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Changing rainfall and temperature trends and variability at different Spatiotemporal scales threaten coffee production in certain elevations

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ABSTRACT

Local-scale analysis and understanding of long-term spatio-temporal climatic patterns are crucial for designing site-specific climate change adaptation strategies in the Ethiopian Arabica coffee context. We conducted a comprehensive examination of long-term spatio-temporal trends and variability of rainfall and temperature during different phenological stages of Arabica coffee growth across elevation zones in five major coffee-growing districts of southwestern Ethiopia. Employing Mann–Kendall tests, Sen's slopes, coefficients of variation, and anomalies, we identified a significant increasing trend ($P \leq 0.05$) in mean annual and seasonal rainfall at a rate of 5.09, 5.43, 6.44, 6.49, and 6.26 mm/year for Ale, Yayu, Gera, Goma, and Limu Seka respectively, accompanied by year-to-year variability. Maximum and minimum temperatures exhibited a similar increasing trend and year-to-year variability across all study sites and altitude zones. Minimum temperature increased at a similar rate of 0.2 °C per decade in all districts, while maximum temperature increased at a rate of 0.2 °C/decade for Ale and 0.3 °C /decade in Gera, Goma, Limu Seka, and Yayu. High- and mid-altitude areas of three of our study sites (Ale, Gera, and Goma) are already experiencing conditions outside optimal coffee production ranges, as rainfall has exceeded ideal conditions. Should the current trends persist, however, other areas are at risk, as rising variability in the mean amount of rainfall and temperature can disrupt coffee phenological stages, reducing yield and quality. The increasing trend of maximum and minimum temperatures has already been identified as a threat to lowland and midland coffee-producing areas, with some hoping that the highlands might be a refuge for coffee production in the future. Unfortunately, changing rainfall patterns also threaten coffee production in the highlands in our study areas. Our results suggest the importance of local-scale analysis and a clear understanding of specific contexts using fine-resolution gridded climate datasets in areas where weather stations are scant and sparsely distributed.

Introduction

Ethiopia is renowned as the origin and a significant producer, consumer, and exporter of premium-quality Arabica coffee (*Coffea arabica* L), and the inherent quality of coffee produced across elevation zones have garnered global attention (ECFF and Kew Garden, 2017; Moat et al., 2017). In 2021, the country harvested approximately 456,000 tons of green beans from 685,000 hectares (FAOSTAT, 2021). Coffee accounts for 30–35 % of Ethiopia's foreign exchange earnings, constituting an average of 5 % of its gross domestic product (GDP) and 10 % of total agriculture production. It is a crucial source of livelihood for 25 % of the country's population (Olana Jawo et al., 2023).

Yet Ethiopia's coffee sector faces imminent threats from climate change (Bunn et al., 2015; Chemura et al., 2021). While climate change impacts diverse human activities, with agriculture being particularly affected (Asfaw et al., 2018; Abegaz, 2020a), coffee is one of the most

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climate-sensitive plants (DaMatta et al., 2019; Hein et al., 2019), and coffee producers confront challenges in regions experiencing warming and heightened meteorological variability (Yang et al., 2020). High rainfall variability, insufficient rainfall, and temperatures outside the optimal range can disrupt both yields and quality (Kath et al., 2021). Climate change may also upend the geography of suitable cultivation areas and increase vulnerability to pests and disease (Kassie et al., 2015).

Similarly to coffee producers elsewhere, growers in East Africa contend with these challenges (Davis et al., 2012; Moat et al., 2017; Sisay, 2018), and their production performance is strongly correlated with temperature and rainfall variability and trends (Bunn et al., 2015). Indeed, climate-driven transformations will likely reshape which areas are suitable for coffee production, as well as the yield and quality of remaining production areas (Davis et al., 2012; Craparo et al., 2015; Ahmed et al., 2021; Kath et al., 2021). Increasing maximum temperatures, for example, could threaten coffee production at lower and mid-altitude ranges (Jaramillo et al., 2009).

