Journal of Ghana Science Association, Volume 23(2)

Date of Publication: 12th March 2026
ISSN: 2737-713X

SPATIOTEMPORAL PATTERNS AND LONG-TERM TRENDS OF CLIMATE VARIABLES: ANALYZING TEMPERATURE INCREASE AND RAINFALL VARIABILITY FROM 1983 TO 2022 IN NORTH GONDAR ZONE, ETHIOPIA

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Abstract

This study analyzed the spatiotemporal variability and long-term trends of temperature and rainfall over 40 years (1983–2022) in the North Gondar zone, Amhara region, Ethiopia. Monthly climate data for Adiarkay, Debark, and Janamora districts were obtained from the NASA POWER database. To examine rainfall and temperature variability, descriptive statistics and the Coefficient of Variation (CV) were employed, while wet and dry conditions were assessed using the Standardized Anomaly Index (SAI). Trend detection and magnitude estimation were conducted using the non-parametric Mann–Kendall trend test and Sen's slope estimator, respectively, at annual and seasonal time scales. The results reveal high variability in annual rainfall, with Adiarkay and Janamora receiving below-regional average precipitation and Debark exceeding it. The annual rainfall trend showed a statistically insignificant decrease in Adiarkay and Janamora but an increase in Debark. Seasonal analysis indicated significant variability, with extreme fluctuations during the spring season and a dominant contribution of the summer season to total rainfall. Temperature trends demonstrated statistically significant increases in maximum, minimum, and mean annual temperatures in most districts, with Janamora showing the strongest warming signals. The study underscores the influence of rising temperatures and fluctuating rainfall on the region's rain-fed agriculture and food security. These climatic dynamics highlight the need for adaptive strategies to mitigate adverse socio-economic impacts and enhance community resilience.

Keywords
Man kendall, North Gondar zone, Temperature, Rainfall

Introduction

Human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming, with global surface temperature reaching 1.1°C above 1850 – 1900 in 2011 – 2020. Global greenhouse gas emissions have continued to increase, with unequal historical and ongoing contributions arising from unsustainable energy use, land use and land-use change, lifestyles and patterns of consumption and production across regions, between and within countries, and among individuals (Lee et al., 2023). Climate change is a global development challenge that is causing widespread impacts on socioeconomic development through the increased intensity of weather extremes such as droughts, heatwaves, shifts in seasons, and intense storms (NAP, 2020).

Scientists have observed changes in Africa's climate during the past century, with records showing increased warming over Africa's land mass. Climate change is already having negative effects on Africa. It is impacting the health of land and marine-based ecosystems, and the health and food security of many of the region's most vulnerable people (Carabine et al., 2014). Africa's relationship with climate change is multifaceted and intricate, encompassing a range of social impacts. Much of Africa still relies on agriculture-based economies. Climate change adversely affects agricultural productivity due to issues like drought, diminishing water resources, and extreme weather events, consequently reducing food production and increasing the risk of food insecurity. Africa is heavily dependent on water resources, and many regions already experience water scarcity. Climate change exacerbates problems related to decreasing water resources, drought, and water shortages (Dal, 2023). Human influence on the climate system is now detected with increased certainty, both globally and in most regions. Since the mid-20th century, the increase in anthropogenic greenhouse gas concentrations has led to surface warming over almost the entire globe, while at the same time, the ocean has continued to warm and store energy (Allen et al., 2014).

The climates of Africa are both varied and varying; varied because they range from humid equatorial regimes, through seasonally arid tropical regimes, to sub-tropical Mediterranean-type climates, and varying because all these climates exhibit differing degrees of temporal variability, particularly with regard to rainfall (Hulme et al., 2001). The continent of Africa is warmer than it was 100 years ago. Warming through the twentieth century has been at the rate of 0.5°C/century, with slightly larger warming in the June-August and September – November seasons than in December – February and March – May (Low, 2006). The African continent continued to observe a warming trend, with an average rate of change of around +0.3°C/decade between 1991 and 2022, compared to +0.2°C/decade between 1961 and 1990. The recent trend is slightly faster than the global average warming trend of around +0.2°C/decade for the 1991 – 2022 period. All six African sub-regions have experienced an increase in the temperature trend over the past 60 years compared to the period before 1960 (Agency, 2023).

The East Africa region has a diverse climate which is strongly influenced by areas of high elevation along the East African Rift Valley, and long coastlines with the Red Sea, Gulf of Aden and Indian Ocean. Elevation is a key factor in temperature and precipitation variation across the region with highland regions experiencing cooler and wetter climates compared to the hotter, more arid lowlands (Richardson et al., 2022). Climate change poses a threat to the sustainability of food production among small-scale rural com-munities in Sub-Saharan Africa that are dependent on rain-fed agriculture (Atube et al., 2021). Agricultural production in East Africa will be severely impacted by climate change. Many livelihoods across the region are heavily dependent on agriculture and as such food security will be negatively affected, especialy for marginal rainfed farming and fragile pastoral livelihoods which are particularly vulnerable. Higher temperatures will increase water and heat stress for crops and livestock, lowering the productivity of pastoral livelihoods and negatively impacting the production of important crops such as maize, wheat, cotton, and coffee (Richardson et al., 2022).

