Trends of Climate Change and Variability in Different Agroecological Zones of Sidaama Region, Ethiopia: Application of Innovative Trend Analysis

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Abstract

This paper analyzes climate change trends and variability in the Sidaama region, comparing three agroecological zones (AEZs). The dataset, covering 1981 to 2020, was sourced from the National Meteorological Institute of Ethiopia using a 4x4 km grid. The trend in precipitation and temperature was assessed using Innovative Trend Analysis (ITA), the MK test, and Sen's slope, while the variability was analyzed through the Precipitation Concentration Index (PCI), Coefficient of Variance (CV), and Rainfall Anomaly Index (RAI). Results showed mean annual rainfall of 942.4 mm, 1101.2 mm, and 757.0 mm for the highland, midland, and lowland zones, respectively, with 2020 being the wettest year and 2015 the driest across all zones. Rainfall demonstrated a decreasing trend, while both maximum and minimum temperatures increased. The midland zone experienced the most significant changes, with a rainfall decrease of approximately 12.1 mm/year and a mean annual maximum temperature increase of 0.063°C/year. Most results across tests were consistent, except for a few instances. PCI indicated moderate intra-annual and inter-seasonal rainfall variability, while RAI results highlighted varying drought conditions, particularly affecting the lowland zone. Without timely interventions, these climatic changes could worsen poverty, malnutrition, and migration in the region, necessitating adaptive strategies like enhanced water conservation, climate-resilient agricultural practices, and afforestation to counteract deforestation-induced precipitation declines.

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1. Introduction

Climate change poses a significant challenge to global sustainable development, impacting ecosystems, economies, and livelihoods (IPCC, 2023; Singh et al., 2024). Developing nations, particularly Ethiopia, are especially vulnerable due to their dependence on rainfed agriculture, limited adaptive capacity, and existing socio-economic issues (IPCC, 2023). The increase in the frequency and severity of extreme weather events has been a direct consequence of climate change. Regions are facing prolonged droughts, severe flooding, and dramatic temperature fluctuations, significantly affecting food security, water resources, and biodiversity (Friederike et al., 2024). The Intergovernmental Panel on Climate Change (IPCC) highlights that human activities have caused unprecedented global warming, with temperatures now about 1.1°C higher than pre-industrial levels (IPCC, 2023). This warming has exacerbated weather extremes, including heatwaves and erratic rainfall, disproportionately impacting climate-sensitive sectors like agriculture (Masson-Delmotte et al., 2019). Sub-Saharan Africa, which contains over 60% of the world's arable land and a population reliant on rain-fed farming, faces acute vulnerabilities (Serdeczny et al., 2017). Ethiopia exemplifies these challenges, with climate variability disrupting agricultural productivity and worsening food insecurity and socio-economic inequalities(Alemayehu et al., 2020; Belay et al., 2021).

While initiatives like the Paris Agreement aim to limit global warming to 1.5°C (Erickson & Brase, 2019), varying climate impacts require localized, evidence-based strategies. Agroecological zones (AEZs) have distinct climatic, topographic, and soil characteristics, necessitating tailored adaptation measures(Haas, 2018). However, many studies generalize trends over broad regions, neglecting localized variability (Jjemba, 2021). This is particularly evident in Ethiopia's Sidama Region, where smallholder farmers face diverse climatic risks across highland, midland, and lowland AEZs (Yilma, 2001).

Ethiopia's agrarian economy, which employs 70% of its population and accounts for 34% of GDP, is highly susceptible to climate change(Ebrahim et al., 2022; National Plan Commission et al., 2021). Over the last 40 years, average temperatures have increased by 0.37°C (Mekonnen et al., 2024), coinciding with declining rainfall during crucial cropping seasons(Belay et al., 2021). The Belg (spring) and Kiremt (summer) rains, vital for crops like maize and teff, have become increasingly erratic, leading to recurring droughts every 5–10 years, compared to historical cycles of 20–30 years (Alemayehu & Bewket, 2016; Asfaw et al., 2018).

The Ethiopian government's development strategies, such as the "Home-Grown Economic Reform Agenda" (2020–2030), prioritize climate adaptation and resilience(National Plan Commission et al., 2021). Nevertheless, smallholder farmers in southern and eastern regions are particularly vulnerable to climatic shocks, demonstrated by the devastating 2022 drought that affected millions (Calderon et al., 2022). Climate fluctuations significantly impact the agricultural sector, where many farmers depend on rainfed methods, leading to lower yields and increased food insecurity (Gezie, 2019; Mohammed, 2020).

Research on climate trends in Ethiopia has yielded mixed results. Studies across different AEZs reveal inconsistencies in rainfall and temperature trends (Tesfaw et al., 2024). Some findings indicate minor increases in summer and annual rainfall in parts of Oromia (Assefa & Mengistu, 2021), while others report contrasting trends in temperature extremes (Gashaw et al., 2023). In southern Ethiopia, variations in temperature and rainfall have intensified droughts and flooding, heightening vulnerability (Tesfaw et al., 2024). Despite growing research, these inconsistencies highlight the need for localized, high-resolution studies to better understand climate trends.

Few studies have explored spatiotemporal climate trends in the Sidaama region, with research mainly concentrated on drought-prone districts or specific river catchments (Belihu et al., 2018; Matewos & Tefera, 2020; Mekuyie, 2021). Moreover, conventional trend analysis methods like Mann-Kendall and Sen's slope estimator have dominated climate research in

Ethiopia (Hordofa et al., 2022; Jiqin et al., 2023), including the Sidaama region. However, these traditional methods are limited in identifying subtle trend changes, especially in non-monotonic data, and often overlook intra-annual variability and hidden trends. Although effective for detecting monotonic trends, they fail to differentiate among various data quantiles (Şen, 2017).

Hence, this study aims to address these methodological gaps by using the Innovative Trend Analysis (ITA) method, a novel approach that captures trend behavior across different data segments. By combining ITA with conventional methods like the Mann-Kendall test and Sen’s slope estimator, this research seeks to validate findings and enhance the reliability of trend assessments.

This study intends to bridge existing gaps by employing ITA as the primary analytical tool while validating with Mann-Kendall and Sen’s slope analyses. Focusing on Sidama’s three AEZs (Highland, Midland, and Lowland) from 1981 to 2020, it assesses annual and seasonal rainfall and temperature trends, evaluates variability, and compares findings across different agroecological contexts. By incorporating ITA, this research enhances methodological rigor in detecting complex climate trends, providing actionable insights for climate-resilient planning in Ethiopia’s critical agricultural regions.

2. Materials and methods

2.1. Description of the Study Area

Sidaama National Regional State (SNRS) is a south-central Ethiopian region (Fig.1a) with a population density of 694.6 people/square km. It lies between 6°14’–7°18’ N latitude and 38°20’–39°20’ E longitude. The region, covering 6539 km^2, has 30 districts, Hawassa city, and six town administrations (Planning and Development Bureau, 2023), with an estimated population of 5,301,868 (CSA, 2023). The region's annual population growth rate is 2.9%, which is expected to double in the next 24 years. This region, which is part of Ethiopia's Great East African Rift Valley, has a diverse climate and has been categorized into three agroecological zones: highlands (30.54%), midlands (45.30%), and lowlands (24.16%). The region's elevation ranges from 1132 m.a.s.l. at Lake Abaya to 3311 m.a.s.l. at Garamba Mountain (Planning and Development Bureau, 2023). The administrative map of the study area is depicted in Fig. 1.

Most households in the region rely on subsistence agriculture, with *waasa (the product of enset or* Ensete ventricosum) being the staple food. Cash crops include Sidaama Coffee (a popular Arabica coffee) and khat. Other crops include: barley, wheat, maize, and teff; cereals such as beans, peas, haricot beans, and soya beans; and fruits such as avocado, mango, banana, and apple; and vegetables. This region is well known for its coffee production and well-developed agricultural cooperatives (Ware et al., 2023).

Among the 30 rural districts of the region, three were purposefully selected based on agroecological zones because of their vulnerability to climate change and variability, and their impact varies from one AEZ to another.
Traditionally, the Sidaama region is divided into three agroecological zones**:** Highland (*Alicho*), Midland (*Woricho*), and Lowland (*Gammoojje*).

1. Highland (Alicho) – Wet and Cool Temperate Climate
The highland zone, covering 15% of Sidaama's total land, lies at an elevation above 2500 m.a.s.l., receiving 1,200–1,800 mm of annual rainfall and experiencing temperatures between **10–15°C**. This region is the source of major rivers, including the Gannaale River, which flows into Somalia's Wabishabele River. Livelihoods are based on cultivating *enset* (*Weese*), wheat, barley, peas, beans, and apples, alongside small-scale livestock rearing (Worana & Atsimegiorgis, 2022).
2. Midland (Woricho) – Moist to Humid, Warm Subtropical Climate
The midland zone, constituting 48% of Sidaama's land, lies between 1,500–2,500 m.a.s.l., with 1,000–1,800 mm of annual rainfall and temperatures ranging from 15–20 °C. It is the economic hub of the region, dominated by coffee and khat cultivation, with enset as a staple food and maize as an essential crop. Vegetables (cabbage, carrots) and fruits (banana, avocado, mango) are grown for household consumption and the market. Livestock rearing is practiced, though limited availability of grazing land restricts herd sizes (Worana & Atsimegiorgis, 2022).

