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Tesfay Mekonnen Weldegerima

tesfaym270@gmail.com

Arba Minch University

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Tesfay Mekonnen Weldegerima

Faculty of Meteorology and Hydrology, Water Technology Institute, Arba Minch University, Arba Minch P.O. Box 21, Ethiopia;

corresponding author: tesfaym270@gmail.com

ORCID: <https://orcid.org/0000-0002-3786-9784>

Abstract

Rainfall is a fluctuating hydroclimatic variable in Ethiopia, and its deficit often causes intense and frequent drought conditions. This study investigates rainfall and drought dynamics across eight homogeneous rainfall zones (HRZs) of Ethiopia from 1981 to 2023, using the CHIRPS dataset. Significant variations were observed with FMAM (February to May) rainfall exhibiting higher variability and predominantly negative trends, while JJAS (June to September) and annual rainfall exhibited positive trend that is significant in several zones. The drought indices consistently identify significant drought periods, including 1984, 2002, 2009, 2015, and 2022, along with wet periods of 1997, 2019, 2020, and 2023. These indices specify moderate to severe droughts, particularly in northern and southeastern Ethiopia, and extreme droughts in northeastern Ethiopia. The study highlights the relevance of the CHIRPS for drought monitoring in Ethiopia, while also providing insights into the increase in drought frequency and intensity, modifying the regional hydrological resource.

Keywords: CHIRPS dataset; climate zones; rainfall variability and trends; drought patterns; Ethiopia

1. Introduction:

Drought is a recurrent hydro-climatic catastrophe distinguished by a state of inadequate moisture resulting from a deficiency in rainfall during a specific duration, and

rainfall will remain insufficient for a season or longer if it persists (McKee et al., 1993; Wilhite, 2016). It is causing tremendous multi-dimensional impacts at regional and at global levels (Singh et al., 2019; Wu et al., 2001). The spatiotemporal extent of drought varies from local to global coverage in space and from a day to a decade in time (Aryal et al., 2022; Dai, 2011; Spinoni et al., 2015) triggering a substantial effect on ecosystems, water supplies, and agricultural output (Bayissa et al., 2017; Beguería et al., 2010; Liu et al., 2014). Trenberth, (2011) reported that as compared to the 1960s the magnitude and frequency of drought have increased in 1990s, affecting the hydroclimatic cycle in many parts of the world including Africa. It can also result in famine, diseases, economic losses, and land degradation. Hence, monitoring the distribution and timing of drought is critical for sustainable water resource planning and adaptations.

There exist four main drought classes based on the shortages of rainfall for different sectors; (i) Meteorological Drought, triggered by insufficient rainfall in an area for a prolonged period; (ii) Hydrological Drought, associated with the deficiency of water resources in different water reservoirs; (iii) Agricultural Drought, occurred when there is a lack of soil moisture and a consequent crop; and (vi) Socio-Economic Drought, associated with the lack of water resource systems to fulfil the water demand of a society and consequently affects the socio-economic development (Aryal et al., 2022; Gu et al., 2020; Mishra & Singh, 2010; Tallaksen & Van Lanen, 2023). However, there may be a significant relationship between meteorological drought and the other types of drought. For example, meteorological drought caused by rainfall shortage may lead to lower surface runoff and amount of groundwater for a prolonged period, resulting in hydrological drought (Hao & Singh, 2015; Haslinger et al., 2014; Mishra & Singh, 2010).

Drought indicators are fed different data sources such as ground-based observations, hydrological simulations, forecasting data, as well as remote sensing data for better assessments of hydro-meteorological and vegetation conditions (Hao et al., 2017). The limited availability of real-time, monthly, or long-term consistent ground-based observations is becoming a shortcoming for drought monitoring (Nongmaithem et al., 2025; Zhong et al., 2019). However, satellite-based remote sensing measurements are alternatively providing promising measurements of precipitation with high temporal resolutions (Bitew & Gebremichael, 2011; Chen et al., 2005; Hong et al., 2007; Weldegerima & Gebresilassie, 2025). Nowadays, many precipitation measuring satellites are available with various retrieval algorithms and spatiotemporal resolutions. The

present study relies on satellite and ground-based rain gauge observations. Satellite based rainfall data set helps for continuous and consistent monitoring of droughts in space and time, and has been widely used for hydro-meteorological applications (Das et al., 2022; Ghozat et al., 2022; Nongmaithem et al., 2025).

The accuracy of the remote sensing-based rainfall estimations must be evaluated against ground measurements using rigorous statistical tools across diverse climatic zones (Alijanian & Dehghani, 2023; Salami et al., 2024; Teshome & Zhang, 2019). Consequently, various studies evaluated the accuracy of CHIRPS data, which is used in this study, in Central and East Africa (eg, Ethiopia, Uganda, Nigeria, Zambia), and reported promising skills with recommending the product for various hydroclimatic assessments (Bayissa et al., 2017; Das et al., 2022; Dinku et al., 2018; Tessema et al., 2022).

Ethiopia faces drought conditions approximately every seven to ten years (Liou & Mulualem, 2019)). During the last few decades, there have been notable rise in the frequency and severity of droughts in the country. Notably, the drought that occurred between 1984 and 1985 had a devastating impact, affecting the lives of more than two hundred thousand individuals and resulting in the loss of millions of livestock (Viste et al., 2013). These drought impacts are also adding pressures on the economy, GDP, crops and farm animals rearing as well as mortality. Funk et al., (2005) reported the pressing impact of drought on water availability particularly in the most populated pockets of the rift valley and central highlands of Ethiopia.

Ethiopia's climate is changing, although the specific trends and their implications are not fully understood yet. The climate of Ethiopia is affected by several mechanisms such as; the north to south seasonal propagation of the Inter Tropical convergence Zone (ITCZ), spatial patterning and teleconnections of global oceanic and atmospheric circulations (Diro et al., 2011; Dubache et al., 2019). The role of the ITCZ in modulating the seasonal rainfall of Ethiopia is described under section 2.2.

Many studies link the rainfall variability and associated droughts to the El Niño phenomenon (Korecha & Barnston, 2007; Weldegerima et al., 2018; T. T. Zeleke et al., 2017). For example, Korecha & Barnston, (2007) outlined that the recurrent droughts in Ethiopia are correlated with the reduction in rainfall associated with the positive anomalous sea surface temperatures across the Pacific Ocean, the El Niño episode.

Consequently, El Niño is used for early warning and forecasting of seasonal droughts (Wolde-Georgis et al., 2000), and is causing seasonal rainfall failure and excessive dryness in different regions of the country in recent periods.

A study by Zeleke et al., (2017) found that the northern and north eastern parts of Ethiopia faced more recurrent as well as severe drought occurrences, particularly in 1983/1984, during the 1979-2014 study period. Their analysis also reflected that droughts were more frequent and intense for the south and southwest parts of the country in 1997. Liou & Muluaalem, (2019) assessed spatiotemporal drought in Ethiopia using various remote sensing products and revealed, the central plateaus and north western parts of Ethiopia, that are known for their cultivation of a variety of crops, show decreasing rainfall and normalized difference vegetation index (NDVI), indicating drought experience throughout the 2001 to 2018 study periods. Previously, El Kenawy et al., (2016) investigated the patterns in frequency and intensity of droughts in Ethiopia for a relatively long study period of 54 years (1960-2013); the study revealed high spatial heterogeneity of droughts, spotting ten different spatially defined regions. Most of these studies were conducted either at a single station level or averaged over the whole of Ethiopia, lacking a comprehensive analysis of recent patterns and severity of drought in homogeneous rainfall regions.

While previous hydro-climatic studies in Ethiopia used rigid political administrative boundaries or broad watershed delineations to evaluate rainfall and drought dynamics, these methods generalize or masks highly localized rainfall characteristics. To cover this gap this study adopts an approach based on Homogeneous Rainfall Zones (HRZs). Moreover, drought assessments are constrained by scarce ground observations and severe temporal data discontinuities, the integration of CHIRPS in this study successfully overcomes these data gaps while providing a more spatially continuous and climatologically sound assessment of sub-regional rainfall trends.

The present study primarily focuses on characterizing rainfall and drought patterns across eight homogeneous rainfall zones of Ethiopia by using the RAI and SPI indices and satellite-based rainfall estimates (CHIRPS) for the period 1981- 2023. The examination of rainfall and drought distribution in both spatial and temporal dimensions gives a better understanding of drought dynamics at local rainfall homogenous regions, and is vital for various hydro-climatic practices such as farm planning, irrigation supplement scheduling, water resource management in different reservoirs, and other

climate adaptation plans. The analysis results may help farmers, researchers, and policy makers as an input for early planning based on their crop calendars and irrigation water management, as well as efficient utilization based on drought scenarios of their specific HRZ.

2. Materials and Methods:

2.1 Study Area Description

Ethiopia is situated within the geographic coordinates of 3°N to 15°N latitude and 33°E to 48°E longitude, positioning it in the eastern part of Africa (Fig. 1). The region exhibits a highly complex and varied topography, which significantly influences its ecological and climatic conditions. Elevations throughout the country range dramatically, from approximately 116 meters beneath ocean level in the north-eastern region to peaks reaching 4,550 meters above ocean level in the northcentral uplands. This vast variation in elevation contributes to diverse microclimates and habitats across the landscape. The interplay of these climatic factors, combined with the diverse altitudinal range of the country, results in a rich mosaic of ecosystems and agricultural practices, making the region a focal point for studies related to climate impact, agriculture, and biodiversity.

2.2 Seasonal Climate and Rainfall Homogeneous Zones

Ethiopia's climate is largely characterized with the periodic variations of the Inter Tropical convergence Zone (ITCZ) position and accompanying atmospheric circulations, as well as by its diverse landscape (Fazzini et al., 2015). Due to the landscape, it is common to experience a range of climates, from the arid to semi-arid climate prevailing in the lowlands to the moist climate in the mountains. Rainfall shows a variation with an increase in amount from north to south; however, it is also affected by temperature and local wind patterns (Alemayehu & and Bewket, 2017).

Many studies have classified Ethiopia based on different climate parameters into various distinct homogeneous regimes. The Ethiopian Meteorology Institute (EMI) classified the country into eight homogeneous rainfall zones based on rainfall-producing systems affecting the region and seasonality patterns (Korecha & Sorteberg, 2013). The present study adopts these homogeneous rainfall zones to evaluate the spatiotemporal patterns of rainfall and drought in Ethiopia. The location and spatial coverage of the HRZs are presented in Fig. 1, and the seasonal distribution of rainfall is illustrated in Fig. 2.