Ethiopia is a country with diverse climatic regions, ranging from lowland deserts and semi-arid zones to temperate zones and highland areas. Ethiopia is vulnerable to many of the effects of climate change, including increases in average temperature and changes in precipitation. This threatens health, livelihoods and the progress that Ethiopia has made in recent years. Under a high emissions scenario, mean annual temperature is projected to rise by about 4.8°C on average from 1990 to 2100 (WHO, 2015). Ethiopia has three rainy seasons; June – September (Kiremt), October – January (Bega), and February – May (Belg). Kiremt, which is the main rainy season for most part of Ethiopia, accounts for 50 – 80 percent of the total annual rainfall over the regions having high agricultural productivity and major water reservoirs. It is for this reason that the most severe droughts usually result from the failure of the Kiremt rainfall to meet Ethiopia's agricultural and water resource needs. Western and northern Ethiopia have monomodal rainfall patterns with the rainfall amount peaking in Kiremt. The temporal distribution in these monomial rainfall areas shrinks from south to north, ranging from over eight months of rain over the southwest to only three months of rain over the northwest (NAP, 2019). Temperatures are also very much modified by the varied altitude of the country. In general, the country experiences mild temperatures for its tropical latitude because of topography. Mean annual temperature distribution over the country varies from about 10°C over the highlands of northwest, central and southeast to about 35°C over north-eastern lowlands (NMA, 2007).

Both climate variability and change have been occurring in Ethiopia. Evidences show that since 1960 the mean annual temperature of the country has risen by about 1.3°C, an average rate of 0.28°C per decade, and spatial and temporal rainfall variability has been increasing. As such, Ethiopia has been experiencing the impacts of both climate variability and change. Climate change has led to recurrent droughts and famines, flooding, expansion of desertification, loss of wetlands, loss of biodiversity, decline in agricultural production and productivity, shortage of water, and increased incidence of pests and diseases such as spread of cereal stemborers and malaria to higher elevation areas (Zegeye, 2018).

Examining the spatiotemporal dynamics of meteorological variables in the context of changing climate, particularly in countries where rain-fed agriculture is predominant, is vital to assess climate-induced changes and suggest feasible adaptation strategies (Asfaw et al., 2018). Understanding the long-term trends and variability of climate over space and time in various regions is a critical step in obtaining the necessary details on how it has been changing and affecting the country's economy and development. Such data is critical for developing appropriate strategies to deal with current and future trends in climate variability and change (Ware et al., 2023).

Several studies have examined the historical trend of both temperature and rainfall in different parts of the country. Among these studies a study conducted by (Benti and Abara, 2019), on trend analyses of temperature and rainfall and their response to global CO_2 emission in Masha, Southern Ethiopia result revealed that, in all seasons, the temperature was significantly increased while the summer, annual rainfall was decreased and these could continue moving until 2050 year. Another research done by Addisu et al. (2015) on time series trend analysis of temperature and rainfall in lake Tana sub-basin, Ethiopia found that the mean, maximum and minimum temperature had a general increasing trend; whereas, rainfall amount showed a general decreasing trend in Lake Tana Sub-basin. In addition a study conducted by (Getachew, 2018) on trend analysis of temperature and rainfall in south Gonder zone, Ethiopia, result revealed that the trend analysis total annual rainfall at all stations showed that positive trends but statistically insignificant. On the other hand, spring season rainfall reveals a downward trend whereas summer season rainfall reveals upward trend in all stations which is also statistically insignificant. Like that of rainfall Mann Kendall trend test analysis for mean annual temperature shows statistically significant positive trends for Addis Zemen and Nefas Mewcha station but negative trends for Mekane Eyesus station. Moreover Alemayehu et al. (2020) have examined Spatiotemporal variability and trends in rainfall and temperature in Alwero watershed, western Ethiopia and found that, annual and seasonal rainfall show low inter-annual variability except for Bega which shows moderate coefficient of variation. Annual and bega rainfall shows statistically signifcant increasing trend at. Belg rainfall shows statistically non-signifcant increasing trend. There is no clear trend in kiremt rainfall. In the watershed, mean annual minimum and maximum temperatures show statistically non-signifcant decreasing trends.

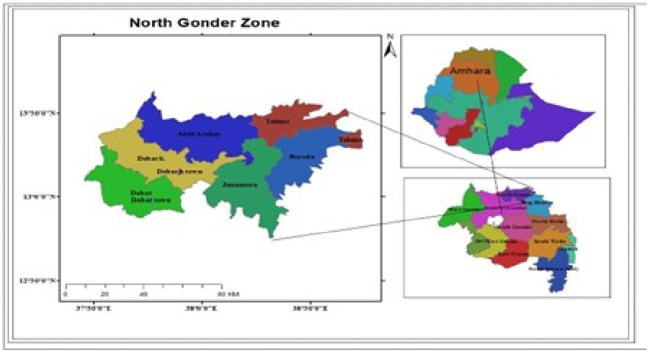

Figure 1. Map of the study area.

Even if a study on trend analysis of temperature and rainfall is conducted in various parts of the country, but no prior study was conducted in the study area. The major climatic elements that give climatic visibilities are temperature and rainfall. Hence, these two principal elements largely variable both spatially as well as temporarily at local, regional and global level (Getachew, 2018). So, investigating spatiotemporal variability and trend of both temperature and rainfall in the study area is essential, since the study area is one of the food insecure and drought prone areas in the region. In addition, majority of farmer's agriculture mainly depends on rain-fed agriculture. Therefore, this study aims to investigate the variability and trend of precipitation and temperature in the area. To achieve the objectives 40 years of climate data (from 1983 – 2022) for each district (Adiarkay, Debark, and Janamora) was taken from NASA POWER | Data Access Viewer. As a result, seasonal and annual rainfall data and maximum, minimum, and annual mean temperature were analyzed by using different statistical tools and formulas to detect trends of both temperature and precipitation. The findings of the study address the following objectives:

1. What looks like a spatiotemporal trend of temperature and rainfall?
2. Examining spatial variability of temperature and precipitation in the area.