3. Lowland (Gammoojje) – Dry and Hot Tropical Climate.
The lowland agroecological zone, covering 30% of Sidaama's land, is semi-arid, with an elevation of less than 1,500 m.a.s.l., annual rainfall of 400–1,000 mm, and temperatures between 20–30°C. Agriculture is primarily subsistence-based, with maize and haricot beans being staple crops, while sorghum, coffee, and khat are grown at higher elevations. The region is known for large-scale livestock production but faces recurrent droughts and food insecurity, making many households dependent on humanitarian aid (Worana & Atsimegiorgis, 2022).

Three meteorological stations (one from each district) were selected to make a trend analysis of climate change (temperature and rainfall). The selected meteorological stations include Arbegona (highland), Leku (midland), and Hantate (lowland) (Fig. 1b).

Factors that are taken into consideration during the selection of AEZs and meterology stations include the location of the AEZ, which is highland, midland, and lowland, in line with the traditional AEZ classification in Ethiopia, and its proportion in the respective villages or centers (Deressa & Hassan, 2010). The second factor is the availability of at least a full year's worth of temperature and rainfall data to help the trend analysis (annual and seasonal) of climatic variables; and the third one is the physical distance between the meteorological stations chosen to represent each AEZ and the number of stations within an AEZ (Amphune & Ababa, 2019). In this regard, in each district, there is only one station that is representative of the distinct AEZ, and only one center is selected from each.

Ethiopia's rainfall season (including Sidaama region) is classified into three time points: Summer/*Hawado* (major rainy season, June - September), Spring/*Badheessa* (short rainy season, February - May), and Winter/Arro (dry season from October to January) (Alemayehu & Bewket, 2017; Matewos & Tefera, 2020). The analysis of the trend and variabilities of rainfall and temperature is based on this classification. For this research, the selected agroecological zones, metrological stations, and their descriptions are indicated in Table 1.

2.2. Data Source and Quality Control

The National Meterology Institution (NMI) of Ethiopia provided the gridded dataset (4x4 km spatial resolution) for daily total rainfall from 1981 to 2020 and daily maximum and minimum temperature from 1981 to 2018. The researchers tried to obtain station data for the study area from the NMI. However, this dataset was incomplete, with many missing values, poor quality, and a lack of continuity. For some stations, it gives only 10-year data; for others, it gives 15 years and less which makes the trend analysis crippled. Hence, the researchers preferred to use the gridded dataset to analyze the trend and unpredictability of rainfall and temperature. Other researchers (Ademe et al., 2020; Alemayehu et al., 2020; Matewos & Tefera, 2020) have also recommended the use of gridded datasets for climate analysis in the country.

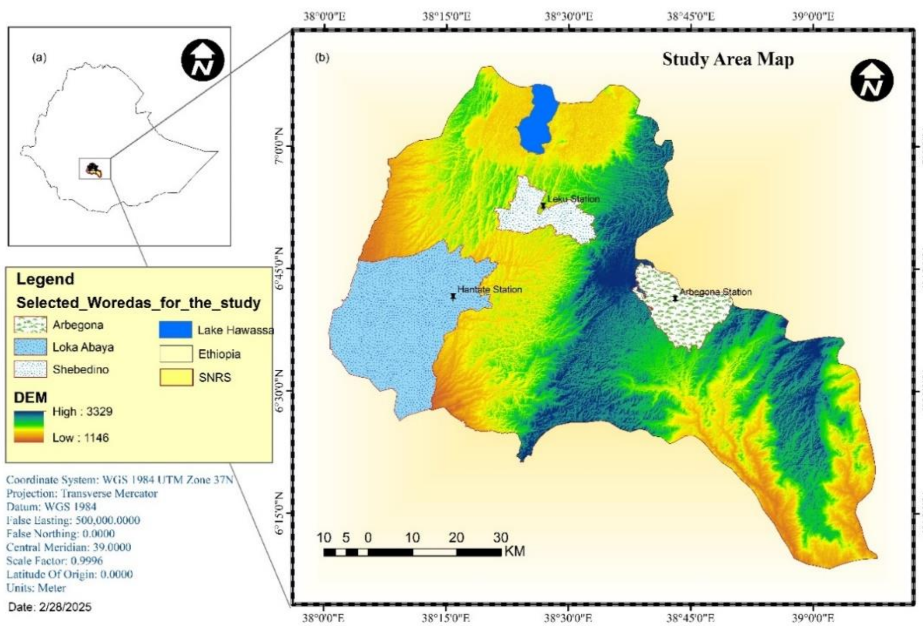


Figure 1. Administrative Map of the Study Area

The data obtained from NMI for total daily precipitation, daily maximum and daily minimum temperatures were converted into monthly, seasonal, and annual data using Excel 16. The analysis was carried out based on seasonal and annual data. Seasonal rainfall was obtained by adding the rainfall of the corresponding months. The existence of missing data was checked by multiple imputation methods in SPSS (version 27) and it was noted that no missing data was observed indicating the quality of the dataset used.

Table 1. Study Stations, Longitude, Latitude and Agroecological Zones

Station	Latitude	Longitude	Altitude	AEZ	Duration
Arbegona	6.69	38.72	2582	Highland	1981-2020
Leku	6.88	38.44	1911	Midland	
Hantate	6.70	38.27	1698	Lowland	

Source: National Meterology Institution, 2023

2.3 Methods of Data Analysis

Time series data on temperature and rainfall were analyzed to assess trends and variability in climate change. Excel 16 was used for data preprocessing, including converting daily data into monthly and annual values and organizing datasets for further analysis. RStudio (version 4.3.2) was employed to conduct trend analysis using Innovative Trend Analysis (ITA) and the Mann-Kendall test, along with Sen's slope estimation. Additional analyses, such as the Precipitation Concentration Index (PCI) and Rainfall Anomaly Index (RAI), were performed as part of the assessment. The detailed analytical techniques are explained in the following sections.

2.3.1 Trend Analysis of Precipitation and Temperature

Innovative Trend Analysis:

Innovative trend analysis (ITA) is based on a subsection of time series plotted on a Cartesian coordinate system. The ITA method offers both qualitative and quantitative interpretations together with a great deal of visual ability for trend detection in graphical representations (Alashan, 2020). The method highlights the fact that when two time series data are plotted against one another and are equal, the grid point system produces a dispersion of points along the 1:1 (45°) line (Pastagia & Mehta, 2022; Şen, 2017). In this method, the recorded climate time series data are divided into two equivalent subseries, and then, both subseries are organized in ascending order. Thereafter, the 1:1 (45°) axis of no trend, which shows increasing (area above the 1:1 line) and decreasing (area below the 1:1 line) trends, divides the figure into two distinct triangles. A positive trend is shown by data points that fall in the top triangle area of the 1:1 line, whereas lower triangular data points indicate a negative trend. For a more thorough analysis, the scatter points on 1:1-line graphs are also separated into three linguistic clusters: low, medium, and high (Aher & Yadav, 2021; Pastagia & Mehta, 2022). The first subseries values are plotted on the horizontal (X) axis against the second subseries values on the vertical (Y) axis, leading to a scatter diagram. If the scatter points are above or below the 1:1 line with approximately parallel positions, then there is an increasing (decreasing) trend in the records, which is referred to as a monotonic trend. A nonmonotonic trend occurs when all of the scatter points are not exactly above, below, or parallel to the 1:1 line. In this case, the horizontal axis of the graph is split into ranges that include low, medium, and high (Alashan, 2020). In addition, in this work, the following equation (Şen, 2017) was employed to compute the innovative trend slope (SI).

$$S_I = \frac{2(m_2 - m_1)}{n} \text{.............. (1)}$$

where m_2 is the second half's arithmetic average; m_1 is the first half's arithmetic average; and n is the total number of observations in the time series data. In ITA, the trend slope represents the rate of change in rainfall or temperature over time, where a positive S value indicates an increasing trend and a negative value signifies a decreasing trend. The slope indicator helps categorize the trend direction, with positive values suggesting an upward trend and negative values indicating a decline. Meanwhile, the slope standard deviation measures the variability in the estimated trend slope, where a higher value indicates greater fluctuations, and a lower value suggests a more stable trend. These metrics provide valuable insights into long-term climate variations (Alifujiang et al., 2020).