While there has been much work on the future of coffee under climate change at the global and national scales, Ethiopia has a quite diverse geography (Fazzini et al., 2015), with temperature and rainfall affected by elevation patterns in ways that may not be well captured by data from meteorological stations alone. Rainfall, for example, is closely linked to topography and other biophysical factors at the local scale, resulting in significant variability across small distances (Osima et al., 2018; Steeneveld, 2014). As a result, a better understanding of the local-scale variation in climatic patterns that are likely to shape coffee farmers' livelihoods would be helpful for designing and implementing location-specific climate change adaptation interventions (Bracken et al., 2023; Mulugeta et al., 2019).

This study, therefore, aims to document recent local trends and variability in rainfall and temperature across altitude ranges in five coffee-producing districts in southwestern Ethiopia. We have three primary objectives: 1) assess local-scale trends and variability in rainfall and temperature; 2) differentiate these patterns across altitudes and seasons relevant to coffee production; and 3) identify locations where current trends threaten to leave the optimal temperature and precipitation envelopes for coffee production.

Numerous studies have been conducted to assess variability in historical climate patterns in Ethiopia (Benti and Abara, 2019; Alemayehu et al., 2020; Gemeda et al., 2021; Alemayehu, 2022), with conflicting results regarding long-term trends in rainfall (Seleshi and Zanke, 2004; Verdin et al., 2005; Bewket and Conway, 2007; Cheung et al., 2008; Mengistu et al., 2014). Most of these studies rely on meteorological station data to assess rainfall and temperature patterns across large areas (Conway and Schipper 2011). Unfortunately, meteorological stations are sparse and unevenly distributed in many parts of the country, and missing data is a common problem (Conway et al., 2004; Dinku et al., 2007).

Gridded fine-resolution satellite-based climate data can support such analysis in areas where weather stations are scant. Hence, we used high-resolution gridded rainfall and temperature estimates from the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) data, which aims to analyze the spatio-temporal variability and trends of rainfall and temperature from 1981 to 2022. We disaggregate the districts into three altitudinal zones (low, mid, and high) to compare rainfall and temperature variability and trends in different production environments to identify locations that are deviating from optimum coffee production conditions.

Our results provide vital information for coffee growers and decision-makers about the importance of local-level analysis, topographic heterogeneity, and the differences across seasons, which may help them design appropriate site-specific adaptation interventions for Arabica coffee production. We find that, while high-altitude regions in our study area might have been thought to provide a refuge for coffee production amid warming temperatures, they are also increasingly at risk of experiencing rainfall levels outside the optimal envelope for coffee production raising questions about the potential for expansion into these areas.

Materials and methods

Study area

East Africa is characterized by heightened variability in rainfall and temperature, and both maximum and minimum temperatures are on an upward trajectory (Gebrechorkos et al., 2019; IPCC, 2021). Heavily reliant on rain-fed agriculture, the region is acutely vulnerable to changes in climate variables (Ochieng et al., 2016; Gebrechorkos et al., 2019).

Profound climate variability has been observed over the last fifty years in Ethiopia, with documented increases in average minimum and maximum temperatures by 0.25 °C and 1 °C, respectively (World Bank, 2021). Rainfall patterns in the country are characterized by significant year-on-year volatility, with different regions displaying both ascending and descending trends (Conway and Schipper, 2011; Kiros et al., 2016; Ademe et al., 2020; Alemayehu et al., 2020; Gemeda et al., 2021;Taye et al., 2021). It is expected that by 2050s the country will see additional warming in all seasons of about 1.4–2.9 °C relative to 1961–2000 (Conway and Schipper, 2011). The Intertropical Convergence Zone (ITCZ) causes inter-annual rainfall variability across the country, shaping annual and seasonal rainfall distributions (Worku et al., 2019). Ethiopia has three main seasons: the short wet season (Belg), the main rainy season (Kiremt), and the dry season (Bega) (NMSA, 1996; Korecha and Barnston, 2007). The variability and changes in the distribution of rainfall and temperature across these seasons critically affect the phenological stages of coffee plants and related operations, as described in Table 1.