Materials and Methods

Description of the study area

North Gondar zone is located between 120 45' - 130 38' N latitudes and 370 27' - 380 44' E longitudes (Figure 1). The zone is bordered on the north by Tigray region, on the south and on the west by central Gondar zone, and on the East by Tigray region and waghemra zone. The total area of the zone is 83933 km2 which is divided in to six districts namely Adiarkay, Beyeda, Dabat, Debark, Janamora and Telemt. There is a great difference in altitude which ranges from 1100 m.a.s.l to 4543 m.a.s.l at mount Ras Dashen. The zone has very diverse Agro ecological division. Based on the information obtained from north Gondar zone office, 41.2%, 27%, 29.65% and 21.15% of the area has Hot (kola), Temperate (weyna dega), cool temperate (dega) and cool (wurch) climate respectively (NGZO, 2024).

Data sources and acquisition

The study used monthly temperature and rainfall time series data for the last 40 years (1983 – 2022) downloaded from NASA POWER | Data Access Viewer (`https://power.larc.nasa.gov/data-access-viewer/`). This data is used to analyze spatiotemporal variation and trend of temperature and rainfall in the study area. Due to the absence of data from relevant ground-based stations for each station we have not included validation analysis.

Data analysis methods

The data obtained from NASA POWER | Data Access Viewer has been analyzed by using different data analysis methods.

Coefficient of Variation

CV is calculated to evaluate the variability of the rainfall. A higher value of CV is the indicator of larger variability, and vice versa which is computed as:

$$CV = \frac{\sigma}{\mu} \times 100 \tag{1}$$

where CV is the coefficient of variation; σ is standard deviation and μ is the mean precipitation (Asfaw et al., 2018).

Standardized Anomaly index

Standardized anomaly index of rainfall has been calculated to examine the nature of the trends. It enabled the determination of the dry and wet years in the record and is used to assess frequency and severity of droughts and it is computed as:

$$SAI_i = x - \frac{\bar{x}}{\sigma} \tag{2}$$

Where Xi is the annual rainfall of the particular year; $\bar{x}$ is the long term mean annual rainfall over a period of observation and σ is the standard deviation of annual rainfall over the period of observation.

Negative values indicate a drought period as compared to the chosen reference period while the positive ones indicate a wet situation (Alemu and Bawoke, 2020). Classification of SPI by (McKee et al., 1993) is also presented in (Table 1):

Table 1. Classifications of SPI (McKee et al., 1993)

SPI Values	Drought/Wetness condition
2 and above	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
-2.0 and less	Extremely dry

Man Kendall Trend Test

The annual maximum, minimum, and annual mean temperature and annual and seasonal rainfall values of each station have been analyzed in this study. The existence of positive and negative trends among all the considered variables was determined using non parametric trend test methods. The widely used non parametric method (Mann- Kendall test) was adopted to determine the significance of the trend, and also it was quantified by using Sen's slope. A normalized test statistics (Z score) was used to check the statistical significance of the increasing or decreasing trend of precipitation and temperature values. A positive (negative) value of Z indicates an upward (downward) trend. The statistic Z has a normal distribution. To test for either an upward or downward monotone trend (a two-tailed test) at ∝ level of significance, Ho is rejected if the absolute value of Z is greater than Z1-$\alpha/2$, where Z1- $\alpha/2$ is obtained from the standard normal cumulative distribution tables. In MAKESENS the tested significance levels ∝ are 0.001, 0.01, 0.05 and 0.1.

The Mann – kendall test statstic S is given as:

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

Where xj and xk are the annual values in years j and k, j > k respectively, and

$$\operatorname{sgn}(x_j - x_k) = \begin{array}{rl} 1 & \text{if } x_j - x_k > 0 \\ 0 & \text{if } x_j - x_k = 0 \\ -1 & \text{if } x_j - x_k < 0 \end{array}$$

Variance of S is computed by the following equation:

$$VAR(S) = \frac{1}{18}\left(n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p-1)(2t_p+5) \right)$$

where:
n: the number of data points
q: the number of tied groups (tied groups is a set of sample data having the same value)
t_p: the number of data values in the p-th group

The values of S and $VAR(S)$ are used to compute the test statistic Zbased on Salmi et al. (2002) is as follows:

$$Z = \left. \begin{array}{rl} \frac{S-1}{\sqrt{VAR(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}} & \text{if } S < 0 \end{array} \right\} \tag{3}$$

The authors employed the Mann-Kendall trend test and Sen's slope estimator for several reasons. The Mann-Kendall test was widely used to detect trends and is particularly useful in determining whether there is a statistically significant trend in different climate parameters. It has the advantage of handling missing values and is not sensitive to outliers, which makes it suitable for analyzing long-term climate data. Complementing this, Sen's slope estimator provides a means of quantifying the magnitude of the trend for each climate variable. Its results are straightforward to interpret, as it offers a clear estimate of the rate of change over time. Taken together, these tests provide a comprehensive analysis of temperature and precipitation trends by revealing both the statistical significance and the magnitude of changes in the climate variables under consideration.