Innovative Trend Analysis (ITA) surpasses traditional methods like the Mann-Kendall test and Sen's slope in analyzing rainfall and temperature trends. Unlike rigid statistical approaches, ITA offers remarkable flexibility across diverse datasets and provides an intuitive graphical representation for easy visual interpretation (Alifujiang et al., 2023). Plotting data in two halves of the time series simplifies trend detection, revealing both monotonic and nonmonotonic patterns—including increasing-decreasing and decreasing-increasing trends (Alifujiang et al., 2020). ITA is user-friendly, requiring no complex computations, and effectively identifies sub-trends within low, middle, and high categories, delivering a more comprehensive understanding of climate patterns (Gedefaw et al., 2018). However, to validate the results of the ITA method, the outcomes were checked with other methods, such as the Spearman Rho test and the MK test.

Mann–Kendall Test (MK-test):

The Mann-Kendall (MK) test is a widely used non-parametric statistical method for detecting monotonic trends in time series data. It was first proposed by Mann (1945) and later formalized by Kendall (1975). The test is particularly suitable for analyzing climate variables such as temperature, rainfall, and other environmental data because it does not require the data to be normally distributed and is resistant to outliers. The test evaluates whether there is a statistically significant trend (increasing or decreasing) in a dataset over time. It is based on ranking the data rather than using actual values, making it robust against non-normality and missing data.

Mathematical Formulation

Given a time, series dataset $X_{1,}X_{2,\dots,}X_n$ with n observations, the Mann-Kendall statistic (S) is computed as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\ (X_j - X_i) \text{ .... (2)}$$

where the sign function is defined as:

$$sgn\ (X_j - X_i)\ \text{-} \begin{cases} +1, if\ X_j - X_i > 0 \\ 0, if\ X_j - X_i = 0 \\ -1, if\ X_j - X_i < 0 \end{cases} \text{ ------------------- (3)}$$

The **variance** of S is given by:

$$var(S) = \frac{n(n-1)(2n+5) - \sum t_i(t_i - 1)\ (2t_i + 5)}{18} \text{ ----------------(4)}$$

where t_i represents the number of tied values for the i^{th} tied group.

The standardized test statistic (Z) is calculated as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{var(S)}}, \ if\ S > 0 \\ 0, \ if\ S = 0 \\ \frac{S+1}{\sqrt{var(S)}}, \ if\ \ S < 0 \end{cases} \text{------------------------------ (5)}$$

The significance of the trend is assessed using a two-tailed test based on the standard normal distribution. For a given significance level (α), the null hypothesis (H_0) assumes that there is no trend, while the alternative hypothesis (H_1) suggests a significant increasing or decreasing trend:

If $|Z| > Z_{\alpha/2}$, the null hypothesis is rejected, indicating a significant trend in the data.$Z_{\alpha/2}$

If $|Z| \leq Z_{\alpha/2}$, no significant trend is detected.

The MK test has been widely used in climate trend studies in Ethiopia (Ademe et al., 2020b; Belay et al., 2021a; Ware et al., 2023a) and other parts of the world (Kumar et al., 2017; Sibiya et al., 2024).

Sen's Slope Estimator

While the Mann-Kendall test identifies the presence of a trend, Sen's slope estimator (Sen, 1968) quantifies the magnitude of the trend in a time series. It is a non-parametric method that calculates the median of the slopes between all possible pairs of data points, making it robust to outliers and non-normal distributions. For a dataset including n time-sequenced observations, the slope between each pair of observations is computed as:

$Q_i = \frac{X_j - X_k}{j-k}$ for all $1 \leq k < j \ \leq n$ ---------------------- (6)

where:

$X_j\ and\ X_k$ are data values at times $j\ and\ k$, respectively.

$j\ and\ k$ represents the time difference between observations.

The Sen's slope estimator Q is given by the median of all calculated slopes:

Q = median $(Q_1, Q_2, \dots, Q_m)$ ------------------------------ (7)

where $m = \frac{n(n-1)}{2}$ represents the total number of slope estimates.

To assess the uncertainty in the estimated slope, a confidence interval is computed using the normal distribution approach. The lower and upper confidence limits (Q_L, Q_U) are determined by:

$Q_L = Q_{(m-C_\alpha)}$ --(8)

$Q_U = Q_{(m+C_\alpha)}$ ---(9)

Where C_α is derived from the standard normal distribution corresponding to the desired confidence level (e.g., 95%).

A positive slope (Q > 0) indicates an increasing trend over time.

A negative slope (Q < 0) suggests a decreasing trend.

If Q = 0, no trend is detected.

2.3.2 Climate Variability Analysis

Precipitation Concentration Index:

The precipitation concentration index (PCI) values measure the extent of seasonality in rainfall (Alemayehu et al., 2020b). The PCI indicates the rainfall concentration in terms of distribution and variability and is computed on an annual scale (Oliver, 1980).

The formula is:

$$PCI_{annual} = \frac{\sum_{i=1}^{12} pi^2}{(\sum_{i=1}^{12} pi)^2} \times 100 \text{ .... } (10)$$

where P_i = the amount of rainfall in the i^{th} month and where $\sum pi^2$ = the summation over the 12 months.

Accordingly, PCI values are interpreted as a uniform monthly distribution of rainfall (PCIs below 10), seasonality in the distribution of rainfall (PCIs between 11 and 20), and high variability in monthly rainfall amounts (PCIs above 20) (Amphune, 2019; C. Li et al., 2020).

Coefficient of Variation:

The coefficient of variation (CV) is a statistical measure of the dispersion of data points in a data series around the mean. A CV's greater value is an indicator of greater spatial variation, conversely. It is computed using the following equation. The inter-annual variability of temperature and precipitation in the chosen AEZs was assessed in this research through the utilization of CV (Oliver, 1980).

$$CV = \frac{\delta}{x} \times 100 \qquad (11)$$

In the given context, CV denotes the coefficient of variation, n stands for the standard deviation (SD) of rainfall and temperature, and X indicates the long-term mean of the aforementioned variables, CV values < 20% denote less variability, between 20% and 30% denote moderate variability, and >30% denote high variability of rainfall among the agroecological zones (Belay et al., 2021b; Habte et al., 2021; Harka et al., 2021).

Rainfall Anomaly Index:

The rainfall anomaly index (RAI) developed by Van Rooy in 1965 (Paul Tume, 2021a) was used to delineate drought and extremely moist periods via data obtained from the NMI of Ethiopia for forty (40) years (1981 to 2020). The precipitation values of each agroecological period of study were ranked in ascending and descending order, where the means of the ten lowest and ten highest values (two extremes) were used in the calculation of the RAI. The mean precipitation value for the study period was also calculated. The formula for calculating positive and negative RAIs is:

$+3\left[\frac{RF-MRF}{MH10-MRF}\right]$ (Positive anomaly) and; ------------ (12)

$-3\left[\frac{RF-MRF}{ML10-MRF}\right]$ (negative anomaly), ---------------- (13)

where:

RAI = the rainfall anomaly index

RF = the rainfall for the year in question

MRF represents the mean annual precipitation over the entire period, and MH10 and ML10 represent the means of the 10 highest and 10 lowest values of rainfall (RF), respectively. The RAI was classified as extremely dry (≤ -3); very dry (-2 to -2.99); moderately dry (-1 to -1.99); slightly dry (-.50 to -0.99); near normal (-0.49 to 0.49); slightly wet (0.50 to 0.99); moderately wet (1.00 to 1.99); very wet (2.00 to 2.99) and extremely wet (≥ 3) (Paul Tume, 2021b).

3. Results of the Study

The results of the analysis are presented in terms of tables and graphs in two main sections.

Trends of Rainfall and Temperature in the Study Area

As the results indicate, in all AEZs of the study area, the highest annual rainfall was registered in 2020, where it was 1723.8 mm for Highland, 1599.5 mm for Midland, and 1529.9 mm for Lowland. Ware et al. (2023b) also obtained a similar result using a dataset from the website TerraClimate for the whole region. The Highland AEZ exhibited the lowest rainfall in 1991 (500.4 mm—the driest year), with mean annual precipitation being 942.44 mm within the 40 years. 1991 was a drier year in the region, with many areas receiving significantly less than the long-term average rainfall, leading to prolonged drought conditions (Ware et al., 2023c). Midland exhibited the lowest rainfall in 2015 (584.6 mm - driest), with a mean annual precipitation of 1101.2 mm. Ethiopia experienced a severe drought in 2015, affecting various regions, including Sidaama, as part of a series of droughts since 1980 (Ware et al., 2023c). In the Lowlands, the lowest was registered in 2012 (728.4 mm—the driest) with a mean annual rainfall of 757 mm (Table 2). 2012, similar to 1991, experienced below-average annual rainfall, resulting in severe drought conditions, with studies indicating that 2012 was among the region's most severe drought years (Matewos, 2019).

The observed extreme variations (both wet and dry years) may indicate increasing climate variability due to climate changes. The frequency of drought years suggests a need for improved water resource management, drought mitigation, and climate adaptation strategies, particularly in the Lowland areas. The differences in the drought years among the AEZs also indicate that there is the need for area-specific intervention in the process of responding to the climate changes and variabilities. The anomalously high rainfall in 2020 could have implications for flood risks, soil erosion, and agricultural productivity, requiring further investigation into its causes and impacts.