Most coffee production in Ethiopia takes place in the western, southwestern, southern, and eastern regions. The Jimma and Iluababor zones of Oromia state in southwest Ethiopia are one of the country's most significant production areas (Alemayehu, 2022). Our study examined five districts in this area: Limu Seka, Gera, and Goma in Jimma zone and Yayu and Ale districts in the Ilubabor zone (Fig 1(a)). These districts are regarded as major Arabica coffee growing locations and are one of few places where coffee grows naturally, in moist evergreen montane forests (Fig. 1(b) (Geeraert et al., 2019).

We used a two-stage sampling strategy to select these specific districts. First, we selected southwest Ethiopia based on its coffee production potential. Then, we selected sample districts based on their diverse altitudinal range, coffee production potential, land coverage, and dependency of smallholder farmers on coffee. In southwest Ethiopia, coffee accounts for more than 69 % of smallholder agricultural land, and smallholders account for 77 % of total household income from coffee (Samuel et al., 2019). The study area encompasses a diverse topography, with elevations ranging from 1233 to 3028 m above sea level, resulting in variations in rainfall and temperature across space and time. The area has a unimodal rainfall pattern that follows the seasonal distribution outlined in Table 1 (Abazinab et al., 2022).

Data

Gridded long-term historical annual and monthly rainfall data for the years 1981–2022 were obtained from the Climate Hazards Group Infrared Precipitation with Station data (CHIRPS-v2) at a 5 km spatial resolution (http://chg.geog.ucsb.edu/data/chirps) to analyze spatio-temporal rainfall patterns. The CHIRPS climate data incorporates global climatology, satellite estimates, and gauge observations to estimate total precipitation (Funk et al., 2015). Maximum and minimum monthly temperature data were obtained from Climate Hazards Center Infrared Temperature with Stations version 5 of the European Centre for Medium-Range Weather Forecasts *Re*-Analysis (CHIRTS-ERA5) dataset.

Table 1
Summary of impacts of changes in rainfall and temperature on coffee phenological stages in different seasons.

Season scale	Seasonal characteristics	Coffee phenological stage	Rainfall related risks	Temperature related risks
Belg (February to May)	Small rainy periods and high Tmax values are common	Coffee flowering, fruit initiation, and early development (ECFF and Kew Garden, 2017)	Too high and too low rainfall affect flowering and fruit development (Kath et al., 2021).	-High exposure to solar radiation coupled with longer periods of water scarcity damage the crop physiology,affects flowering, fruit development, and bean yield (Da Silva Angelo et al., 2019; Zullo et al., 2011; Bracken et al., 2023)
-Kiremt (June to September)	Main rainy season, frequent rains and homogeneous temperatures mainly in July and August	Season for final coffee fruit development and ripening (ECFF and Kew Garden, 2017)	Too high precipitation increases the prevalence of disease and insects and increases the risk of bean defects (Jaramillo et al., 2009). Low rainfall during this season increases plant stress and the risk of small-sized coffee beans (Kath et al., 2021)	Too high temperature (> 23 °C) leads to coffee bean defects and loss of coffee beverage quality(Camargo, 2010). Mean temperature <15 °C depresses coffee plant growth (DaMatta et al., 2018)
-Bega (October to January)-	Dry season, mostly associated with hot dry days and cool nights.	Season for Coffee harvesting and processing (ECFF and Kew Garden, 2017).	High and erratic rain reduces coffee quality, increases harvest losses, and affects harvesting and processing operations. Causes ripe coffee cherries to drop, generates decay and cracks on coffee cherries, and leads to green coffee bean defects (Kath et al., 2021)	Temperatures above 23 °C accelerate fruit development and ripening, harm coffee beans' physical quality, and lead to the loss of coffee beverage quality. Continuous exposure to temperatures > 30 °C leads to stress, depressed growth, and abnormalities (Camargo, 2010; Tesfaye et al., 2012; DaMatta and Ramalho, 2006)
Annual	3 main seasons, unimodal rainfall pattern	Overall suitability (Steinhart, 2005; Wintgens, 2012)	>2200 mm of mean annual rainfall is unsuitable for coffee production (Wintgens, 2012).	Less than 14–17 °C depresses growth, and greater than 26 °C mean annual is potentially unsuitable. Greater than 32 °C mean Tmax is totally unsuitable (Descroix and Snoeck, 2004; Wintgens, 2012). Pest and disease prevalence increases as temperatures rise (Jaramillo et al., 2009)

