

## Article

# Assessing Rainfall and Temperature Trends in Central Ethiopia: Implications for Agricultural Resilience and Future Climate Projections

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## Abstract

In the past three decades, localized research has highlighted shifts in rainfall patterns and temperature trends in central Ethiopia, a region vital for agriculture and economic activities and heavily dependent on climate conditions to sustain livelihoods and ensure food security. However, comprehensive analyses of long-term climate data remain limited for this area. Understanding local climate trends is essential for enhancing agricultural resilience in the study area, a region heavily dependent on rainfall for crop production. This study analyzes historical rainfall and temperature patterns over the past 30 years and projects future climate conditions using downscaled CMIP6 models under SSP4.5 and SSP8.5 scenarios. Results indicate spatial variability in rainfall trends, with certain areas showing increasing rainfall while others experience declines. Temperature has shown a consistent upward trend across all seasons, with more pronounced warming during the short rainy season (Belg). Climate projections suggest continued warming and moderate increases in annual rainfall, particularly under SSP8.5 by the end of the 21st century. It is concluded that both temperature and rainfall are projected to increase in magnitude by 2080, with higher Sen's slope values compared to earlier periods, indicating a continued upward trend. These findings highlight potential breaks in agricultural calendars, such as shifts in rainfall onset and cessation, shortened or extended growing seasons, and increased risk of temperature-induced stress. This study highlights the need for localized adaptation strategies to safeguard agriculture production and enhance resilience in the face of future climate variability.

**Keywords:** climate change; climate projection; Mann–Kendall test; spatio-temporal dynamics; central Ethiopia



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## 1. Introduction

Climate change represents one of the most pressing challenges of the 21st century, posing significant threats to ecosystems, agriculture, water resources, and human livelihoods. These threats are especially pronounced in regions vulnerable to fluctuating weather patterns, exacerbated by increased greenhouse gas emissions [1]. Since 1850, the global average temperature has risen by approximately 0.78 °C, and climate projections estimate

an additional increase of 1.5 °C to 2 °C by the end of the 21st century [2]. Among the most critical climate variables are rainfall and temperature, which serve as fundamental indicators of environmental conditions and strongly influence ecological systems and food security [3]. Even minor shifts in these variables can significantly impact food production, particularly in low-income, agriculture-based economies where crop production is predominantly rain-fed [4]. Given unequivocal evidence on increasing global warming and associated negative impacts on development and poverty reduction [1], development pathways have shown commitment in addressing such an imminent challenge through different mechanisms. A case in point is the Sustainable Development Goals (SDGs) (2015–2030), which, through its 13th goal, aims to take urgent action to combat climate change and its impacts by improving resilience and adaptive capacity to climate-related impacts' [5]. The Goals clearly emphasize the need to build adaptive capacity at both national and local levels to minimize the impacts of climate change on poverty reduction and sustainable development. Similarly, the empirical literature on climate change adaptation highlights the importance of strengthening adaptive capacity at the community and household levels to effectively reduce climate change-induced impacts [6]. To this end, many developing countries have been implementing different policies and programs that build the adaptive capacities of vulnerable communities to climate change-related impacts.

Africa has already experienced a considerable rise in temperature over the past century, a trend projected to intensify further, with forecasts suggesting an increase of 2 °C to 6 °C over the next 100 years [2]. The impacts of this change have emerged as one of the formidable challenges undermining development and poverty reduction endeavors in Sub-Saharan Africa (SSA) [7]. East African countries such as Ethiopia, Kenya, and Tanzania are exhibiting rising trends in extreme temperature indices and increasingly erratic rainfall patterns [8]. These climatic changes pose serious risks to agriculture, water security, and health systems across the region.

In Ethiopia, the mean annual temperature increased by 1.3 °C between 1960 and 2006 and is projected to rise by up to 1.8 °C by the 2050s and 3.7 °C by the end of the century under the high-emission scenario (RCP8.5) [9]. This warming trend, coupled with uncertain rainfall patterns, poses a major threat to national development, particularly in agriculture-dependent communities.

Climate studies at various scales reveal inconsistent rainfall and temperature trends across Ethiopia. Rainfall distribution is highly variable, with some regions experiencing increases while others face declines [10]. For instance, while some national studies reported no significant change in annual rainfall, they did highlight a significant decline in rainfall during the main rainy season (June–September) in south-western and central Ethiopia [11]. Other findings suggest decreasing trends in both annual and main-rainy-season rainfall in northern and western Ethiopia [12]. In contrast, central Ethiopia has experienced declining short-rainy-season (March–May) rainfall but an increase in annual and main-rainy-season rainfall [13]. Temperature patterns also vary locally. Climate model projections suggest overall warming across all seasons in Ethiopia, though regional differences are modest [10]. A study specific to central Ethiopia noted a significant increase in both maximum and minimum annual temperatures in midland and lowland areas [14]. However, many national and regional studies fail to account for localized variations due to differences in topography, limiting their practical usefulness to farmers and policymakers. While these studies have identified general climate patterns [10–14], few have combined long-term observed station data with downscaled CMIP6 projections to assess climate risks at the local scale in central Ethiopia [15,16].

This study addresses that gap by analyzing historical and projected rainfall and temperature trends using both observational data and high-resolution CMIP6 outputs.

The findings provide a basis for more targeted adaptation planning and support efforts to strengthen agricultural resilience in this climate-vulnerable, data-scarce region. Despite the availability of global and national climate data, there is limited research utilizing CMIP6 projections specifically for central Ethiopia. This restricts the development of precise, location-specific strategies to build agricultural resilience.

To address this critical gap, the primary objective of this study was to analyze the key climatic factors affecting agricultural production in central Ethiopia, specifically the onset and cessation of rainfall, frequency of dry spells, length of the growing season, and total seasonal rainfall. The research assessed both historical (1993–2023) and projected climate trends using observed meteorological data and downscaled outputs from CMIP6 global climate models under two emissions scenarios: SSP4.5 (medium) and SSP8.5 (high). The broader goal was to improve our understanding of local climate variability and contribute to evidence-based strategies for climate-resilient agricultural planning.

The study focused on eight meteorological stations representing diverse elevations and agroecological zones across central Ethiopia. A range of climate indices including the Precipitation Concentration Index (PCI), Rainfall Anomaly Index (RAI), coefficient of variation (CV), and dry spell analysis were applied to explore changes in agriculturally relevant climate variables.

The research was guided by the following questions:

1. What have been the historical trends in rainfall and temperature across the selected stations in central Ethiopia from 1993 to 2023, and how are these variables projected to change by the 2050s and 2080s under SSP4.5 and SSP8.5 emission scenarios?
2. What are the implications of these trends for rain-fed agriculture and the development of climate resilience strategies for smallholder farmers in the region?

Although many of the climate indices employed in this study are well-established, their combined and focused application to central Ethiopia—a region that is both climate-vulnerable and data-scarce—offers novel, location-specific insights. The integration of long-term observational data with CMIP6 projections enhances the reliability of the findings and provides a crucial evidence base for risk assessment and adaptation planning.

In summary, this research not only evaluated historical and future climate dynamics but also interpreted their potential implications for improving agricultural resilience in rain-fed systems. Here, resilience is defined as the ability of smallholder farming systems to adapt to and recover from climate-related shocks, such as rainfall variability, dry spells, and temperature extremes while maintaining productive and sustainable agricultural practices. The findings are intended to support extension services, policymakers, and development practitioners in designing more adaptive and climate-resilient strategies for smallholder farming communities in central Ethiopia.

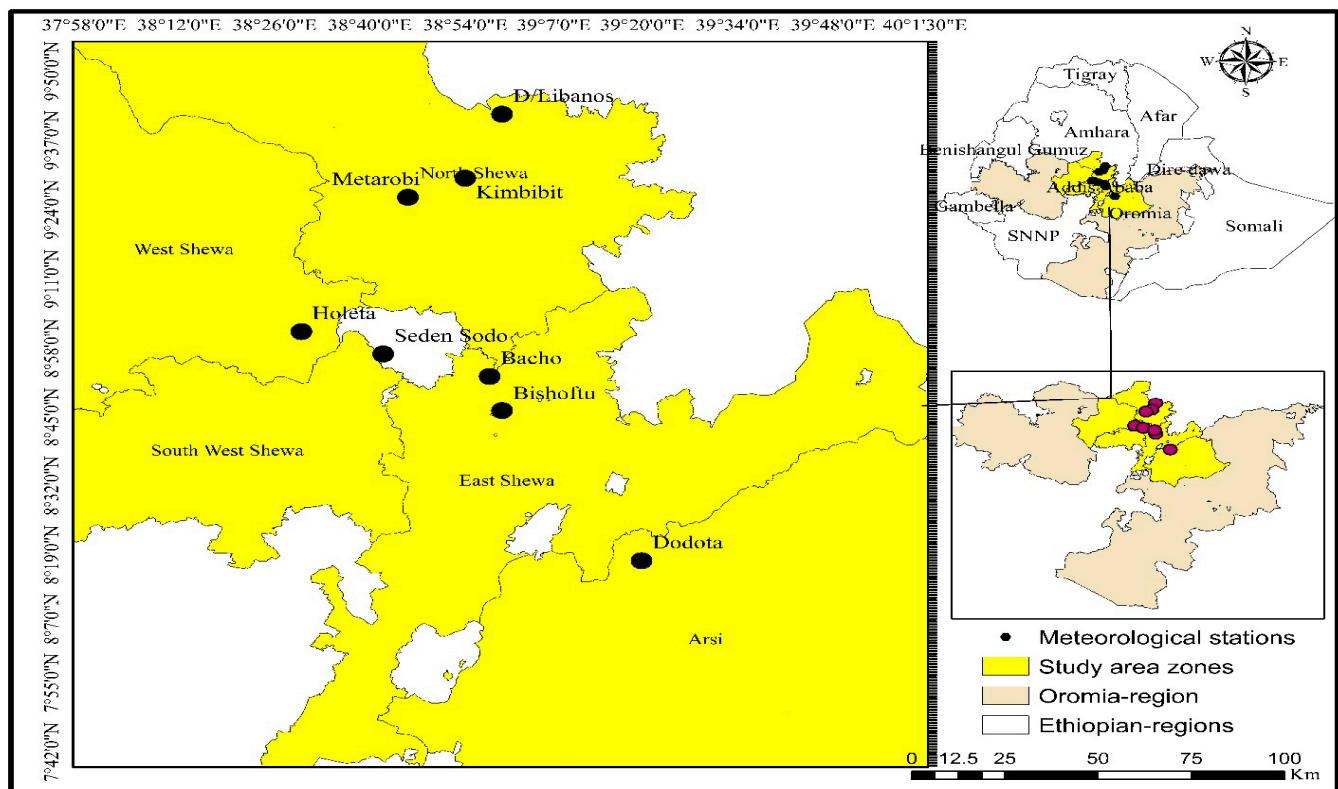
## 2. Methodology

### 2.1. Description of the Study Area

This study included five administrative zones—Arsi, East Shoa, North Shoa, South-western Shoa, and Western Shoa—located between 8.3° N latitude and 39.330° E longitude. The altitude in these zones ranges from 1800 to 2900 m above sea level (Table 1) [17]. The study focused on the Oromia Regional State, with meteorological stations selected in Dodota, Bishoftu, Kimbibit, Debrelibanos, Meta Robi, Holeta, Becho, and Sedensodo (Figure 1).

**Table 1.** Geographic information of the selected meteorological stations in central Ethiopia.

| Stations   | Average Rainfall | Average Minimum Temperature | Average Maximum Temperature | Latitude (° N) | Longitude (° E) | Altitude (m) Above Sea Level |
|------------|------------------|-----------------------------|-----------------------------|----------------|-----------------|------------------------------|
| Dodota     | 855.69           | 12.71                       | 27.40                       | 8.3            | 39.33           | 1800                         |
| Bishoftu   | 790.79           | 11.33                       | 27.19                       | 8.77           | 38.99           | 1900                         |
| D/Libanos  | 907.71           | 9.11                        | 22.40                       | 9.70           | 38.99           | 2000                         |
| Kimbibit   | 984.44           | 7.60                        | 20.82                       | 9.50           | 38.90           | 2900                         |
| Metarobi   | 1084.70          | 10.10                       | 27.62                       | 9.44           | 38.76           | 2400                         |
| Holeta     | 1196.80          | 8.34                        | 23.78                       | 9.02           | 38.50           | 2400                         |
| Seden sodo | 1099.70          | 9.97                        | 27.43                       | 8.95           | 38.70           | 1800                         |
| Bacho      | 997.92           | 9.28                        | 27.52                       | 8.88           | 38.96           | 1800                         |

**Figure 1.** Map of eight meteorological stations included in the study.

These areas were selected due to their ecological diversity, agriculture being a key livelihood for the population, and vulnerability to climate variability, which make them representative of the broader region of central Ethiopia. Their variation in altitude, climate, and soil types provides a suitable basis for analyzing the relationship between agro-climatic conditions.