Table 2. Highest and Lowest Annual Rainfall Registered in each Agroecological Zones (1981 to 2020)

AEZ	Highest RF (mm)	Year	Lowest RF (mm)	Year	Mean ARF (mm)
Highland	1723.8	2020	500.4	1991	942.44
Midland	1599.5	2020	584.6	2015	1101.2
Lowland	1529.9	2020	728.4	2012	757

Source: Calculated based on NMI, 2023, RF = Rainfall; ARF = Annual rainfall

In the Highland AEZ, the highest mean maximum temperature was registered in 2018 (26.2 °C), and the lowest was observed in 2011 (18.8 °C). In Midland, the average maximum temperature was registered in 2012 (30 °C) and the Lowland AEZ exhibited the highest maximum temperature in 2015 (29.8 °C). Both the Midland and Lowland exhibited the lowest maximum temperature in 1989, with 26. °C and 25.9 °C, respectively. There is a high variation between the highest and lowest mean annual minimum temperature for the Highland AEZ, where the highest was observed in 2017 (16.8 °C) and the lowest was registered in 1997 (6.5 °C). In Midland AEZ, the highest mean annual minimum temperature was observed in 2017 (15.9 °C), whereas the lowest was observed in 1999 (10.9 °C). There was a higher difference between the highest mean annual minimum temperature and the lowest one for Lowland AEZ as well, where the highest was registered in 1982 (13.6 °C) and the lowest in 1986 (5.5 °C) (Table 3).

Table 3. Mean Highest and Lowest maximum and Minimum Temperatures Registered in each AEZ

AEZ	Highest Tmax (°C)	Year	Highest Tmin (°C)	Year	Lowest Tmax (°C)	Year	Lowest Tmin (°C)	Year
Highland	26.223	2018	16.787	2017	18.791	2011	6.569	1997
Midland	30.008	2012	15.913	2017	26.056	1989	10.931	1999
Lowland	29.871	2015	13.663	1982	25.973	1989	5.567	1986

Source: Calculated based NMI, 2023

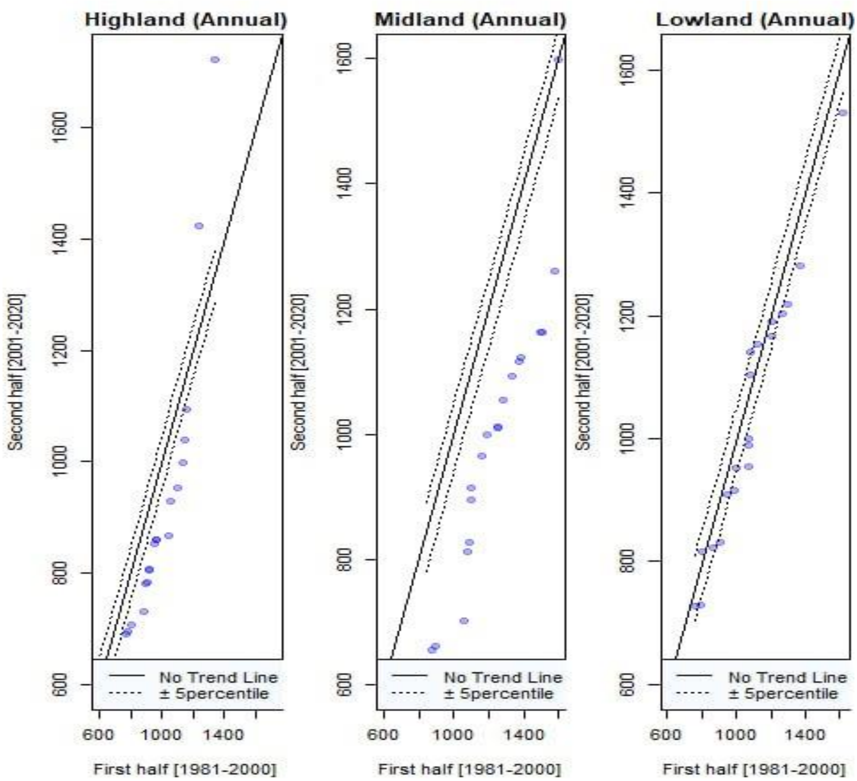
Trends in Annual Rainfall based on Innovative Trend Analysis (1981 to 2020)

The trend in precipitation for Highlands was nonmonotonic. However, there was an extreme increase in the high positive trend (Figure 2). The trend slope of -3.094 indicates relatively small but decreasing trend where the rainfall has been decreasing by approximately 3.1 mm/year. The trend indicator (-0.636) suggests a moderate decreasing trend (Table 4). The trend in precipitation for Midland was monotonic and decreasing (Figure 2). When compared to Highland, the Midland showed a much sharper decreasing trend with a slope of -12.07 or there was approximately a 12.07 mm/year decrease of rainfall, indicating a significant decrease. The trend indicator (-1.976) also confirms the strong and constant decreasing trend. On the other hand, the trend of precipitation for the Lowlands seems to be monotonic and nearer to the "no trend line" (Figure 2). However, most of it exhibited a negative (decreasing) trend, which can be divided into low, middle, and high negative categories. However, as the trend slope indicates, this AEZ exhibited the least sharp decreasing trend compared to others where there was only 2.2 mm/year decrease in precipitation. This was also confirmed by a weaker or very minor decreasing in trend indicator (-0.414). In general, although the magnitude differs, the trend of precipitation for the three AEZs has been decreasing (Table 1 and Figure 2) where Midland exhibited the highest decrease throughout the study period. This could be due to the deforestation caused by agricultural land expansion and fragmentation of the land to invest in afforestation/reforestation. These findings highlight the potential risks of reduced water availability for agriculture and ecosystems, emphasizing the need for sustainable land management and reforestation efforts to mitigate further decline. The result is congruent with some studies in Ethiopia, where all the agroecological zones exhibit a decreasing rainfall trend (Berihun et al., 2023; Engda et al., 2024), while it contrasts with others where the Highland exhibited an increasing trend of rainfall (Sahilu et al., 2024).

Table 4. Innovative Trend Analysis (ITA) Statistics for Annual Rainfall, Maximum and Minimum Temperature (1981 to 2020)

Parameter	Arbegona (Highland)			Leku (Midland)			Hantate (Lowland)		
	PRCP	Tmax	Tmin	PRCP	Tmax	Tmin	PRCP	Tmax	Tmin
Trend SLP	-3.094	0.001	0.035	-12.07	0.063	0.047	-2.227	0.029	0.065
Trend IND.	-0.636	0.015	0.065	-1.976	0.44	0.689	-0.414	0.206	1.186
Slope SD	0.948	0.005	0.012	0.658	0.005	0.001	0.357	0.001	0.003
Correlation	0.861	0.867	0.713	0.948	0.848	0.980	0.977	0.977	0.963

PRCP = Precipitation; SLP= Slope; IND= Indicator; SD= Standard deviation Calculated based NMI, 2023

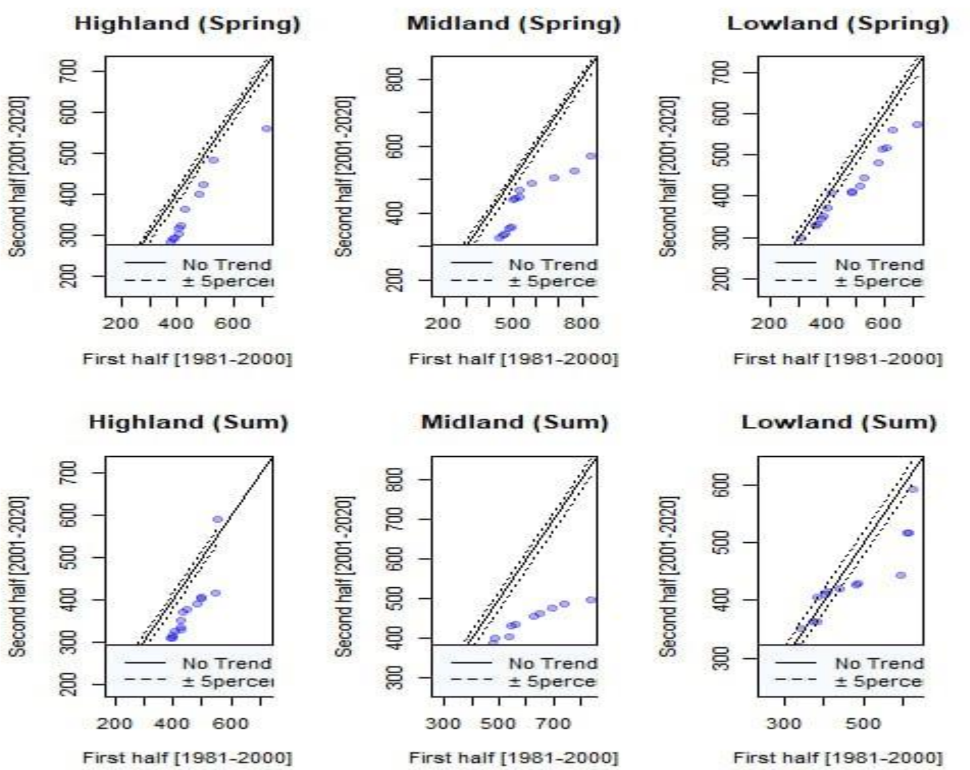


Note: Annual = Annual rainfall

Figure 2. Trends of the Annual Rainfall for the Three Agroecological Zones based on the Innovative Trend Analysis