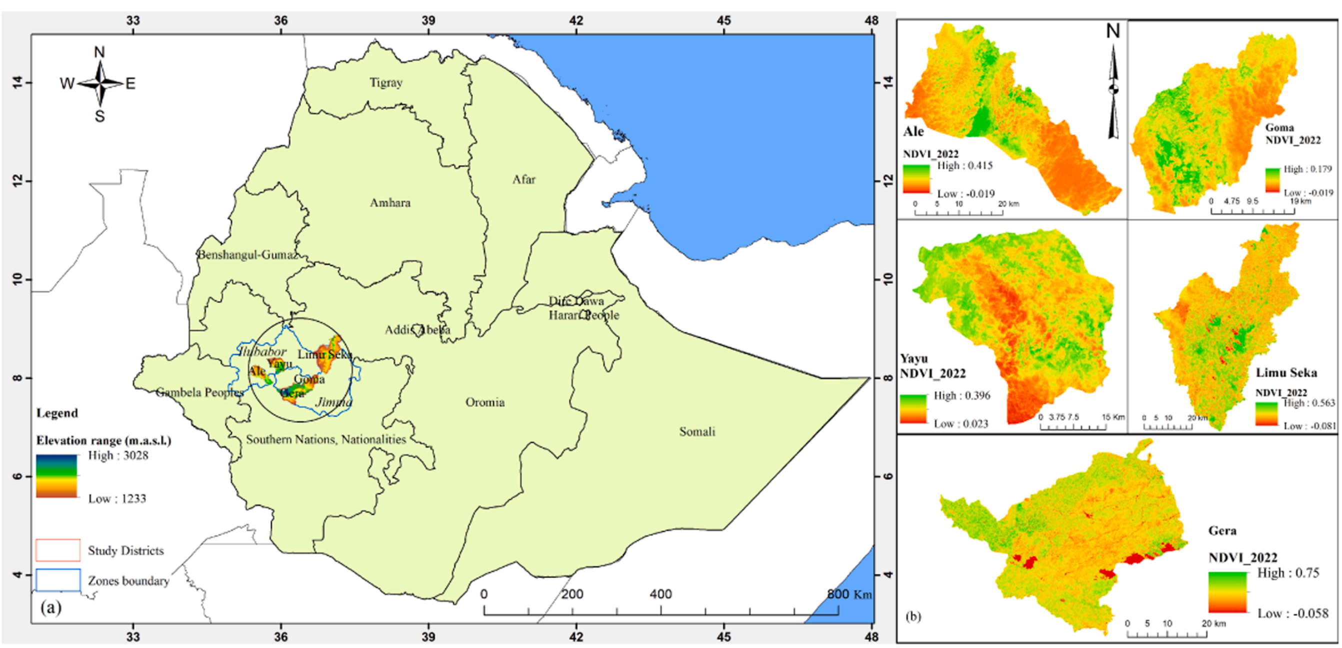

Fig. 1. (a) Map of the study area showing spatial location and altitude ranges in meters above sea level (m.a.s.l.), (b) Normalized Difference Vegetation Index (NDVI) of study districts showing the amount of green vegetation in the area, where higher values (up to a maximum of 1) indicate greater vegetation health. Created using Landsat 8 data obtained from EarthExplorer (usgs.gov) in ArcMap version 10.8 captured on February 2022.

The data set is based on ERA5 reanalysis, which incorporates a high-resolution (0.05°) climatology model and is well suited to research in Ethiopia (Funk et al., 2015; Steinkopf and Engelbrecht, 2022) (https://data.chc.ucsb.edu/experimental/CHIRTS-ERA5/). We then aggregated these data to seasonal and annual temporal resolutions for subsequent analysis (Table 2).

Methods

We analyzed the rainfall datasets at annual and seasonal resolutions, based on the three locally relevant seasons outlined in Table 1, to correspond to evidence on optimal conditions for coffee phenology (Korecha and Barnston, 2007; NMSA, 1996). Rainfall and temperature variability, anomaly, trends, and spatial distribution were analyzed as follows.

