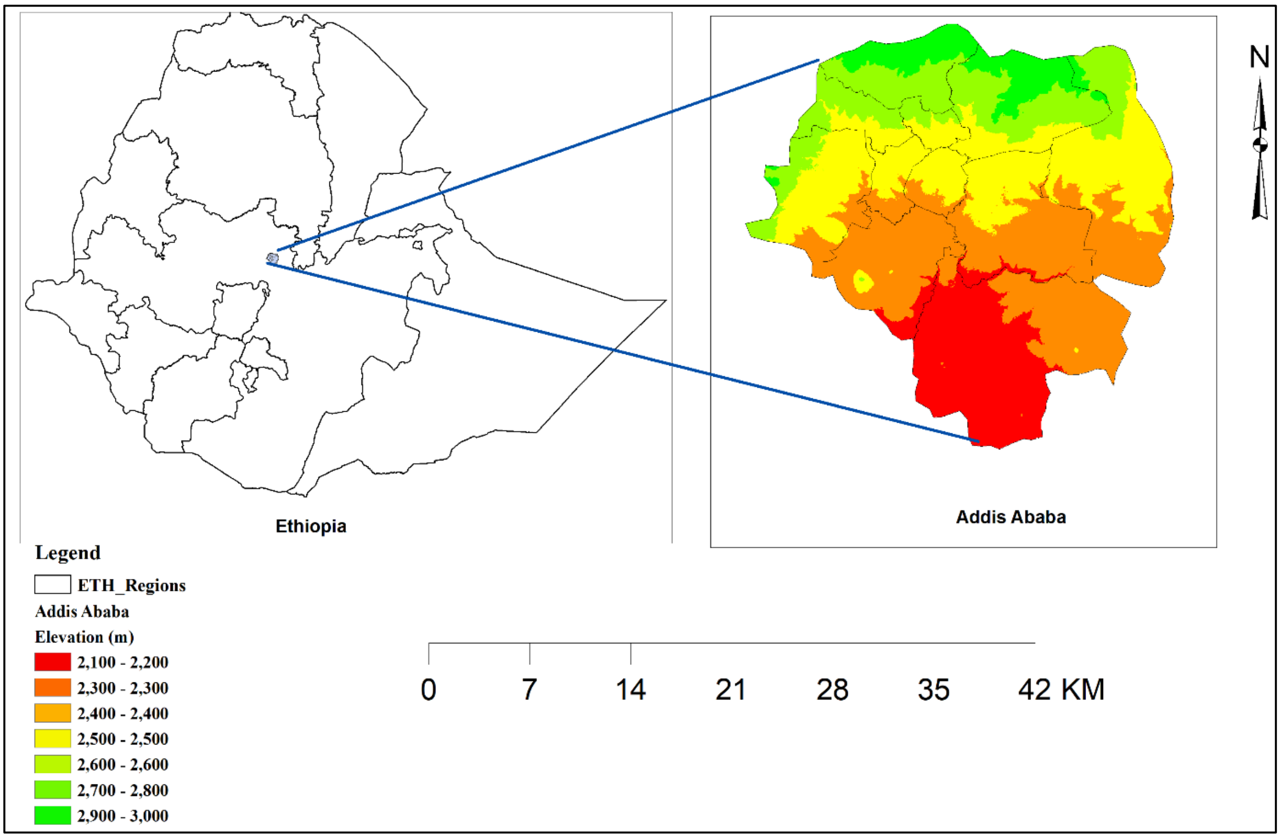

Figure 1. *Study area Map (source, Earth data SRTM 30m Digital Elevation Model).*

2.2. Data Source

To accomplish the intended objective, this study utilized the following datasets. For this study, the daily meteorological data, like rainfall, Maximum, and minimum temperature data's used from the Ethiopian Meteorological Institute (EMI) from 1981 to 2022. The gridded data have 4*4km pixel size resolution to cover the whole Addis Additionally; the study acquired the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) with a spatial resolution of 30 meters from the USGS EROS Archive.

2.3. Materials

This study utilized the Climate Data Tool (CDT) to perform data quality checks and to compute the climatology of rainfall and temperature for the study area. Python was employed to conduct trend analyses, including the Mann-Kendall test and Sen's slope estimator, as well as to calculate the Standardized Anomaly Index (SAI), Coefficient of Variation (CV), and various extreme climate indices. Additionally, Geographic Information System (GIS) tools were used to generate maps of the study area.

2.4. Methodology

This study evaluated the spatiotemporal dynamics of temperature and rainfall in Addis Ababa using a combination of statistical and geospatial methods in order to meet its stated goals. Using robust statistical tests and high-resolution climate datasets, the analysis concentrated on long-term trends, variability, and extremes. The methods and resources used in this investigation are described in the methodology section that follows.

Modified Mk Trend test

The Modified Mann-Kendall (MK) trend test is a non-parametric statistical test used to detect trends in time series data. It is a variation of the original Mann-Kendall test that incorporates modifications to handle ties and improve the test's power. The Modified MK test is widely used in hydrology, environmental sciences, and other fields to analyze trends in data where the assumptions of normality may not be met [18].

The Modified Mann-Kendall (MK) trend test is a statistical method utilized to identify trends in time series data, commonly applied in fields such as hydrology and environmental sciences [7]. Its objective is to determine whether there is a monotonic trend (either increasing or decreasing) in a dataset over a given period. The methodology involves several key steps. Firstly, data collection is imperative, where the variable of interest, such as rainfall or temperature, is recorded chronologically. Next, the data points are ranked according to their magnitudes, with ties handled by assigning average ranks. Kendall's Tau, a measure of association between ranked data and their corresponding time points, is then calculated. This is followed by the computation of the Modified MK statistic, which is based on Kendall's Tau and the sample size. The variance of this statistic is also calculated to assess the variability in the data. Subsequently, a Z-statistic is derived, representing the ratio of the Modified MK statistic to its variance. The significance of the trend is determined by comparing the absolute value of the Z-statistic to a critical value, usually obtained from statistical tables or software. If the absolute Z-statistic exceeds this critical value, the trend is deemed statistically significant at a certain confidence level. Positive and negative Z-statistics indicate increasing and decreasing trends, respectively, with the magnitude reflecting the trend's strength. Additionally, sensitivity analysis can be conducted to evaluate the trend detection's robustness. Finally, the results of the Modified MK trend test, along with relevant statistics and interpretations, are reported to convey the findings effectively [6, 7, 14].

The Modified Man Kendal test can be calculated by

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sng(x_j - x_k) \tag{1}$$

$$sng(x_j - x_k) = \begin{Bmatrix} if\, x_j - x_k > 0, +1, \\ if(x_j - x_k) = 0, 0 \\ if(x_j - x_k) < 0, -1 \end{Bmatrix} \tag{2}$$

Where n is the number of the variable set, x_j and x_k are the sequential variables at times j and k,

$$Var(s) = \frac{n(n-1)(2n+5) - \sum t_i(i)(i-2)(2i+5)}{18} \tag{3}$$

Where t_t denotes the number of this to an extent i.

The standard test statistic Zs is calculated using the equation.

$$Z_s = \begin{Bmatrix} \frac{s+1}{\sigma} or\ S > 0 \\ 0\ for\ S = 0 \\ \frac{s+1}{\sigma} or\ S < 0 \end{Bmatrix} \tag{4}$$

The Zs (test statistic) used a measure of the significance of the trend. This test statistic is used to test the null hypothesis, Ho. If |Zs| is greater than Zα/2, where α represents the chosen significance level (e.g 5% with Z 0.025 = 1.96), then the null hypothesis is invalid, implying that the trend is significant [25].