Results and Discussion

Annual rainfall variability

Rainfall distribution varies both geographically and temporally. This variation is influenced by differing climatic controls across locations and over time. In this section, we analyze the annual and seasonal rainfall variations, as well as the rainfall trend analysis in the study area. According to Mesfin et al. (2021), the mean annual rainfall of Amhara Region is 1,150 mm with different spatial distribution and temporal variability. While the recent study showed that, the mean rainfall of Amhara (ANRSE) based on 71 station and satellite merged data obtained from the Ethiopian Meteorology Institute (EMI) during 1981 – 2020 (40 years) was 990.2 mm (Mekoya et al., 2024). As shown in Table 2, the mean annual rainfall ranges from 850.5 mm in Janamora to 1,548.2 mm in Debark. The findings of the study indicate that rainfall is highly variable in the study area. The mean annual rainfall in Adiarkay and Janamora is below the region's average annual rainfall. Similar to the regional distribution of annual rainfall, the study area also exhibits spatiotemporal variation in rainfall patterns. The annual average rainfall in Adiarkay was 901.1 mm, with a standard deviation of 432 mm and a coefficient of variation (CV) of 48%. In contrast, Debark had an annual average rainfall of 1,548.2 mm, while Janamora recorded 850.5 mm, with standard deviations of 702.4 mm and 368.5 mm, respectively. The coefficients of variation for Debark and Janamora were 45% and 43%, respectively. According to Borku et al. (2024), the CV is used to classify the degree of variability of rainfall events as follows: less variable (CV < 20), moderate (20 < CV < 30), highly variable (CV > 30), very high (CV > 40%), and extremely high (CV > 70%). Based on this classification, all districts in the observed data exhibited coefficients of variation above 40%, indicating very high variability in precipitation across the study area.

To determine the monotonic trends of climate data time series, the Mann-Kendall trend test was employed. A 40-year rainfall dataset was used to assess the trend. The Mann-Kendall trend test for annual rainfall exhibited a statistically insignificant trend for all stations. Similarly (Getachew, 2018) and Marelign (2020) found insignificant trend in annual rainfall. As indicated in Table 3, annual rainfall shows a non-significant decreasing trend in both Adiarkay and Janamora districts, while it displays a non-significant increasing trend in the Debark district. Annual rainfall shows a decreasing trend in Adiarkay and Janamora, with annual declines of 2.4 mm and

Table 2. Annual Rainfall variability

Stations	No of years	Maximum	Minimum	Mean	Std. deviation	CV
Adi arkay	40	2334.15	210.93	901.178	431.9606028	0.479328837
Debark	40	4043.30	516.79	1548.21	702.4220988	0.453699497
Jan amora	40	1780.65	237.3	850.53625	368.5086322	0.433266227

Table 3. Annual rainfall Mann-Kendall's trend test results

Stations	No of Years	First year	Last year	Test Z	Significance	Sen's slope estimate (Q)
Adi arkay	40	1983	2022	-0.48	Not significant	-2.47
Debark	40	1983	2022	0.24	Not significant	2.42
Jan amora	40	1983	2022	-0.94	Not significant	-6.71

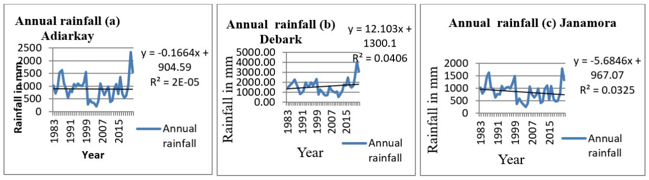

Figure 2. Trends of annual rainfall for (a) Adiarkay, (b) Debark and (c) Janamora Source: (NASA POWER | Data Access Viewer

6.7 mm, resulting in total reductions of 96 mm and 268 mm over four decades, respectively. In contrast, the annual rainfall trend in Debark shows an increment of 2.42 mm per year, amounting to an increase of 96.8 mm over the same period. These results indicate a significant decline in annual rainfall recorded in Janamora (Table 3).

As shown in Figure 2(a), maximum rainfall at the Adiarkay station occurred in 2021, with a total of 2,334.15 mm, while the minimum rainfall was recorded in 2004, totaling 210.93 mm. Figure 2(b) also indicates that the maximum and minimum total rainfall in the Debark district were recorded in 2021 and 2011, with totals of 4,043.30 mm and 516.79 mm, respectively. As noted in Figure 2(c), the maximum and minimum annual rainfall in the Janamora district were recorded in 2021 and 2004, with totals of 1,780.65 mm and 237.3 mm, respectively. In general, based on these findings, it can be concluded that the region received a significantly high amount of rainfall in 2021, as maximum rainfall was recorded across all districts during this year.

Seasonal rainfall trend analysis

Ethiopia's topography is characterized by large regional differences; it is considered an arid country, but precipitation trends exhibit high annual variability. Kiremt rains account for 50–80 percent of the annual rainfall totals, and most severe droughts usually result from failure of the kiremt (USAID, 2016). As indicated in Table 4, average summer rainfall ranges from 697.6 mm in Janamora to 1,298.3 mm in Debark. The average summer rainfall in Adiarkay was 749.6 mm, with a standard deviation of 351.8 mm and a coefficient of variation (CV) of 46%. In contrast, Debark recorded a mean summer rainfall of 1,298.3 mm, with a standard deviation of 561.2 mm and a CV of 43%, while Janamora had a mean of 697.6 mm, with a standard deviation of 293.8 mm and a CV of 42%. As shown in Table 4, average spring rainfall ranges from 107.4 mm in Adiarkay to 162.8 mm in Debark. The average spring rainfall in Adiarkay was 107.4 mm, with a standard deviation of 100.5 mm and a CV of 93%. In Debark, the average was 162.8 mm, with a standard deviation of 131.1 mm and a CV of 80%. Meanwhile, Janamora recorded a spring average rainfall of 109.5 mm, with a standard deviation of 97.7 mm and a CV of 89%.