The area experiences a bimodal rainfall distribution, with a short rainy season from February to May and a long rainy season from June to September. Annual rainfall ranges from 790.79 to 1196.80 mm, and temperatures vary between 7.6 °C and 27.62 °C.

The diverse agro-climatic zones of the region support a combination of subsistence and mixed farming, which includes raising livestock (such as cattle, sheep, and goats) and cultivating a variety of crops, including cereals (teff, wheat, maize, barley), legumes (beans,

chickpeas), and vegetables [18]. The predominant soil types in central Ethiopia are Nitisols, Andosols, and Vertisols [19].

## 2.2. Baseline and Projected Climate Data Source

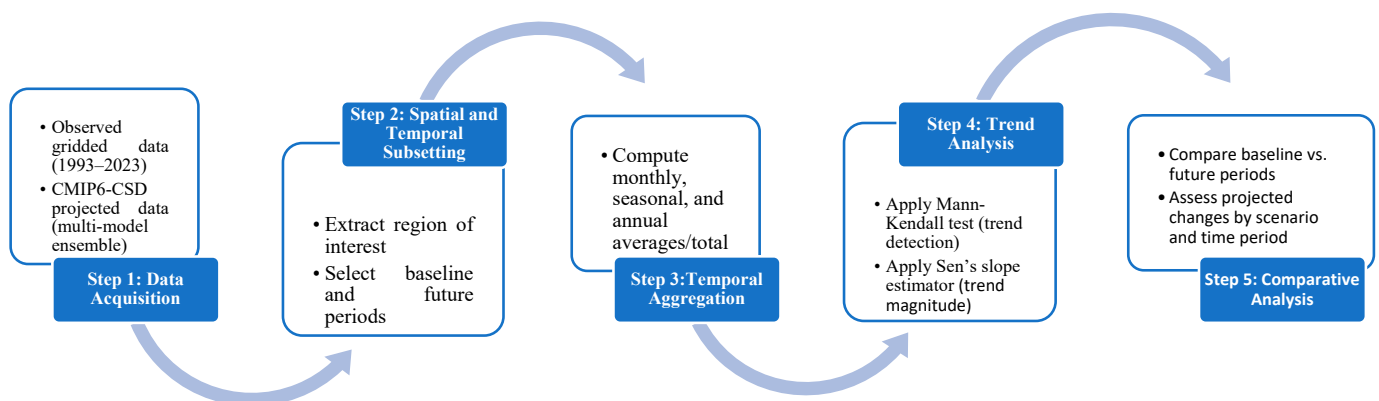
Long-term (30 years) daily rainfall and temperature (minimum and maximum) grid data from 1993 to 2023 were obtained for eight stations located in central Ethiopia from the National Meteorological Agency of Ethiopia (NMA). Daily climate data documentation shows no more than 10% of missing values [20] throughout the reference period (X-Y) used (Table 1).

The projected future climate data were downscaled from CMIP6 climate model outputs under two Shared Socioeconomic Pathways (SSPs): SSP4.5 (medium-emissions scenario) and SSP8.5 (high-emissions scenario). Projections were made for two future time horizons: 2025–2062 (centered on 2050) and 2063–2099 (centered on 2080). These data were analyzed using combinations of five general circulation models (GCMs). Changes in rainfall and temperature for the 2025–2062 (mid-term), 2063–2099 (long-term), and current baseline period were determined based on outputs from the GCMs and data of the meteorological stations used for analysis (Table 1), respectively. The scenarios estimated included future daily, monthly, and seasonal temperature and rainfall changes for the years under consideration. Shared Socioeconomic Pathways are methods or assumptions used to capture future climate scenario development processes by integrating economic, social, and physical factors that affect climate change. The SSPs, namely SSP4.5 low-emissions scenario and SSP8.5 high-emissions scenario, are a possible range of emission scenarios in the years of the 21st century [21].

## 2.3. Overview of Analytical Approach

To provide a clear understanding of the study design, the analytical steps were organized into a series of sequential steps. This study utilized gridded climate data for both the historical (1993–2023) and future periods. The observed gridded data were obtained from the National Meteorological Agency of Ethiopia (NMA), and the projected data were sourced from a five-model ensemble of CMIP6 simulations provided by the Climate Services for Development (CSD) platform. Both datasets are spatially complete, quality-controlled, and free from missing values or data gaps. As such, standard preprocessing steps such as bias correction, gap filling, or quality control were not required.

The analytical steps followed in the study from temporal aggregation to trend analysis and climate scenario comparison are summarized in the flowchart below (Figure 2).



**Figure 2.** The main analytical steps followed in this study.



## 2.4. Data Quality Checking and Pre-Assessment

### 1. Outlier Detection

Outlier detection is crucial for ensuring the reliability of rainfall time series, especially since such data are often non-normally distributed. In this study, Tukey's fence method was employed for trimming outliers, as recommended for skewed climatological data [22]. This method uses the interquartile range (IQR) to identify extreme values. An observation is considered an outlier if it lies below  $Q1 - k \times IQR$  or above  $Q3 + k \times IQR$ , where  $k$  is a constant (commonly 1.5 or 3). This robust, non-parametric approach helps maintain data integrity and does not assume a specific distribution.

### 2. Homogeneity Test

Homogeneity testing is essential in climatology to detect changes in the data that may be due to non-climatic factors, such as changes in instrumentation, station relocation, or observational practices [23]. A homogeneous time series implies that the statistical properties of the data (e.g., mean, variance) remain consistent over time.

In this study, the Standard Normal Homogeneity Test (SNHT) and related methods based on adjusted partial cumulative deviations from the mean were considered, as outlined by [24]. The test statistic  $R/n$  (where  $R$  is the range of cumulative deviations and  $n$  is the sample size) was calculated to detect irregularities within dataset. According to the thresholds established in [24], for a sample size  $n = 30$ , the following statements apply:

A value of  $R/n > 1.5$  indicates irregularity at the 5% significance level.

A value of  $R/n > 1.4$  indicates irregularity at the 10% significance level.

### 3. Randomness and Temporal Independence

To assess the randomness and independence of the rainfall time series, the autocorrelation function (ACF) was applied, particularly focusing on lag-1 autocorrelation  $r_{1r1}$ , as described by [25]. Lag-1 autocorrelation measures the correlation between each observation and its immediate predecessor in the time series. It detects the following: persistence (positive autocorrelation)—when current values tend to be similar to previous values; and randomness (no autocorrelation)—when no significant relationship exists between successive values. Serial correlation at lag-1 was computed to assess whether the data show past events, which is important for selecting appropriate statistical models and interpreting long-term climate trends.

## 2.5. Analyzing and Characterizing the Historical and Future Climate of the Study Area

This section presents the analytical approaches used to evaluate the spatial and temporal variability of historical and future climate in the study area. Key climatic indicators such as rainfall distribution, anomalies, variability, dry spells, and growing season characteristics were assessed using recognized statistical and modeling techniques.

### Precipitation Concentration Index (PCI)

It was used to assess the monthly distribution of rainfall. It was computed using the `precintcon` package version 1.3.5 in RStudio version 2023.06.1+524, which allows for statistical analysis of rainfall characteristics. According to [26], PCI values are interpreted as follows:

- <10: Uniform rainfall distribution throughout the year;
- 11–20: Moderately seasonal rainfall concentration;
- >21: Strong rainfall concentration in a few months.

**Agronomic relevance:** PCI helps identify periods of rainfall concentration, which influence crop water availability, planting periods, and the risk of waterlogging or stress. High PCI values may indicate unreliable rainfall spread, reducing crop productivity and increasing drought risk during growth stages.

#### Rainfall Anomaly Index (RAI)

To identify wet and dry years and examine long-term rainfall trends, the Rainfall Anomaly Index (RAI) was calculated using the SPEI package version 1.7 in RStudio version 2023.06.1+524. The RAI is a simple yet effective index that captures deviations from the long-term average:

Positive RAI values indicate wetter-than-average years.

Negative RAI values indicate drier-than-average years.

Drought severity classification based on RAI is as follows: extreme RAI < −1.5; moderate:  $-1.5 \leq \text{RAI} < -1.0$ ; mild:  $-1.0 \leq \text{RAI} < 0$ ; and wet year: RAI > 1.0.

**Agronomic relevance:** RAI identifies abnormal rainfall years, helping assess historical drought and flood events. This supports strategic planning for crop selection, drought-resilient varieties, and agriculture investment.

#### Coefficient of Variation (CV)

Rainfall variability was assessed using the coefficient of variation (CV), a standardized measure of dispersion. It was calculated as follows [27]:

$$CV(\%) = \frac{\sigma}{\bar{X}} \times 100$$

where

$\sigma$  = standard deviation of annual rainfall;

$\bar{X}$  = mean annual rainfall.

**Agronomic relevance:** CV measures interannual rainfall variability, which affects the reliability of rain-fed agriculture. High CV values signal increased risk for planting failures and uncertain yields.

#### Onset and Cessation of Rainfall

The onset of the rainy season was defined as the first period with at least 20 mm of rainfall over three consecutive days, starting from 1 June for the Kiremt season (long rainy season) and 1 February for the Belg season (short rainy season), provided no rainfall longer than 7 consecutive days occurred in the subsequent 30 days.

Rainfall cessation was determined as the point when soil moisture fell to 10 mm per meter of soil, based on the water balance module in the INSTAT climate tool [28].

**Agronomic relevance:** Timely and consistent onset and cessation are crucial for deciding planting and harvesting periods. Variability in these parameters can cause delayed sowing, shorter growing periods, and yield reductions.

#### Length of Growing Period (LGP) and Number of Rainy Days

The Length of the Growing Period (LGP) was defined as the duration between the onset and cessation of rainfall, extended until an additional 100 mm of soil moisture is lost due to evapotranspiration, as per FAO guidelines [28].

**Agronomic relevance:** LGP determines the length of time crops have adequate moisture for growth. Shorter LGPs limit the types of crops that can be grown, while the number of rainy days affects the risk of intra-season dry spells.

#### Dry Spell Analysis

To assess dry spell risk during the growing season, a first-order Markov chain model was used in INSTAT+ to calculate the probability of experiencing dry spells lasting 5, 7,

10, and 15 consecutive days. This analysis is crucial for understanding the likelihood of moisture stress during critical crop growth stages, such as germination and flowering, especially in regions dependent on rain-fed system [29].

## 2.6. Analysis of Trends of Annual and Seasonal Rainfall and Temperature Parameters

To investigate the presence and magnitude of trends in rainfall and temperature data, two robust non-parametric methods were employed: the Mann–Kendall (MK) trend test and Sen’s slope estimator. These methods are widely used in hydrometeorological and climate studies due to their robustness to missing values, non-normal distributions, and outliers [30].

### 2.6.1. Mann–Kendall (MK) Trend Test

The Mann–Kendall test [31] is a rank-based, non-parametric statistical test used to identify monotonic trends in a time series. It has been extensively used in climatological and hydrological time series analysis. This analysis provides insight into climate variability and long-term changes crucial for agricultural planning, water resource management, and climate change adaptation in rain-fed systems [32].

The MK test statistic is given by

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

where

$N$  is the number of data points;

$x_j$  and  $x_i$  are sequential data values.

The sign function,  $\text{sgn}(x_j - x_i)$ , is defined as follows:

$$\text{sgn}(x_j - x_i) = \begin{cases} +1 & \text{if } (x_j - x_i) > 0 \\ 0 & \text{if } (x_j - x_i) = 0 \\ -1 & \text{if } (x_j - x_i) < 0 \end{cases}$$

If the dataset contains tied values, the variance of  $S$  is calculated as follows:

$$\text{var}(S) = \frac{1}{18} \left[ N(N-1)(2N+5) - \sum_{i=1}^M t_i(t_i-1)(2t_i+5) \right]$$

where

$t_i$  is the number of ties for the  $i^{\text{th}}$  value,

$m$  is the number of tied groups.

For  $N$  larger than 10,  $Z_{MK}$  approximates the standard normal distribution [33], computed as follows:

$$Z_{MK} = \begin{cases} \frac{S-1}{\sqrt{\text{var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{var}(S)}} & \text{if } S < 0 \end{cases}$$

A positive  $Z_{MK}$  suggests an increase trend, while a negative  $Z_{MK}$  indicates a decrease trend. The significance of the trend is tested at the 5% level using the critical  $Z$  value of  $\pm 1.96$  for a two-tailed test [30].