Trends in Seasonal Rainfall based on Innovative Trend Analysis

In the Highland AEZ, rainfall exhibited a nonmonotonic decreasing trend in both the spring and summer seasons. The result indicated a monotonic decreasing (negative) trend in both the spring and summer seasons for the Midland region, whereas the rainfall indicated a monotonic decreasing trend in the spring season and a nonmonotonic trend for the summer season in the Lowland region. This indicates that the Middle land area experienced a decreasing trend in rainfall throughout the research period. In contrast, spring was the common season where rainfall decreased in all of the AEZs, which may harm crop production and affect the livelihood of smallholder farmers, who solely depend on rain-fed agriculture in the three AEZs of the region. Similar studies also showed that there has been decreasing trend of rainfall in many parts of Ethiopia (Kerebo et al., 2024).



Note: Spring = Spring season rainfall; Sum = Summer season rainfall

Figure 3. Trend in Seasonal Rainfall via Innovative Trend Analysis

Annual and Seasonal Rainfall Trends based on the MK-test and Sen's Slope (1981 to 2020)

As specified in the methodology section, tendencies of annual precipitation were also analyzed via the MK test and Sen's slope test for the reference period (1981 to 2020). The results obtained through the analysis indicate that Highland and Lowland AEZs exhibited a nonsignificant decreasing (negative) trend, whereas the Midland AEZ experienced a significant decreasing (negative) trend (p value ≤ 0.01) (Table 5) for annual rainfall. When we compare the results of the ITA and the abovementioned tests, they are similar (i.e., decreasing trend) for all the AEZs.

Table 5. Trends in Annual and Seasonal Rainfall based on the MK Test and Sen's slope (1981 to 2020)

AEZ	Annual		Spring (Bdheeessa)		Summer (Hawado)		Winter (Arro)	
	MK	SS	MK	SS	MK	SS	MK	SS
Highland	-1.17	-3.7	-1.01	-2.00	-1.71	-2.66	-0.15	-0.16
Midland	-3.04**	-11.8	-2.7**	-6.14	-2.49**	-4.22	-2.0*	-2.41
Lowland	-0.12	-0.63	-1.23	-2.0	0.048	0.07	0.91	0.98

AEZ = Agroecology; MK = Mann–Kendall test; SS = Sens slope; ** = Significant at the 0.01 level (2-tailed); * = Significant at the 0.05 level (2-tailed); Bdhessa, Hawado, and Arro = represent spring, summer, and winter seasons, respectively, in the local language, Sidaamu Afoo.

Similar to the annual rainfall, in the spring season, a nonsignificant decreasing trend occurred for the Highland and Lowland AEZs. On the other hand, the Midland AEZ exhibited a significant negative (decreasing) trend (p value ≤ 0.01) (Table 5). This result is also in line with that of Matewos and Tefera (2020). Different trends were observed among the three AEZs in the summer. While the Highlands showed a nonsignificant negative trend, the Midlands experienced a significant decreasing trend for all tests (p value ≤ 0.01). In contrast, the Lowlands experienced a nonsignificant increasing (positive) trend for both tests (Table 5).

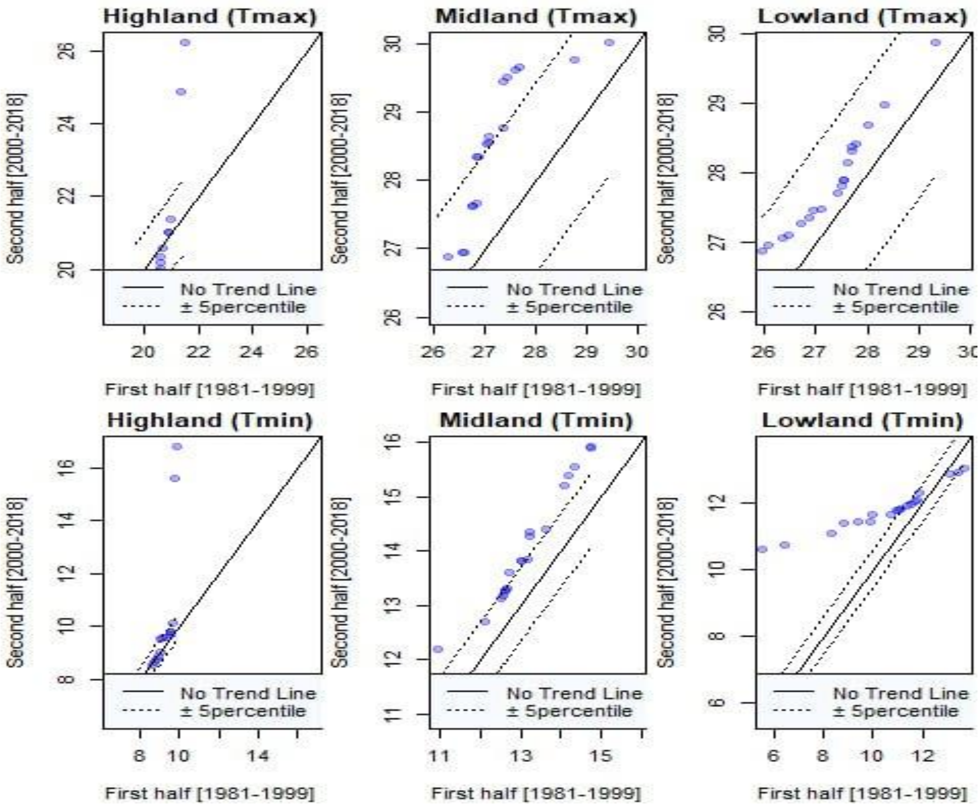
The observed trends in seasonal rainfall across different Agroecological Zones (AEZs) have significant implications for **agricultural production and productivity, food security, and rural livelihoods** in the study area. The study reveals concerning trends of declining rainfall in key agricultural seasons, particularly for the Midland AEZ, which could threaten food security, livelihoods, and economic stability in the region. Policy and adaptation strategies may include encouraging drought-tolerant crops, investing in irrigation, strengthening weather forecasting, and implementing soil conservation measures to retain moisture and improve productivity.

Trends in Mean Annual Maximum and Minimum Temperatures based on Innovative Trend Analysis

The research examined the mean annual maximum and minimum temperatures in a manner akin to that used in the rainfall study. The findings are shown in Table 4 and Figure 4. The trend in the mean annual maximum temperature for the Highlands was nonmonotonic (both decreasing and increasing). There was also an extreme increase in the high category positive trend, with a positive slope (0.001 °C/year). However, as the trend of slope indicates, the increase is negligible. The trend indicator (-0.636) shows despite the variability, there is a moderately strong trend. In the Midland area, it exhibited an increasing monotonic trend (Figure 4) with a positive slope (0.063 °C/year) and a moderate increase. The trend indicator (0.44) also confirms a moderately strong increasing trend (Table 4). A similar trend of mean annual maximum temperature was also observed for Lowland with monotonic low- and middle-category increasing trends with a positive slope (0.029). However, the increase is small which is also confirmed by the trend indicator (0.206) that shows a weak increase (Table 4 and Figure 4).

The mean annual minimum temperature trend for the Highland AEZ exhibited a nonmonotonic trend during the study period (38 years). No trend was observed in the middle category (Figure 4). However, the magnitude of the trend slope (0.035 °C/year) indicated a small but visible increasing positive trend in minimum temperature where the trend indicator (0.065) also shows weak but positive trend (Table 4). On the other hand, the Midland AEZ showed a monotonic increasing trend, with middle and high category increases similar to those of the maximum temperature (Figure 4). A moderate increasing trend is also observed through a positive slope (0.7 °C/year) supported by a comparatively strong increasing trend indicator

(0.689). An increasing and decreasing trend in the mean annual minimum temperature trend was also observed for the Lowlands in the nonmonotonic low, middle, and high categories. However, an increasing trend was also observed through a positive slope (0.065 °C/year). The trend indicator (1.186) also suggests a strong increasing trend of minimum temperature in the lowland AEZ, which is the highest of all (Table 4 and Figure 4).