In general, based on the findings of the study, rainfall is extremely variable during the spring season compared to the summer season. In all districts, a coefficient of variation greater than 70% was recorded during the spring season, while coefficients of variation above 40% were observed during the summer season. The results also revealed that the summer (main rainy) season contributes 83.1%, 83.8%, and 82% to the annual total rainfall for Adiarkay, Debark, and Janamora, respectively. In contrast, the spring (small rainy) season contributes only 12%, 10.5%, and 13% to the annual total for the same districts. Thus, it can be concluded that the summer season, which is the main rainfall season in the region, contributes the highest amount of rainfall in the study area. The region also experiences heavy rainfall during this summer season. This finding is consistent with the results of (Taye et al., 2013) who reported that the contribution of kiremit (Long rainy season from June to September) rainfall to the annual total rainfall was very high in all study stations in western Amhara region. This result aligns with the findings of (Ayalew et al., 2012), who found that Kiremt (summer) rainfall contributed the highest percentage of rainfall at the region. Additionally, a report by (NAP, 2019) showed that as kiremt, which is the main rainy season for most part of Ethiopia, accounts for 50 – 80 percent of the total annual rainfall over the regions having high agricultural productivity and major water reservoirs.

Regarding the seasonal rainfall analysis of the study area, the following trends have been observed (Table 5). The summer season showed a decreasing trend at all stations, which is statistically insignificant, with the exception of Janamora station, which recorded a significant downward trend. As indicated in Table 5, summer rainfall shows an annual decline of 3.03

Table 4. Spring and summer rainfall analysis

Stations	No of years	Season	Maximum	Minimum	Mean	Std. deviation	CV
Adi arkay	40	Spring	453.51	0	107.46375	100.5323128	0.935499765
		Summer	1849.2	195.11	749.63325	351.8625289	0.469379565
Debark	40	Spring	509.79	0	162.88075	131.1270207	0.80504922
		Summer	3379.67	379.68	1298.344	561.296121	0.432316952
Janamora	40	Spring	500.98	0	109.536	97.72119566	0.892137705
		Summer	1449.26	221.48	697.634	293.8582029	0.42122116

Table 5. Seasonal RF Mann-Kendall's trend test results

Stations	No of years	Season	Test Z	Significance	Sen's slope estimate (Q)
Adi arkay	40	Summer	-0.62	Not significant	-3.037
		Spring	0.17	Not significant	0.160
Debark	40	Summer	-0.02	Not significant	-0.001
		Spring	0.93	Not significant	1.877
Janamora	40	Summer	-1.67	+	-8.285
		Spring	-0.38	Not significant	-0.335

+ Significant at 0.1

mm and 9.18 mm over four decades in Adiarkay. In contrast, Debark experienced a minimal annual decrease of 0.001 mm, while Janamora showed a decline of 8.28 mm. On the other hand, the spring season revealed an increasing trend in Adiarkay and Debark, although this trend was also statistically insignificant. Conversely, an insignificant decreasing trend was recorded at Janamora station. Based on the findings of the study, it can be concluded that, except for the summer season in Janamora district, which shows a significant trend, changes in summer and spring seasons displayed insignificant trends across all districts.

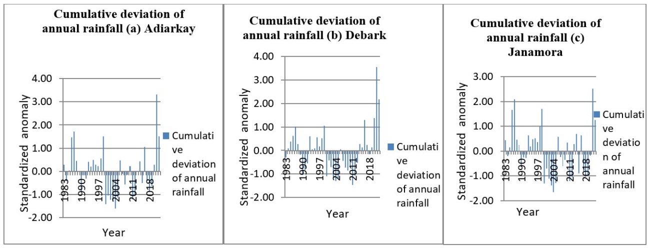

Figure 3. Anomalies of annual rainfall for (a) Adiarkay, (b) Debark and (c) Janamora Source: (NASA POWER | Data Access Viewer)

Anomalies of annual rainfall

The annual rainfall anomalies presented in Figure 3 reveal variations in the amount of rainfall both spatially and temporally. According to the results, the study area consistently experienced above-average rainfall during the period from 1993 to 1999, with positive anomalies recorded at all stations. In contrast, from 2000 to 2005, the area consistently experienced below-average rainfall, as negative anomalies were observed at all three stations during this period. Additionally, consecutive negative anomalies were recorded at each station during different time periods. Moreover, the rainfall amount in 2021 emerged as the highest recorded during the observation period. According to the drought severity classification used by (McKee et al., 1993), the region experienced an extreme wet event in 2021. In contrast, the lowest rainfall was recorded in 2004, with a Standardized Precipitation Index (SPI) of -1.6 in both Adiarkay and Janamora districts, while Debark recorded an SPI of -1.4 during the same year. Based on the SPI classification by (McKee et al., 1993), Adiarkay and Janamora experienced severely dry conditions in 2004, whereas Debark faced moderately dry conditions in 2011. In general, out of 40 years of rainfall records, 20 years (50%) showed below-average rainfall for Adiarkay and Janamora districts, while Debark had 19 years (47.5%) below the long-term average. As shown in Figure 2, rainfall distribution in the area was characterized by wet and dry years. This observation aligns with the findings of (Ayalew et al., 2012) who reported that rainfall in the Amhara region is marked by sporadic fluctuations between wet and dry years.