Ethiopia's climate is characterized by three seasons of four months each, locally named as ONDJ (no rain season), FMAM (small rain season), and JJAS (main rain season), which are characterized by dry, short rains and long rains (Gissila et al., 2004). During the ONDJ season, cool and dry air associated with the trade winds, formulated by the thermal high of western Asia and north Africa, blows from northeast to southwest keeping the region with dry season. However, some areas south and southwestern parts receive rainfall significant rainfall during October and December in this season. In FMAM, the country experiences abundant rain, particularly at the southern and south-eastern regions (HRZ_VII, HRZ_III, HRZ_VI, and HRZ_VI), associated with the southwestern migration of winds predominantly from the Congo Basin. This season is critical for the early planting of crops and the replenishment of soil moisture, supporting agricultural activities in these areas. In JJAS, which is the major rain-bearing season for most parts (HRZ_I, HRZ_II, HRZ_III, HRZ_IV, HRZ_VI, and HRZ_VII), abundant rainfall is obtained, initiated by the west African monsoon and equatorial warm and humid winds, ITCZ, and the orographic diversity of the area. This season covers most parts of the country including the two season beneficiary areas of south and south western Ethiopia (HRZ_III, HRZ_IV, HRZ_VI and HRZ_VII)). The Kiremt season is vital for the country's agricultural productivity, as it accounts for approximately 65% to 90% of the annual rainfall (Li et al., 2016). Moreover, it is a crucial factor in food security, contributing to 80% to 95% of the total yield of staple crops grown for food (Gissila et al., 2004). The spatiotemporal pattern of seasonal and annual rainfall distribution for each HRZ is presented in Fig. 3.

2.3 The CHIRPS dataset

The precipitation measurement for this analysis was found from the CHIRPS dataset, which offers a robust record of monthly precipitation from 1981 to 2023. CHIRPS is a land-based precipitation dataset that has been developed to improve the spatial and temporal resolution of precipitation observations globally (Funk et al., 2015). It encompasses a latitude range from 50°N to 50°S, and has been accessible since 1981 to date. The dataset integrates multiple data sources, including satellite-derived estimates, in-situ measurements, and global climatological data. The in-situ precipitation measurements are collected from different meteorological services at national and regional levels.

Compared to existing satellite-based global precipitation datasets, CHIRPS provide enhanced geographical and temporal resolution, making it particularly suitable for analysing rainfall variability at smaller basin scales and across a range of temporal resolutions, from daily to higher time intervals. The dataset is especially valuable in regions like Africa, where the scarcity of ground-based observational stations and inherent spatiotemporal gaps pose challenges for climate analysis (Schreck III & Semazzi, 2004). In addition, the spatial distribution and temporal consistency of hydrometeorological stations in Ethiopia are declining in recent times due to various aspects such as technical deficiencies, financial deficits, limited infrastructure, and skilled personnel shortages (Tola et al., 2025). Hence, the use of satellite-based measurements for hydrometeorological analysis is becoming essential.

In Ethiopia, the performance of CHIRPS is checked at various basins on different time scales (Ayehu et al., 2018; Dinku et al., 2018; Gashaw et al., 2023; Hordofa et al., 2021; Shalishe et al., 2022; Tadesse et al., 2022; Weldegerima & Gebresilassie, 2025). For example, Hordofa et al., (2021) evaluated CHIRPS against three products of Global Precipitation Measurement Integrated Multi-Satellite Retrieval (GPM-IMERG; IMERG-E, IMERG-L, and IMERG-F) within Ethiopia's central rift valley basin (Ziway Lake Basin), while both products can estimate ground-based observations at both monthly and seasonal time resolutions, CHIRPS shows better performance. (Ayehu et al., 2018) compared the ARC2, CHIRPS, and TAMSAT3 rainfall measurements in the upper Blue Nile, and their result reveal that CHIRPS demonstrates better agreement with ground observations, showing high correlation, better bias value, and low root mean square error. Recently, Weldegerima & Gebresilassie, (2025) evaluated CHIRPS against the Africa Rainfall Climatology (ARC) and Tropical Applications of Meteorology using SATellite (TAMSAT) in southern Ethiopia and found that the CHIRPS outperforms ARC and TAMSAT exhibiting a correlation of 0.96 and a Bias of 1.02, recommending its applicability for hydroclimatic assessments and drought monitoring.

The algorithm's capacity to integrate remote sensing observation, rain gauge measurements, and reanalysis outputs, together with its better spatial and temporal resolutions, has been credited with CHIRPS's superior performance over other satellite rainfall estimates (Funk et al., 2015). Consequently, by providing an alternative to comprehend the fluctuations of rainfall over space and time, CHIRPS can aid in improved decision making in locations with inadequate measurement (Belay et al., 2019). The

CHIRPS v2.0, version 2 data utilized in this study offers multiple temporal resolutions, including daily, 5-day, 10-day, and monthly intervals, with a spread of $0.05^\circ \times 0.05^\circ$, thereby enabling detailed analysis of precipitation dynamics (Funk et al., 2015). The CHIRPS dataset is accessible from the university of California, Santa Barbara database, and for further overview of the CHIRPS satellite-derived precipitation products, readers can refer to the work of (Funk et al., 2015), which provides an in-depth examination of the methodologies and validation processes associated with these rainfall datasets.

3. Data Analysis Methods:

3.1 Evaluation of Rainfall variability

3.1.1 Coefficient of Variability (CV)

The Coefficient of Variability (CV) is a widely used statistical estimate that measures the variation of a data distribution as compared to the mean value. The CV allows researchers to standardize the measure of variability and is often presented in a percentage. The CV is mathematically expressed as follows (Eq.1)

$$CV(\%) = \left(\frac{\sigma}{\mu} \right) \times 100\% \quad (1)$$

Where CV represents the variation coefficient, σ for standard deviation, and μ for average rainfall. The extent of variation in rainfall is ordered as follows: CV values up to 20% is less variable, between 20% and 30% is moderately variable, and above 30% is highly variable (Green, 1969).

3.1.2 Percent of Normal Precipitation (PNP)

The analysis of the percent of normal precipitation is a crucial component in understanding the patterns and trends of precipitation within a specific region or period. This method of analysis involves comparing the observed precipitation values to the extended average (≥ 30 -year mean period) or "normal" precipitation for a location and time range, typically as stated in (Gocic & Trajkovic, 2014; Mzezewa et al., 2010). Gocic & Trajkovic, (2014) defined that the normal rainfall for an area is 100%, whereas readings less than 100% indicate drought conditions. The analysis of the percent of normal precipitation gives a valuable perception of the variabilities of rainfall distribution, particularly within the framework of climate change. While the PNP is the easiest way to monitor rainfall, it is insufficient for making decisions when utilized in isolation (Werick et al., 1994).

3.2 Mann–Kendall Trend and Sens slope Analysis

This study used the Mann-Kendall test (Kendall, 1948; Mann, 1945) which is a non-parametric trend detecting statistical tool that is commonly employed to detect the existence and significance of trends in timely ordered data. The tool is intensively applied in hydrological and meteorological variables, including streamflow, rainfall, and temperature (Almazroui & Şen, 2020). The Mann-Kendall test works by comparing every observation in the time series with all subsequent values. The test statistic, S , is estimated by subtracting the number of positive differences and negative differences between all pairs of data points (X_k , $k = 1, 2, 3 \dots, n$) as in Eq 2.

$$S = \sum_{k=1}^{n-1} \sum_{i=k+1}^n \text{sgn}(X_i - X_k) \quad (2)$$

where X_i and X_k represent the mean seasonal values for consecutive years i and j , respectively, with $i > j$, and n denotes the duration of the observations. The direction of all the entire set of differences $X_i - X_k$ is calculated as:

$$\text{sign}(X_i - X_{jk}) = \begin{cases} +1 & \text{if } (X_i - X_k) > 0 \\ 0 & \text{if } (X_i - X_k) = 0 \\ -1 & \text{if } (X_i - X_k) < 0 \end{cases} \quad (3)$$

S is the test statistic taken into consideration for the time series, in which the span of observation $n > 10$ is having mean $E(S) = 0$ and the variance is given as follows (Eq4),

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^m t_i(t_i-1)(2t_i+5)}{18} \quad (4)$$

The standardized test statistic Z is then employed to decide whether the estimated trend is significant or not, using S and n . If $|Z|$ exceeds 1.96, it indicates that the observed trend in the time series is not by random chance. This threshold corresponds to a 5% level of significance, meaning that there is only a 5% probability of not accepting the null hypothesis while it is true.

Sen's Slope Estimator, developed by the statistician Pranab K. Sen (Sen, 1968), is a robust statistical measure applied to assess the magnitude of trends in timely distributed data, and is useful in hydro-meteorological researches, including analysing rainfall characteristics (Lu et al., 2016; PZ & KV, 2021). This method is particularly effective for datasets that may not meet the assumptions of traditional linear regression, such as

normality and homoscedasticity. The slope (Q) of the data pairs is determined by the following formula:

$$Q_i = \frac{x_j - x_k}{j - k}, i = 1, 2, \dots, N, j > k \quad (5)$$

We can obtain as many slope estimations Q_i as $N = n(n-1)/2$ for the time series having n values. Once all pairwise slopes are computed, the next step is to find the median of these slopes, which is given as in Eq.6. The calculated median of all slopes is the Sen's indicator after all values of slopes are arranged in minimum to maximum values order.

$$Q_{\text{med}} = \begin{cases} Q_{|N+1/2|} & \text{if } N \text{ is odd} \\ \frac{Q_{|N/2|} + Q_{|(N+2)/2|}}{2} & \text{if } N \text{ is even} \end{cases} \quad (6)$$

3.3 Meteorological Drought Monitoring

3.3.1 Rainfall Anomaly Index (RAI)

The RAI first established by Van Rooy in 1965 (Van Rooy, 1965) allows researchers to quantify the severity of rainfall anomalies, facilitating the identification of both drought and excess rainfall conditions. In this study, by applying RAI calculations to the CHIRPS precipitation dataset, we could effectively categorize rainfall anomalies into distinct classes as outlined by (Aydin, 2024; Fluixá-Sanmartín et al., 2018). The RAI drought indicator is ideal for semiarid and tropical environments, particularly in East Africa, due to its simple calculation process that only requires rainfall data (Aryal et al., 2022).

The RAI is estimated by using the formula in Eq.7:

$$RAI = \pm 3 \frac{p_i - \bar{p}}{\bar{E} - \bar{p}} \quad (7)$$

Where, p_i represents the measure of the precipitation at time i , $\bar{p}$ presents the average of the observed precipitation measures, $\bar{E}$ is the average monthly measure of the 10 lowest (for $p_i - \bar{p} < 0$) and 10 largest (for $p_i - \bar{p} > 0$) extreme values. And, the ± 3 is a scaling factor taken as positive for $p_i - \bar{p} > 0$, while negative for $p_i - \bar{p} < 0$ as described in (Raziei, 2021).