### 2.6.2. Sen’s Estimator of Slope

This method estimates the magnitude of an existing trend as the change per unit time (e.g., per year). Although it is robust to outliers and extreme values, in this study, the method was applied to datasets without missing values. The slope or magnitude of the



trend in rainfall and temperature was then calculated following the procedure described in [34].

$$Q_i = \frac{x_j - x_i}{j - i}, \text{ for all } j > i$$

If the number of observations  $N$  is odd, the Sen's slope  $Q$  is the median of the  $Q_i$  values. If  $N$  is even,  $Q$  is the average of the two central values:

$$Q = \begin{cases} \frac{Q_{N+1}}{2} & \text{if } N \text{ is odd number} \\ \frac{1}{2} \left( Q_{(\frac{N}{2})} + Q_{(\frac{N+2}{2})} \right) & \text{if } N \text{ is even number} \end{cases}$$

Sen's slope estimates the rate of change per year for rainfall and temperature variables. While the method is robust to outliers and missing values, in this study, it was applied to complete datasets with no missing values.

This test assumes a linear trend and quantifies changes per unit time. It was used to analyze trends in the following:

Annual, seasonal, and monthly rainfall totals;

Rainfall characteristics such as onset date, cessation date, Length of the Growing Period (LGP), number of rainy days, and length of dry spells.

Trend analysis followed the procedure described by [34], while additional methods related to rainfall characteristics were based on [35].

## 2.7. Future Climate Projection

Projected changes in rainfall and temperature for the 2050s and 2080s were analyzed using outputs from five general circulation models (GCMs) (Table 2). These models were selected from the Coupled Model Intercomparison Project Phase 6 (CMIP6) archive based on the following: (i) their evaluated performance in simulating historical climate conditions over East Africa; (ii) the availability of data under both SSP2-4.5 and SSP5-8.5 scenarios representing moderate- and high-emission pathways with radiative forcing of  $4.5 \text{ W/m}^2$  and  $8.5 \text{ W/m}^2$  by 2100, respectively; and (iii) their ability to capture a wide range of climate sensitivities [36,37].

Previous research has demonstrated that these models successfully simulate key regional climate dynamics, including the seasonal migration of the Inter-Tropical Convergence Zone (ITCZ) and variability influenced by ENSO and the Indian Ocean Dipole (IOD), which strongly affect rainfall patterns in the central Ethiopian highlands [38]. The use of multiple GCMs provides an ensemble approach that helps account for uncertainty in future projections [39].

Daily downscaled climate data for rainfall and temperature were obtained from the Copernicus Climate Data Store (CDS) and aggregated to monthly, seasonal, and annual timescales using INSTAT version 3.37. As the data were derived from high-resolution, quality-controlled CMIP6 outputs that are spatially complete and free of missing values, no additional bias correction was applied. The analysis focused on projected trends and relative changes (e.g., anomalies) rather than absolute values, in line with established practices in regional climate impact studies.

To evaluate projected climate changes relative to historical conditions, the observed data were used as a baseline. Projected changes in air temperature were calculated as absolute differences between future and baseline periods:

$$\Delta T = T_{mp} - T_{mb}$$

where  $\Delta T$  is the absolute change in temperature,  $T_{mp}$  is the projected temperature, and  $T_{mb}$  is the baseline temperature. Rainfall change was estimated using the relative percentage change as follows:

$$RF\% = \frac{(RFp - RFb)}{RFb} \times 100$$

where  $RF\%$  is the percentage change in rainfall,  $RFp$  is the projected rainfall, and  $RFb$  is the baseline rainfall [1].

**Table 2.** Description of the general circulation model simulations.

| Model        | Institution                                        | Country | Atmospheric Resolution (Latlon) | Reference |
|--------------|----------------------------------------------------|---------|---------------------------------|-----------|
| CanESM2      | Canadian Centre for Climate Modelling and Analysis | Canada  | $2.8^\circ \times 2.8^\circ$    | [40]      |
| EC Earth Veg | European research institutions                     | Europe  | $1.5^\circ \times 2^\circ$      | [41]      |
| HadGEM2      | Met Office Hadley Centre                           | UK      | $1.25^\circ \times 1.9^\circ$   | [40]      |
| IPSL-CM4     | Institute Pierre-Simon Laplace                     | France  | $1.9^\circ \times 3.75^\circ$   | [42]      |
| Awi_CM_1_1MR | Alfred Wegener institute                           | Germany | $1^\circ \times 1^\circ$        | [43]      |

Source: [2].

### 3. Results and Discussion

#### 3.1. Climate Trend and Variability Analysis Using Climatic Features

##### Trends of Seasonal and Annual Rainfall: Implications for Agricultural Resilience

The data on the annual and seasonal rainfall patterns in central Ethiopia from 1993 to 2023 for eight weather stations is summarized in Table 3. The analysis shows distinct spatial and temporal variability in rainfall trends, which have significant implications for agriculture. Bacho, Bishoftu, Kimbibit, and Metarobi have shown an increasing trend in rainfall during the short rainy season. This positive development is particularly beneficial for crop production in these areas. Increased moisture during this early part of the growing season supports land preparation, seed sowing and early crop development. The enhancement of these critical stages can lead to improved yields and reduced vulnerability to early-season drought stress. On the other hand, Debrelibanos, Holeta, Dodota, and Seden Sodo experienced decreasing rainfall during this season. This decline aligns with findings [44], highlighting the risks associated with reduced early-season moisture, such as delayed planting, poor germination, and increased risk of crop failure. For that matter, these regions may require targeted interventions, such as drought-tolerant crop varieties and improved soil moisture conservation practices.

During the main growing period in the area, understanding rainfall patterns is critical for agricultural success. A general increase in rainfall during this season was noted at most stations, with Kimbibit recording a particularly significant rise. Such trends can be agriculturally favorable by enhancing soil moisture, crop germination and growth, and more yields. This trend aligns with regional studies indicating increased precipitation during the main rainy season in parts of central Ethiopia [45]. However, excess rainfall during this season may also lead to flooding, erosion, and waterlogging. These issues may require drainage infrastructure, terracing, and erosion control measures. These findings underscore the dual nature of increased rainfall both as a benefit and a risk and point to the need for adaptive land and water management practices to sustainably manage rainfall variability during the growing season [46].

**Table 3.** Annual and seasonal Mann–Kendall test and Sen’s slope for rainfall in central Ethiopia (from 1993 to 2023).

| Period             | Statistics | Station |          |              |        |        |           |            |          |
|--------------------|------------|---------|----------|--------------|--------|--------|-----------|------------|----------|
|                    |            | Bacho   | Bishoftu | Debre-Ibanos | Dodota | Holeta | Kimb-Ibit | Seden-Sodo | Metarobi |
| Annual             | Zs         | 0.598   | 0.845    | −1.704       | 0.300  | 0.000  | 5.063     | −2.184     | 6.711    |
|                    | B          | 1.752   | 1.692    | −2.860       | 0.016  | 0.004  | 7.368     | −6.249     | 9.500    |
| Long rainy season  | Zs         | 0.396   | 0.8496   | 1.494        | 1.707  | 1.078  | 3.263     | −2.511     | 3.684    |
|                    | B          | 1.278   | 1.142    | 1.558        | 0.868  | 1.081  | 3.970     | −6.207     | 1.700    |
| Short rainy season | Zs         | 1.985   | 4.600    | −2.689       | −3.610 | −3.105 | 5.157     | −1.719     | 3.795    |
|                    | B          | 3.226   | 1.727    | −2.882       | −1.701 | −2.045 | 1.992     | −1.053     | 0.411    |
| Dry season         | Zs         | −1.101  | −0.092   | −4.758       | 2.300  | 3.202  | 2.011     | 1.612      | 2.694    |
|                    | B          | −0.131  | −0.0702  | −0.968       | 0.974  | 0.583  | 0.452     | 0.562      | 0.165    |

Note: Zs = Mann–Kendall test;  $\beta$  = Sen’s slope.

Annual rainfall trends provide a broader perspective on long-term climate variability. Positive annual trends are as follows: Kimbibi: +7.368 mm/year, and Metarobi: +9.500 mm/year. These increases suggest improved long-term water availability, which could support agricultural activity, groundwater recharge, and livestock watering. Similar findings have been reported in other parts of central Ethiopia, where rising rainfall trends have been linked to opportunities for agricultural intensification [45,46]. In contrast, Seden Sodo recorded a negative annual rainfall trend (−6.249 mm/year), raising concerns about water scarcity, reduced crop yields, and increased vulnerability to drought. This downward trend highlights the need for adaptation strategies, including rainwater harvesting, irrigation development, and drought-tolerant crop selection, to ensure long-term agricultural resilience.

The contrasting trends across stations underscore the importance of site-specific climate risk assessments and targeted interventions. Farmers will need to adapt their practices to capitalize on favorable conditions by refining planting schedules and selecting suitable crop varieties. Beyond describing climatic changes, the synthesized indices highlight increased risks to agricultural systems, including more frequent droughts, heightened heat stress on sensitive crops like wheat, and altered growing seasons. These risks emphasize the need for targeted adaptation strategies such as adopting drought-tolerant crops and improving water management to build resilience in rain-fed farming systems [10,47].

The observed rainfall trends reveal spatial disparities in seasonal water availability across central Ethiopia. Stations like Kimbibi and Metarobi, with increasing rainfall during both rainy seasons, may benefit from improved moisture conditions that support productivity and reduce climate risk. Conversely, declining trends in stations such as Seden Sodo and Dodota, especially during critical planting periods, present risks of delayed sowing, moisture stress, and yield reduction. These patterns highlight the need for localized adaptation such as drought-resilient crops, soil moisture conservation, and supplemental irrigation. While positive trends support intensification, negative trends call for enhanced risk management and sustainable land-use practices.

### 3.2. Rainfall Variability and Its Agricultural Implications

#### 3.2.1. Coefficient of Variation: Agricultural Resilience Implications

Between 1993 and 2023, central Ethiopia exhibited notable variations in seasonal and annual rainfall (Table 4). Mean annual rainfall ranged from 790.79 mm to 1196.80 mm, with annual CV values between 14.30% and 24.00%. The CV is a key indicator of rainfall reliability; lower values indicate stable conditions favorable for agriculture, while higher values reflect unpredictability and associated risks.

**Table 4.** Long-term mean annual rainfall variability across the studied station in central Ethiopia for the years 1993–2023.

| No | Station      | Annual  |        |        | Long Rainy Season |        |        | Short Rainy Season |       |        | Dry Season |       |        |
|----|--------------|---------|--------|--------|-------------------|--------|--------|--------------------|-------|--------|------------|-------|--------|
|    |              | Mean    | SD     | CV (%) | Mean              | SD     | CV (%) | Mean               | SD    | CV (%) | Mean       | SD    | CV (%) |
| 1  | Bacho        | 997.92  | 187.21 | 18.80  | 721.78            | 111.03 | 15.40  | 230.30             | 92.90 | 40.30  | 45.84      | 31.65 | 69.10  |
| 2  | Bishoftu     | 790.79  | 189.76 | 24.00  | 597.32            | 139.14 | 23.30  | 148.15             | 82.00 | 55.30  | 45.32      | 36.31 | 80.10  |
| 3  | Debrelibanos | 907.71  | 209.62 | 23.10  | 701.33            | 157.92 | 22.50  | 160.42             | 79.76 | 49.70  | 45.96      | 28.54 | 62.10  |
| 4  | Dodota       | 855.69  | 163.66 | 19.10  | 551.09            | 124.17 | 22.50  | 200.08             | 83.05 | 41.50  | 104.52     | 70.00 | 67.00  |
| 5  | Holeta       | 1196.80 | 170.60 | 14.30  | 909.28            | 127.20 | 14.00  | 221.96             | 84.03 | 37.90  | 65.58      | 1.58  | 63.40  |
| 6  | Kimibibit    | 984.44  | 225.68 | 22.90  | 802.34            | 200.96 | 25.00  | 140.82             | 57.60 | 40.90  | 41.27      | 34.73 | 84.10  |
| 7  | Sedensodo    | 1099.70 | 277.72 | 25.30  | 853.42            | 246.35 | 28.90  | 92.30              | 82.47 | 42.90  | 53.93      | 46.24 | 85.70  |
| 8  | Meta Robi    | 1084.70 | 210.20 | 19.40  | 821.92            | 230.74 | 28.10  | 197.77             | 81.55 | 41.23  | 55.01      | 40.71 | 74.00  |

The Kiremt (main rainy) season consistently showed the lowest CVs across all stations, confirming its reliability for agricultural activities. Holeta recorded the lowest seasonal variability (CV 14.30%), supporting stable planting conditions. In contrast, Seden Sodo experienced the highest annual (CV 25.30%) and seasonal (Kiremt CV 28.90%) variability, suggesting greater vulnerability to rainfall fluctuations.

During the short rainy (Belg) season, rainfall was not only lower but also more variable. Kimibibit, for example, recorded the lowest mean rainfall (140.82 mm) with a CV of 40.90%, while Bacho had the highest mean (230.3 mm) and similarly high variability (CV 40.30%). These findings align with earlier studies [48,49], confirming that Belg and Bega seasons are less dependable for agriculture due to higher variability.