Note: Tmax = Maximum temperature; Tmax = Minimum temperature

Figure 4. Trends of Annual Maximum and Minimum Temperatures

Concerning maximum temperature, the results of the MK test and Sen's slope indicate that the Highland AEZ exhibited a nonsignificant decreasing trend for the annual and spring seasons, whereas it exhibited a significant increasing trend in the summer season for both tests (p value ≤ 0.05). In contrast to the Highland AEZ, maximum temperature exhibited a significant increasing trend (P value ≤ 0.01) annually and during the spring and summer seasons in the Midland AEZ. Similarly, in the lowland AEZ, the annual and all-season maximum temperature values exhibited increasing trends. However, while the annual and spring seasons experienced a significant increase (P value ≤ 0.05), the summer season experienced a nonsignificant increasing trend (Table 6 and Figure 4). While the Highlands exhibited a slightly decreasing trend in maximum temperature, both the Midlands and Lowlands experienced an increasing trend within the study period (40 years), where the magnitude was greater in the Midlands. Similar results were also reported by Matewos & Tefera (2020) and Gashaw et al. (2023) in their respective study areas.

Table 6. Trends of Annual and Seasonal Maximum Temperature based on the MK test and Sen's Slope (1981 to 2018)

AEZ	Annual		Spring (Bdheeessa)		Summer (Hawado)		Winter (Arro)	
	MK	SS	MK	SS	MK	SS	MK	SS
Highland	-1.20	-0.02	-1.79	-0.02	2.18*	0.02	-2.75	-0.04
Midland	3.59**	0.059	3.51**	0.06	3.85**	0.08	1.81*	0.02
Lowland	2.33*	0.029	2.47*	0.041	1.71	0.03	1.94*	0.03

AEZ= Agroecology; MK= Mann–Kendal test; SS = Sen's slope; **= Significant at the 0.01 level (2-tailed); * = Significant at the 0.05 level (2-tailed)

It was also found that for minimum temperature, the Highlands exhibited a nonsignificant increasing trend for the annual and summer seasons, as measured by both tests. However, it experienced a nonsignificant decreasing trend in the spring. In the Midland AEZ, a significant increasing trend (P value ≤ 0.01) was observed for the mean annual value measured via both tests, whereas a significant (p value ≤ 0.05) trend was observed for the spring and summer seasons. In contrast, the Lowland experienced a significant increasing trend in the mean annual minimum temperature, as measured by the Mk test (p value ≤ 0.01). A nonsignificant increasing trend was observed during the spring seasons, whereas the summer season experienced a significant (p value ≤ 0.01) increasing trend for both tests (Table 7 and Figure 4).

In general, both the maximum and minimum temperatures increased in the sample AEZs of the region, which implies that climate change has occurred in the study area. It can be concluded that Midland and Lowland AEZs are experiencing significant warming trends, causing crop stress, drought risks, and food shortages. Rising temperatures may disrupt crop development, increase evapotranspiration, and cause soil moisture loss. The Midland AEZ faces the highest risks of livelihood instability, potentially leading to increased migration, income diversification, and reliance on climate adaptation measures. Urgent climate adaptation strategies, including heat-tolerant crop varieties, irrigation expansion, and soil moisture conservation, are crucial to safeguard smallholder livelihoods.

Table 7. Trends of Annual and Seasonal Minimum Temperature based on the MK test and Sen's slope (1981 to 2018)

AEZ	Annual		Spring (Bdheeessa)		Summer (Hawado)		Winter (Arro)	
	MK	SS	MK	SS	MK	SS	MK	SS
Highland	0.25	0.003	-0.79	-0.011	0.013	0.00	0.53	0.009
Midland	3.39**	0.05	1.94*	0.04	2.15*	0.03	3.09**	0.076
Lowland	2.86**	0.06	1.63	0.05	3.7**	0.08	1.76	0.06

AEZ = Agroecology; MK = Mann–Kendal test; SS = Sen's slope; ** = significant at the 0.01 level (2-tailed); * = significant at the 0.05 level (2-tailed)

Comparison of the Trend Tests

It can be concluded from the results obtained by all the tests (ITA, MK test and Sen's slope), that the results of all the tests are similar except for a few instances, where the cross-validation of the findings ensure the reliability of the entire tests in detecting the trend of rainfall and temperature throughout the study period and area.

Measures of Variability of Climate among the Three Agroecological Zones

As discussed in the methodology, rainfall variability in the study area was assessed via the PCI, CV and RAI.

Variability in Rainfall

Precipitation Concentration Index

The results indicate that 77.5% of the study period had a moderate rainfall distribution, while 20% experienced uniform rainfall, and only 2.5% experienced erratic rainfall in the Highlands. In the Midland and Lowland regions, 87.5% and 92.5%, respectively, of the study period exhibited moderate rainfall, whereas 10% and 7.5%, respectively, exhibited uniform distributions. Only 2.5% of the study period experienced erratic rainfall in the

Midland area, whereas in the Lowland, the period did not experience erratic rainfall.

Table 8. Annual Precipitation Concentration Index (PCI) (1981 to 2020)

Category	Highland			Midland			Lowland		
	PCI value	Years	%	PCI value	Years	%	PCI value	Years	%
<10 (Uniform)	9.13-9.97	8	20%	9.19-9.92	4 (1983, 1993,2005, 2010)	10%	9.53-9.94	3 (1982, 2020,1991)	7.5%
Between 10 and 15(Moderate)	10.02-13.12	31	77.5 %	10.35-14.98	35	87.5 %	10.09-14.91	37	92.5 %
Between 15 and 20 (irregular)	17.22	1(2018)	2.5%	15.37	1 (2012)	2.5%	0	0	0
>20 (highly irregular)	0		0	0	0		0	0	0

Compared with the other areas, the Lowland experienced less uniform (7.5%) rainfall. This indicates that the selected AEZs experienced mostly moderate rainfall, even though erratic rainfall was less likely to experience a future trend of rainfall variability (Table 8 and Figure 5).

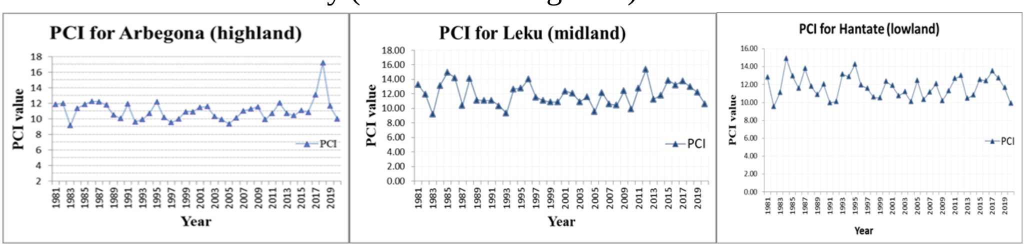


Figure 5. Annual Precipitation Concentration Index (PCI) for the three AEZs

Coefficient of Variation (CV) for Rainfall and Temperature

The coefficient of variation (CV) of annual, spring, and summer rainfall and, annual maximum and minimum temperatures were summarized in Table 9.

Table 9. Results of Coefficient of Variation for the Three AEZs (1981 to 2020)

Category	Highland	Midland	Lowland
PRCPAN	24.1%	23.6%	19.8%
PRCPSP	33.3%	34.7%	28.2%
PRCPSUM	28.4%	28.5%	27.6%
TmaxAN	6.6%	4.1%	3.0%
TminAN	21.0%	8.2%	15.1%

PRCP = Precipitation; AN = Annual; SP = spring; SUM = summer

The results of annual rainfall indicated moderate variability for Highland (24.1%) and Midland (23.6%), while there was less variability for Lowland (19.8%) during the study period in the study area. During the spring season, the Highland (33.3%) and Midland (34.7%) exhibited high variability, while the Lowland experienced moderate variability (28.2%). The results of the study (Highland and Midland) are in congruence with those of Gashaw et al (2023) for the spring season. In addition, the CV of the summer season revealed moderate variability for all the AEZs, i.e., highland (28.4%), midland (28.5%), and lowland (27.6%) indicating a slight shortage of rainfall during the summer (Table 9).

Regarding annual mean maximum temperature, all the AEZs experienced less variability throughout the study period. However, the annual mean minimum temperature exhibited different levels of variability among the AEZs, moderate variability was observed in the Highland, and both Midland and Lowland exhibited less variability throughout the study period (Table 9). This indicates that although there were increasing trends in both maximum and minimum temperatures for all the AEZs (Tables 6 and 7; Figure 4), the variability for both types of temperatures was less in the study area.

Rainfall Anomaly Index (RAI)

The annual and seasonal rainfall anomaly indices (RAIs) based on time series data for the three selected agroecological zones in the Sidaama Region were computed for 40 years. Table 10 lists the dry and wet years for each selected AEZ.