3.3.2 Standard Precipitation Index (SPI)

The most common drought indicator, Standardized Precipitation Index (SPI) introduced by (Mckee et al., 1993) is a broadly recognized and essential metric for assessing rainfall anomalies, making it invaluable for drought monitoring, water resource management, and

climate analysis. The SPI helps identify both excessive and insufficient rainfall, providing critical insights into climatic trends and variability. The calculation of SPI involves converting the rainfall time series into a standardized gaussian distribution by first determining the mean and standard deviation. Each monthly rainfall total is then converted into a Z-score, which reflects its deviation from the mean. By fitting these Z-scores to a probability model, typically a gamma distribution model, SPI values are generated (Shiau, 2020). Equation 8 expresses the calculation of the gamma distribution function.

$$G(x) = \frac{1}{\beta^\alpha \Gamma(\alpha)} x^{\alpha-1} e^{-\frac{x}{\beta}} \quad (8)$$

$$\text{Where, } \alpha = \frac{1}{4A} \left(1 + \sqrt{1 + \frac{4A}{3}} \right), \text{ and } \beta = \frac{\bar{x}}{\alpha}, A = \ln(\bar{x}) - \frac{\ln \sum \ln(x)}{n}$$

The parameter α and β are the shape and scale parameter, with values greater than zero; n represents the number of rainfall observations, x is a measurement of rainfall in a data sequence, and $\bar{x}$ is the mean value of rainfall. The formula for the gamma function, $\Gamma(\alpha)$ is presented by Eq. 9.

$$\Gamma(\alpha) = \int_0^\infty y^{\alpha-1} e^{-y} dy \quad (9)$$

Given that the Gamma function is indefinite for values $X=0$, particularly as rainfall values may include zeros, the cumulative probability $H(x)$ is articulated by Eq.10

$$H(x) = q + (1 - q)G(x) \quad (10)$$

Where q is the chance that the amount of rainfall is zero. The SPI values can be presented as defined in Bordi et al., (2001); and Lloyd-Hughes & Saunders, (2002) as follows:

$$SPI = - \left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3} \right); t = \sqrt{\ln \frac{1}{(H(x))^2}}; 0 < H(x) \leq 0.5 \quad (11)$$

$$SPI = t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}; t = \sqrt{\ln \frac{1}{(1 - H(x))^2}}; 0.5 < H(x) \leq 1 \quad (12)$$

Where the values of the constants are given as, $c_0 = 2.515$, $c_1 = 0.802$, $c_2 = 0.010$, and $d_1 = 1.432$, $d_2 = 0.189$, $d_3 = 0.001$, and the transformation variable t is calculated as;

$$t = \begin{cases} \sqrt{\ln \frac{1}{(H(x))^2}} & 0 < H(x) \leq 0.5 \\ \sqrt{\ln \frac{1}{(1-H(x))^2}} & 0.5 < H(x) \leq 1.0 \end{cases} \quad (13)$$

These values are categorized to indicate varying levels of drought and non-drought situations, accordingly negative values indicating drought conditions and positive values indicating surplus rainfall (Table 1). SPI can be computed over different times, such as for 1 month, for 3 months, for 6 months, or 12 months and so on.

3.4 Examination of Drought Characteristics

3.4.1 Duration (D), Magnitude (M), and Intensity (I)

Drought duration denotes to the time interval that a region experiences drought condition (Tsakiris et al., 2007). It is typically measured from the onset of drought until its end. The time span that a drought has lasted can be determined by counting the number of times that it has occurred repeatedly (Gidey et al., 2018; Svoboda et al., 2012). In this study, depending on the number of successive drought incidence periods, an investigation into the duration of the drought was conducted using the formula below (Eq. 14).

$$D = \sum_{i=1}^n \frac{d_i}{x} \quad (14)$$

Where, D is Drought duration(month), d_i is duration of drought occurrences, and x is the overall number of drought events throughout the investigated time interval.

Similarly, Drought magnitude quantifies the severity of drought situations, often articulated in terms of the cumulative deficit of rainfall or the severity of the drought indicator as used by (Gidey et al., 2018). The statistical analysis of drought magnitude (M) in this paper is computed as defined in (McKee et al., 1993) as shown in (15);

$$M = -\left(\sum_{j=1}^x SPI_{ij}\right) \quad (15)$$

where M represents the magnitude of drought, x represents the count of drought months, j is the drought months, and SPI_{ij} is the SPI value during the i^{th} month and j^{th} year.

Additionally, a statistical analysis of the drought Intensity (I) in the research area from 1981 to 2023 was conducted. I measure the severity of drought at any particular point in time, reflecting the potential impacts on the environment, crop production, water resources, and human beings. Understanding drought intensity is crucial for effective resource administration and scheduling. The calculation of drought intensity in the current analysis is adopted from (Gidey et al., 2018) as below Eq. (16):

$$I = \frac{M}{D} \quad (16)$$

Where I is drought intensity, M is drought magnitude, and D represents drought duration.

3.4.2 Frequency, Severity, and Spatial Extent

The number of drought occurrences over time in this research was calculated by firstly identifying the quantity of instances where the index fell under a precalculated threshold, indicating the occurrence of a dry condition. The study mathematically represented the frequency of drought incidence as in (Gidey et al., 2018) as follows (Eq. 17):

$$F = \left(\frac{N}{T} \right) \times 100 \quad (17)$$

Where F is relative frequency of drought events in percentage, N denotes the amount of drought episodes, and T represents the study years, which is 43 years in this case.

The severity of drought in the current research is evaluated by analysing the duration and magnitude of each drought event. The duration of drought is estimated by the quantity of successive time periods (e.g., months or years) where the SPI remained below the drought threshold.

4. Results and Discussion:

4.1 Rainfall Patterns Analysis

The spatiotemporal analysis focusing on the seasonal and annual rainfall for the HRZs in Ethiopia from 1981 to 2023 provided in this section. The rainfall pattern is investigated using variability measures; CV and PNP, and trend measures; Mann-Kendall and Sen's slope.

4.1.1 Variability of Rainfall

The temporal rainfall characteristics of the seasonal and yearly rainfall for the homogeneous rainfall regions in Ethiopia are summarized in Table 2. The mean seasonal rainfall differs from 116 to 478 mm and 164.3 to 848.4 mm during the FMAM and JJAS, respectively. The FMAM rainfall was highly variable, with most CV values greater than 20% while most JJAS's CV values are generally less than 20%. FMAM rainfall is highly variable in HRZ_I with a CV of above 30%, where FMAM rainfall in this zone is generally erratic. During JJAS, HRZ_VII shows the highest variability of approximately 21%, moderate interannual variability is experienced in most of the HRZs in this season. Similarly, the annual rainfall distribution differs from the minimum amount of 657.1 mm to the maximum amount of 1309.2 mm in HRZ_I and HRZ_III, respectively. In comparison to the seasonal time scale, the annual rainfall is relatively less variable, where

CV values are less than 20% for all HRZs over the study period. The area average variability also confirms this, indicating less variable rainfall distribution.

Fig. 3 illustrates the spatial distribution and temporal variability of seasonal and annual rainfall time series in Ethiopia's HRZs. Fig. 3a show that FMAM rainfall receiving areas, particularly HRZ_I, HRZ_III, HRZ_IV, HRZ_VI, HRZ_VII, and small parts of HRZ_VIII (southern parts of Afar, central and southwestern parts of Ethiopia) receive greater than 40 mm. In contrast, the rest get no or less rainfall. During JJAS, the Rainfall distribution strongly concentrates in the country's western, central, and northern parts. In this season HRZ_II, HRZ_III, and HRZ_VI receive greater than 160 mm annually, whereas the other places particularly the eastern half of the country and southern parts receive no or less rainfall (Fig. 3b). The annual rainfall shows plenty spread of above 400 mm in the western half of the country and limited distribution in the eastern parts (HRZ_I, HRZ_V, and HRZ_VIII) with less than 400mm (Fig. 3c). Fig. 3d demonstrates the time series variation of the average annual rainfall in the region, which ranges from 476 mm in 1984 to 780 mm in 2023. Previously, a study by (Ayalew et al., 2012) showed the annual rainfall in Amhara region of Ethiopia shows negative anomalies, particularly in the 1980s. The results of this study also coincide with their analysis, indicating that 1984/1985 was recorded as the dry years in most parts of Ethiopia, particularly in South Wollo and the Tigray region (Mera, 2018; Zeleke et al., 2017). Studies associate these dry years with ENSO effects; for example, according to Wolde-Georgis et al. (2022), the ENSO event in 2015/2016 had the strongest El Niño phenomena, causing famine and related impacts in many regions of Ethiopia than that of the 1980s.

Fig. 4 indicates seasonal and annual PNP rainfall line plots for the time series from 1981 to 2023 study period. The FMAM demonstrates significant years of dry, wet, to extremely wet years, most of the years being normal. The years, but not limited to 1984, 1992, 2009, and 2022, can be mentioned among the dry years, and the years, but not limited to 1981, 1987, 1996, 2010, 2018, 2020, and 2023, are extremely wet years experienced during this season. The JJAS shows mostly normal rainfall distribution of 80 to 100%, except in notable very humid years (eg, 1988, 2007, 2019, and 2020). The annual rainfall experienced a dry year in 1984 and extremely wet years during 1998, 2019, and 2023. Generally, the annual rainfall experiences normal conditions during the study period based on the above-mentioned PNP classes. According to Kiros et al., (2016)'s analysis in Geba river in northern Ethiopia, which coincides with the current results, the

years 1984,1992,2000, and 2009 are among the dry periods mentioned by negative anomalies of rainfall relative to the climatological record.

The uneven spatial distribution of rainfall over Ethiopia is shown in Fig. 5 by using CV and PNP metrics. Fig. 5a indicates that the FMAM rainfall during the study period was highly variable, with $CV > 30\%$ in the northwest (HRZ_I) and northeast (HRZ_II) parts of Ethiopia and less variable $CV < 15\%$ the southwest parts (HRZ_III, HRZ_VI, and HRZ_VII). whereas in JJAS rainfall is less variable throughout the country except in some southeast tip parts of HRZ_VIII. The annual rainfall variability depicts a similar pattern to the JJAS season; however, it gets an extension of covering the whole HRZ_VIII indicating that yearly rainfall over the zone is more variable compared to the JJAS. Similarly, Fig. 5b illustrates that during FMAM most parts of the country received below-normal rainfall except some pocket areas of northeast (a portion of HRZ_I) and south Ethiopia (HRZ_VIII) which experience above-normal (Wet) conditions. On the other hand, during JJAS most parts experience normal conditions except northeast and southwest (HRZ_III, HRZ_VII, and HRZ_VIII) which, experience dry conditions, and north most tip (HRZ_II) and south parts (HRZ_VI and HRZ_VIII) which experience humid conditions. The annual rainfall is still similar to the JJAS keeping most areas experiencing normal rainfall as indicated by the PNP.

4.1.2 Rainfall Trends Analysis

Table 3 displays the seasonal and annual rainfall trends of the HRZs in Ethiopia for the 1981 to 2023 periods. FMAM rainfall was generally reduced with a significant reduction in HRZ_V with about 1.7 mm, whereas rainfall in HRZ_II and HRZ_III had increased. The rate of increasing rainfall is significant only in HRZ_III, with a magnitude of about 1.2 mm per year. The JJAS rainfall had increased in all HRZs over all of Ethiopia. In this season, the rainfall increase was significant in HRZ_I and HRZ_III with a magnitude of 2.0 and 1.3 mm per year, respectively. Similarly, the annual rainfall shows an upward trend over all of Ethiopia except HRZ_V which was downward. The trend is significant in HRZ_III and HRZ_VII, with amagnitude of 3.7 and 6.4 mm per year, respectively. Both seasonal and annual rainfall express a significant increase in HRZ_III, which covers the west-central part of Ethiopia. This could be an indicator that the JJAS (long rain season) benefiting regions of western Ethiopia are also getting plenty of rainfall during the FMAM (short rain season).