Standardized Anomaly Index (SAI)

The Standardized Anomaly Index (SAI) is another method for evaluating climate variability. It is used to examine the type of trend by identifying the dry and wet years within the study period [17]. It can be determined using an equation.

$$\text{SAI}\ (Z) = \frac{(x - \mu)}{\sigma} \tag{5}$$

Where X shows the annual or seasonal precipitation, μ denotes the mean of annual or seasonal observation, and σ represents the standard deviation of annual or seasonal precipitation throughout the observation. The SAI value shows dry period if the value is negative while indicates wet condition if the value is positive compared to the chosen reference period. According to [23] Z > 2 show extremely wet condition, Z value ranging from 1.9 to 1.5 indicate very wet condition, Z value ranging between 1.49 and 1.0 show moderately wet condition, Z value ranging from 0.99 to −0.99 show near normal rainfall condition while Z value ranging from −1 to −1.49 show moderately dry condition. On the other hand, Z value ranging from −1.5 to −1.99 show severely dry condition whereas Z < - 2 show extremely dry condition.

Coefficient of Variation

The coefficient of variation is the most common method used to analyze rainfall variations. Equation (1) is used to calculate the amount of rainfall and temperature variation in a certain area [5].

$$Cv = \left(\frac{\mu}{\sigma}\right) * 100 \tag{6}$$

Where μ denotes the mean, σ the standard deviation, and CV the coefficient of variation, the degree of variability is divided into three categories: low (CV<20), moderate (20< CV <30), and high (CV>30). A greater degree of variability is indicated by a higher CV value [2].

3. Result

3.1. Mean Monthly Rainfall and Temperature of Addis Ababa

The mean monthly rainfall of Addis Ababa show (Figure 2) that high rainfall observed in June, July, August and September month that is the main rainy season for the area. On the other hand small rainfall was observed in October, November, December and January (Bega) months. This are the dry season for the area. February, March, April and May are the second rainy season for the area Belg season moderate amount of rainfall observed.

Figure 2 illustrates the mean monthly temperature of Addis Ababa. The results indicate that the highest temperatures are generally observed during the months of March to May, marking the warmest period of the year. Moderate temperatures occur in February and June, serving as transition months between the warm and cool phases. In contrast, relatively cooler conditions dominate from July through January months.

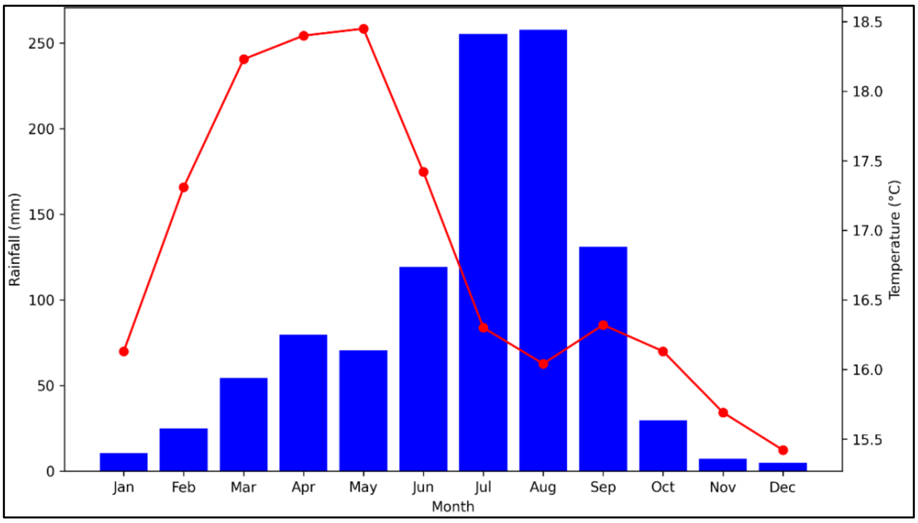

Figure 2. *Mean Monthly rainfall (blue) and temperature (Red line) of Addis Ababa City.*

3.2. Mean Seasonal Rainfall and Temperature Distribution of Addis Ababa City

The Figure 3 show that the mean seasonal (Bega, Belg, and Kiremt) rainfall distribution of Addis Ababa. Bega represents the dry season for most of the country, including Addis Ababa. The mean Bega rainfall distribution indicates high rainfall in the western part of the city, with lower rainfall observed in the southern part.

The Belg season serves as the second rainy season for most of the country, including Addis Ababa. The mean Belg rainfall distribution illustrates high rainfall, exceeding 225mm, across all parts of the country. Specifically, central, western, and southeast parts of the city experience high rainfall. Conversely, moderate rainfall covers the eastern, southern, and northwest parts.

Kiremt serves as the main rainy season for most of the country, including Addis Ababa. The mean Kiremt rainfall distribution reveals high rainfall across all parts of the city, particularly in the northern, northwest, and northeast regions. In contrast, the southern part experiences moderate rainfall compared to other areas.

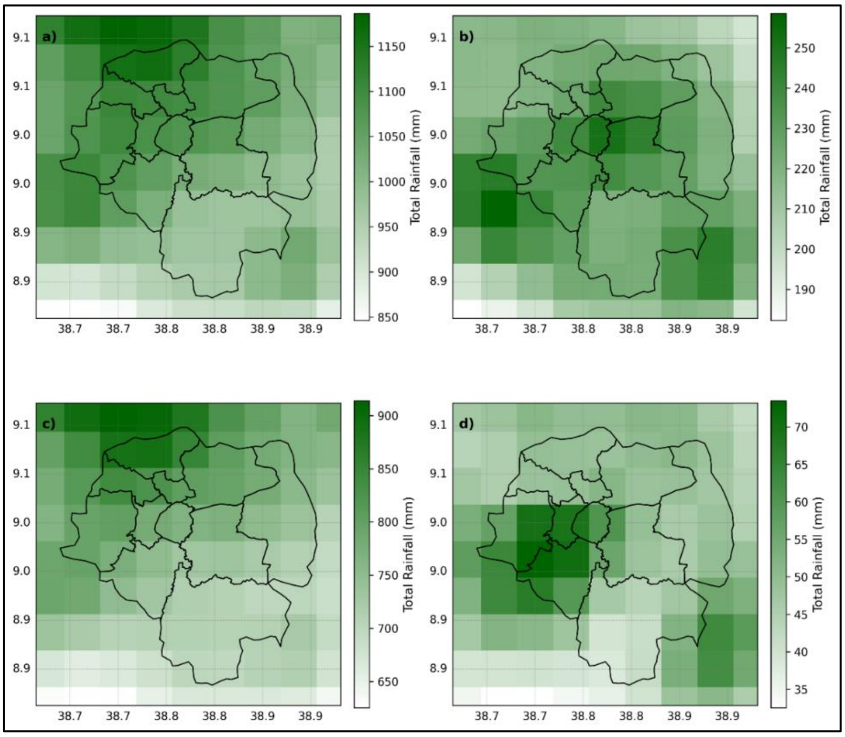

Figure 3. *Mean seasonal Rainfall distribution of Addis Ababa City a) Annual, b) Belg, c) Kiremt) and d) Bega.*

Figure 4 illustrates the spatial distribution of the mean seasonal temperature across Addis Ababa. Warmer conditions are consistently observed in the southern, central, western, and eastern parts of the city throughout all seasons, whereas the northern, northwestern, and northeastern areas experience relatively cooler temperatures. During the Belg season, the southern part of the city exhibits the highest mean temperatures.