The results revealed that the Midland AEZs had more wet years (RAI ≥ 3) than did the highland and lowland AEZs, whereas the Lowland AEZs experienced more extremely dry years (RAI≤-3). The extreme driest years for the Highlands were 1991, 2015, 2017, and 2012 in terms of severity, while 2015, 2009, 2017, and 2012 were the drought years in the Midland area. Similarly, 2015, 2012, 1984, 1985, and 1999 were the driest years in terms of severity in the Lowlands. The years 2012 and 2015 were common drought years in all the AEZs of the region, whereas 2017 was a common drought year for the Highlands and Midlands. Lebeza et al. (2023), Belay et al. (2021), and Mera (2018) also identified 2015 as a common dry year in their respective studies because El Niño events affect the livelihood of smallholder farmers in many rural parts of Ethiopia. Other studies also note that Ethiopia has experienced twelve major/extreme historical droughts since the 1980s during 1984/85, 1987/88, 1991, 1994, 1997, 2002/03, and 2010/11 and 2015/16 (Belay et al., 2021; Lemma et al., 2022a; Matewos, 2019). In this study area, when the "slight drought" to "extreme drought" classification was considered, the Highlands and Lowlands presented more dry years within the study period (19 years), whereas the Midlands experienced only 15 years of dry conditions, although the magnitude was greater in the lowlands of the study area (Table 10).

Table 10. Results of the Annual Rrainfall Anomaly Index (RAI) for the three AEZs (1981 to 2020)

Index Classifications of V. Rooy (1965)	Agroecology		
	Highland	**Midland**	**Lowland**
Extremely wet years	1998, 2019, 2020	1996, 1987, 1988, 1983, 2020	1996, 2020, 1983
Very dry	2005, 2004, 1997, 1984, 2003, 2009	2011, 2002, 1984, 1999	2003, 2009, 2004, 1991
Extremely dry	1991, 2015, 2017, 2012	2015, 2009, 2017, 2012	2015, 2012, 1984, 1985, 1999

Source: Computed based on NMI data, 2023

While analyzing the seasonal RAI, only spring and summer were considered because the incidence of extreme dryness (drought) or extreme wetness manifests during these two seasons, which affects crop production since the smallholder farmers in the study area depend on rainfed agriculture.

Accordingly, the Highlands experienced the driest spring (RAI, -4.25) in 1997 and summer (RAI, -4.72) in 2018. This AEZ experienced the wettest spring (RAI, 7.43) in 1990 and summer (RAI, 7.36) in 2019. Similarly, the Midland exhibited the driest spring (RAI, -3.80) during 2015 and summer (RAI, -4.06) during 2009, whereas it experienced the wettest spring (RAI, 7.01) and summer (RAI, 6.43) in 1987 and 1988, respectively. In the Lowlands, the driest springs (RAI, -5.36) and summers (RAI, -3.73) were observed during 2012 and 1993, respectively, whereas the years 1983 and 2019 had the wettest springs (RAI, 5.51) and summers (4.28), respectively (Table 11).

Table 11. Results of the Seasonal Rainfall Anomaly Index (1981 to 2020)

Index Classification of V. Rooy (1965)	Agroecology					
	Arbegona/Highland		Leku/Midland		Hantate/Lowland	
	Spring	Summer	Spring	Summer	Spring	Summer
Extremely wet years	1990, 1983, 2018,	2019, 2011, 1998, 1982	1987, 1983, 1990	1988, 1996, 1994, 2019, 1986	1983,1987, 1981, 1990	2019, 1983, 1996, 1988
Very dry years	2003, 2015, 2009, 1988, 2005, 2004, 1984	2015, 1987, 2009, 2004, 1993, 1990, 1997	2011, 1984 1999	2004, 2018, 2016, 1987 2000	1999, 2000, 1985, 1988, 2008, 2003	2009, 2016, 1999, 2003
Extremely dry years	1997, 2012, 1991	2018, 1991, 2017	2012, 2015 2009, 2017, 2008	2009, 2015, 2017, 1993 2002	2012, 2015, 2009, 1984	1993, 2004, 1990, 1987, 2015, 2002

Source: Calculated by NMI Data

In addition, within 40 years, the Highlands experienced three extremely dry seasons (1997, 2012, and 1991) and seven very dry seasons (2003, 2015, 2009, 1988, 2005, 2004, and 1984). Similarly, three extremely dry (2018, 1991, and 2017) and seven very dry (2015, 1987, 2009, 2004, 1993, 1990,

1997) summer seasons occurred. In the Midland, five extremely dry (2012, 2015 2009, 2017, 2008) and three very dry (2011, 1984, 1999) spring seasons occurred, whereas five extremely dry (2009, 2015, 2017, 1993, 2002) and five very dry (2004, 2018, 2016, 1987, 2000) summer seasons occurred within the stated period. The Lowlands experienced four extremely dry (2012, 2015, 2009, 1984) and six very dry (1999, 2000, 1985, 1988, 2008, 2003) spring seasons, whereas the AEZ experienced six extremely dry (1993, 2004, 1990, 1987, 2015, 2002) and four very dry summer seasons (2009, 2016, 1999, 2003) (Table 11). Most of these dry spring and summer years were extreme drought years in the country and coincided with other findings (Belay et al., 2021; Matewos, 2019), indicating that the livelihood of the smallholder farmers might have been affected by these extreme climate conditions in the sample AEZs. In comparison, the Highland presented three extremely dry spring seasons and three summer seasons within 40 years. In the Midland area, five spring and five summer seasons occur. Similarly, the Lowlands experienced four and six extremely dry spring and summer seasons, respectively, indicating that the Lowlands were more affected by drought conditions because the crop production of this AEZ was mostly dependent on the spring season (Table 11).

4. Discussion

The findings of this study provide a comprehensive understanding of climate trends and variability in the Sidaama Region of Southern Ethiopia from 1981 to 2020. The study examined trends in rainfall and temperature across three agroecological zones (AEZs) using Innovative Trend Analysis (ITA), with additional validation from the Mann-Kendall (MK) test, Sen's slope, and Spearman's rho test. Furthermore, the study assessed seasonal variations in rainfall patterns and changes in maximum and minimum temperatures.

The results reveal marked interannual variability across the agroecological zones. For instance, while 2020 recorded the highest rainfall in all zones—1723.8 mm in the Highland, 1599.5 mm in the Midland, and 1529.9 mm in the Lowland—other years such as 1991 in the Highland (500.4 mm), 2015 in the Midland (584.6 mm), and 2012 in the Lowland (728.4 mm) were characterized by severe droughts. This contrast, along with the significant differences in maximum and minimum temperature records across zones, underscores a trend of increasing climate variability. These variations, corroborated by similar findings in recent studies (Ware et al., 2023) highlight the urgent need for targeted water resource management and climate adaptation strategies to address both flood risks and prolonged drought conditions in these distinct agroecological settings.

The analysis of annual precipitation trends revealed a declining pattern across all three AEZs, with the midland region exhibiting the sharpest decline (-12.07 mm/year), followed by the highland (-3.094 mm/year) and the lowland (-2.227 mm/year). The trend indicator values further confirmed these patterns, with the midland AEZ showing a significant and strong decreasing trend, likely driven by deforestation, agricultural land expansion, land degradation and land fragmentation to invest in afforestation or reforestation. These findings highlight the potential risks of reduced water availability for agriculture and ecosystems, emphasizing the need for sustainable land management and reforestation efforts to mitigate further decline. The decline in precipitation is consistent with previous studies in Ethiopia such as Matewos & Tefera (2020) and (Lebeza et al., 2023) which have highlighted similar reductions in rainfall due to environmental degradation and climate change. It also aligns with that of (Gashaw et al., 2023), which reported significant rainfall declines in Ethiopia, and (Balcha et al., 2023), noting reduced precipitation in southern regions due to climate variability. (Gebrechorkos et al., 2019) confirmed drying trends in East African highlands, attributing them to shifts in the Intertropical Convergence Zone (ITCZ), consistent with the Sidaama findings.

Seasonal rainfall trends indicated that the Midland AEZ experienced a monotonic decreasing trend in both spring and summer, suggesting that this AEZ has been particularly vulnerable to declining rainfall over time. The highland AEZ also exhibited a decreasing trend in spring but showed a nonmonotonic pattern in summer. In contrast, the lowland AEZ demonstrated a decreasing trend in spring while showing a nonmonotonic trend in summer, indicating potential fluctuations in seasonal precipitation. Spring was the common season where rainfall decreased in all of the AEZs. This is especially concerning for smallholder farmers, as spring rainfall is vital for farming activities. A decrease in spring rainfall could negatively impact crop yields and threaten food and livelihood security, particularly for those in Midland and Lowland regions, who rely exclusively on this rainfall for their annual crop harvests. The spring (*badheessa*) dependent cropping system requires policy and adaptation strategies that may include encouraging drought-tolerant crops, investing in irrigation, strengthening weather forecasting, and implementing soil conservation measures to retain moisture and improve productivity. A study by Toni et al., 2022 and Matewos and Tefera (2020) also indicated a declining spring season trend. A study by Hubertus et al., 2023 indicated that farmers in South Wollo (Ethiopia) observe increasingly erratic spring rains, marked by delayed initiation and early termination, corroborated by satellite-derived data indicating increased rainfall variability. Other researches also indicate a declining tendency in spring precipitation in East Africa, especially during the March-May period (Gebrechorkos et al., 2019) confirming the Sidaama's findings, although other Sub-Saharan African regions exhibit varied tendencies, with certain locations having heightened rainfall intensity and variability (Maidment et al., 2015).