Accordingly, it can be noted that both seasonal and annual scales have indicated a robust and significant increase of rainfall particularly with in the HRZ_III, which cover the west-central and southwest parts of Ethiopia. These results indicate that the regions in western Ethiopia that JJAS is their main rain season are also experiencing significant wetting trends during the FMAM, which is the second rain season, representing a distinct sub-regional climate shift. The current findings are consistent with previous results the of Williams & Funk, (2011) which reported that the decrease in FMAM rainfall in east Africa could be linked to the eastward movement of the circulation pattern created above the Indian ocean. Most previous rainfall trend studies in different geographical regions of Ethiopia e.g. (Declan Conway & Woldeamlak, 2007; Seleshi & Zanke, 2004) found no significant or clear trend of seasonal and annual rainfall. Whereas, (D Conway, 2000) identified that the rainfall in the Upper Blue Nile basin of Ethiopia have markedly decreased in the 1990s compared to the 1980s. Cheung et al., (2008) found a notable increase in rainfall during the JJAS in the central and southwestern portions of the country, which agrees with the JJAS rainfall trend of this study, that the whole study area (all HRZs) shows an increasing trend, which is significant in two HRZs. On the other hand, Aforki, (2012) found a declining in annual rainfall of all the locations analysed in the Giba River basin in northern Ethiopia, except one station showing an increase.

4.2 Drought Patterns Analysis

This section provides a spatiotemporal analysis of drought patterns in different HRZs over Ethiopia from 1981 to 2023. The drought is investigated using RAI and SPI.

4.2.1 RAI Analysis

Fig. 6 shows the study area's seasonal and annual drought conditions using the RAI from 1981 to 2023, indicating the dry and moisture rich periods. The seasonal RAI demonstrates that the current study area exhibited both extremely dry and extremely wet conditions while the near-normal conditions dominated during the study period (Fig. 6a & Fig. 6b). Most of the HRZs experience similar patterns of dry (eg, FMAM 2009 & 2022 and JJAS 1987 & 2009) and wet (eg, FMAM 1987 & 2011 and JJAS 1988 & 2007) conditions. Similarly, the annual RAI exhibited dry and wet conditions. The historical drought years of 1984, 2015, and 2022 are well portrayed in Fig. 6c. The years 1982, 1997, and 2020 are among the wet years experienced in most of the HRZs. The area-

averaged RAI shows the occurrence of dry and wet conditions interchangeably (Fig. 6d). Accordingly, for the annual RAI, twenty years showing a positive value of RAI, starting from extremely humid to humid, and twenty-three years showing a negative value of RAI, starting from extremely dry to dry, were noted. During the 43 years under investigation, the amount of drought years and rainy years is roughly equal. The years 1984 and 2009 are among the notable extremely dry years, whereas 1997, 2019 and 2023 are among the extremely humid years based on the annual RAI. As shown in Fig. 6d the drought event in the 1984 was worst predominantly in the northern half of the country, however the impact was experienced in all HRZs.

Fig. 7 shows the spatial patterns of RAI for the seasons of water scarce and excess rainfall when averaged during the whole period under investigation. The RAI intensity shows that almost all HRZs experienced dry conditions in the seasonal and annual timescales during the year 2009, except some pocket areas of HRZ_III & HRZ_VII in FMAM; HRZ_I, HRZ_III & HRZ_IV in JJAS; and HRZ_III & HRZ_VIII in the annual time scales that experience moderately wet conditions (Fig. 7a). On the other hand, during the wettest year 2020, most areas exhibit wet conditions except limited areas that exhibit dry conditions during the FMAM, JJAS, and Annual periods (Fig. 7b). Generally, the intensity of RAI, as shown in Fig. 7c, reveals that the central and northern (HRZ_I, HRZ_II, and HRZ_III) parts of the investigated area experienced dry situations in FMAM. At the same time, the rest exhibited wetness when averaged over the whole study period. Similarly, in JJAS, the study area exhibited dry and wet situations, the dry conditions being strong at the country's central belt (HRZ_III, HRZ_IV, and HRZ_V). JJAS is the main rain season in the northern and north western (HRZ_I, HRZ_II, and HRZ_III) parts of the country. During this season the tropical rain belt of the ITCZ is located in its north most location, above northern Ethiopia (Leroux, 2001). The annual RAI intensity shows that the north-eastern, south-eastern, and southwestern parts experienced more pronounced dry conditions than other parts. The results agree with previous studies of (Mekonen et al., 2020; Mohammed et al., 2018) whose research identified that the north-eastern portions of Ethiopia as areas that are susceptible to droughts. This is an implication of the impact in the erratic nature of the rainfall in this arid or semiarid areas where water availability is already less reliable, creating severe agricultural stress.

CHIRPS-based spatiotemporal analysis of RAI significantly extracts the dry and wet conditions of the HRZs. A study by (Lemma et al., 2022) had previously found a clear identification of the rainfall deficit and rainfall surplus years in different regions of Ethiopia by using RAI.

4.2.2 SPI Analysis

The evaluation of seasonal drought using SPI exhibits the existence of drought events through the analysis time. Based to the SPI-3 results, there have been drought events in every decade (Fig. 8). The years 1984, 1998, and 2011 experienced extremely dry conditions, while many years experienced severely dry to moderately dry events. On the other hand, the years 1981, 1989, 1999, 2019, 2020, and 2023 experienced extremely wet conditions. Similarly, the SPI-6 and SPI-12 revealed dry conditions during 1984, 1990, 1992, 2002, 2009, and 2011 while wet periods were noted during the years 1998, 2007, 2017, 2020 and 2023. The present -drought pattern findings are consistent with previous investigations on spatial and temporal droughts in Ethiopia by (Lemma et al., 2022; Yisehak & Zenebe, 2021) who found similar patterns of drought and mentioned the years 1984 and 2011 as the worst drought years across many river basins of Ethiopia.

While SPI analysis at the annual time scale gives insights into dry and wet conditions experienced, the seasonal SPI analysis gives detailed information on dry events that may remain hidden in the annual timescales during the investigated period. The presence of severe or extreme dry episodes is not evident from the annual scale analysis of SPI-3 and SPI-6 indicators over the study domain (Fig. 8a). For both the annual and seasonal levels, the analysis of SPI-3 and SPI-6 exposed the presence of rainfall variations with an overall rising extent beginning in the 1990s. Nonetheless, it is evident from the seasonal analysis that the study domain saw extremely dry occurrences during FMAM (Fig. 8b) and moderate wet events during JJAS (Fig. 8c).

Fig. 9 illustrates the annual timescale drought for the eight homogeneous zones. The results reveal that the HRZs located in the northern and central parts of the country experienced extremely dry conditions as compared to the eastern and south eastern shares.

Important information about the dry and wet occurrences may be obscured by the results of short-term indicators (SPI-3) findings aggregated across the study region. To better understand the drought occurrences throughout Ethiopia, this study examined the dry and wet conditions across various seasons, topographical units, and regions. For this reason, Fig. 10 illustrates the seasonal and annual drought occurrences for the individual

homogeneous zones and averaged throughout Ethiopia. As shown by Fig. 10a, the FMAM drought is characterized by frequent drought occurrences during the starting decades (1981-2000) at the HRZ_II, HRZ_III, and HRZ_VII whereas for the HRZ_I, HRZ_IV, HRZ_V, HRZ_VI, and HRZ_VIII the drought occurrence was more frequent during the late decades (2000-2023). The area's average drought shows more frequent dry conditions from 1998 up to 2012. The identified dry years are consistent with the results of (Liou & Mulualem, 2019) identify the years 2002, 2003, 2004, 2009, 2010, and 2012 as dry years for the north, central, west, and southwest location in Ethiopia.

Likewise, in JJAS, the dry periods are concentrated mostly during 1981-2005, except in HRZ_IV, which shows a balanced dry condition in both halves (Fig. 10b). Averaged over all of Ethiopia, the dry conditions are more severe and frequent in the first 20 years as compared to the latter years. Most of the drought years during this rainy season are associated with El Niño effects, as it suppresses the moisture transport to East Africa and related regions. During the positive Enso phase (El Niño), the country experiences a deficit in rainfall, leading to droughts, particularly in the north western regions of Ethiopia (Gleixner et al., 2017; Korecha & Barnston, 2007). The years 2009/2010 and 2014/2015 are among the notable El Niño phases, where JJAS rainfall in many parts of Ethiopia gradually declined and remained below average (Liou & Mulualem, 2019). However, there are regions in the south and south eastern (HRZ_VI and HRZ_VIII) parts of the country in which JJAS is not a rainy season, and hence the effect of El Niño is low. Korecha & Barnston, (2007) noted that the occurrence of dry conditions in the JJAS causes more sever effects in the north as compared to the south where no much rain is expected in this season.

Fig. 10c presents the annual dry and wet event occurrences of the HRZs averaged over Ethiopia. HRZ_III, HRZ_VI, HRZ_VII, and HRZ_VIII show moderately dry to severely dry events, whereas HRZ_I, HRZ_II, HRZ_IV, and HRZ_V experienced severely dry to extremely dry conditions. Notably, modest to extreme wet events are also recorded across the homogeneous zones. The spatial average annual SPI shows that the years 1984, 2002, and 2009 are from the worst dry periods in Ethiopia, whereas the years 1997, 2006, 2019, 2020, and 2023 are recorded as wet years. The study findings are in line with the outputs of Viste et al., (2013) whose drought analysis using grid-based rainfall data set in Ethiopia revealed that large-scale drought years occurred particularly during 1984, 2002, and 2009.

The incidence of drought at different areas of the HRZs shows high variability from year to year and zone to zone, revealing high seasonal and annual rainfall variation among the zones. In some years, drought periods, such as 1984 and 2009, the drought persisted throughout the country; however, in other years, such as 1999, 2002, and 2015, the drought event mostly affected specific regions or particular localities. Consequently, there was no HRZ without drought experience at seasonal or annual scales during the investigated period. Viste et al., (2013) noted that in some years, drought occurs all over Ethiopia for the seasonal and annual timescales. To this end, the consequence of rainfall shortness on agriculture during the seasonal and annual time scales is considerable. Hence, these seasonal and annual rainfall shortages accompanied by the rainfed-agricultural failure denominate Ethiopia as the drought-prone country in the world (Mera, 2018).

4.3 Drought Characteristics

Analysis of the meteorological drought characteristics allows us to recognize the spatial-temporal extent, severity, together with the frequency of drought conditions. Table 4 and Table 5 show the characteristics of the drought occurrences that experienced from 1981 to 2023. The investigation exposed that drought events last from one year to seven years in a row (Table 4). The consistent longest drought events of seven years were 1999, 2000, 2002, 2003, 2004, and 2005. The findings also revealed that the severe historical dry periods of 1984 and 2002 were accompanied by drought years before and after. The dry year 2009, which was preceded and followed by wet years, is exceptional. Generally, the drought during the study period varies from a minimum of 1 year and maximum of 7 years in most parts of Ethiopia.