During the Bega season, most areas show cooler mean temperatures, with warmer conditions persisting in the southern part. In the Belg season, moderate mean temperatures are observed citywide, following a clear north-south gradient: cooler in the northern areas and warmer in the south. Similarly, during Kiremt, mean temperatures are slightly elevated in the southern parts compared to the rest of the city, while northern areas remain relatively cooler.

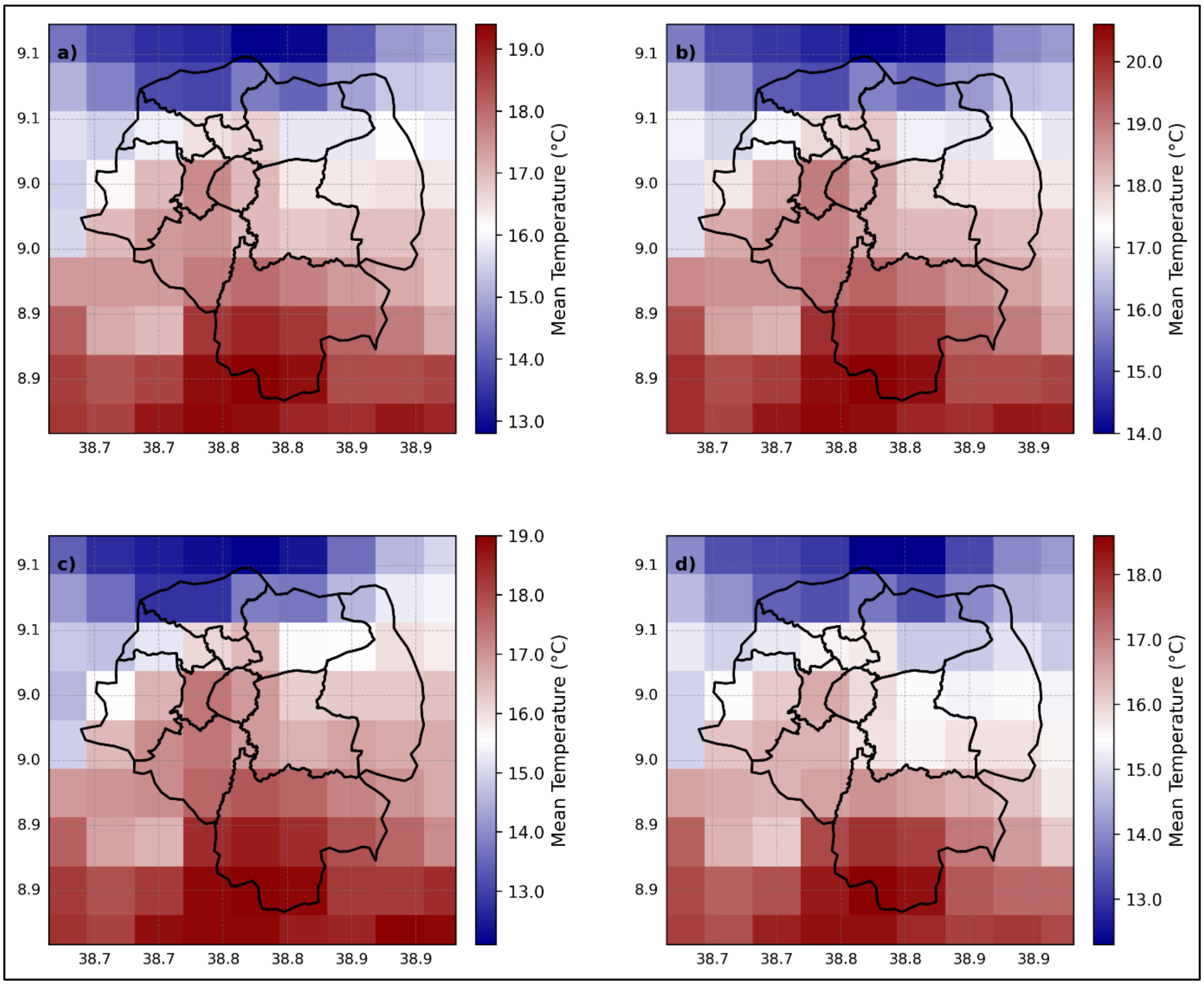

Figure 4. *Mean Annual seasonal Temperature distribution of Addis Ababa City a) Annual, b) Belg, c) Kiremt) and d) Bega.*

3.3. Trend Analysis

3.3.1. Modified Mann-Kendall and Sen's Slope Analysis of Rainfall Trends in Addis Ababa

The Modified Mann-Kendall (MMK) test and Sen's slope estimator revealed no statistically significant rainfall trends in Addis Ababa during the period 1981-2022 across the annual and seasonal time scales Figure 5. Annual rainfall exhibited a near stable pattern with a marginally positive Sen's slope of 1.38 mm $year^{-1}$ ($p = 0.33$), indicating the absence of long-term wetting or drying signals at the city-wide scale. Similarly, Belg rainfall (February-May) showed a non-significant declining tendency (slope = -1.53 mm $year^{-1}$, $p = 0.30$), suggesting a possible reduction in early-season rainfall, though the high interannual variability masks any consistent trend. The Kiremt season (June-September), which contributes the bulk of rainfall in Addis Ababa, demonstrated a weakly increasing trend (slope = 2.22 mm $year^{-1}$, $p = 0.09$). Although this result did not reach statistical significance at the 5% level, it indicates a potential upward tendency in the main rainy season, which could have implications for water availability and agricultural productivity. In contrast, the Bega season

(October-January), characterized by low rainfall totals, displayed no meaningful trend (slope = 0.29 mm $year^{-1}$, p = 0.31). Overall, these findings suggest that while rainfall in Addis Ababa has remained relatively stable over the past four decades, subtle tendencies exist particularly the slight decline in Belg rainfall and a possible increase in Kiremt rainfall. These results are consistent with the broader literature on Ethiopian hydro climate, where long-term rainfall trends are often weak or statistically insignificant due to the strong influence of inter-annual variability and large-scale climate drivers such as ENSO and the Indian Ocean Dipole.

3.3.2. Modified Mann-Kendall and Sen's Slope Analysis of Temperature Trends in Addis Ababa

The Mann-Kendall trend analysis combined with Sen's slope estimator Figure 6 revealed a significant increasing trend in both maximum (Tmax) and minimum (Tmin) temperatures across all seasons and annually for the period 1981-2022 in Addis Ababa. For Tmax, the annual mean temperature shows a statistically significant increasing trend (p = 0.0002) with a Sen's slope of 0.060 ℃ per year, indicating an overall warming of approximately 2.37 ℃ over the 42-year period. Seasonally, the Belg season exhibits the strongest warming signal for Tmax, with a significant increase (p < 0.0000001) and a slope of 0.085 ℃ per year, followed by Kiremt (p = 0.00075; slope = 0.045 ℃/yr) and Bega (p = 0.00029; slope = 0.052 ℃/yr). These results indicate that the early rainy season (Belg) is warming more rapidly than other periods, while the main Kiremt and dry Bega seasons are also experiencing notable warming.