Spatially, Bacho, Dodota, Meta Robi, and Holeta showed more stable annual rainfall (CVs below 19.4%), possibly due to topographic and climatic factors such as proximity to the ITCZ and elevation-induced microclimates. Stations with higher variability likely experience influence from irregular weather systems.

These patterns reinforce that the Kiremt season is the most agriculturally dependable, contributing substantially to annual rainfall often over 600 mm in major crop-growing areas like Benishangul, southern Amhara, and western Oromia [50]. Conversely, higher CVs during Belg and Bega seasons increase agricultural risk, requiring targeted strategies such as short-cycle, drought-resistant crops, soil conservation, and climate-smart practices.

Recent studies in regions like Dire Dawa confirm the effectiveness of such strategies, including early-maturing varieties, integrated fertility management, and improved water harvesting [51].

Low CVs (e.g., 14.3% at Holeta) during Kiremt suggest high planting reliability and reduced risk, while high Belg CVs (e.g., 40.9% at Kimibibit) indicate increased threats of sowing failure and yield loss. This findings underline the importance of resilient farming systems, crop diversification, drought-tolerant varieties, and moisture conservation to reduce vulnerability in rain-fed agriculture. Farmers' adaptive capacity will be central to sustaining productivity under variable climate conditions.

### 3.2.2. Precipitation Concentration Index Insights into Rainfall Distribution and Agricultural Resilience Implications

The Precipitation Concentration Index (PCI) assesses the distribution and intensity of rainfall throughout the year, offering important insights for agricultural planning. In central Ethiopia, PCI values from 1993 to 2023 reveal moderate to high rainfall concentration across all stations, with annual PCI values ranging from 15.920 to 27.004 (Table 5). According to PCI classification, values between 11 and 20 indicate moderate concentration, while those above 20 suggest highly uneven rainfall distribution.

**Table 5.** Descriptive statistics for mean rainfall concentration index in central Ethiopia (from 1993 to 2023).

| No | Station      | Annual | Long Rainy Season | Short Rainy Season | Dry Season |
|----|--------------|--------|-------------------|--------------------|------------|
| 1  | Bacho        | 27.004 | 28.301            | 38.754             | 54.189     |
| 2  | Bishoftu     | 19.242 | 29.604            | 45.772             | 61.841     |
| 3  | Debrelibanos | 21.176 | 32.672            | 37.883             | 58.437     |
| 4  | Dodota       | 15.920 | 29.070            | 43.082             | 56.467     |
| 5  | Holeta       | 18.219 | 28.500            | 38.265             | 56.630     |
| 6  | Kimibibit    | 23.836 | 35.626            | 38.003             | 58.167     |
| 7  | Sedensodo    | 18.720 | 28.360            | 40.536             | 64.195     |
| 8  | Meta Robi    | 18.784 | 28.605            | 61.890             | 42.944     |

Dodota recorded the lowest annual PCI (15.920), indicating relatively uniform rainfall, which is favorable for reducing prolonged dry spells and improving cropping reliability. In contrast, Kimibibit, Debrelibanos, and Bacho recorded high PCI values (>21.176), reflecting rainfall concentrated over short periods. Such concentration raises the risk of hydrological extremes like flooding, waterlogging, and erosion, especially when heavy rainfall is not evenly distributed across the growing season, potentially disrupting crop establishment and degrading soil quality.

During the main rainy season (Kiremt), PCI ranged from 28.301 to 35.626, revealing uneven rainfall distribution even within the primary cropping period. These conditions can lead to temporary water surpluses that exceed soil infiltration capacity, especially in areas lacking proper drainage.

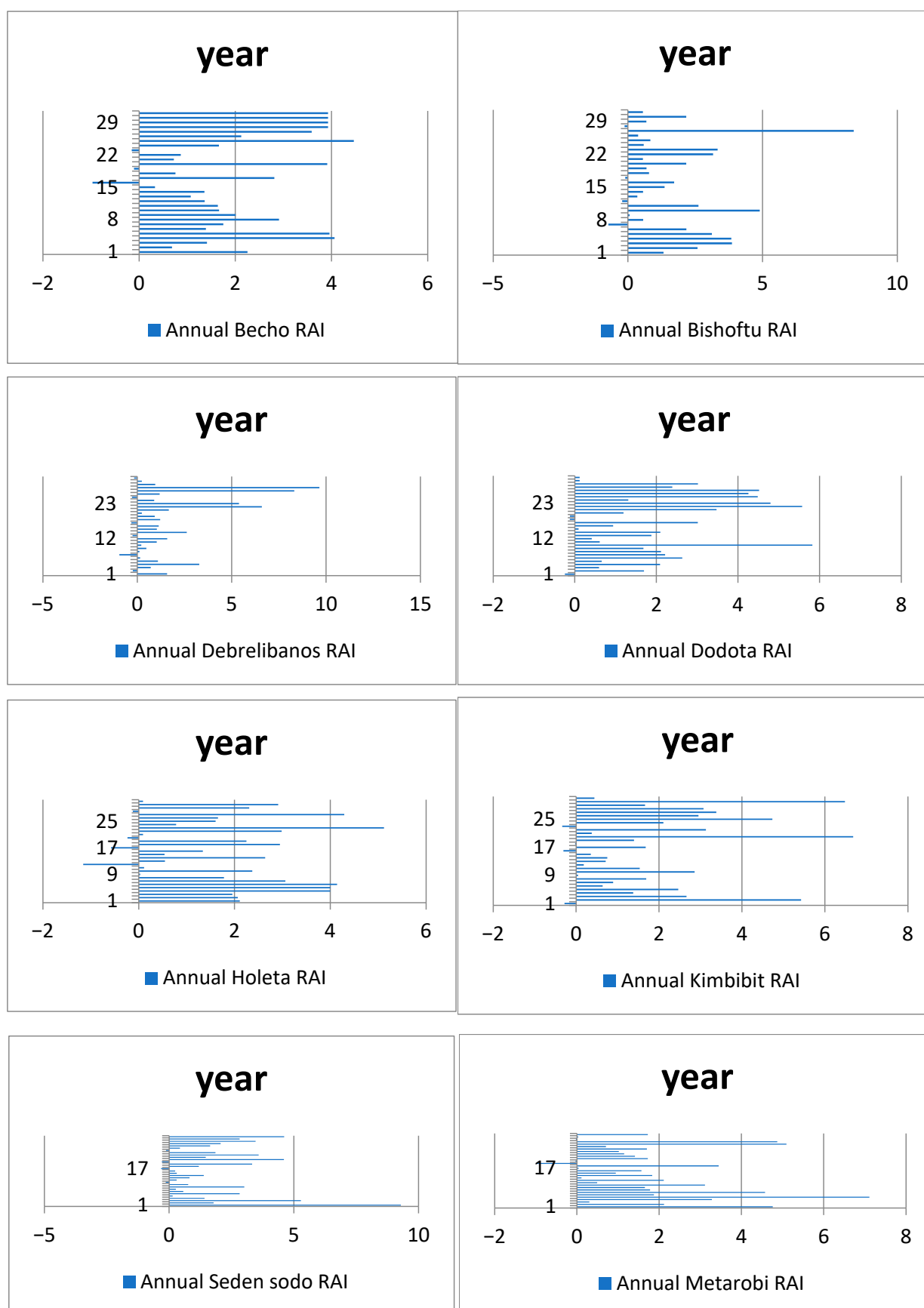
Even more extreme are PCI values during the short rainy (Belg) and dry (Bega) seasons, ranging from 37.883 to 61.890 and 42.944 to 64.195, respectively. This irregularity undermines effective moisture retention, increases surface runoff, and reduces the reliability of these seasons for agricultural production. As such, water harvesting, soil conservation, and preparedness for dry spells are particularly vital during these periods.

These results align with previous studies [52], that associate high PCI in Ethiopia's highlands with increased risks of erosion, runoff, and flooding threats that negatively affect agricultural productivity and food security. High PCI values, especially those above 21, indicate rainfall is concentrated in short bursts, leading to intra-seasonal dry spells and inefficient water use during key crop stages such as germination and flowering.

To enhance agricultural resilience in areas with high rainfall concentration, targeted adaptation measures are essential. These include mulching, soil bunds, water harvesting systems, resilient crop varieties, and early-warning systems for extreme events. Without such strategies, concentrated rainfall patterns will continue to challenge yield stability and sustainable rain-fed agriculture in central Ethiopia.

### 3.2.3. Rainfall Anomaly Index (RAI): Interannual Rainfall Variability and Agricultural Implications

The Rainfall Anomaly Index (RAI) offers insight into interannual rainfall variability by measuring deviations from the long-term mean. From 1993 to 2023, RAI data (Figure 3) reveal marked year-to-year fluctuations in central Ethiopia, reflecting alternating periods of wet years and mild droughts.



**Figure 3.** Annual Rainfall Anomaly Indexes of the study stations in central Ethiopia for the period (1993–2023).



Debrelibanos recorded the highest positive RAI value (9.65), indicating years of excessive rainfall that may cause flooding, runoff, and waterlogging, particularly harmful during critical crop growth stages. Conversely, several stations experienced negative RAI years, suggesting mild drought: Bacho (2008,  $-0.97$ ), Bishoftu (1999,  $-0.72$ ), Debrelibanos (1999,  $-0.95$ ), Dodota (1993,  $-0.24$ ), Seden Sodo (2009,  $-0.32$ ), Metarobi (2011,  $-0.98$ ), and Kimbibit (2015,  $-0.33$ ).

While these droughts are classified as mild, their agricultural impact remains significant especially during planting, germination, or flowering phases. Even short-term rainfall deficits can disrupt farming calendars, reduce yields, and threaten food security.

A concerning pattern since mid-2006 is the increased frequency of negative anomalies, particularly at Bacho, suggesting a possible shift in rainfall dynamics consistent with regional climate change projections. RAI classification [53] confirms a mix of wet and dry years, reflecting high rainfall unpredictability and increased risk for rain-fed farming systems.

To address these challenges, resilience-building strategies are essential. These include flexible planting calendars, drought-tolerant crop varieties, improved seasonal forecasting, early-warning systems, and small-scale irrigation and rainwater harvesting.

#### Agricultural Resilience Implications

The growing frequency of negative RAI values, especially over the past decade, signals rising exposure to rainfall deficits, undermining planting reliability and yield stability. To enhance resilience, farmers must adopt climate-smart practices such as drought-resilient crops, dynamic planting schedules, and climate information services. Strengthening these adaptive capacities is vital for managing interannual variability and sustaining productivity in rain-fed agriculture.

#### 3.3. Onset, Cessation, and Duration of the Growing Season: Implications for Crop Planning and Food Security

Understanding onset and cessation timing is vital for crop planning in central Ethiopia's rain-fed systems. Table 6 shows substantial spatial variability in growing season characteristics from 1993 to 2023.

**Table 6.** Trends and descriptive statistics of rainfall characteristics of the study areas for the study period (1993–2023).

| No | Station     | Onset |     |      |        |      | Endset |     |      |        |     | LGp |     |      |        |      |
|----|-------------|-------|-----|------|--------|------|--------|-----|------|--------|-----|-----|-----|------|--------|------|
|    |             | Max   | Min | Mean | Median | CV   | Max    | Min | Mean | Median | CV  | Max | Min | Mean | Median | CV   |
| 1  | Bacho       | 182   | 153 | 165  | 169    | 0.8  | 299    | 275 | 287  | 281    | 2.8 | 143 | 95  | 119  | 112    | 11.7 |
| 2  | Bishoftu    | 207   | 109 | 165  | 169    | 16.1 | 302    | 275 | 286  | 278    | 3.1 | 192 | 72  | 116  | 109    | 25.3 |
| 3  | Debrelibano | 203   | 158 | 178  | 179    | 5.5  | 301    | 275 | 283  | 282    | 2.8 | 136 | 72  | 105  | 103    | 12.8 |
| 4  | Dodota      | 207   | 153 | 178  | 179    | 8.0  | 315    | 276 | 278  | 276    | 3.0 | 136 | 69  | 99   | 97     | 17.3 |
| 5  | Holeta      | 183   | 153 | 165  | 165    | 5.7  | 279    | 276 | 276  | 276    | 0.2 | 125 | 93  | 110  | 111    | 8.6  |
| 6  | Kimibibit   | 201   | 153 | 177  | 177    | 6.0  | 310    | 275 | 284  | 282    | 3.3 | 145 | 84  | 107  | 105    | 14.6 |
| 7  | Sedensodo   | 187   | 153 | 162  | 161    | 6.0  | 286    | 276 | 276  | 276    | 0.7 | 124 | 89  | 113  | 115    | 8.8  |
| 8  | Meta Robi   | 201   | 153 | 172  | 172    | 7.8  | 310    | 275 | 293  | 294    | 3.0 | 154 | 85  | 120  | 122    | 13.1 |

The earliest median onset was recorded at Seden Sodo (DOY 161, 10 June) and the latest at Debrelibanos and Dodota (DOY 179, 28 June). While this 18-day range seems small, it significantly affects crop timing, especially for sensitive crops like wheat and teff. Early onset extends the growing period, while delayed onset increases the risk of crops not maturing before the rainy season ends.