Spatial Distribution of Rainfall

The spatial variability of summer, spring, and annual rainfall was interpolated using NASA Power climate data for each district. The interpolation was performed for the woreda shapefile using the Inverse Distance Weighting (IDW) method. Figure 4 illustrates the annual and seasonal distribution of rainfall in the area. The results reveal that, although there is no significant variation in the distribution of spring and annual rainfall across each district, there was an uneven distribution of summer rainfall in the area. Maximum annual rainfall was recorded in Adiarkay, while the annual rainfall distribution in Debark and Janamora does not vary greatly. Comparatively, summer rainfall shows more uneven distribution than both annual and spring rainfall. As depicted in the figure, the maximum and minimum summer rainfall were observed in Debark and Janamora, respectively, even though the summer

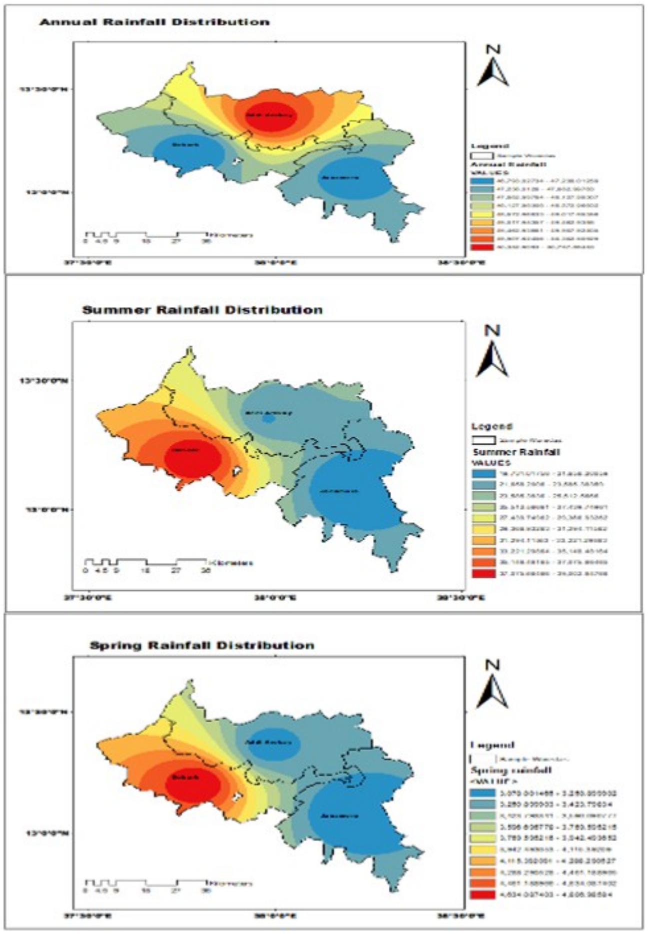

Figure 4. Annual and seasonal spatial distribution of rainfall

rainfall distribution in Janamora does not differ greatly from that in Adiarkay. Moderate summer rainfall was observed in the peripheral parts of Adiarkay and Debark. The uneven distribution of the main rainy season (summer) may be attributed to variations in altitude, topography, and agroecology.

Temperature variability and trend

Ethiopia has a tropical monsoon climate with wide topographic-induced variation. Three climatic zones can be distinguished: a cool zone consisting of the central parts of the western and eastern section of the high plateaus, a temperate zone between 1500 m and 2400 m above sea level, and the hot lowlands below 1500 m. Mean annual temperature varies from less than 7 – 12°C in the cool zone to over 25°C in the hot lowlands (FAO, 2016). Annual maximum, minimum, and mean temperatures have been analyzed based on 40 years of observed temperature records for each district. As shown in Table 6, the average annual maximum temperature ranges from 25.9°C in Janamora to 30.8°C in Debark. Meanwhile, the mean annual minimum temperature ranges from 9.9°C in Janamora to 13.4°C in Debark. Based on the findings of the study, the coefficient of variation for mean annual maximum and minimum temperatures does not vary significantly, particularly between Adiarkay and Janamora districts. The coefficient of variation for mean annual maximum temperature in Adiarkay was 2.9%, while it was 2.3% for Debark and 3.0% for Janamora. The mean annual maximum temperature ranges from 28.0°C to 31.5°C in Adiarkay, 29.4°C to 32.4°C in Debark, and 24.4°C to 27.3°C in Janamora. The coefficient of variation for mean annual minimum temperature in Adiarkay is 4.2%, while it is 3.0% for Debark and 4.3% for Janamora. The mean annual temperature ranges from 19.6°C to 22.1°C in Adiarkay, 21.1°C to 23.1°C in Debark, and 16.8°C to 18.8°C in Janamora. The coefficient of variation for mean annual temperature was 3.1% for Adiarkay and Janamora, while it was 2.4% for Debark. In general, the mean annual minimum temperature is more variable than the mean annual maximum temperature in the study area.