For Tmin, a similar pattern of increase is observed. The annual mean Tmin shows a significant upward trend (p = 0.00011) with a Sen's slope of 0.049 ℃ per year. Seasonally, Bega exhibits the highest rate of increase in Tmin (p < 1E-10; slope = 0.065 ℃/yr), suggesting that the coolest season of the year is experiencing pronounced warming, likely reducing cold stress and nighttime cooling. The Belg (p = 0.00003; slope = 0.046 ℃/yr) and Kiremt (p = 0.00236; slope = 0.045 ℃/yr) seasons also show significant warming, although at a slightly lower rate than Bega.

Overall, the consistent increase in both Tmax and Tmin across all seasons indicates a general warming trend in Addis Ababa over the last four decades. The stronger increase in Tmin during the dry Bega season and Tmax during the Belg season could have important implications for agriculture, water resources, and urban heat stress, as both daytime and nighttime temperatures are rising. The combination of statistically significant trends and positive Sen's slopes highlights the robustness of the observed warming signal.

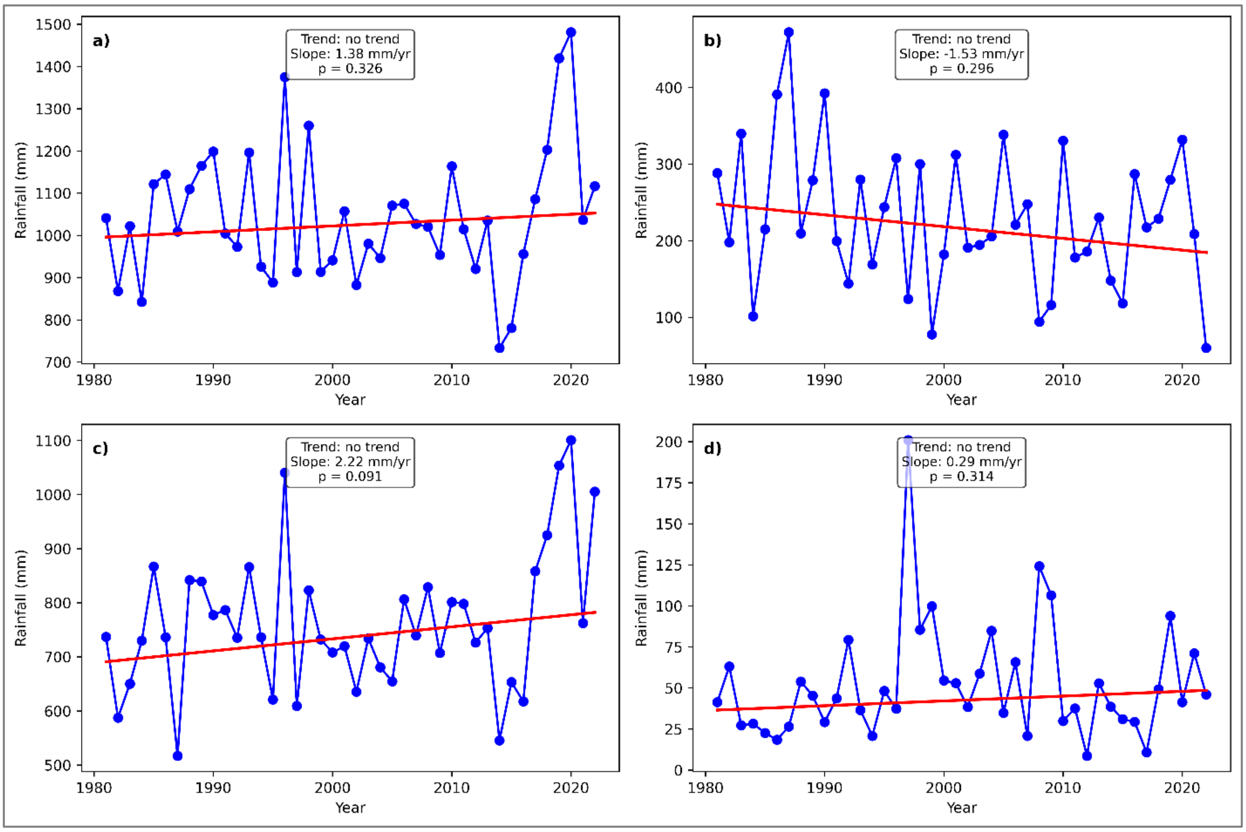

Figure 5*. Annual (a), Belg (b), Kiremt (c) and Bega (d) Rainfall trend analysis.*

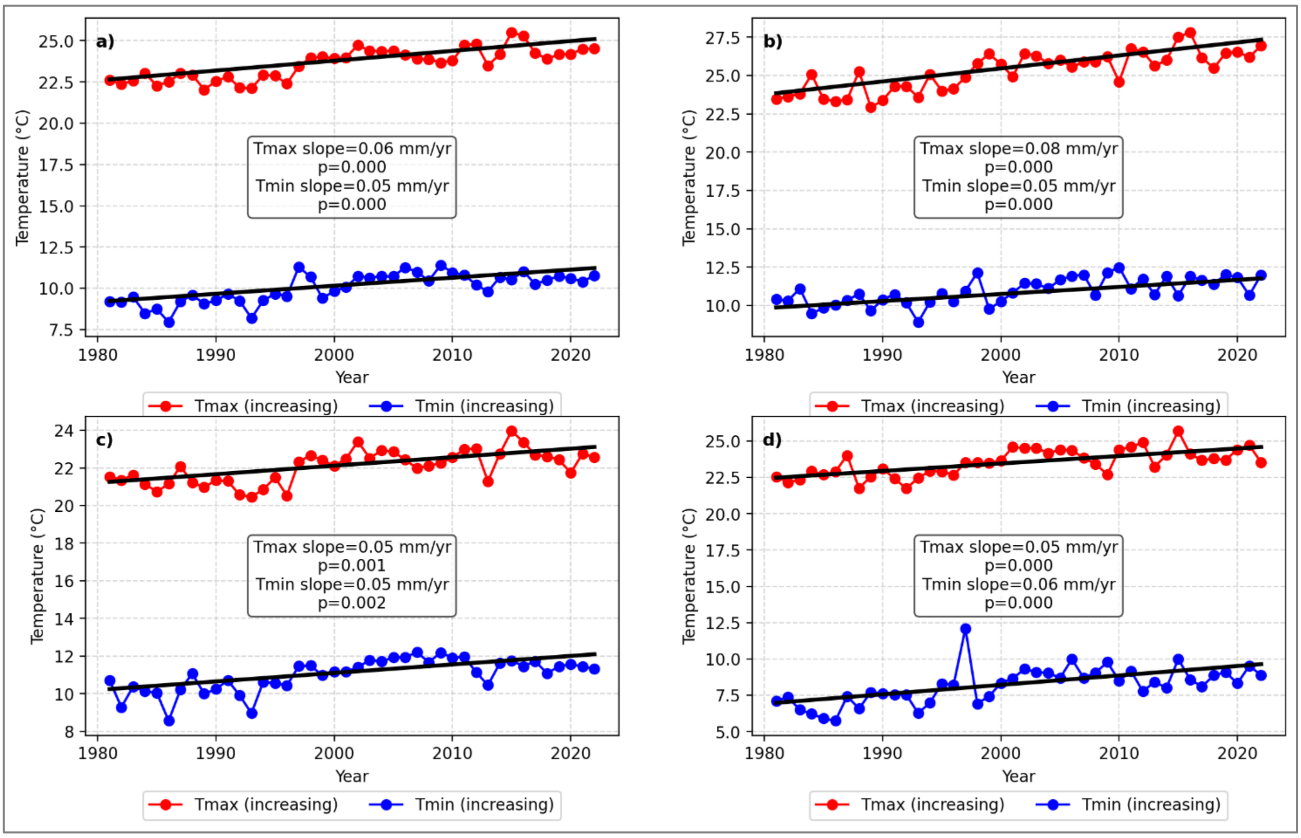

Figure 6. *Annual (a), Belg (b), Kiremt (c) and Bega (d) Tmin and Tmax trend analysis.*

3.4. Standardized Anomaly Index of Addis Ababa City

Rainfall

The Standardized Anomaly Index (SAI) was calculated for rainfall across four temporal scales Annual, Belg, Kiremt, and Bega for the period 1981 - 2022. The results reveal notable inter-annual and seasonal variability.