Onset variability also differed among sites. Bacho had the most stable onset timing ( $CV = 0.8\%$ ), whereas Bishoftu showed the highest variability ( $CV = 16.1\%$ ), complicating planting decisions. Such instability can lead to reduced yields or require changes in cropping calendars, consistent with findings from the Central Rift Valley [54].

Cessation timing varied less. The latest was at Metarobi (DOY 294, 21 October), and the earliest at Holeta and Seden Sodo (DOY 276, 2 October). Duration is influenced by both onset and cessation; delayed cessation benefits late-maturing crops but may increase risks such as pest pressure and post-harvest moisture problems.

Notably, cessation dates were more consistent across stations (low CVs), offering a more reliable reference point for harvest planning. This aligns with previous findings [55] that reported stable season ends in the central highlands.

#### Agricultural Resilience Implications

High onset variability especially at Bishoftu reduces planting predictability and heightens exposure to early-season drought, leading to poor germination, yield loss, or crop failure. In contrast, the stable cessation timing supports harvest planning and risk reduction. Building resilience under these conditions requires flexible planting strategies, adoption of short-maturing or drought-resilient crops, real-time weather updates, and localized advisories. These tools help farmers adapt to shifting seasonal dynamics and improve food security in a changing climate.

#### *3.4. Length of Growing Period and Number of Rainy Days: Indicators of Agricultural Stability and Suitability*

The Length of Growing Period (LGP) is a key factor in the viability of rain-fed agriculture. Data from 1993 to 2023 (Table 6) show a clear link between early rainfall onset and extended growing seasons in central Ethiopia. Earlier rainfall typically results in longer growing periods, supporting findings from recent agro-climatic studies [53,56].

LGP ranged from 97 days at Dodota to 122 days at Metarobi. Most stations exceeded the 90-day threshold considered suitable for staple crops like wheat, teff, and barley [57]. Metarobi (122 days) and Seden Sodo (115 days) offered the longest durations, enhancing crop flexibility. Even the shortest growing season Dodota's 97 days met the minimum requirements for rain-fed agriculture.

Seasonal consistency was notable, with low coefficients of variation: 8.6% at Holeta, 8.8% at Seden Sodo, and under 13% at Bacho and Debrelibanos. This low variability enhances predictability and reliability for crop planning.

The number of rainy days per year further supports agricultural stability. Across all stations, annual rainy days ranged from 97 to 157, with CVs under 19.5% (Table 7). Holeta had the highest number of rainy days (157) and lowest variability ( $CV\ 9.4\%$ ), indicating highly stable moisture conditions. Bacho (121 days) and Seden Sodo (139 days) also showed favorable moisture reliability. Although Bishoftu and Dodota recorded the fewest rainy days (97), their totals still meet crop water needs.

These indicators of sufficient LGP and stable rainy-day frequency suggest central Ethiopia possesses a favorable agro-climatic profile for rain-fed farming. Low interannual variability supports reliable planting schedules and reduces risk from climate extremes, in line with prior studies in the Ethiopian highlands [53,56].

To further enhance resilience, especially in zones with shorter or more variable seasons, support is needed for early-maturing and climate-resilient crop varieties, improved forecasting, soil and water conservation, and localized planting calendars.

**Table 7.** Descriptive statistics of the number of rainy days for study stations in central Ethiopia (from 1993 to 2023).

| No | Station      | Annual NRD Statistics |     |      |        |       |
|----|--------------|-----------------------|-----|------|--------|-------|
|    |              | Min                   | Max | Mean | SD     | CV    |
| 1  | Bacho        | 93                    | 148 | 122  | 15.152 | 12.5% |
| 2  | Bishoftu     | 67                    | 140 | 97   | 18.916 | 19.5% |
| 3  | Debrelibanos | 70                    | 161 | 114  | 19.541 | 17.1% |
| 4  | Dodota       | 67                    | 136 | 97   | 16.104 | 16.6% |
| 5  | Holeta       | 134                   | 184 | 157  | 14.843 | 9.4%  |
| 6  | Kimibibit    | 68                    | 140 | 108  | 14.911 | 13.8% |
| 7  | Sedensodo    | 98                    | 167 | 139  | 16.197 | 11.7% |
| 8  | Meta Robi    | 98                    | 167 | 110  | 18.924 | 17.2% |

Note: NRD = Number of rainy days.

### Agricultural Resilience Perspective

Stable growing seasons and consistent rainy days enable timely sowing and harvesting, reduce exposure to dry spells, and improve crop–climate alignment. Stations like Holeta and Seden Sodo with low rainfall variability offer strong resilience potential. Even more variable areas like Bishoftu maintain an LGP above 90 days, meeting basic crop needs. These indicators can guide early-warning systems, adaptive planting strategies, and targeted support, enhancing resilience in central Ethiopia’s rain-fed agriculture.

### 3.5. Dry Spell Length and Implication for Agriculture

In rain-fed agricultural systems like central Ethiopia’s, dry spells pose a major constraint, especially during key crop growth stages. Regions such as Bacho, Bishoftu, and Dodota are particularly vulnerable due to limited irrigation. Climate-induced dry spells and droughts remain a growing threat, particularly in areas without water infrastructure [58].

Dry spell probabilities (1993–2023) were analyzed for durations of 5, 7, 10, and 15 consecutive dry days (Figure 4). Results show that during the peak rainy season, the risk of extended dry periods drops sharply. The probability of 10- and 15-day dry spells falls below 1% after

- DOY 155 (4 June) at Dodota;
- DOY 160 (9 June) at Seden Sodo;
- DOY 180 (29 June) at Bishoftu.

Similarly, the seven-day dry spell probability drops below 1% after

- DOY 160 at Debrelibanos;
- DOY 180 at Bishoftu.

Five-day dry spells remain under 2% throughout the rainy season at all stations. These findings indicate that, from early to mid-June onward, rainfall becomes regular enough to minimize mid-season moisture stress during critical crop stages like germination and grain filling [59]. This seasonal stability, influenced by the Inter-Tropical Convergence Zone (ITCZ), supports consistent soil moisture and strengthens agricultural resilience compared to regions with erratic rainfall [60].

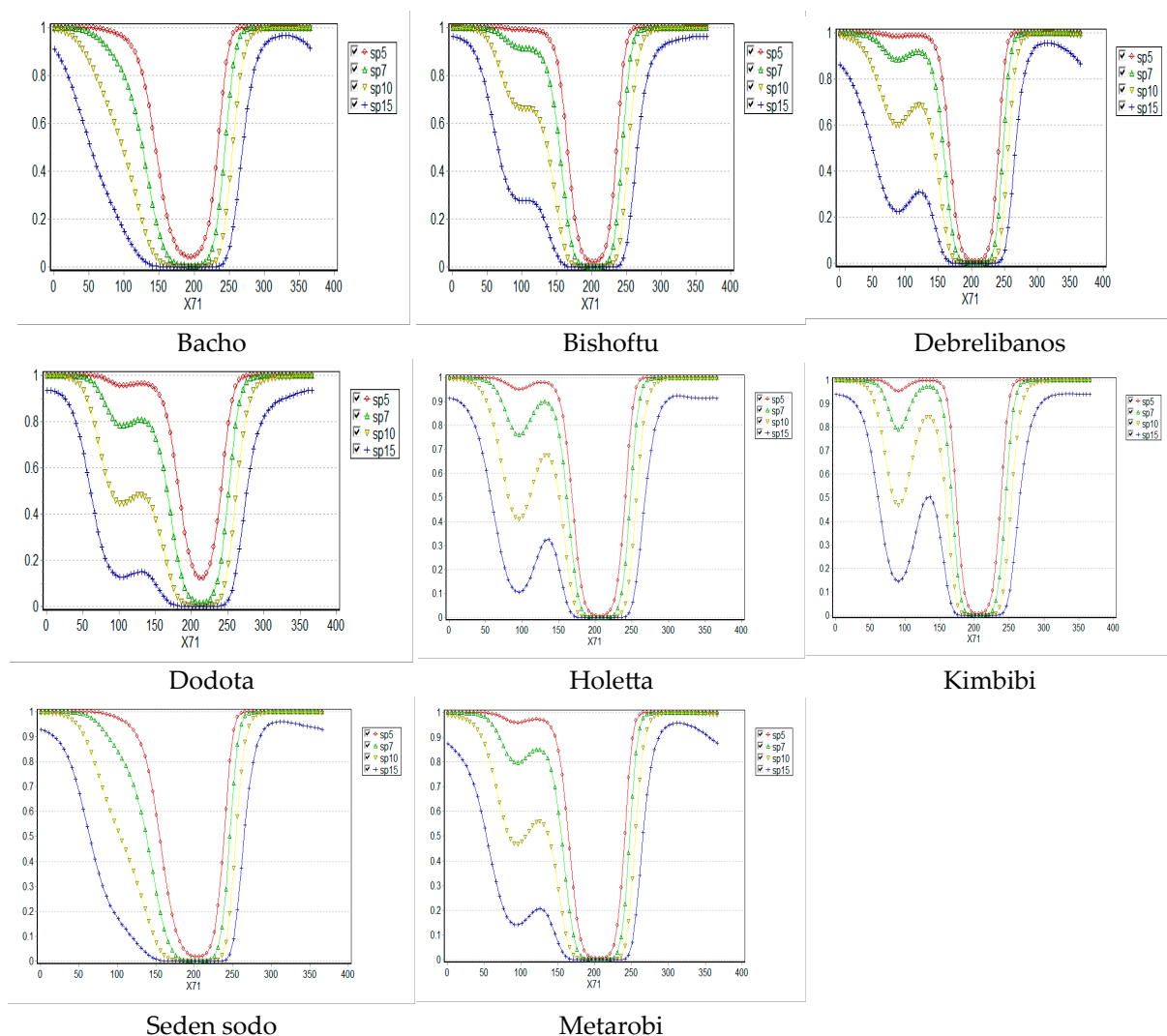
However, emerging climate variability especially in onset and cessation timing poses new risks. Changes in rainfall patterns and increasing temperature extremes may disrupt planting cycles and reduce moisture availability [47,61]. This underlines the need for continued climate monitoring [8].

## Agricultural Resilience Implications

The low probability of prolonged dry spells once the rainy season is established presents a major resilience advantage. To build on this, key strategies include the following:

- Promoting drought-tolerant and early-maturing crop varieties;
- Expanding rainwater harvesting and moisture conservation (e.g., mulching, minimum tillage);
- Strengthening local climate advisories and early-warning systems;
- Aligning planting dates with reliable rainfall onset periods [62].

In conclusion, central Ethiopia's climate currently supports favorable conditions for rain-fed cereal production. Sustaining and enhancing this resilience will require proactive adaptation to future climate variability.



**Figure 4.** Probability of dry spells longer than 5, 7, 10, and 15 days during the Kiremt growing season in central Ethiopia (from 1993 to 2023). Notes: x71 = DOY (days of the year).

### 3.6. Past Minimum and Maximum Temperature Trends

#### 3.6.1. Trends in Maximum Temperature and Agricultural Implications

Analysis of temperature trends from 1993 to 2023 across eight meteorological stations in central Ethiopia reveals a consistent increase in maximum temperature (Tmax), with statistically significant warming observed at most sites (Tables 8 and 9). This warming is

particularly pronounced during the short rainy (Belg) and dry (Bega) seasons, which are naturally warmer and drier.