In Ethiopia climate trend since 1960 showed that mean annual temperature has increased by 1°C, an average rate of 0.25°C per decade, most notably in July through September USAID (2016). The Mann-Kendall trend test for mean annual temperature indicates a significant increasing trend for all stations, with the exception of Debark, where the mean maximum and mean annual temperatures show a non-significant increasing trend. This finding is in line with the finding of Marelign (2020). In addition, the results of Marelign et al. (2019) revealed that the annual average temperature at Debark station showed an increasing trend, although it was statistically insignificant. As indicated in Table 7, the annual mean maximum temperature for Adiarkay shows a gradual increasing trend, with an annual increment of 0.02°C and 0.80°Cover four decades. In contrast, the annual mean maximum temperatures for Debark and Janamora show annual increments of 0.01°C and 0.03°C, with total increases of 0.40°C and 1.20°Cover four decades, respectively. The mean annual temperature also shows annual increments of 0.02°C, 0.01°C, and 0.03°C for Adiarkay, Debark, and Janamora. Temperatures are increasing at all stations, which can be attributed to the current rise in national temperatures. Overall, these findings suggest that the temperature conditions in the area are on the rise, and this trend could worsen if it continues in the future. Furthermore, the study revealed that, except for Janamora district, the average increment of mean annual temperature per decade in the study area is below the long-term average rate for the country.

Anomalies of annual mean temperature

Figure 5 (a, b, and c) illustrates the cumulative deviations of annual mean temperature patterns in the study area for the period from 1983 to 2022. The results indicate a cyclic pattern of variations, with alternating warming and cooling years observed in the study area. As depicted in Figure 5(a), although Adiarkay recorded temperatures above the long-term average in various years, the station experienced consecutive positive anomalies from 2000 to 2005 and from 2000 to 2013, with the highest annual mean temperature of 22.1°C recorded in 2002. Conversely, consecutive negative anomalies were observed from 1983 to 1989 and from 1992 to 1999, with the lowest temperature of 19.6°C recorded in 1999. Figure 5(b) shows

Table 6. Annual average temperature variability

Stations	Temperature	No of Years	Maximum	Minimum	Mean	Std. Deviation	CV
Adiarkay	TMax.	40	31.55	28.05	29.53	0.88	0.029657773
	TMin.	40	12.85	10.96	11.92	0.51	0.042886191
	TMean	40	22.13	19.61	20.73	0.66	0.031923931
Debark	TMax	40	32.41	29.49	30.86	0.73	0.023792551
	TMin	40	14.23	12.70	13.42	0.41	0.030461685
	TMean	40	23.11	21.14	22.14	0.54	0.024374374
Janamora	TMax	40	27.38	24.41	25.92	0.80	0.030684724
	TMin	40	10.75	8.88	9.96	0.43	0.043325273
	TMean	40	18.89	16.84	17.94	0.56	0.031216206

Table 7. Mean Annual Temperature Mann-Kendall's trend test results

Stations	No of years	Temperature	Test Z	Significance	Sen's slope estimate (Q)
Adi arkay	40	TMax.	2.06	*†	0.021
		TMin.	2.90	**‡	0.022
		TMean	2.32	*†	0.022
Debark	40	TMax.	1.22	Not significant	0.014
		TMin.	2.35	*†	0.015
		TMean	1.62	Not significant	0.014
Janamora	40	TMax.	2.71	**‡	0.031
		TMin.	4.25	***§	0.026
		TMean	3.51	***§	0.028

*Significant at 0.05, ** Significant at 0.01, *** Significant at 0.001

the anomalies of annual mean temperature for Debark. As illustrated, while temperatures above the long-term average were recorded in 1990, 1991, 2015, and 2019, consecutive positive anomalies occurred from 2000 to 2013, with a maximum temperature of 23.1°C recorded in 2003. Similar to the positive anomalies, negative anomalies were also observed during various years, with continuous negative anomalies recorded from 1985 to 1989 and from 1992 to 1999, the minimum temperature being 21.1°C in 1985. As shown in Figure 5(c), the annual mean temperature was above the long-term average during 1990, 1991, and 1997, but it remained consistently high from 2000 to 2005, 2008 to 2013, and 2015 to 2020, peaking at 19.0°C in 2002. Consecutive negative anomalies were recorded from 1983 to 1989 and from 1992 to 1996, with the lowest temperature of 17.0°C observed in 1987. Overall, the analysis indicates that the temperature in the study area has been rising in the early decades of the 21st century, as evidenced by the observed positive anomalies across all districts, indicating more frequent and intense warm periods.

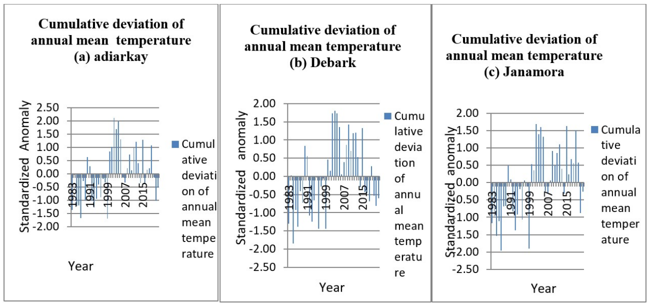

Figure 5. Anomalies of annual mean temperature for (a) Adiarkay, (b) Debark and (c) Janamora: (NASA POWER | Data Access Viewer).