The annual SAI (Figure 7 (a)) fluctuates considerably over the study period, with both negative and positive anomalies observed. Negative anomalies (e.g., 1982: -1.12; 1984: -1.29; 2014: -1.97) indicate below-average rainfall years, while positive anomalies (e.g., 1996: 2.08; 2019: 2.38; 2020: 2.75) reflect above-average rainfall conditions. Overall, the annual pattern suggests alternating wet and dry years with no consistent long-term trend, highlighting the high variability in Addis Ababa's annual rainfall.

The Belg SAI Figure 7b shows substantial fluctuations, ranging from extreme positive anomalies (1987: 2.66; 1990: 1.79) to pronounced negative anomalies (1999: -1.66; 2022: -1.85). These extremes suggest that Belg rainfall is highly variable and prone to both wet and dry episodes, which could have significant implications for agricultural planning and early-season cropping.

The Kiremt season Figure 7c exhibits frequent negative anomalies in the early 1980s (1982: -1.35; 1983: -0.87) and mid-2010s (2015: -0.84; 2016: -1.12), indicating below-average monsoon rainfall. Conversely, strong positive anomalies occur in 1996 (2.13), 2018 (1.24), 2019 (2.23), and 2020 (2.59), representing extremely wet monsoon seasons. This seasonal pattern emphasizes the dominance of high inter-annual variability, consistent with the known variability of the Kiremt rains in Ethiopia.

The Bega SAI Figure 7d shows moderate variability relative to other seasons. While most years cluster around near-zero values, extreme positive anomalies appear in 1997 (4.20), 2008 (2.03), 2009 (1.53), and 2019 (1.17), suggesting unusually wet post-monsoon conditions during these periods. Negative anomalies are less severe and frequent, indicating that dry conditions during Bega are generally milder.

Overall patterns across all seasons, the SAI indicates that rainfall variability is seasonally dependent. The Belg and Kiremt seasons display the highest variability and extremes, reflecting both drought and flood-prone periods, whereas Bega tends to have lower variability with occasional extreme wet years. The alternating positive and negative anomalies underscore the inter-annual and seasonal instability of rainfall in Addis Ababa, which has direct implications for water resources management, agriculture, and climate adaptation strategies.

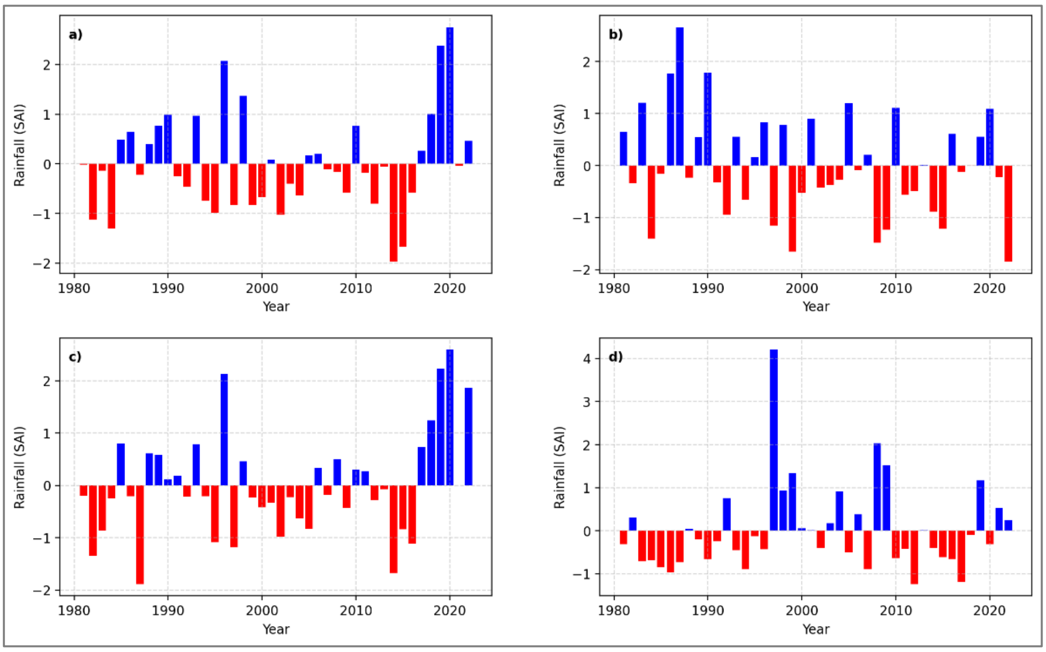

Figure 7. *Annual (a), Belg (b), Kiremt (c), and Bega (d) Rainfall SAI.*

Temperature standardized anomaly index

The Standardized Anomaly Index (SAI) for Tmax and Tmin was computed for Annual, Belg, Kiremt, and Bega periods over the 1981-2022 timeframe. The analysis reveals clear inter-annual and seasonal variability with distinct wetting (warming) and cooling (negative anomaly) periods.

Maximum Temperature

Annual Tmax Figure 8a anomalies fluctuate between negative and positive extremes, indicating years of below-average (cooler) and above-average (warmer) Tmax. Notable negative anomalies are observed in 1982 (-1.33), 1989 (-1.69), and 1993 (-1.61), representing cooler-than-average years. Conversely, strong positive anomalies occur in 1998 (0.38), 2002 (1.23), 2015 (2.06), and 2022 (0.99), indicating above-average Tmax conditions. The annual pattern suggests increasing warming trends in the recent decades, with more frequent positive anomalies after 2000.

The Belg Tmax SAI Figure 8b exhibits considerable variation, with strong negative anomalies in the early 1980s (1981: -1.43; 1986: -1.53) and positive anomalies in the late 1990s and 2000s (1999: 0.89; 2015: 1.76). This indicates that early-year maximum temperatures have periods of cooling followed by pronounced warming in recent decades, reflecting seasonal variability and potential shifts in early-season climatic conditions.

Tmax during the Kiremt season Figure 8c shows a mix of negative anomalies in the 1980s and early 1990s (e.g., 1982: -0.78; 1993: -1.83) and strong positive anomalies in recent decades (2002: 1.58; 2015: 2.22), suggesting an overall warming trend during the monsoon period. This increase in Tmax could have implications for evapotranspiration, crop water stress, and heatwave frequency during the main rainy season.

The Bega Tmax SAI Figure 8d is relatively moderate compared to other seasons but still indicates periods of extreme warming, notably in 2015 (2.38) and 2016 (0.65). Negative anomalies, such as in 1982 (-1.48) and 1988 (-1.92), point to cooler-than-average post-monsoon conditions. This seasonal variability suggests that the transition and dry season are becoming more variable, with intermittent hot years.