Coefficient of variation

We calculated the coefficient of variation (CV), expressed as a percentage, using Eq.1, where a higher CV indicates more variability and

Table 2
Data sets used for analysis and their sources.

data source	Variable	Time steps	Resolution	Year	File format
CHRIPS-v2	Rainfall	Annual, Monthly	0.05°	1981–2022	.tif
CHIRTS-ERA5	Tmin	Monthly	0.05°	1981–2022	.tif
CHIRTS-ERA5	Tmax	Monthly	0.05°	1981–2022	.tif
USGS	DEM	–	90m	-	.tif

vice versa (Funk et al., 2015).

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

where CV is the coefficient of variation, σ is the standard deviation, and μ is the average precipitation or temperature.

Standard anomalies (SA)

We computed standardized anomalies, which measure the difference between a variable in each year and the long-term mean in standard deviations, for rainfall and temperature to describe year-on-year variability (Funk et al., 2015), where negative values represent below-normal rains while positive values reflect above-normal rains (Asfaw et al., 2018; Alemu and Bawoke, 2020), using Eq. (2).

$$A_n = \frac{x_i - \overline{x}_i}{S} \tag{2}$$

where A_n is rainfall anomaly; X_i is the annual rainfall of a given year; $\overline{x}_i$ is mean annual rainfall and S is the standard deviation of annual rainfall over 42 year period.

CV and SA results provide limited information about the interannual or longer-time variability in temperature and rainfall. Hence, to measure the changes in rainfall and temperature relative to the first decade following the approach used by Guan et al. (2015) and Trenberth et al. (2007), the annual anomaly series relative to mean values of 1981–1990 of the study period is calculated, then scaled by the division of its reference period standard deviation.

Trend analysis

We use the non-parametric Mann–Kendall statistic (MK) for trend analysis (Mann (1945) and Kendall (1975)), widely applied in climate change research, to detect increasing or decreasing rainfall and temperature trends using the formula in Eq. (3).

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{sgn}(Xj - Xk) \tag{3}$$

Where S is the Mann-Kendall's test statistic: X_j and X_k are sequential data values on occasion j and k for the time series data of length n, *sgn* designates the sign operator, which takes on the values 1, 0, or −1 as described in Eq. (4), below. Whether S is positive or negative indicates an increasing or decreasing trend, respectively. The statistical significance of the trend can be computed by converting the S value into z-scores using the method in Eq. (5), which then can be evaluated for any selected level of statistical significance (Hussain et al., 2015).

$$\mathrm{sgn}(Xj - Xk) = \left\{ \begin{array}{l} +1, if\ (Xj > Xk) > 0 \\ 0, if\ (Xj > Xk) = 0 \\ -1, if\ (Xj > Xk) < 0 \end{array} \right\} \tag{4}$$

$$Zs = \left\{ \begin{array}{l} \frac{S-1}{\sqrt{\mathrm{var}(s)}} ifS > 0 \\ 0,\ if\ S = 0 \\ \frac{S+1}{\sqrt{var(s)}}\ if\ S < 0 \end{array} \right\} \tag{5}$$

Sen's method

We also apply Sen's slope test, a nonparametric procedure developed by Sen (1968) to quantify the direction and the magnitude of a trend, calculated using the formula in Eq. (6) (Gocic and Trajkovic, 2013). When the trend is linear, the Sen's slope test quantifies changes in the measure of interest per unit time. Sen's slope estimator computes the slope (the linear rate of change) and intercepts. A positive result of Q, the slope, indicates an "upward trend" (rising with time), whereas a negative result of Q indicates a "downward trend" (Abegaz, 2020b; Guo et al., 2020). In general, the slope Qi between any two values of a time series t can be calculated from as below.

$$f(x) = Qt + B \tag{6}$$

where f(x), is data at t year, Q is the slope of the trend line, B is constant. Then the slope Q is estimated as Eq. (7).

$$Qi = \frac{Xj = Xk}{j - k} where j > k \tag{7}$$

where Qi =Sen's slope estimator, Xj and Xk are the data values at times j and k ($j > k$), respectively. The median of these R values of Qi is represented as Sen's estimator of slope which is computed as in Eq. (8).