Studies indicate that the 1983-1986 consecutive dry years destroyed the lives of thousands of farmers, livestock, and associated products in southern Tigray and North Wello (Gidey et al., 2018; Segele & Lamb, 2005; Viste et al., 2013). Previously, Degefu, (1987) highlighted the interaction between tropical and midlatitude low pressure systems which is interrupted by a pressure anomalies over the Sahara and Arabian peninsula during Spring (FMAM) could be responsible for the 1984 nation wide drought. On the other hand Segele et al., (2009) noted the atmospheric anomalies during dry summers (JJAS) could be associated to weaker than normal low-level east African jet, leading in to less moisture transport from the Indian ocean.

Table 5 shows the severity, frequency, and spatial coverage of drought episodes that occurred from the 1981-2023 study period. The results reveal that meteorological drought has occurred across all HRZs. Accordingly, HRZ_I, HRZ_II, HRZ_IV, and HRZ_V experienced extreme drought events at least once, whereas HRZ_III, HRZ_VI, HRZ_VII, and HRZ_VIII did not. The study results agree with the findings of Viste et al., (2013), which noted the year 1984 is the most severe year to the northern half of the country. Similarly, all HRZs except HRZ_IV experienced severe drought, and all HRZs except HRZ_V experienced moderate drought. On the other hand, mild drought occurred at all HRZs ranging from 11 to 23 times. The extreme droughts were more frequent at HRZ_IV and HRZ_V, occurring 3 times for each zone during the study period, while the spatial extent is relatively medium in comparison to the HRZ_VIII, which covers a great area. However, the most frequent drought event experienced in the zone is Mild drought.

5. Conclusions:

Meteorological drought characteristics of eight homogeneous regions in Ethiopia have been analysed by using a remote sensing-based precipitation dataset (CHIRPS) and RAI and SPI drought indices for the 1981-2023 study period. The findings reveal significant variability in space and time in both rainfall patterns and drought occurrences. Seasonal and annual rainfall at HRZ_III was significantly increasing, whereas FMAM rainfall showed a significant decrease at HRZ_V. The findings suggest an increasing annual rainfall during 1981-2023, particularly in the western and central regions, which may influence future drought patterns and agricultural productivity.

The investigation revealed that meteorological drought analysis using RAI and SPI for individual homogeneous rainfall zones provides more consistent drought information than averaged over the whole of Ethiopia. The analysis highlighted critical periods of drought, notably in 1984, 2009, and 2022, alongside wet years such as 1997, 2019, and 2023. Hence, the drought indices calculated in this study agreed with the seasonal and annual historical drought records except for some parts of the country. The application of the SPI provided a robust framework for classifying drought severity, revealing that all zones experienced varying degrees of drought, with extreme dry conditions documented primarily in the HRZ_I, HRZ_II, and HRZ_VIII regions.

Furthermore, the study underscored the importance of utilizing a remote sensing data set (CHIRPS) in monitoring drought dynamics, emphasizing its role in informing

management of water resource, irrigation planning, and climate coping strategies in Ethiopia. The research contributes valuable insights into the complexities of drought in Ethiopia, highlighting the necessity of continuous assessments and strategies to adapt and mitigate the pressing impacts of drought on communities and ecosystems.

Finally, based on the current findings, region specific drought adaptation strategies should be prioritized, particularly in north-eastern areas where drought is more frequent and severe. These may include the promotion of drought tolerant crops, improved irrigation systems, and soil moisture conservation practices in north-eastern areas (HGZ_I). Conversely, considering double cropping window and small-scale water harvesting schemes are suggested in the west-central highlands (HRZ_III) in response to the wettening during the Belg season. There is a critical need to strengthen climate information and early warning systems through the integration of remote sensing rainfall products, where, CHIRPS can provide a concrete blueprint for local climate zones. Improved forecasting and timely dissemination of climate information will support better preparedness and response planning for farmers and local authorities.

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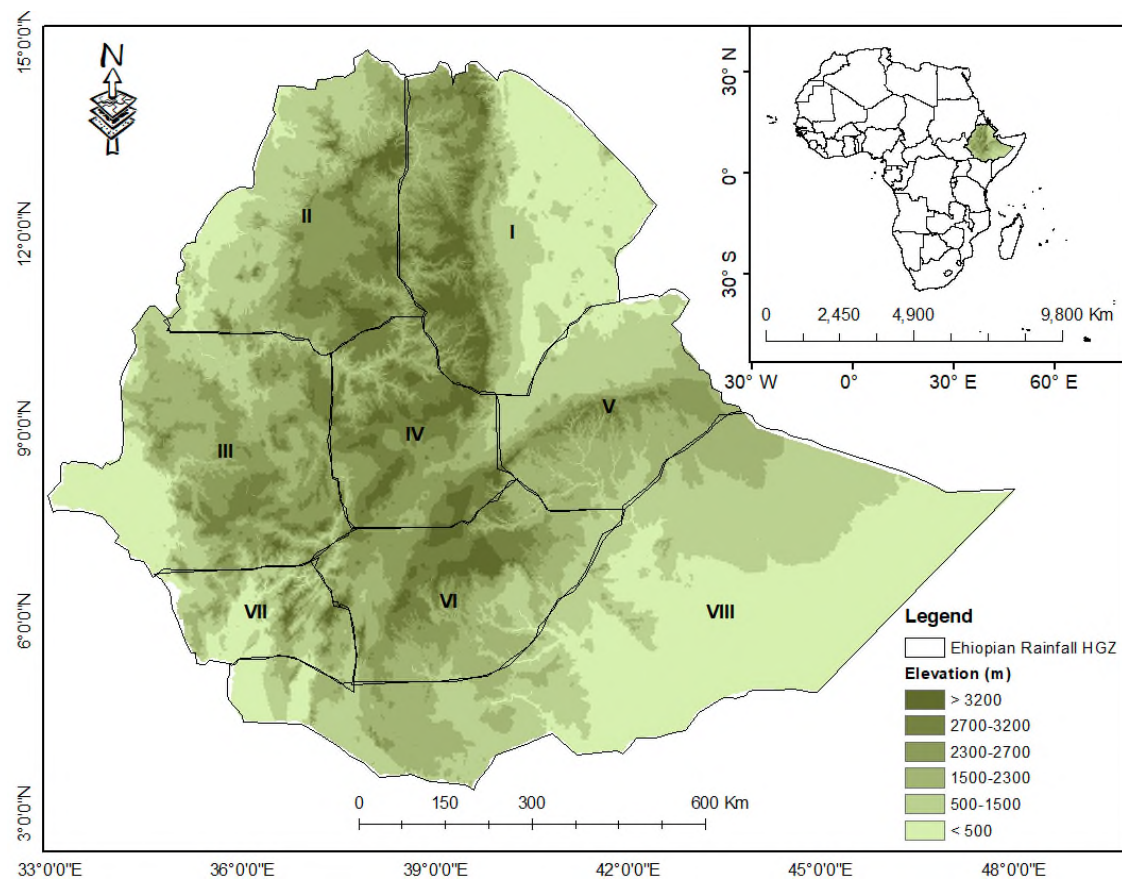


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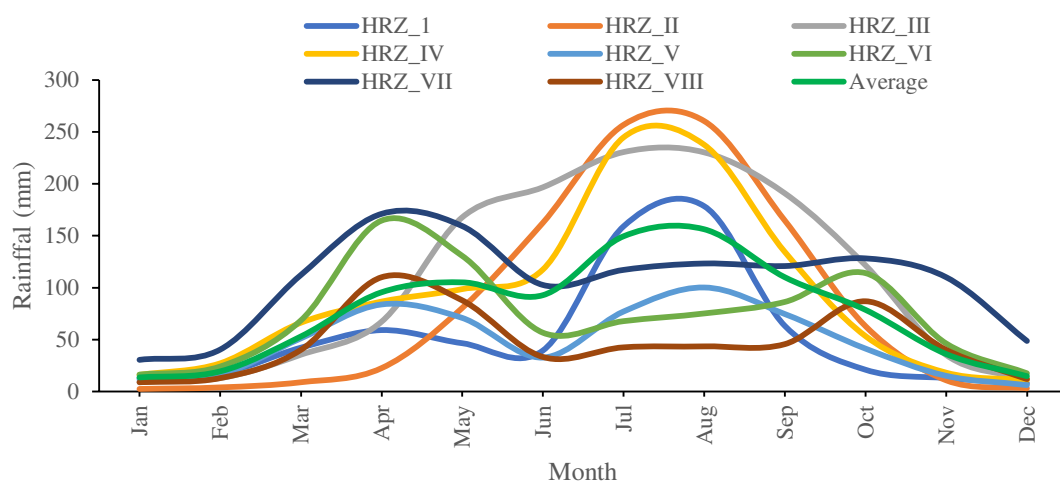


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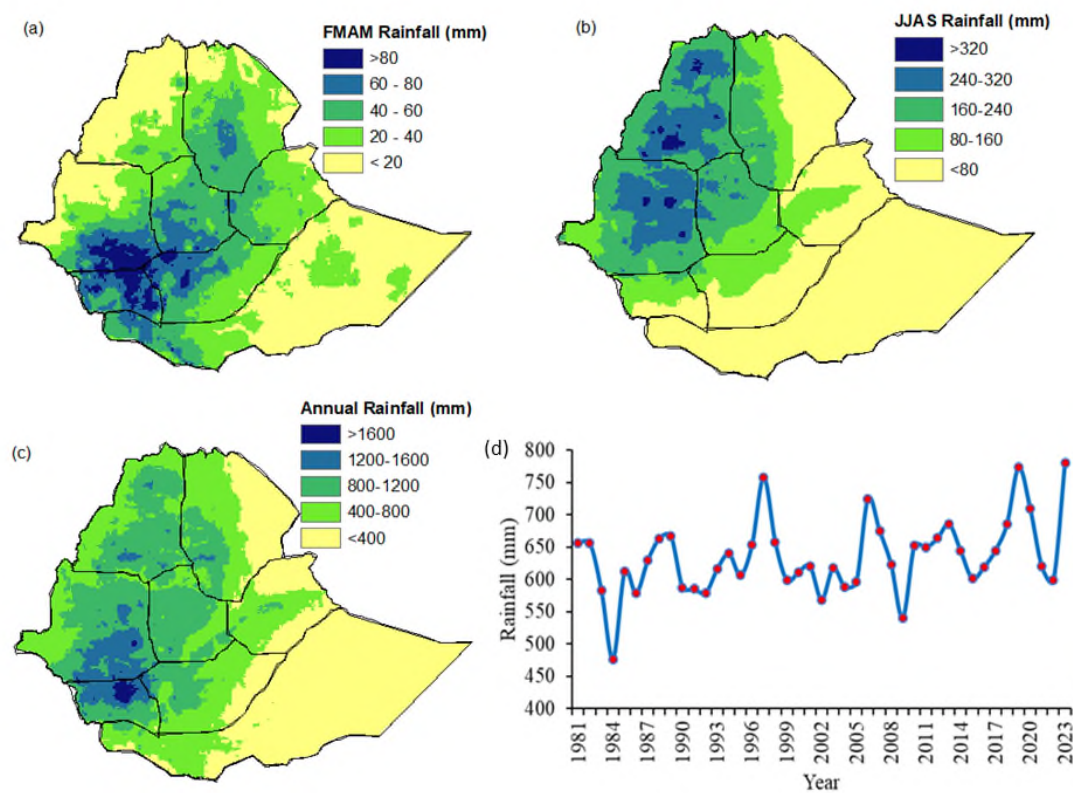