**Table 8.** Descriptive statistics and Mann–Kendall trend test results for annual and seasonal maximum temperature (°C) (from 1993 to 2023) in central Ethiopia.

| Station      | Temperature        | Min (°C) | Max (°C) | Mean (°C) | SD   | CV (%) | Zs     | B      |
|--------------|--------------------|----------|----------|-----------|------|--------|--------|--------|
| Bacho        | Annual             | 24.88    | 28.80    | 27.52     | 0.85 | 3.1%   | 6.305  | 0.058  |
|              | Long rainy season  | 23.45    | 27.60    | 26.03     | 0.89 | 3.4%   | 4.803  | 0.036  |
|              | Short rainy season | 26.073   | 30.83    | 29.29     | 1.06 | 3.6%   | 8.301  | 0.077  |
|              | Dry season         | 25.133   | 28.57    | 27.28     | 0.97 | 3.6%   | 5.563  | 0.070  |
| Bishoftu     | Annual             | 26.11    | 29.00    | 27.19     | 0.74 | 2.7%   | 5.292  | 0.045  |
|              | Long rainy season  | 24.48    | 27.14    | 25.75     | 0.74 | 2.9%   | 4.393  | 0.0358 |
|              | Short rainy season | 25.00    | 30.15    | 28.68     | 1.00 | 3.5%   | 3.479  | 0.028  |
|              | Dry season         | 25.00    | 28.59    | 26.80     | 0.99 | 3.7%   | 6.481  | 0.056  |
| Debrelibanos | Annual             | 20.90    | 28.00    | 22.40     | 1.30 | 5.9%   | 6.422  | 0.081  |
|              | Long rainy season  | 19.80    | 28.00    | 21.52     | 1.60 | 7.5%   | 6.010  | 0.103  |
|              | Short rainy season | 22.00    | 29.00    | 24.00     | 1.30 | 5.5%   | 5.843  | 0.087  |
|              | Dry season         | 20.11    | 26.00    | 21.71     | 1.11 | 5.1%   | 5.286  | 0.046  |
| Dodota       | Annual             | 22.12    | 29.16    | 27.40     | 1.31 | 4.8%   | 2.299  | 0.031  |
|              | Long rainy season  | 21.24    | 29.55    | 27.24     | 1.51 | 5.5%   | 5.865  | 0.054  |
|              | Short rainy season | 21.79    | 30.50    | 28.36     | 1.72 | 6.1%   | 1.020  | 0.026  |
|              | Dry season         | 24.63    | 27.93    | 26.60     | 0.87 | 3.3%   | −1.677 | −0.014 |
| Holetta      | Annual             | 22.13    | 25.73    | 23.78     | 0.86 | 3.6%   | 9.802  | 0.069  |
|              | Long rainy season  | 19.93    | 24.81    | 21.86     | 1.06 | 4.9%   | 12.142 | 0.094  |
|              | Short rainy season | 23.60    | 27.89    | 25.51     | 1.00 | 4.0%   | 10.845 | 0.085  |
|              | Dry season         | 22.68    | 25.92    | 23.97     | 0.86 | 3.6%   | 6.594  | 0.045  |
| Kimbibit     | Annual             | 18.78    | 20.82    | 19.85     | 0.56 | 2.8%   | 5.036  | 0.029  |
|              | Long rainy season  | 18.12    | 20.75    | 19.34     | 0.65 | 3.4%   | 7.010  | 0.043  |
|              | Short rainy season | 19.42    | 22.43    | 20.91     | 0.75 | 3.6%   | 3.355  | 0.020  |
|              | Dry season         | 18.22    | 20.74    | 19.33     | 0.69 | 3.6%   | 2.655  | 0.023  |
| Seden sodo   | Annual             | 21.23    | 27.43    | 24.98     | 1.60 | 6.4%   | 2.834  | 0.042  |
|              | Long rainy season  | 20.80    | 27.81    | 24.08     | 1.51 | 6.3%   | 4.642  | 0.0452 |
|              | Short rainy season | 21.62    | 28.23    | 26.42     | 2.00 | 7.5%   | 2.650  | 0.062  |
|              | Dry season         | 20.59    | 27.44    | 24.46     | 1.57 | 6.4%   | 1.276  | 0.032  |
| Metarobi     | Annual             | 22.83    | 27.62    | 25.37     | 1.16 | 4.6%   | 3.720  | 0.073  |
|              | Long rainy season  | 20.73    | 25.89    | 23.42     | 1.29 | 5.5%   | 4.676  | 0.083  |
|              | Short rainy season | 24.43    | 30.58    | 27.24     | 1.37 | 5.0%   | 4.071  | 0.082  |
|              | Dry season         | 23.35    | 27.54    | 25.51     | 1.06 | 4.2%   | 3.633  | 0.052  |

Note: Zs = Mann–Kendall test;  $\beta$  = Sen's slope.

The Mann–Kendall test and Sen's slope estimator show strong positive trends; for example, Bacho experiences an annual Tmax increase with Zs = 6.305 and  $\beta$  = 0.058 °C/year, while Holetta shows even faster warming during the long rainy season (Zs = 12.142,  $\beta$  = 0.094 °C/year). Higher interannual variability (up to 7.5% CV) at stations like Debrelibanos and Seden Sodo adds uncertainty to seasonal conditions, complicating crop management.

The short rainy season records the highest Tmax values, 29.29 °C at Bacho and 27.24 °C at Metarobi, posing risks for seedling survival due to increased evapotranspiration and soil moisture loss in rain-fed systems. Conversely, the long rainy season (Kiremt) sees lower Tmax averages, benefiting critical stages like flowering and grain filling through cooler, more humid conditions.

Spatial differences in Tmax trends reflect influences from elevation, land use, and microclimates. Though this study does not capture heatwave frequency, rising Tmax extremes and concurrent increases in minimum temperature (Tmin) threaten crop productivity by disrupting phenology, increasing plant stress, and altering soil moisture and nutrient dynamics [9,63].

To mitigate these impacts, adaptive measures such as adjusting planting dates, introducing heat-tolerant crop varieties, and employing moisture-conserving practices (e.g., mulching, conservation tillage) are essential to sustain agricultural productivity under warming conditions.

### 3.6.2. Trends in Minimum Temperature and Agricultural Implications

Minimum temperature (Tmin) trends across central Ethiopia from 1993 to 2023 show a gradual warming with notable spatial and seasonal variability. Significant increases are particularly evident during the long rainy season (Kiremt) at stations such as Seden Sodo and Metarobi (Table 9). Rising night-time temperatures can accelerate plant respiration, reduce net photosynthesis, and lower yield potential, especially for cereal crops. In contrast, cooler Tmin values persist during the dry season in highland areas like Kimbabit, reflecting elevation-driven microclimates amid overall warming.

Tmin variability, measured by the coefficient of variation (CV), tends to be higher than that of Tmax, indicating greater volatility. For example, Holeta shows a high CV (22.9%) during the dry season, suggesting unpredictable night-time cooling that may disrupt off-season planting. Meanwhile, Seden Sodo and Metarobi exhibit more stable Tmin patterns, providing a more predictable environment for crop development. These observations align with previous research in western Amhara, where Tmin showed greater sensitivity to climatic fluctuations.

Statistical analysis via the Mann–Kendall test and Sen’s slope estimator reveals distinct Tmin trends: Debrelibanos experiences a strong positive trend during the long rainy season ( $Z_s = 10.370$ ), indicating warmer nights during critical crop growth stages. Conversely, stations like Bishoftu ( $\beta = -0.073$  °C/year) and Seden Sodo ( $\beta = -0.016$  °C/year) show slight cooling trends, though these changes are currently minor in agricultural terms. Holeta’s positive Tmin trend ( $\beta = 0.055$  °C/year) may reduce the duration of cool periods necessary for vernalization in crops such as wheat and barley.

Agriculturally, increased Tmin during the growing season, particularly in Dodota and Bishoftu, may disrupt flowering and fruiting in temperature-sensitive crops, raise respiration losses, and shorten the growing period of cool-weather crops. However, warmer Tmin combined with reduced frost risk in highland areas like Kimbabit and Holeta could extend cropping windows and permit cultivation of warm-season varieties previously unsuitable for these areas. The concurrent rise in Tmin and Tmax may also increase evapotranspiration, elevating crop water demand and plant stress in rain-fed systems unless compensated by stable rainfall or irrigation [47,59].

In summary, Tmin trends exhibit complex, site-specific warming patterns with important implications for crop physiology, pest and disease pressures, and water management. Strengthening agricultural resilience in central Ethiopia requires integrated climate adaptation approaches, including adoption of heat-tolerant and short-maturing varieties, enhanced water conservation (e.g., mulching, drip irrigation), adjusted planting calendars aligned with shifting temperature regimes, and improved agro-climatic zoning to optimize crop selection.

If these warming trends persist, managing the combined impacts of rising daytime and night-time temperatures will be critical for sustaining agricultural productivity, necessitating innovation, policy support, and farmer-centered adaptation.



**Table 9.** Descriptive statistics and Mann–Kendall test results for annual and seasonal minimum temperature (°C) (from 1993 to 2023) in central Ethiopia.

| Station      | Temperature        | Min (°C) | Max (°C) | Mean (°C) | SD   | CV (%) | Zs     | B      |
|--------------|--------------------|----------|----------|-----------|------|--------|--------|--------|
| Bacho        | Annual             | 7.39     | 10.53    | 9.28      | 0.78 | 8.4%   | 3.990  | 0.043  |
|              | Long rainy season  | 8.17     | 12.52    | 11.36     | 0.91 | 8.0%   | 5.533  | 0.062  |
|              | Short rainy season | 8.24     | 12.43    | 9.72      | 1.00 | 10.3%  | 2.325  | 0.023  |
|              | Dry season         | 3.80     | 9.54     | 6.76      | 1.18 | 17.4%  | 2.788  | 0.043  |
| Bishoftu     | Annual             | 9.42     | 13.09    | 11.33     | 1.00 | 8.9%   | −6.610 | −0.073 |
|              | Long rainy season  | 12.00    | 14.00    | 13.06     | 0.51 | 3.9%   | −4.687 | −0.024 |
|              | Short rainy season | 9.23     | 14.59    | 12.03     | 1.28 | 10.6%  | −6.893 | −0.083 |
|              | Dry season         | 6.22     | 11.93    | 8.87      | 1.54 | 17.00% | −6.708 | −0.107 |
| Debrelibanos | Annual             | 8.06     | 10.14    | 9.11      | 0.50 | 5.1%   | 5.52   | 0.017  |
|              | Long rainy season  | 9.45     | 11.46    | 10.40     | 0.56 | 5.4%   | 10.370 | 0.046  |
|              | Short rainy season | 8.10     | 11.10    | 9.79      | 0.73 | 7.4%   | −0.498 | −0.003 |
|              | Dry season         | 5.90     | 8.20     | 7.10      | 0.60 | 8.4%   | 1.768  | 0.015  |
| Dodota       | Annual             | 10.90    | 15.30    | 12.71     | 0.94 | 7.4%   | −0.362 | −0.001 |
|              | Long rainy season  | 11.79    | 15.75    | 14.00     | 0.97 | 6.9%   | 0.690  | 0.005  |
|              | Short rainy season | 10.76    | 15.70    | 13.24     | 1.25 | 9.5%   | −1.486 | −0.010 |
|              | Dry season         | 8.70     | 15.28    | 10.88     | 1.58 | 14.5%  | 0.000  | −0.001 |
| Holetta      | Annual             | 6.55     | 11.35    | 8.34      | 0.99 | 11.9%  | 3.744  | 0.033  |
|              | Long rainy season  | 6.00     | 10.45    | 9.17      | 0.93 | 10.1%  | 5.968  | 0.055  |
|              | Short rainy season | 5.00     | 12.50    | 8.88      | 1.47 | 16.5%  | 3.170  | 0.039  |
|              | Dry season         | 4.30     | 11.62    | 6.75      | 1.54 | 22.9%  | 3.298  | 0.032  |
| Kimbibit     | Annual             | 6.06     | 9.06     | 7.60      | 0.53 | 7.0%   | 5.161  | 0.027  |
|              | Long rainy season  | 6.50     | 9.80     | 8.20      | 0.64 | 7.8%   | 6.774  | 0.043  |
|              | Short rainy season | 4.45     | 9.54     | 8.12      | 0.90 | 11.1%  | 5.317  | 0.038  |
|              | Dry season         | 5.11     | 9.00     | 6.35      | 0.72 | 11.4%  | −0.530 | −0.006 |
| Seden sodo   | Annual             | 8.70     | 11.95    | 9.97      | 0.69 | 6.9%   | −2.600 | −0.016 |
|              | Long rainy season  | 9.18     | 12.42    | 10.81     | 0.74 | 6.8%   | 0.757  | 0.002  |
|              | Short rainy season | 8.85     | 11.92    | 10.49     | 0.79 | 7.5%   | −1.140 | −0.013 |
|              | Dry season         | 5.32     | 12.24    | 8.61      | 1.47 | 17.1%  | −3.420 | −0.050 |
| Metarobi     | Annual             | 7.31     | 11.60    | 10.10     | 0.83 | 8.2%   | 2.078  | 0.023  |
|              | Long rainy season  | 7.67     | 11.80    | 10.82     | 0.89 | 8.2%   | 2.287  | 0.026  |
|              | Short rainy season | 8.29     | 12.12    | 10.95     | 0.97 | 8.8%   | 2.604  | 0.025  |
|              | Dry season         | 5.98     | 12.04    | 8.37      | 1.12 | 13.4%  | 2.230  | 0.013  |

Note: Zs = Mann–Kendall test;  $\beta$  = Sen's slope.

### 3.7. Assessing Future Climate Change by Analyzing Projected Rainfall and Temperature Trends

#### 3.7.1. Projected Rainfall Changes and Agricultural Implications in Central Ethiopia

Table 10 presents projected rainfall changes across central Ethiopia based on outputs from five global climate models (GCMs) under two Shared Socioeconomic Pathways (SSPs): SSP4.5 (medium emissions) and SSP8.5 (high emissions). These projections cover the mid-century (2050s) and end of century (2080s), compared to the baseline period of 1993–2023.