Validation through the MK test, Sen's slope, and Spearman's rho test corroborated the ITA findings, particularly for the Midland AEZ, which exhibited a significant decreasing trend ($p \leq 0.01$). The Highland and Lowland AEZs also showed decreasing trends, although they were statistically nonsignificant. These results align with previous studies that have identified declining rainfall trends in various parts of Ethiopia (Kerebo et al., 2024).

Analysis of temperature trends indicated a general increase in both maximum and minimum temperatures across the three AEZs. The Highland AEZ exhibited a nonmonotonic trend for maximum temperature with a negligible positive slope (0.001°C/year), whereas the Midland and Lowland AEZs demonstrated a monotonic increasing trend, with the Midland AEZ exhibiting the highest rate of increase (0.063°C/year). The increasing temperature trend in the Midland AEZ was further supported by a moderate trend indicator value (0.44), suggesting a relatively strong warming trend compared to the other zones. Rising temperatures may disrupt crop development, increase evapotranspiration, and cause soil moisture loss. The result is in congruence with Mekonen & Berlie, 2019 where the annual, maximum, and minimum temperature averages grew at rates of 0.0034, 0.0028, and 0.0095 °C each year, respectively. (Serdeczny et al., 2017) also projected the climate change for the Sub-Saharan region point to a warming trend. Similarly, a finding by (H. Li et al., 2024) indicated that annual maximum temperature exhibited a significant rising trend at the Yellow River Basin of China. However, contradicting evidence exists; for instance, (Kruger & Sekele, 2013) reported stable maximum temperature in some Southern African highlands, suggesting regional variations not observed in Sidaama.

Similarly, minimum temperature showed a weak increasing trend in the Highland AEZ (0.035°C/year), while the Midland AEZ exhibited a more pronounced increase (0.047°C/year) with a stronger trend indicator (0.689). The Lowland AEZ also showed an increasing trend (0.065°C/year), indicating that minimum temperature has been rising steadily across all AEZs. These temperature increases align with broader warming trends observed in Ethiopia and other parts of East Africa, driven by global climate change (Matewos & Tefera, 2020). The result is also in agreement with (Tura et al., 2021) that central highlands of Ethiopia also exhibited minimum temperature increasing trend. Other research in Sub-Saharan Africa indicates a general tendency toward rising minimum temperatures; however, several areas, notably South Africa and Malawi, have shown a decreasing trend (Mupangwa et al., 2023).

Rising maximum and minimum temperatures in the Sidaama region's midland and lowland zones pose significant challenges to agriculture, water resources, and livestock. Higher heat accelerates crop growth cycles, resulting in lower yields and increased moisture loss, which endangers rainfed farming. Livestock are more susceptible to heat stress and disease, while elevated temperatures may promote pest proliferation. These factors pressure smallholder farmers, potentially driving migration and necessitating adaptation strategies such as heat-tolerant crop varieties, expanded irrigation, and soil moisture conservation to protect their livelihoods.

Rainfall variability, assessed via PCI, showed moderate distribution with erratic years, and RAI identified drought years like 2012 and 2015, with the lowland zone most affected. This aligns with (Lemma et al., 2022), noting frequent droughts in Ethiopia, and with (Funk et al., 2023), who linked East African droughts to El Niño events. Contradictorily, some tropical regions, like parts of the Amazon (Liao et al., 2024), show increasing rainfall due to ocean warming, highlighting spatial heterogeneity not applicable to Sidaama's inland context.

Rainfall variability, with erratic distribution and recurrent droughts, threatens agriculture, water availability, and food security in the Sidaama region, especially in lowland areas. This may heighten reliance on food aid, force livelihood shifts, and drive migration. Adaptive strategies like water harvesting, drought-resistant crops, and climate-smart practices are essential to mitigate these impacts.

5. Conclusion

The analysis of climate trends and variability in the Sidaama Region reveals significant shifts in rainfall and temperature patterns across agroecological zones (AEZs), posing challenges to agricultural production and smallholder livelihoods.

Rainfall trends indicate a decline in annual and seasonal precipitation across all AEZs, with the most pronounced reductions in the Midlands and Lowlands. The spring (badheessa) season, critical for planting, exhibited a significant decreasing trend, particularly in the Midlands. Annual rainfall variability was moderate in the Highlands but lower in the Midlands and Lowlands, while high variability in spring rainfall increased uncertainty in planting and harvesting periods. The summer season also showed a declining trend, raising concerns about water availability during peak growing periods. The Precipitation Concentration Index (PCI) indicates moderate rainfall distribution throughout most of the study period, with the Lowlands experiencing the least uniform rainfall. This irregularity disrupts cropping cycles and reduces yields, reinforcing concerns about the unpredictability of seasonal rainfall and its impact on agricultural planning.

Temperature trends show a consistent increase in maximum temperatures across the Midlands and Lowlands over the past 38 years, with the Midlands experiencing the highest rise. The Highlands exhibited a slight decrease in maximum temperature during the annual and spring seasons, but a significant increase in summer. Minimum temperatures showed an increasing trend in the Midlands and Lowlands, with moderate variability in the Highlands. Rising temperatures intensify evapotranspiration, reduce soil moisture, and increase heat stress on crops and livestock, while sustained increases in minimum temperature may exacerbate pest and disease prevalence.

The Rainfall Anomaly Index (RAI) highlights frequent extreme dry years, with the Lowlands experiencing the highest number of severe droughts, followed by the Highlands and Midlands. Common drought years, such as 2012 and 2015, were linked to El Niño events, which have historically devastated Ethiopian agriculture. Prolonged droughts have likely reduced crop yields and pasture availability, increasing food insecurity, particularly in the Lowlands, where spring rainfall is crucial for agriculture. These findings underscore the need for urgent climate adaptation strategies.

6. Policy Implication and Recommendations

Policy Implication

The combined effects of declining rainfall, rising temperatures, and increased climate variability threaten the livelihoods of smallholder farmers in the Sidaama region. Reduced water availability, heat stress, and erratic rainfall patterns limit the potential for stable agricultural production, leading to income losses and food shortages. The Lowland AEZ is particularly vulnerable due to its reliance on rainfed agriculture and higher exposure to drought conditions. Without timely interventions, these climatic changes could exacerbate poverty, malnutrition, and migration patterns in the region.

Recommendations

The observed climate trends highlight the need for targeted adaptation measures to enhance agricultural resilience in the Sidaama Region. Policymakers, researchers, and local communities must prioritize climate-smart agricultural practices, such as drought-resistant crop varieties, improved irrigation systems, soil and water conservation techniques, and agroforestry. Strengthening early warning systems and access to climate information will also be crucial in enabling farmers to make informed decisions. Additionally, investment in diversified livelihoods, such as off-farm income sources, can help buffer smallholder farmers against climate-induced shocks.

Given the increasing temperature trends and declining rainfall, appropriate climate adaptation measures are essential to safeguard agricultural productivity and food security. Collaborative efforts among governments, NGOs, and farmers will be key to developing sustainable strategies that mitigate the adverse effects of climate change in different AEZs of the Sidaama Region. Moreover, future research should focus on the long-term impacts of these climate trends on specific crop yields, soil health, and water resources. Developing localized climate models and impact assessments will further enhance the ability to design effective mitigation and adaptation strategies tailored to the needs of smallholder farmers in each AEZ.

7. Limitations of the Study

The study has both strengths and limitations. The National Meterology Institution (NMI) provided a reliable gridded dataset, increasing credibility and reducing missing and incomplete data. The study used various analytical methods, such as innovative trend analysis, Mann-Kendal test, and Sen's slope, to ensure reliability. Comparisons were made among different agroecological zones for area-specific measures. However, the study had limitations, including the lack of recent data from the NMI and the inclusion of more districts for more accurate generalization. Future studies could improve by including recent data on precipitation and temperature, increasing the number of districts/stations as samples, and analyzing forecasting of trend and variability for future years based on past trends.

The Study Period

Study Period: the study covers a 40 years data (1981 to 2020)

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Declarations

Conflict of Interest

The authors declare that there was no likely conflict of interest.

Funding Statement

The financial support was obtained from Hawassa University as part of the corresponding author's PhD study program.

Availability of the Data

One can access the data used in this study from the National Meterological Institute (NMI) of Ethiopia by a justifiable request made to the institution through the institution's email address: datausers@gmail.com. The dataset that is arranged for different tools and used to analyze the current study is available by request from the corresponding author.

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