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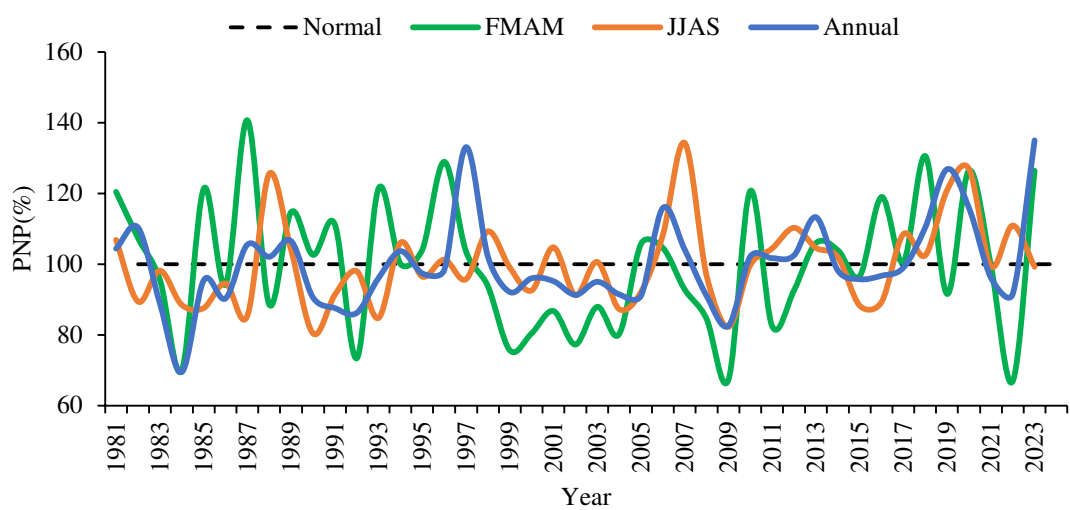


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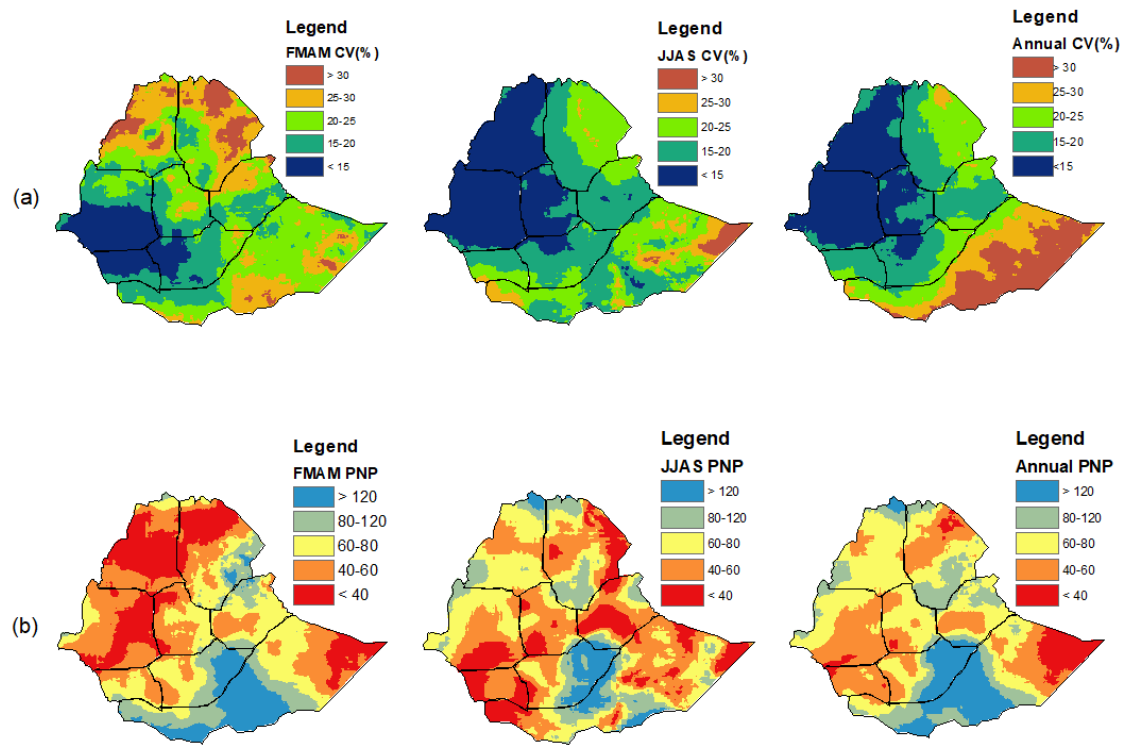
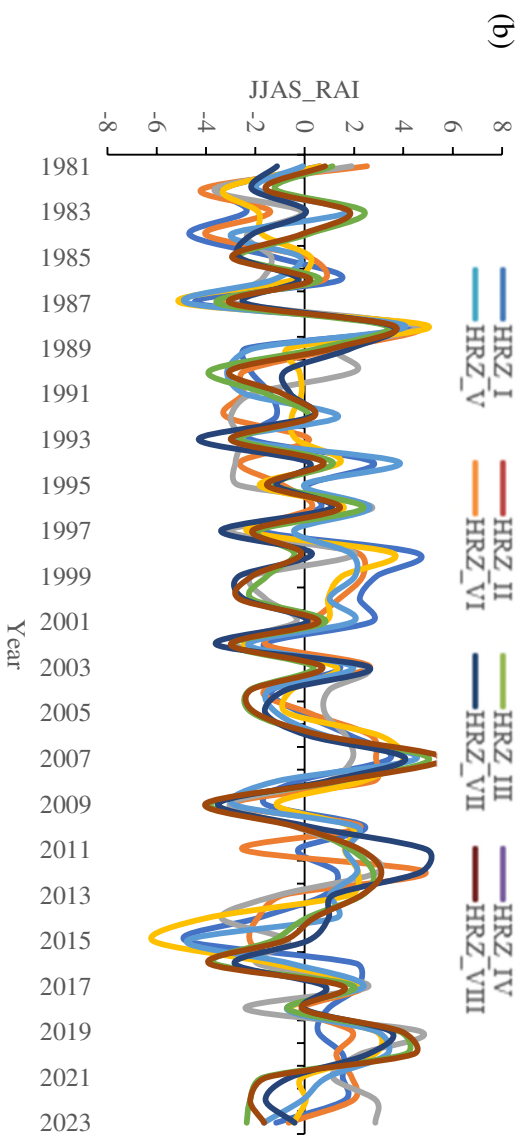
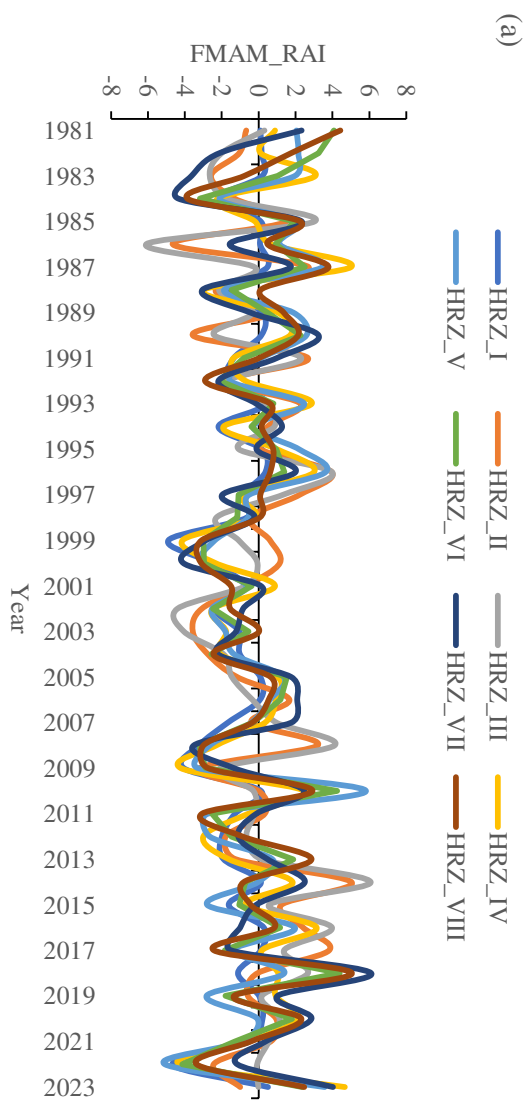


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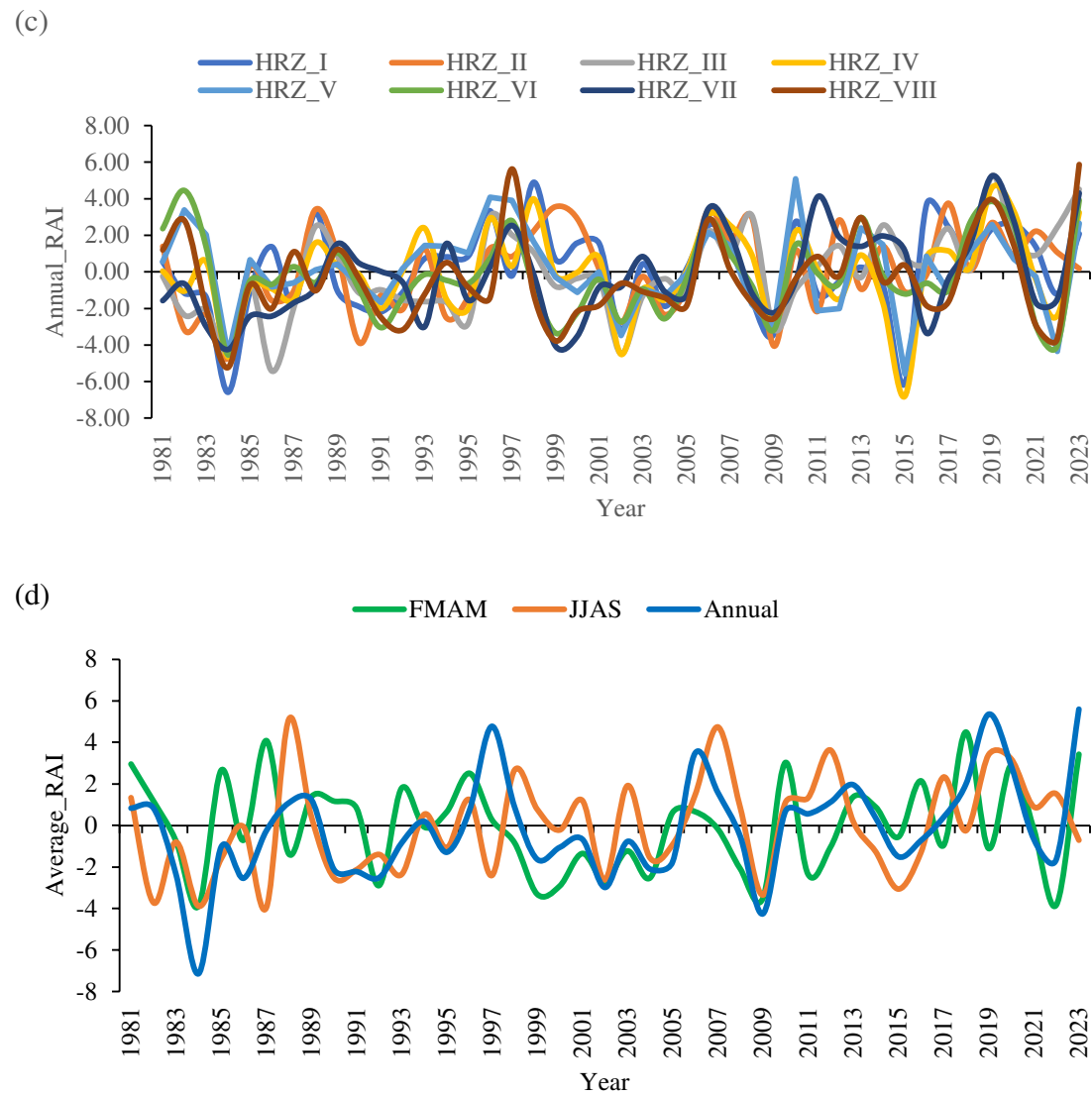