**Table 10.** Changes in mean annual and seasonal rainfall under SSP4.5 and SSP8.5 by 2050s and 2080s from the baseline period.

| Station           | Parameters         | Scenarios         |        |            |        |            |
|-------------------|--------------------|-------------------|--------|------------|--------|------------|
|                   |                    | Baseline          | Ssp4.5 | Change (%) | Ssp8.5 | Change (%) |
|                   |                    | 2050 Rainfall(mm) |        |            |        |            |
| Bacho             | Annual             | 997.9             | 1028.9 | 3.1        | 1037   | 3.9        |
|                   | Long Rainy Season  | 721.8             | 757.4  | 4.9        | 763.2  | 5.7        |
|                   | Short Rainy Season | 230.3             | 255    | 10.7       | 266    | 15.5       |
| Bishoftu          | Annual             | 790.8             | 823    | 4.1        | 840    | 6.2        |
|                   | Long Rainy Season  | 597.3             | 615    | 2.9        | 617.8  | 3.4        |
|                   | Short Rainy Season | 148.2             | 170    | 14.7       | 181.1  | 22.2       |
| Debrelibanos      | Annual             | 907.7             | 943.1  | 3.9        | 967.5  | 6.6        |
|                   | Long Rainy Season  | 701.3             | 760    | 8.4        | 792.7  | 13.0       |
|                   | Short Rainy Season | 160.4             | 170.7  | 6.4        | 183    | 14.1       |
| Dodota            | Annual             | 855.7             | 850    | −0.6       | 851.2  | −0.5       |
|                   | Long Rainy Season  | 551.1             | 549.1  | −0.3       | 550    | −0.2       |
|                   | Short Rainy Season | 200.1             | 198    | −1.0       | 199    | −0.5       |
| Holeta            | Annual             | 1196.8            | 1233.1 | 3.0        | 1245.9 | 4.1        |
|                   | Long Rainy Season  | 909.28            | 1115   | 22.3       | 1211   | 33.2       |
|                   | Short Rainy Season | 222               | 229.2  | 3.2        | 230.3  | 3.7        |
| Kimbibit          | Annual             | 984.4             | 992    | 0.8        | 1012   | 2.8        |
|                   | Long Rainy Season  | 802.3             | 822    | 2.5        | 829.7  | 3.4        |
|                   | Short Rainy Season | 140.8             | 150.8  | 7.1        | 159.9  | 13.6       |
| Seden Sodo        | Annual             | 1099.7            | 1135.5 | 3.3        | 1032.7 | −6.1       |
|                   | Long Rainy Season  | 853.4             | 871    | 2.1        | 887.8  | 4.0        |
|                   | Short Rainy Season | 192.3             | 199.9  | 3.9        | 211    | 9.7        |
| Meta Robi         | Annual             | 1084.7            | 1097.7 | 1.2        | 1120.2 | 3.3        |
|                   | Long Rainy Season  | 821.9             | 841    | 2.3        | 856.5  | 4.2        |
|                   | Short Rainy Season | 197.8             | 200    | 1.1        | 209.2  | 5.8        |
| 2080 Rainfall(mm) |                    |                   |        |            |        |            |
| Bacho             | Annual             | 997.9             | 1047.2 | 4.9        | 1088   | 9.0        |
|                   | Long Rainy Season  | 721.8             | 780.2  | 8.0        | 820.1  | 13.6       |
|                   | Short Rainy Season | 230.3             | 271.4  | 17.8       | 300.1  | 30.3       |
| Bishoftu          | Annual             | 790.8             | 850    | 7.5        | 895.7  | 13.3       |
|                   | Long Rainy Season  | 597.3             | 623.3  | 4.4        | 666.8  | 11.6       |
|                   | Short Rainy Season | 148.2             | 190.1  | 28.3       | 230.4  | 55.5       |
| Debrelibanos      | Annual             | 907.7             | 987    | 8.7        | 1001.5 | 10.3       |
|                   | Long Rainy Season  | 701.3             | 801.4  | 14.3       | 837.7  | 19.4       |
|                   | Short Rainy Season | 160.4             | 191    | 19.1       | 205.5  | 28.1       |
| Dodota            | Annual             | 855.7             | 852    | −0.4       | 852.3  | −0.4       |
|                   | Long Rainy Season  | 551.1             | 550.1  | −0.02      | 551    | −0.0       |
|                   | Short Rainy Season | 200.1             | 199.1  | −0.4       | 199.3  | −0.3       |
| Holeta            | Annual             | 1196.8            | 1266.3 | 5.8        | 1309.3 | 9.4        |
|                   | Long Rainy Season  | 909.28            | 1322   | 45.4       | 1388   | 52.6       |
|                   | Short Rainy Season | 222               | 243.4  | 9.6        | 290.3  | 30.8       |
| Kimbibit          | Annual             | 984.4             | 1032   | 4.8        | 1095.2 | 11.3       |
|                   | Long Rainy Season  | 802.3             | 837.7  | 4.4        | 885.5  | 10.4       |
|                   | Short Rainy Season | 140.8             | 168.7  | 19.8       | 212.6  | 50.9       |
| Seden Sodo        | Annual             | 1099.7            | 1052.9 | −4.3       | 1069.9 | −2.7       |
|                   | Long Rainy Season  | 853.4             | 898.7  | 5.3        | 937.3  | 9.8        |
|                   | Short Rainy Season | 192.3             | 222.3  | 15.6       | 290.4  | 51.0       |
| Meta Robi         | Annual             | 1084.7            | 1240.2 | 14.3       | 1295.7 | 19.5       |
|                   | Long Rainy Season  | 821.9             | 863    | 5.0        | 896.8  | 9.1        |
|                   | Short Rainy Season | 197.8             | 229.1  | 15.8       | 286.3  | 44.7       |

Overall, annual rainfall is expected to increase in most study areas under both scenarios, with more pronounced increases under the high-emissions pathway (SSP8.5). For instance, Bacho shows positive annual rainfall changes of 3.1% under SSP4.5 and 3.9% under SSP8.5 by 2050, growing to 4.9% and 9%, respectively, by 2080. These increases could enhance water availability and benefit crop production in such areas.

Conversely, Dodota and Seden Sodo are projected to experience slight declines in annual rainfall. Dodota is particularly vulnerable, with decreases of  $-0.6\%$  (SSP4.5) and  $-0.5\%$  (SSP8.5) by 2050, worsening to  $-6.1\%$  under SSP8.5 by 2080. Such reductions raise concerns about future water scarcity and agricultural productivity in these moisture-stressed regions [45].

Seasonal projections reveal differing patterns between the main rainy season (Kiremt) and the short rainy season (Belg). Kiremt rainfall is generally expected to increase across most sites. Bishoftu, for example, could see Kiremt rainfall rise by 2.9% (SSP4.5, 2050) and up to 11.6% (SSP8.5, 2080), potentially supporting rain-fed crops such as wheat and maize. However, Dodota stands out with projected slight decreases during Kiremt, signaling potential challenges for crop reliability in the primary rainy season.

Belg season rainfall shows more dramatic spatial variability. Bishoftu may experience up to a 55.5% increase under SSP8.5 by 2080, potentially extending growing periods and enabling additional plantings during typically drier months. In contrast, Dodota faces declines in Belg rainfall, threatening early-season planting critical for smallholder farmers reliant on both rainy seasons for food security. Reduced Belg rainfall may disrupt crop establishment and sowing schedules.

The anticipated rainfall increases offer opportunities to alleviate drought stress and improve productivity but also bring risks. More intense or erratic rainfall could lead to flooding, soil erosion, and nutrient leaching. For example, Bacho's projected rainfall rise may enhance yields but will require improved water management to avoid waterlogging.

Meanwhile, moisture declines in areas like Dodota could exacerbate drought risk, delaying planting and reducing yields. To sustain agriculture, adaptation measures such as drought-tolerant crops, rainwater harvesting, and irrigation infrastructure will be critical.

By the 2080s, especially under SSP8.5, greater rainfall availability may benefit smallholder farmers in much of central Ethiopia. However, as the IPCC Sixth Assessment Report [60] notes, the increasing frequency of extreme events like intense rainfall and prolonged dry spells means farmers must prepare for both water surpluses and shortages.

This study connects projected climate changes with practical agricultural risks and adaptation options, advancing strategies to strengthen resilience in rain-fed systems. The findings support informed policy and decision-making aimed at sustaining smallholder livelihoods amid climate variability [64,65].

In summary, central Ethiopia's projected rainfall changes highlight a landscape of both opportunity and risk: while areas like Bacho may gain from increased rainfall, others such as Dodota face challenges from reduced moisture during key growing seasons. Targeted, localized adaptation strategies including improved water management, climate-smart agriculture, and infrastructure to mitigate flood and drought impacts are essential to secure sustainable agricultural outcomes under future climate uncertainty.

### 3.7.2. Projected Temperature Trend and Implications for Agricultural Resilience

Projected changes in mean annual temperatures across central Ethiopia are critical for assessing future agricultural viability, especially for temperature-sensitive crops such as wheat and barley. According to data presented in Tables 11 and 12, both maximum (Tmax) and minimum (Tmin) temperatures are expected to rise under medium- (SSP4.5) and high- (SSP8.5) emissions scenarios during the mid-century (2050s) and late-century (2080s) periods, relative to the 1993–2023 baseline.

**Table 11.** Projected maximum temperature change of eight stations in central Ethiopia.

| Station        | Parameters         | Scenarios      |        |                  |        |                  |
|----------------|--------------------|----------------|--------|------------------|--------|------------------|
|                |                    | Baseline       | Ssp4.5 | $\Delta T_{max}$ | Ssp8.5 | $\Delta T_{max}$ |
|                |                    | 2050 Tmax (°C) |        |                  |        |                  |
| Bacho          | Annual             | 27.4           | 28.3   | 0.9              | 28.8   | 1.4              |
|                | Long Rainy Season  | 26             | 26.7   | 0.7              | 27.6   | 1.6              |
|                | Short Rainy Season | 29.1           | 29.9   | 0.8              | 30.1   | 1                |
| Bishoftu       | Annual             | 27.1           | 28     | 0.9              | 28.7   | 1.6              |
|                | Long Rainy Season  | 25.8           | 25.9   | 0.1              | 26.5   | 0.7              |
|                | Short Rainy Season | 28.8           | 29.1   | 0.3              | 29.8   | 1                |
| Debrelibanos   | Annual             | 22.3           | 22.3   | 0                | 24.3   | 2                |
|                | Long Rainy Season  | 21.4           | 21.4   | 0                | 23     | 1.6              |
|                | Short Rainy Season | 23.8           | 23.8   | 0                | 25     | 3.6              |
| Dodota         | Annual             | 27.4           | 28.4   | 1                | 29.1   | 1.7              |
|                | Long Rainy Season  | 27.2           | 28.1   | 0.9              | 28.9   | 1.7              |
|                | Short Rainy Season | 28.4           | 29     | 0.6              | 29.3   | 0.9              |
| Holeta         | Annual             | 23.8           | 24.7   | 0.9              | 25.1   | 1.3              |
|                | Long Rainy Season  | 21.9           | 22.3   | 0.4              | 23.4   | 1.5              |
|                | Short Rainy Season | 25.5           | 26.1   | 0.6              | 27.2   | 1.7              |
| Kimbibit       | Annual             | 19.9           | 21.1   | 1.2              | 23     | 3.1              |
|                | Long Rainy Season  | 19.3           | 20.9   | 1.6              | 22.2   | 2.9              |
|                | Short Rainy Season | 20.9           | 21.3   | 0.4              | 21.9   | 1                |
| Seden Sodo     | Annual             | 25             | 25     | 0                | 26     | 1                |
|                | Long Rainy Season  | 24.1           | 24.1   | 0                | 24.1   | 0                |
|                | Short Rainy Season | 26.4           | 26.4   | 0                | 27     | 0.6              |
| Meta Robi      | Annual             | 25.4           | 28.8   | 3.4              | 29     | 3.6              |
|                | Long Rainy Season  | 23.4           | 24.1   | 0.7              | 25.1   | 1.7              |
|                | Short Rainy Season | 27.2           | 28.1   | 0.9              | 29.3   | 2.1              |
| 2080 Tmax (°C) |                    |                |        |                  |        |                  |
| Bacho          | Annual             | 27.4           | 28.9   | 1.5              | 29.2   | 1.8              |
|                | Long Rainy Season  | 26             | 28.3   | 2.3              | 28.8   | 2.8              |
|                | Short Rainy Season | 29.1           | 30.9   | 1.8              | 31.1   | 2                |
| Bishoftu       | Annual             | 27.1           | 29     | 1.9              | 29.7   | 2.6              |
|                | Long Rainy Season  | 25.8           | 27.4   | 1.6              | 27.8   | 2                |
|                | Short Rainy Season | 28.8           | 30.1   | 1.3              | 30.8   | 2                |
| Debrelibanos   | Annual             | 22.3           | 24.3   | 2                | 24.3   | 2                |
|                | Long Rainy Season  | 21.4           | 24     | 2.6              | 24     | 2.6              |
|                | Short Rainy Season | 23.8           | 25     | 1.2              | 25     | 1.2              |
| Dodota         | Annual             | 27.4           | 29.5   | 2.1              | 29.8   | 1.2              |
|                | Long Rainy Season  | 27.2           | 29.3   | 2.1              | 29.9   | 2.4              |
|                | Short Rainy Season | 28.4           | 30     | 1.6              | 30.3   | 2.7              |
| Holeta         | Annual             | 23.8           | 26.1   | 2.3              | 26.7   | 2.9              |
|                | Long Rainy Season  | 21.9           | 24.2   | 2.3              | 24.4   | 2.5              |
|                | Short Rainy Season | 25.5           | 28.3   | 2.8              | 28.7   | 3.2              |
| Kimbibit       | Annual             | 19.9           | 24.1   | 4.2              | 24.4   | 4.5              |
|                | Long Rainy Season  | 19.3           | 23.3   | 4                | 23.8   | 4.5              |
|                | Short Rainy Season | 20.9           | 22.5   | 1.6              | 22.9   | 2                |
| Seden Sodo     | Annual             | 25             | 25     | 0                | 25     | 0                |
|                | Long Rainy Season  | 24.1           | 24.1   | 0                | 24.1   | 0                |
|                | Short Rainy Season | 26.4           | 26.4   | 0                | 26.4   | 0                |
| Meta Robi      | Annual             | 25.4           | 29.5   | 4.1              | 29.9   | 4.5              |
|                | Long Rainy Season  | 23.4           | 26.3   | 2.9              | 26.8   | 3.4              |
|                | Short Rainy Season | 27.2           | 29.4   | 2.2              | 29.8   | 2.6              |