Overall trends across all seasons, Tmax SAI demonstrates a clear warming tendency, particularly from the late 1990s onward, with positive anomalies becoming more frequent and intense. The increasing Tmax, especially during the monsoon (Kiremt) and post-monsoon (Bega) seasons, may exacerbate drought conditions, heat stress, and impact local agriculture and water resources. The results highlight the importance of seasonal monitoring for climate adaptation and mitigation planning in Addis Ababa.

Minimum Temperature

Annual Tmin SPI Figure 9a mostly remain negative during the early period (1981-1986), indicating cooler-than-average minimum temperatures, with strong negative deviations in 1986 (-2.38) and 1993 (-2.09). Positive anomalies appear in the later period, particularly after 1997, such as in 1997 (1.44), 2006 (1.42), and 2022 (0.86), suggesting a warming trend in nighttime or minimum temperatures over recent decades.

Tmin anomalies during Belg Figure 9b show high inter-annual variability. Early negative anomalies (e.g., 1982: -0.75; 1984: -1.71) reflect colder early-season conditions, while strong positive anomalies in 1998 (1.40), 2009 (1.40), and 2022 (1.24) indicate warmer early-year minimum temperatures. This suggests increasing warming in Belg minimum temperatures in the last two decades.

Tmin during Kiremt Figure 9c shows pronounced negative anomalies in early 1980s and early 1990s (e.g., 1982: -1.97;

1993: -2.35), followed by positive anomalies in the 2000s (e.g., 2003: 0.91; 2007: 1.39), indicating an overall increase in night-time temperatures during the monsoon season. These rising Tmin values may intensify heat stress during warm nights and reduce diurnal temperature range.

The Bega Tmin SAI Figure 9d shows intermittent negative anomalies in the early period (1981: -0.83; 1986: -1.93) and positive anomalies in the later years, particularly in 1997 (3.11), 2006 (1.43), and 2015 (1.44), indicating a trend toward warmer minimum temperatures in the post-monsoon and early dry season. The exceptionally high anomaly in 1997 (3.11) suggests an extreme warming event during this period.

Overall trends across all seasons, Tmin exhibits a clear warming pattern, with more frequent and intense positive anomalies after 1997. The increasing Tmin may contribute to rising nighttime temperatures, which can have ecological and human health impacts, reduce nighttime cooling, and exacerbate drought and heat stress during the warm seasons. Seasonal monitoring is crucial to understanding the implications of these changes for climate adaptation strategies.

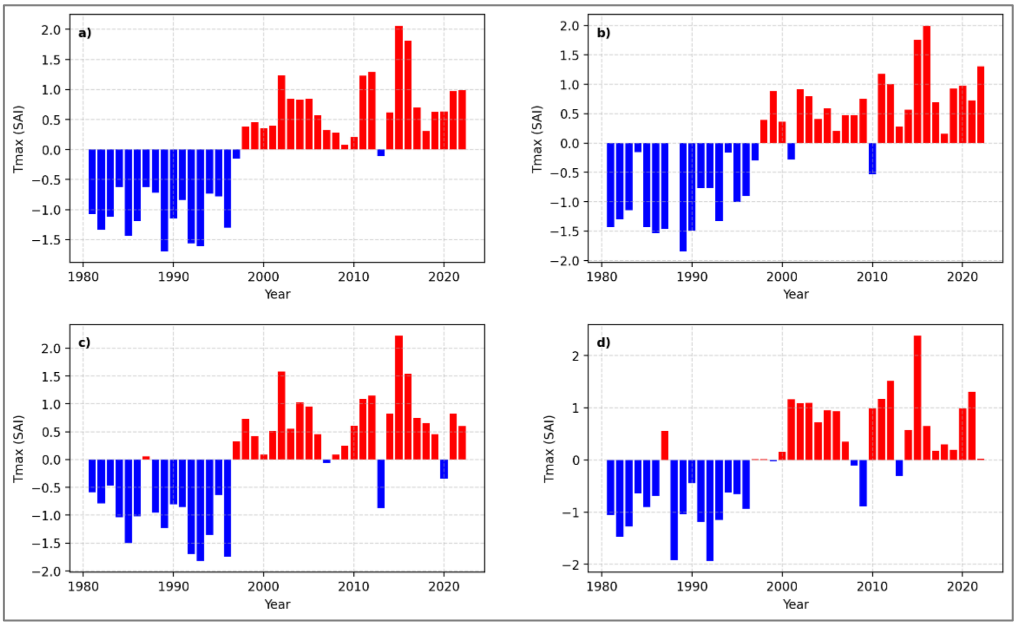

Figure 8. Annual (a), Belg (b), Kiremt (c) and Bega (d) Tmax SAI.

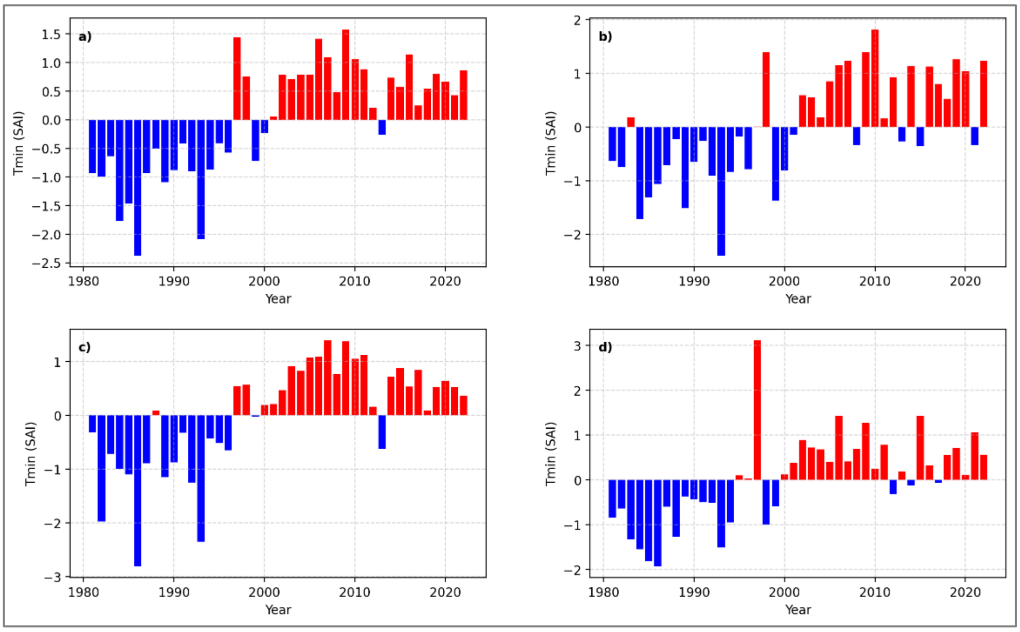

Figure 9. Annual (a), Belg (b), Kiremt (c) and Bega (d) Tmin SAI.

3.5. Coefficient of Variation of Rainfall and Temperature, over Addis Ababa (1981-2022)

The coefficient of variation (CV) analysis revealed notable differences in inter-annual and seasonal variability among rainfall, minimum temperature (Tmin), and maximum temperature (Tmax) over Addis Ababa. Rainfall Figure 10a exhibited pronounced variability across seasons, with the Bega season showing very high variability (67.65%), followed by Belg with high variability (39.84%). In contrast, annual (15.1%) and Kiremt (17.06%) rainfall CV values indicated relatively low variability, highlighting the stability of the main rainy season (Kiremt) compared to the short rains (Belg) and dry season (Bega).