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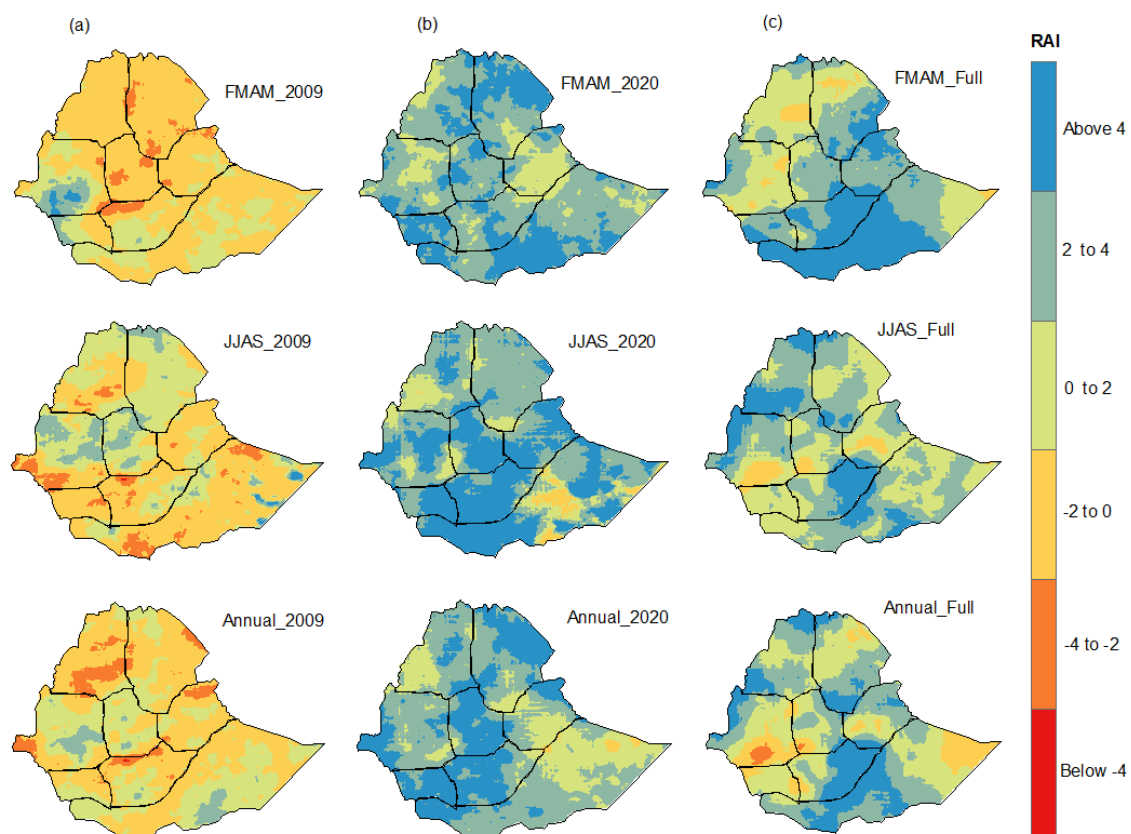
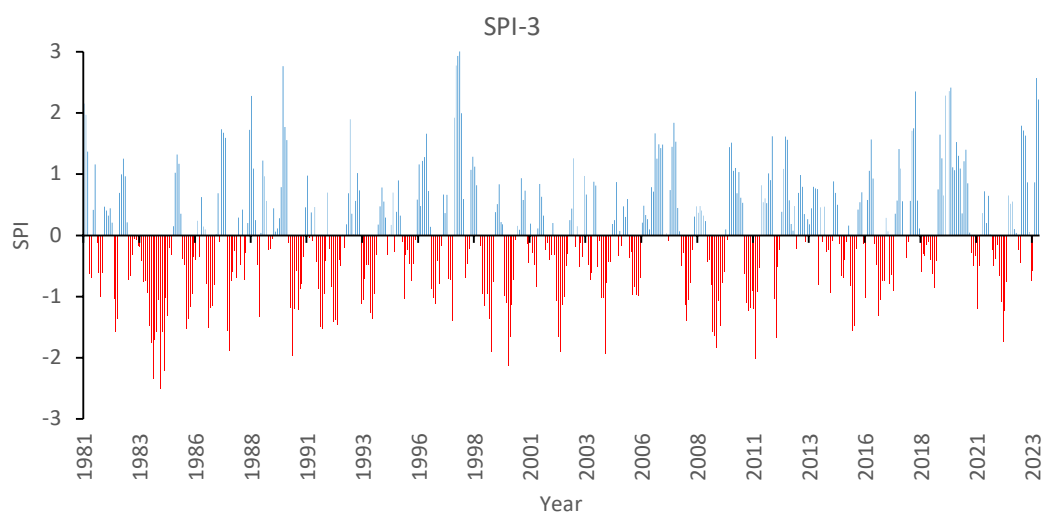


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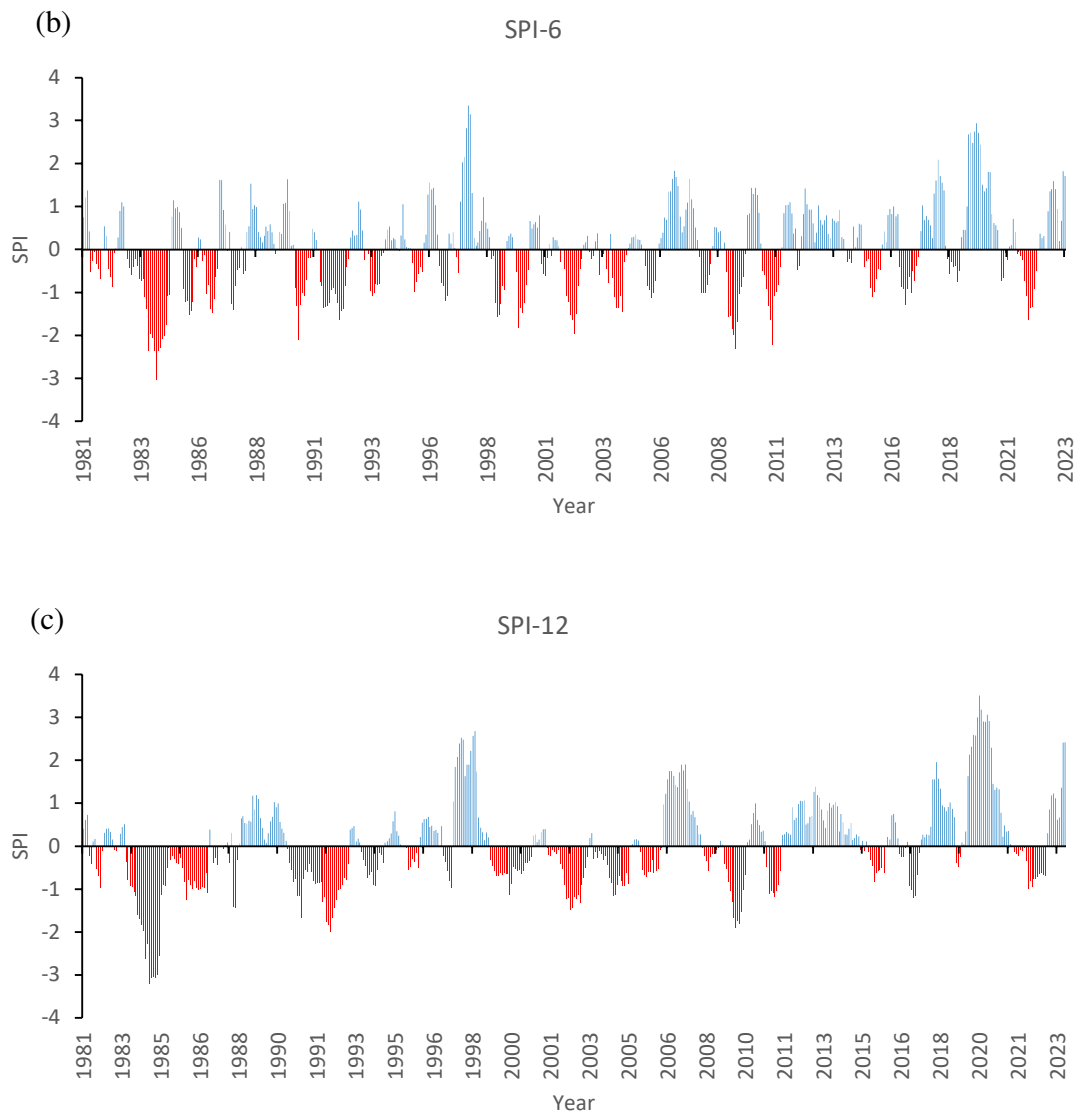