 $\Delta T_{max}$  = maximum temperature change.

**Table 12.** Projected minimum temperature change of eight stations in central Ethiopia.

| Station        | Parameters         | Scenarios      |        |                  |        |                  |
|----------------|--------------------|----------------|--------|------------------|--------|------------------|
|                |                    | Baseline       | Ssp4.5 | $\Delta T_{min}$ | Ssp8.5 | $\Delta T_{min}$ |
|                |                    | 2050 Tmin (°C) |        |                  |        |                  |
| Bacho          | Annual             | 9.3            | 9.9    | 0.6              | 10.1   | 0.8              |
|                | Long Rainy Season  | 11.4           | 12.3   | 0.9              | 13.5   | 2.1              |
|                | Short Rainy Season | 9.7            | 10.3   | 0.6              | 11     | 1.3              |
| Bishoftu       | Annual             | 11.3           | 12.1   | 0.8              | 13.3   | 2                |
|                | Long Rainy Season  | 13.1           | 14.2   | 1.1              | 14.9   | 1.8              |
|                | Short Rainy Season | 12             | 13.2   | 1.2              | 14     | 2                |
| Debrelibanos   | Annual             | 9.1            | 10.3   | 1.2              | 11.3   | 2.2              |
|                | Long Rainy Season  | 10.4           | 11.5   | 1.1              | 11.9   | 1.5              |
|                | Short Rainy Season | 9.8            | 10.4   | 0.6              | 11.7   | 1.9              |
| Dodota         | Annual             | 12.8           | 13.3   | 0.5              | 14.2   | 1.4              |
|                | Long Rainy Season  | 14             | 14.7   | 0.7              | 15.5   | 1.5              |
|                | Short Rainy Season | 13.2           | 13.7   | 0.5              | 14.1   | 0.9              |
| Holeta         | Annual             | 8.4            | 9.6    | 1.2              | 10.5   | 2.1              |
|                | Long Rainy Season  | 9.3            | 10     | 0.7              | 11.2   | 1.9              |
|                | Short Rainy Season | 9.1            | 9.7    | 0.6              | 10.4   | 1.3              |
| Kimbibit       | Annual             | 7.6            | 8.2    | 0.6              | 9.1    | 1.5              |
|                | Long Rainy Season  | 8.2            | 8.9    | 0.7              | 9.8    | 1.6              |
|                | Short Rainy Season | 8.1            | 9      | 0.9              | 10.1   | 2                |
| Seden Sodo     | Annual             | 10             | 10     | 0                | 10     | 0                |
|                | Long Rainy Season  | 10.8           | 10.8   | 0                | 10.8   | 0                |
|                | Short Rainy Season | 10.5           | 10.5   | 0                | 11     | 0.5              |
| Meta Robi      | Annual             | 10.1           | 10.7   | 0.6              | 11.7   | 1.6              |
|                | Long Rainy Season  | 10.8           | 11.5   | 0.7              | 12.3   | 1.5              |
|                | Short Rainy Season | 11             | 12.2   | 1.2              | 13.1   | 2.1              |
| 2080 Tmin (°C) |                    |                |        |                  |        |                  |
| Bacho          | Annual             | 9.3            | 11     | 1.7              | 11.5   | 2.2              |
|                | Long Rainy Season  | 11.4           | 13.9   | 2.5              | 14.1   | 2.7              |
|                | Short Rainy Season | 9.7            | 12     | 2.3              | 12.5   | 2.8              |
| Bishoftu       | Annual             | 11.3           | 14.1   | 2.8              | 14.5   | 3.2              |
|                | Long Rainy Season  | 13.1           | 15     | 1.9              | 15.3   | 2.2              |
|                | Short Rainy Season | 12             | 14.3   | 2.3              | 14.7   | 2.7              |
| Debrelibanos   | Annual             | 9.1            | 12.1   | 3                | 12.7   | 3.6              |
|                | Long Rainy Season  | 10.4           | 12     | 1.6              | 12.7   | 2.3              |
|                | Short Rainy Season | 9.8            | 12.3   | 2.5              | 12.9   | 3.1              |
| Dodota         | Annual             | 12.8           | 14.3   | 1.5              | 14.8   | 2                |
|                | Long Rainy Season  | 14             | 15.6   | 1.6              | 15.9   | 1.9              |
|                | Short Rainy Season | 13.2           | 14.5   | 1.3              | 14.8   | 1.6              |
| Holeta         | Annual             | 8.4            | 11.1   | 2.7              | 11.7   | 3.4              |
|                | Long Rainy Season  | 9.3            | 12.1   | 2.8              | 12.7   | 3.4              |
|                | Short Rainy Season | 9.1            | 11     | 1.9              | 11.4   | 2.3              |
| Kimbibit       | Annual             | 7.6            | 10.2   | 2.6              | 10.5   | 2.9              |
|                | Long Rainy Season  | 8.2            | 10.3   | 2.1              | 10.9   | 2.7              |
|                | Short Rainy Season | 8.1            | 11.1   | 3                | 11.5   | 3.4              |
| Seden Sodo     | Annual             | 10             | 10     | 0                | 10     | 0                |
|                | Long Rainy Season  | 10.8           | 10.8   | 0                | 11     | 0.2              |
|                | Short Rainy Season | 10.5           | 11     | 0.5              | 11.2   | 0.7              |
| Meta Robi      | Annual             | 10.1           | 12.3   | 2.2              | 12.6   | 2.5              |
|                | Long Rainy Season  | 10.8           | 12.4   | 1.6              | 12.9   | 2.1              |
|                | Short Rainy Season | 11             | 13.3   | 2.3              | 13.9   | 2.9              |

 $\Delta T_{min}$ . = minimum temperature change.

### Maximum Temperature Projections

As outlined in Table 11, all stations are projected to experience notable increases in Tmax under both scenarios, with the magnitude of warming is more pronounced under SSP8.5. For example, Bacho is projected to warm by 0.9 °C (SSP4.5) and 1.4 °C (SSP8.5) by 2050, increasing further to 1.5 °C and 1.8 °C by 2080, respectively. Similar patterns are evident at Bishoftu, Holeta, and Metarobi, suggesting a widespread warming trend across the region.

These results are consistent with IPCC projections, which indicate that average temperatures in East Africa may increase by 2–3 °C by mid-century and by 4–6 °C by the end of the century under high-emission pathways [60]. While moderate temperature increases can sometimes enhance photosynthesis and accelerate crop growth potentially benefiting crops like wheat, such gains are contingent upon sufficient soil moisture and well-distributed rainfall. Otherwise, warming could lead to negative effects such as increased evapotranspiration, soil moisture loss, and more frequent heat stress events, particularly during sensitive growth stages.

### Minimum Temperature Projections

Minimum temperatures are also expected to rise, albeit at a slightly lower rate than Tmax. As seen in Table 12, Bacho may experience a Tmin increase of 0.6 °C (SSP4.5) and 0.8 °C (SSP8.5) by 2050, while Debrelibanos could see Tmin rise by as much as 3.6 °C by 2080 under SSP8.5.

These changes have significant agronomic implications. Warmer night-time temperatures disrupt the diurnal temperature cycle vital for crop development by increasing night-time respiration, which lowers net photosynthetic gain and biomass accumulation, particularly in C3 crops like wheat and barley [63]. Elevated Tmin also intensifies evapotranspiration and heightens crop water demand, placing additional strain on rain-fed systems that already face seasonal water limitations.

Moreover, increased Tmin can extend periods of thermal stress into the night, compounding the adverse effects of high daytime temperatures. For crops that require vernalization or cooler early-season conditions, such as wheat, this may lead to premature flowering, shortened grain-filling periods, and ultimately, reduced yield and grain quality [66].

### Agricultural Resilience Implications

The projected warming trends, especially under SSP8.5, highlight a dual challenge for agriculture in central Ethiopia: managing both the physiological effects of heat on crops and the associated increase in water demand. While some warming may offer marginal benefits under well-managed conditions, the overall risks of heat stress, pest and disease outbreaks, and water scarcity are likely to outweigh potential gains in productivity.

To enhance resilience, targeted adaptation strategies will be essential. These include the following:

- Adoption of heat-tolerant and short-maturing crop varieties to minimize the exposure of crops to peak heat periods.
- Improved soil and water conservation practices, such as mulching and conservation tillage, to retain moisture and buffer against heat stress.
- Enhanced pest and disease surveillance and management, particularly for crops grown during the increasingly warm Belg season.
- Climate-informed planting calendars that align crop cycles with evolving thermal conditions and minimize risk exposure.

In conclusion, the projected rise in Tmax and Tmin across central Ethiopia underscores the need for proactive and localized adaptation strategies. Building agricultural systems



that can thrive amid warming conditions will be central to securing food security and rural livelihoods in the region. A forward-looking approach that integrates climate-smart technologies, policy support, and farmer-led innovation is essential for sustaining agricultural resilience in the face of ongoing and future climate change.

#### 4. Conclusions

This study aimed to analyze historical and projected climate trends in central Ethiopia and assess their implications for rain-fed agriculture, a vital livelihood source in the region. By leveraging long-term meteorological data from 1993 to 2023 alongside future climate projections under multiple emission scenarios, the study identified critical patterns of temperature and rainfall variability that directly influence agricultural productivity.

Key findings show a consistent upward trend in both maximum and minimum temperatures across most study areas, with stronger warming projected under high-emission scenarios (SSP8.5). These temperature increases, particularly during sensitive crop growth stages, are expected to exacerbate evapotranspiration and heat stress, thereby challenging crop yields and food security. Rainfall patterns exhibit spatial heterogeneity, with some locations like Bacho projected to experience moderate increases in total and seasonal rainfall, while others such as Dodota face declines, especially during crucial planting seasons. The increased frequency and duration of dry spells further complicate planting schedules and moisture availability for crops.

These climate trends underscore the necessity of localized and adaptive strategies to sustain agricultural resilience. The study highlights the importance of promoting drought-tolerant and heat-resilient crop varieties, improving water harvesting and irrigation infrastructure, adopting soil moisture conservation techniques, and enhancing early-warning systems tailored to local agro-climatic conditions. Strengthening institutional support and integrating indigenous knowledge with scientific insights emerge as critical pathways to enable smallholder farmers to cope with current and anticipated climate stresses.

Furthermore, the study's findings directly address the objective to connect climate variability with agricultural risk, providing actionable evidence for policymakers and stakeholders to design context-specific adaptation measures. Future research should focus on quantifying the direct impacts of these climatic shifts on crop phenology and yield, as well as evaluating socioeconomic barriers to adaptation, to inform comprehensive climate-smart agricultural policies.

In conclusion, this study confirms that while central Ethiopia's climate exhibits natural resilience conducive to rain-fed farming, ongoing and projected warming, alongside changing rainfall regimes, presents substantial risks. Proactive, evidence-based adaptation and collaborative management among researchers, policymakers, and farming communities are essential to safeguard food security and promote sustainable agricultural development in the face of a changing climate.

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