On the other hand, both Tmin and Tmax Figure 10b and c displayed consistently low variability across all seasons and annually, with CV values ranging between 3.91% and 15.44%. The relatively higher CV of Tmin during the Bega season (15.44%) still falls within the low variability class, underscoring the stability of temperature in comparison to rainfall.

Overall, the results suggest that rainfall is the dominant source of climatic variability in Addis Ababa, particularly during the transitional seasons (Belg and Bega), while temperature remains relatively stable throughout the year.

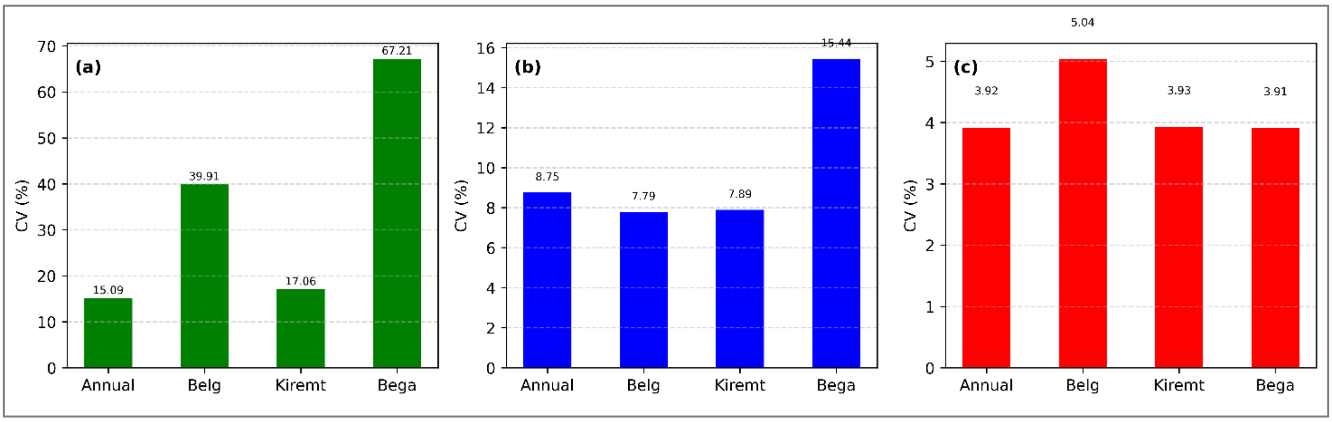

Figure 10. CV analysis of annual and seasonal climate variables in Addis Ababa: Rainfall (a), Tmin (b) and Tmax (c).

3.6. Extreme Temperature Analysis

3.6.1. Heat Stress in Addis Ababa (1981-2022 Baseline)

Heat stress events were evaluated using a Tmax threshold of 26.84 ℃ (90th percentile). The results show that Belg season consistently experienced the highest number of heat days Figure 11a, often exceeding 50 days in some years (e.g., 1999, 2003, 2015, 2016), reflecting the prevalence of high temperatures during the short rainy season. The Kiremt season experienced a moderate number of heat days, usually under 15 days per year, whereas the Bega season recorded very few heat days, often close to zero, indicating that the dry season is relatively cooler and less prone to heat stress.

Annual heat days ranged from 0 to 106 days, demonstrating significant interannual variability. Peak heat stress years, such as 2016 and 2015, were dominated by exceptionally high heat days during the Belg season, highlighting that short rains are the most critical period for heat stress in Addis Ababa. Overall, the distribution of heat days emphasizes the seasonal and interannual variability, with the Belg season being the most sensitive to extreme high temperatures.

3.6.2. Cold Stress in Addis Ababa (1981-2022 Baseline)

Cold stress events Figure 11b were assessed using a Tmin threshold of 7.18 ℃ (10th percentile). The annual number of cold days varied considerably over the study period, ranging from 0 to 106 days per year. The Bega season consistently experienced the highest number of cold days, with some years recording over 90 days, reflecting the pronounced cool conditions during this dry season. In contrast, the Belg and Kiremt seasons recorded relatively few cold days, typically less than 10 days per year, indicating that these seasons are generally warmer. The distribution of cold days highlights the strong seasonal variability, with the dry season (Bega) being the most susceptible to cold stress, while the rainy (Kiremt) and short rains (Belg) seasons are largely unaffected.

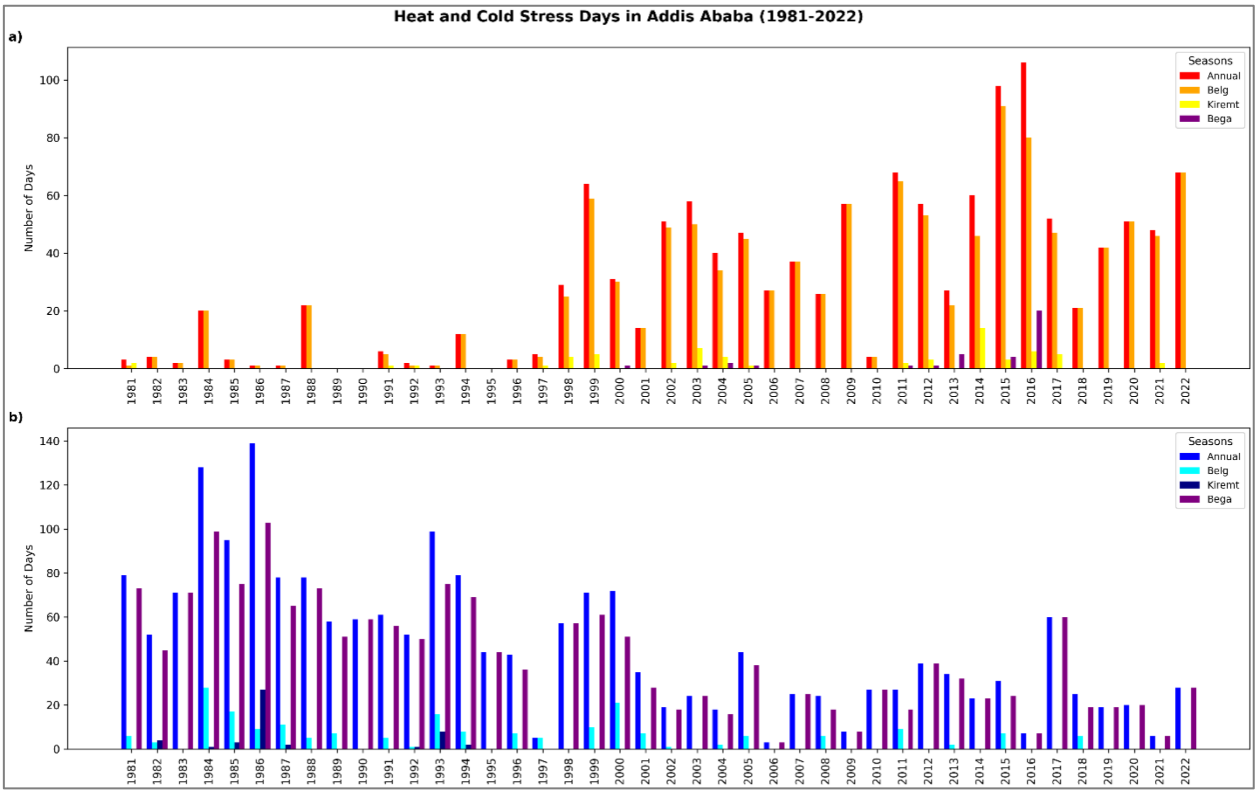

Figure 11. *Annual and seasonal heat and cold stress days in Addis Ababa (1981-2022) based on percentile thresholds.*