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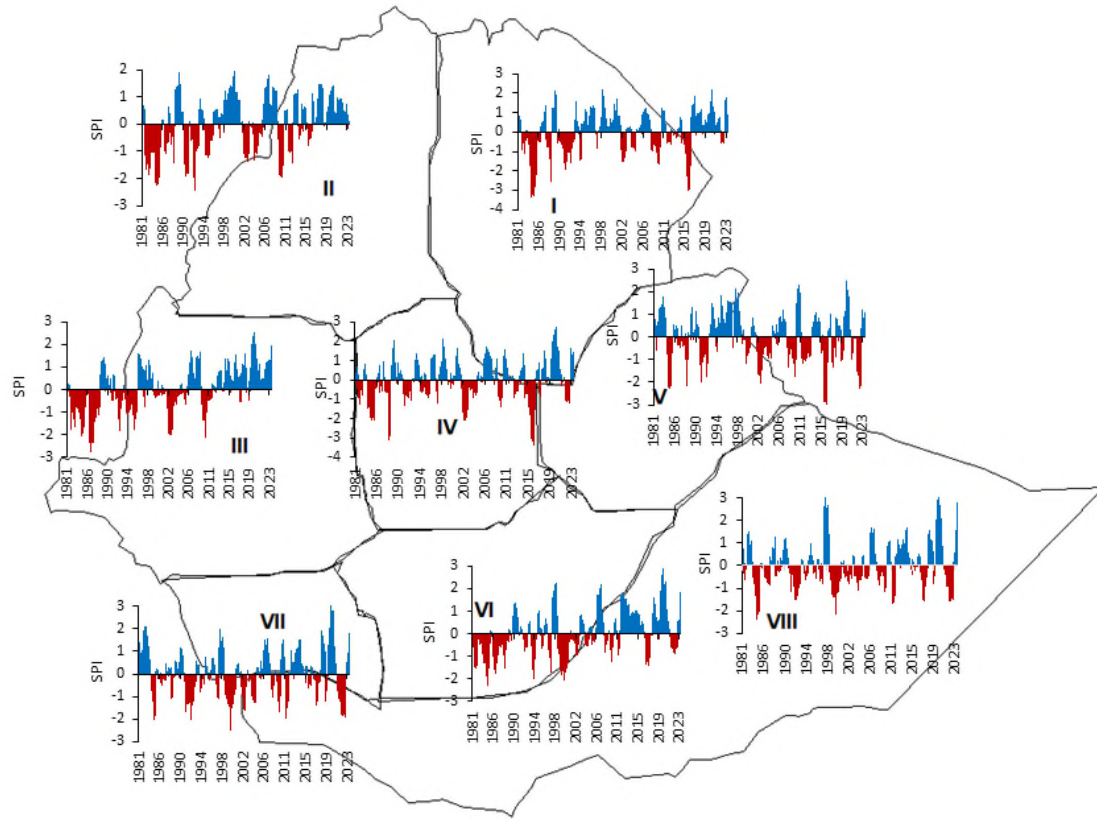


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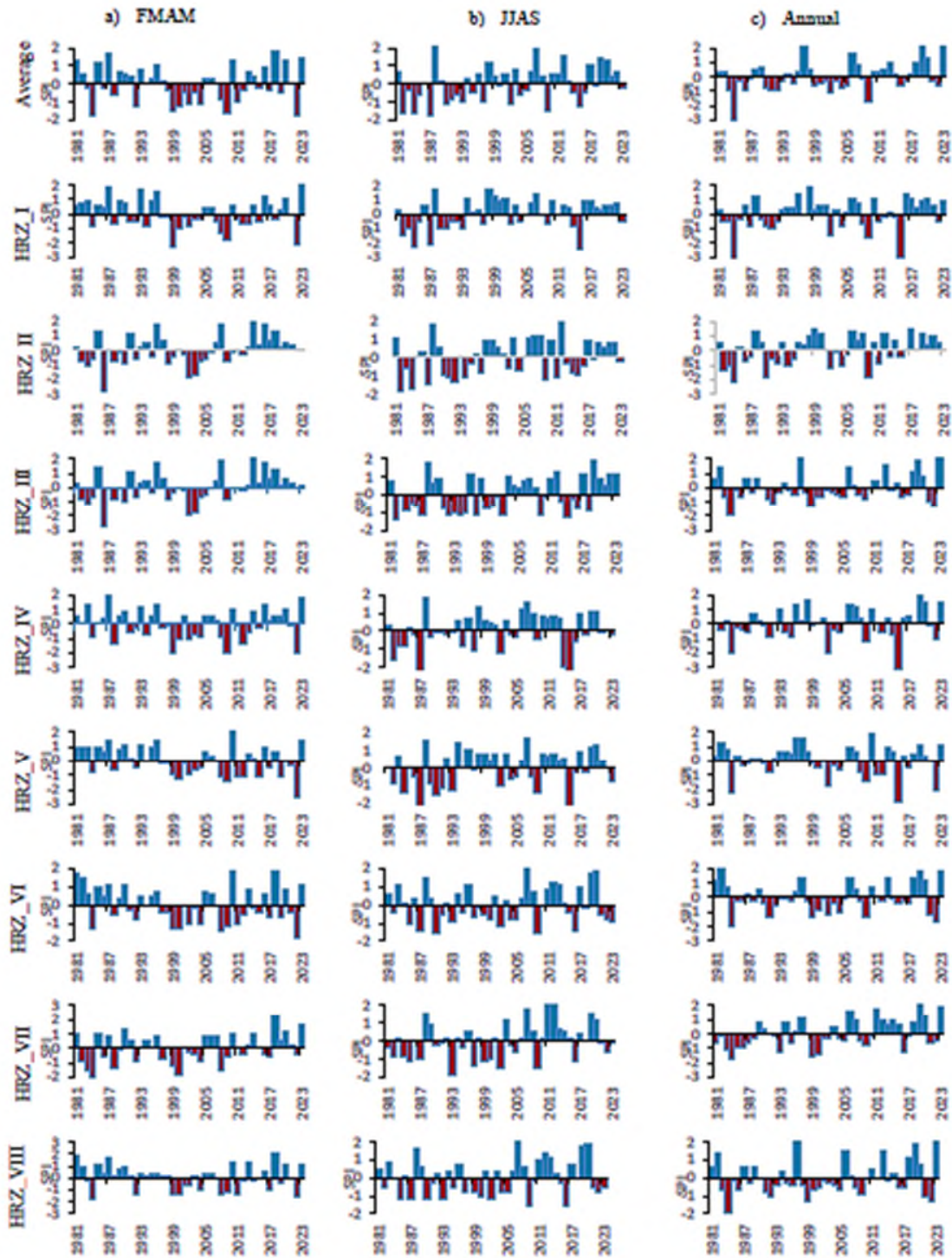


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Table 1. Overview of drought and non-drought conditions classifications based on the RAI and SPI frameworks.

Category	<i>RAI class</i>	SPI class
Extremely dry	$RAI \leq -4.00$	$SPI \leq -2.00$
Severely dry	$-3.99 < RAI \leq -3.00$	$-1.99 < SPI \leq -1.50$
Moderately dry	$-2.99 < RAI \leq -2.00$	$-1.49 < SPI \leq -1.00$
Near normal	$-1.99 < RAI \leq 1.99$	$-0.99 < SPI \leq 0.99$
Moderately wet	$2.00 < RAI \leq 2.99$	$1.00 < SPI \leq 1.49$
Severely wet	$3.00 < RAI \leq 3.99$	$1.50 < SPI \leq 1.99$
Extremely wet	$RAI \geq 4.00$	$SPI \geq 2.00$

Table 2. Statistical description of seasonal as well as annual rainfall in the eight homogeneous zones and averaged over the whole of Ethiopia during 1981 to 2023.

Season	Stat.	HRZ_I	HRZ_II	HRZ_III	HRZ_IV	HRZ_V	HRZ_VI	HRZ_VII	HRZ_VIII	Average
FMAM	Min	76.2	45	166.7	164.1	94.7	249.1	322	162.9	194.1
	Max	268.3	197.8	418.9	415.7	377.9	551.6	705.1	361.9	394.5
	Mean	164.6	116	283.4	278	223	386.1	478.3	248.7	272.3
	Std	45.8	35.5	49.1	61.8	61.3	78.9	84.9	51.2	45.3
	Cv(%)	27.8	30.6	17.3	22.2	27.5	20.4	17.8	20.6	16.6
JJAS	Min	283.1	720.7	773.2	521.7	187.4	228.8	296.7	135.2	414.5
	Max	572.3	984.2	954.8	877.5	359.3	376.4	684.2	208.3	610.6
	Mean	438.1	843.7	848.4	732.2	282.4	285	459.6	164.3	506.7
	Std	72.3	68.6	52.5	74.6	43.2	37.8	95.5	17.9	47
	Cv(%)	16.5	8.1	6.1	10.2	15.3	13.3	20.8	10.9	9.3
Annual	Min	446.5	850.3	1102.3	855.3	387.2	679.1	957.9	408.6	730.2
	Max	796.4	1174.1	1516.2	1284.9	730.5	1082.9	1695.7	808.8	1100.3
	Mean	657.1	1039	1309.2	1108.3	579.1	865.2	1255.1	560.7	921.7
	Std	73.1	86.2	89.7	87.8	74.7	99.9	179.2	84.4	71.8
	Cv(%)	11.1	8.3	6.9	7.9	12.9	11.5	14.3	15	7.8

Table 3. Trend results of the homogeneous rainfall zones for seasonal and annual rainfall over 1981-2023.

Time	Trend	HRZ_I	HRZ_II	HRZ_III	HRZ_IV	HRZ_V	HRZ_VI	HRZ_VII	HRZ_VIII
FMAM	Z	-0.774	0.733	2.512	-0.073	-2.302	-1.214	1.737	-1.214
	P	0.439	0.464	0.012	0.942	0.021	0.225	0.082	0.225
	ss	-0.550	0.380	1.223	-0.085	-1.667	-1.533	1.800	-0.903
JJAS	Z	1.968	1.800	2.093	1.549	1.402	0.251	1.654	0.733
	P	0.049	0.072	0.036	0.121	0.161	0.802	0.098	0.464
	ss	1.955	1.732	1.335	1.563	0.710	0.167	1.892	0.154
Annual	Z	1.371	1.915	3.830	1.235	-0.377	0.167	2.784	0.879
	P	0.170	0.055	0.001	0.217	0.706	0.867	0.005	0.379
	ss	1.268	2.251	3.726	1.200	-0.523	0.174	6.423	0.864

Note: values designated in bold indicates significant trend at 95% level of confidence.

Table 4. Breakdown of meteorological drought start date, end date, duration, magnitude e, and intensity.

Start	End	Duration	Magnitude	Intensity
1983	1986	4	-1.08	-0.27
1990	1993	4	-0.74	-0.19
1995	1995	1	-0.21	-0.21
1999	2005	7	-0.48	-0.07
2009	2009	1	-0.78	-0.78
2015	2016	2	-0.11	-0.06
2021	2022	2	-0.46	-0.23

Table 5. Analysis of drought characteristics across the HRZs from 1981 to 2023.

HRZs	Extreme		Severe		Moderate		Mild		Coverage (%)
	Drought	%	Drought	%	Drought	%	Drought	%	
HRZ_I	2	4.6	1	2.3	1	2.3	15	34.9	14.6
HRZ_II	1	2.3	2	4.6	5	11.6	11	25.6	12.6
HRZ_III	0	0.0	1	2.3	4	9.3	23	53.5	14.7
HRZ_IV	3	7.0	0	0.0	2	4.6	14	32.6	7.5
HRZ_V	3	7.0	2	4.6	0	0.0	14	32.6	8.2
HRZ_VI	0	0.0	2	4.6	6	14.0	19	44.2	9.6
HRZ_VII	0	0.0	2	4.6	4	9.3	18	41.9	4.5
HRZ_VIII	0	0.0	1	2.3	4	9.3	23	53.5	28.2