Discussion

The observed high inter-annual rainfall variability across the three districts can be attributed to the combined influence of large-scale atmospheric circulation systems and local physiographic controls. Rainfall in northern Ethiopia is primarily governed by the seasonal migration of the Intertropical Convergence Zone (ITCZ), the strength of the Indian Ocean monsoon flow, and moisture transport from the Congo Basin and the Red Sea. Variations in the timing, intensity, and persistence of these systems likely explain the alternating wet and dry years observed in the anomaly analysis. The comparatively higher rainfall amounts recorded in Debark can be explained by its higher elevation and orographic enhancement of precipitation. As moist air masses ascend the escarpments of the Simien highlands, condensation increases rainfall totals, whereas Adiarkay and Janamora located in relatively lower and more rain-shadow-affected zones receive reduced precipitation. The exceptionally high rainfall recorded in 2021 across all districts is consistent with anomalously strong La

Niña conditions that enhanced moisture influx into the Horn of Africa, while the severe drought conditions observed in 2004 coincide with documented regional drought episodes linked to El Niño–Southern Oscillation (ENSO) variability. The statistically insignificant declining trend in annual rainfall for Adiarkay and Janamora suggests a gradual weakening of moisture availability over the study period, potentially linked to shifts in large-scale circulation patterns and increasing land-surface degradation that may be reducing local evapotranspiration feedbacks. In contrast, the weak increasing trend in Debark indicates that highland areas may retain relatively stable rainfall regimes due to topographically induced cloud formation. The extreme variability of spring (Belg) rainfall compared to summer (Kiremt) rainfall reflects the inherently unstable nature of the Belg season, which is highly sensitive to short-term atmospheric disturbances and ocean–atmosphere interactions. Belg rainfall is primarily influenced by the easterly and southeasterly moisture fluxes from the Indian Ocean, which are more variable than the dominant monsoonal flow controlling Kiremt rainfall. The declining trend in summer rainfall at Janamora may be associated with localized land-cover changes and increased surface warming, which can alter convective processes and suppress rainfall formation. Additionally, highland–lowland thermal contrasts may be shifting the spatial distribution of convective activity away from traditional rainfall belts. The dominance of summer rainfall (over 80% of annual totals) underscores the high vulnerability of the study area to Kiremt rainfall failure. Any disruption to this single critical rainy season is therefore likely to have disproportionate impacts on crop production, water availability, and food security, especially in predominantly rain-fed agricultural systems. The statistically significant warming trends observed across all districts are consistent with broader national and regional climate change patterns. However, the stronger warming signal detected in Janamora may be explained by its higher elevation and lower vegetation cover, which can amplify surface energy absorption due to reduced evapotranspiration and soil moisture feedbacks. Highland regions are increasingly recognized as climate-change hotspots due to elevation-dependent warming, where thinner atmospheric layers and reduced cloud cover enhance radiative heating. This phenomenon may partly explain why Janamora exhibits higher warming rates than Adiarkay and Debark. Furthermore, land-use changes, including deforestation, agricultural expansion, and settlement growth, may have intensified local warming by reducing surface albedo and increasing heat retention. The observed rise in minimum temperatures suggests enhanced nighttime heat trapping, which is often linked to increased greenhouse gas concentrations and changing land-surface properties

Novelty and Contribution of the Study

This study offers a novel district-level assessment of long-term climate variability and trends in a data-scarce and climate-vulnerable region of northwestern Ethiopia using a harmonized satellite-derived dataset. Unlike previous studies that focused on single stations or broader regional averages, this work provides a comparative multi-district analysis that reveals pronounced micro-climatic differences driven by topography and agro-ecological gradients. The integration of standardized anomaly analysis, non-parametric trend detection, and spatial interpolation techniques enables a comprehensive spatiotemporal characterization of climate dynamics over four decades. The identification of extreme rainfall events (notably 2021) and persistent warming hotspots (particularly in Janamora) provides actionable climate intelligence for localized adaptation planning. By linking observed climatic trends with agro-ecological vulnerability and food security implications, this study bridges the gap between climatological analysis and development-relevant policy insights, offering a replicable methodological framework for climate risk assessments in other data-limited regions of Sub-Saharan Africa.

Conclusion and Recommendation

The study concludes that the North Gondar zone is characterized by significant spatiotemporal variability in rainfall and temperature trends over the past four decades. While Debark district experienced increasing rainfall trends, Adiarkay and Janamora showed decreasing but statistically insignificant trends. Seasonal rainfall variability, particularly during the spring, was exceptionally high, with summer rainfall being the principal contributor to annual totals. The temperature trends revealed consistent and significant warming, especially in minimum and mean annual temperatures, posing threats to the agro-ecological sustainability of the area. Given the reliance of local communities on rain-fed agriculture, these climatic changes are likely to adversely affect agricultural productivity and food security. It is therefore recommended that regional policymakers and stakeholders prioritize climate adaptation strategies, including the promotion of drought-resilient crops, improvement of water management systems, and diversification of livelihoods to enhance community resilience. Additionally, the establishment of continuous climate monitoring stations and community-based early warning systems would support timely responses to climatic variability. Further interdisciplinary research combining meteorological data with socio-economic factors is essential to develop comprehensive mitigation and adaptation frameworks tailored to the unique agroecological contexts of North Gondar.

Funding

This research received no external funding.

Competing interests

The authors declare that they have no competing financial or non-financial interests regard to this work.

Author contributions

MA - conceptualized the study while AM - the con-investigator conducted the data collection, AWB - edited and prepared for publication.

Data availability

The datasets used during the study are available from the corresponding author upon reasonable request.

Consent for publication

All authors have read and agreed to the final version of the manuscript for submission and publication.

Ethical approval and consent to participate

Not Applicable.

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