4. Discussion

The present study provides a comprehensive assessment of rainfall and temperature variability in Addis Ababa over the period 1981-2022, revealing both seasonal and inter annual patterns and trends. The observed seasonal rainfall distribution, characterized by high rainfall during Kiremt and moderate precipitation during Belg, aligns with previous studies on Ethiopian hydro climate [19, 38]. The dry Bega season exhibits minimal rainfall, consistent with the long-established bimodal rainfall regime in central Ethiopia [6]. Spatial analysis indicated that northern and northeastern areas receive higher rainfall during the main rainy season, while southern parts remain relatively drier, reflecting local topographic influences on precipitation patterns [19, 38].

Trend analysis using the Modified Mann-Kendall and Sen's slope estimator indicates no statistically significant changes in annual and seasonal rainfall, consistent with prior studies reporting weak or non-significant long-term rainfall trends across the Ethiopian highlands [32]. Despite this stability, slight decreases in Belg rainfall and a modest increase in Kiremt rainfall were observed, suggesting potential shifts in early and main rainy season dynamics, which may affect water resources management and agricultural planning.

Temperature trends reveal significant warming in both maximum (Tmax) and minimum (Tmin) temperatures across all seasons. Annual Tmax increased by 0.060℃ per year, totaling approximately 2.37℃ over four decades, while Tmin rose at 0.049℃ per year. These findings are consistent with global and regional warming trends reported by the [21] and previous Ethiopian studies [6, 27, 37]. The stronger increase in Tmax during Belg and in Tmin during Bega highlights seasonal asymmetry in warming, with potential implications for heat stress, agricultural productivity, and urban microclimates [4]. The rising Tmin, particularly during Bega, may reduce nighttime cooling and exacerbate heat-related health risks.

The Standardized Anomaly Index (SAI) further underscores interannual variability, with pronounced extremes in Belg and Kiremt rainfall, while Bega remains comparatively stable. This finding aligns with prior research highlighting high variability of Ethiopian rainfall due to ENSO and the Indian Ocean Dipole [8, 29]. Temperature anomalies also exhibit increased frequency and magnitude of positive deviations after 2000, reflecting accelerated warming consistent with observed urban heat island effects in rapidly growing African cities [24, 26].

Coefficient of Variation analysis confirms that rainfall exhibits higher variability than temperature across all seasons, emphasizing rainfall as the dominant source of climatic instability in Addis Ababa. This finding alien with study in Wereilu district, Northeastern Highlands of Ethiopia it stated that varying degrees of temporary rainfall variability, extending from moderate to high [19]. Extreme temperature assessments reveal that Belg experiences the highest number of heat stress days, whereas Bega records the greatest number of cold stress days, indicating seasonally dependent vulnerabilities relevant for public health and agriculture. This finding consistent with study in Ethiopia [13, 19].

Overall, these results provide critical insights into the spatiotemporal dynamics of rainfall and temperature in Addis Ababa, highlighting significant warming trends and variable rainfall patterns. The findings support targeted adaptation strategies, including climate-resilient urban planning, water resource management, and seasonal agricultural practices.

5. Conclusion

This study presents the assessment of rainfall and temperature dynamics in Addis Ababa over the period 1981-2022, highlighting both temporal and spatial variability across annual and seasonal scales. The analysis of mean monthly and seasonal rainfall shows that the main rainy season (Kiremt) contributes the largest rainfall amounts, with particularly high totals in the northern and northeastern parts of the city. The Belg season serves as a secondary rainy period, with moderate rainfall distributed mainly across the central, western, and southeastern parts of the city. In contrast, the Bega season is characterized by low rainfall, establishing a distinct dry season pattern. These seasonal differences emphasize the critical role of Kiremt and Belg in water availability and urban hydrology.

Temperature analysis reveals a consistent spatial gradient, with warmer conditions predominantly in the southern, central, and eastern portions of Addis Ababa, while northern, northwestern, and northeastern areas remain relatively cooler throughout all seasons. Mean monthly temperatures indicate that the warmest period occurs from March to May, with moderate temperatures in transitional months (February and June), and cooler conditions persisting from July through January. Seasonal temperature patterns further reinforce this gradient, with the southern areas consistently experiencing higher mean temperatures than northern parts.

Trend analyses using the Modified Mann-Kendall test and Sen’s slope estimator show no statistically significant changes in rainfall across annual and seasonal scales, although subtle tendencies are observed, such as a slight decline in Belg rainfall and a potential increase in Kiremt rainfall. In contrast, both Tmax and Tmin show a significant increasing trend across all seasons and annually. Specifically, Tmax exhibits the strongest warming signal during Belg, while Tmin increases most markedly during Bega. These trends suggest that both daytime and nighttime warming are influencing the city’s climate, with important implications for heat stress, urban planning, and agriculture.

The SAI highlights the high inter-annual and seasonal variability of rainfall, particularly during the Belg and Kiremt seasons, whereas Bega demonstrates relatively lower variability. Temperature anomalies show a clear warming signal, particularly after the late 1990s, with Tmax anomalies indicating more frequent and intense warm years and Tmin anomalies suggesting rising nighttime temperatures. Coefficient of variation analysis confirms that rainfall remains the most variable climate parameter, while temperature is relatively stable, although seasonal differences are evident.

Extreme temperature assessments reveal that heat stress events are most prevalent during Belg, with some years exceeding 50 heat days, whereas cold stress is most pronounced during Bega, with several years recording over 90 cold days. These findings underscore the seasonal susceptibility of Addis Ababa to both heat and cold extremes and highlight the potential influences on human health, agriculture, and water resources.

Overall, this study provides a detailed baseline of climate variability, trends, and extremes for Addis Ababa over the past four decades. The observed warming trends, coupled with the spatial variability of rainfall and temperature, have critical implications for climate adaptation strategies, urban planning, and resource management. The results emphasize the need for continuous monitoring of seasonal and inter-annual climate variability to support sustainable development and climate resilience in the city.

Abbreviations

AU	African Union
CDT	Climate Data Tool
CV	Coefficient of Variation
DEM	Digital Elevation Model
GIS	Geographic Information System
MK	Mann-Kendall
SRTM	Shuttle Radar Topography Mission
SAI	Standardized Anomaly Index
Cwb	Subtropical Highland
UNECA	United Nations Economic Commission for Africa

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Author Contributions

Zelalem Alemayehu Kebede: Data curation, Formal Analysis, Investigation, Software, Visualization, Writing - original draft

Geberemariyam Adane: Data curation, Formal Analysis, Methodology, Validation, Writing - review & editing

Tarekegn Abera: Conceptualization, Supervision

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript entitled "Spatio-Temporal Dynamics of Rainfall and Temperature in Addis

Ababa: Variability, Trends, and Extremes.." All authors have contributed to the research and writing of this manuscript and have disclosed any financial or personal relationships that could be perceived as influencing the work reported in this paper. We confirm that this manuscript has not been published elsewhere and is not under consideration by any other publication.

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