$$\mathrm{Sen\dot{}s\,estimator} = \left\{ \begin{array}{l} \frac{Q(R+1)}{2}\ if\ R\ is\ odd \\ 0.5 * \left(\frac{QR}{2} + \frac{Q(R+2)}{2} \right) if\ R\ is\ even \end{array} \right\} \tag{8}$$

Spatial analysis

We conducted our spatial analysis of rainfall and temperature using the boundaries of Ethiopia's smallest administrative units (kebele), with boundary data obtained from the Ethiopian mapping agency. Using a 90-meter resolution digital elevation model (DEM) derived from the Shuttle Radar Topography Mission (USGS, 2008), we computed the mean altitude for each kebele. We considered kebeles with altitudes of less than 1500 masl as low-, 1500–1800 masl as mid-, and greater than 1800 masl as high-altitude areas on the basis of a broad classification of agroecological zones in Ethiopia (Walker et al., 2003). For all subsequent analysis, we aggregated our data to the kebele level by taking the mean of the raster values falling within kebele boundaries. All the data analysis was conducted using R statistical software (R Core Team, 2022) version 4.2.2 by deploying appropriate packages (Pohlert, 2021; Bivand et al., 2023; Bivand and Koh, 2023; Hijmans, 2023; Pebesma and Bivand, 2005, 2023).

Result and discussion

Temporal variability and trends of annual rainfall

The average annual rainfall, over the past 42 years in the study area is presented. The annual rainfall increases in all parts of the study area. The districts receive mean annual rainfall ranging from 1585.4 to 1897.94 mm (table. 3). The Mann-Kendall test (MK) result is consistent with a significantly increasing trend of mean annual rainfall over all the study areas at $p = 0.05$. The magnitude of the annual rainfall trend (Sen's slope) indicates an upward trend at a rate of 5.09, 5.43, 6.44,

Table 3
Mean annual rainfall, and trends of the study sites over 42 years (1981–2022).

Statistics	Ale	Yayu	Gera	Goma	Limu Seka
Mean (mm)	1774.71	1585.40	1897.94	1765.24	1674.79
CV (%)	8.28	8.59	8.9	9.81	9.22
MK	2.2	2.8	3.26	2.83	3.18
Sen's slope	5.09↑	5.43↑	6.44↑	6.49↑	6.26↑
P	**0.03**	**0.005**	**0.0011**	**0.005**	**0.001**

Bolded values are statistically significant at Zs > 1.96 (α = 0.05) at 5 % level of significance, ↑ = positively increasing trend,.

6.49, and 6.26 mm/year for Ale, Yayu, Gera, Goma, and Limu Seka respectively.

These results are consistent with previous studies in western and southwestern Ethiopia (Alemayehu et al., 2020; Gemeda et al., 2021), though they contradict with a declining trend in annual rainfall reported by Seleshi & Zanke (2004), Fekadu (2015) and Gobie & Miheretu (2021) in the periods before 2005. The contradicting results observed are because of various factors related to the variation in the amount of rainfall in different parts of Ethiopia, including El Niño Southern Oscillation (ENSO) events resulting in extremely low and high rainfall (Mera, 2018) and, the sea surface temperature of the Atlantic and Indian Oceans coupled with low-level winds from these oceans via westerly and easterly winds, which play a role in the inter-annual rainfall variability of Ethiopia (Ummenhofer et al., 2009).

Rainfall anomalies relative to the mean of 1981–1990 also indicate both positive and negative deviations of annual rainfall from the long-term mean. The positive anomalies occur more often than negative anomalies, implying that there were more wet years in the study districts during the period from 1981 to 2022 (Fig. 2(b)). The largest negative rainfall anomalies were recorded in the periods before 2005 for all study sites, which is consistent with other studies in Ethiopia (Fekadu, 2015; Gobie and Miheretu, 2021). The wettest years indicated in the analysis also agree with other reports (NMA, 2007; Elzopy et al., 2021).

Despite these concerning patterns, annual rainfall in the study areas remain within coffee's optimal production range of 1250–2200 mm

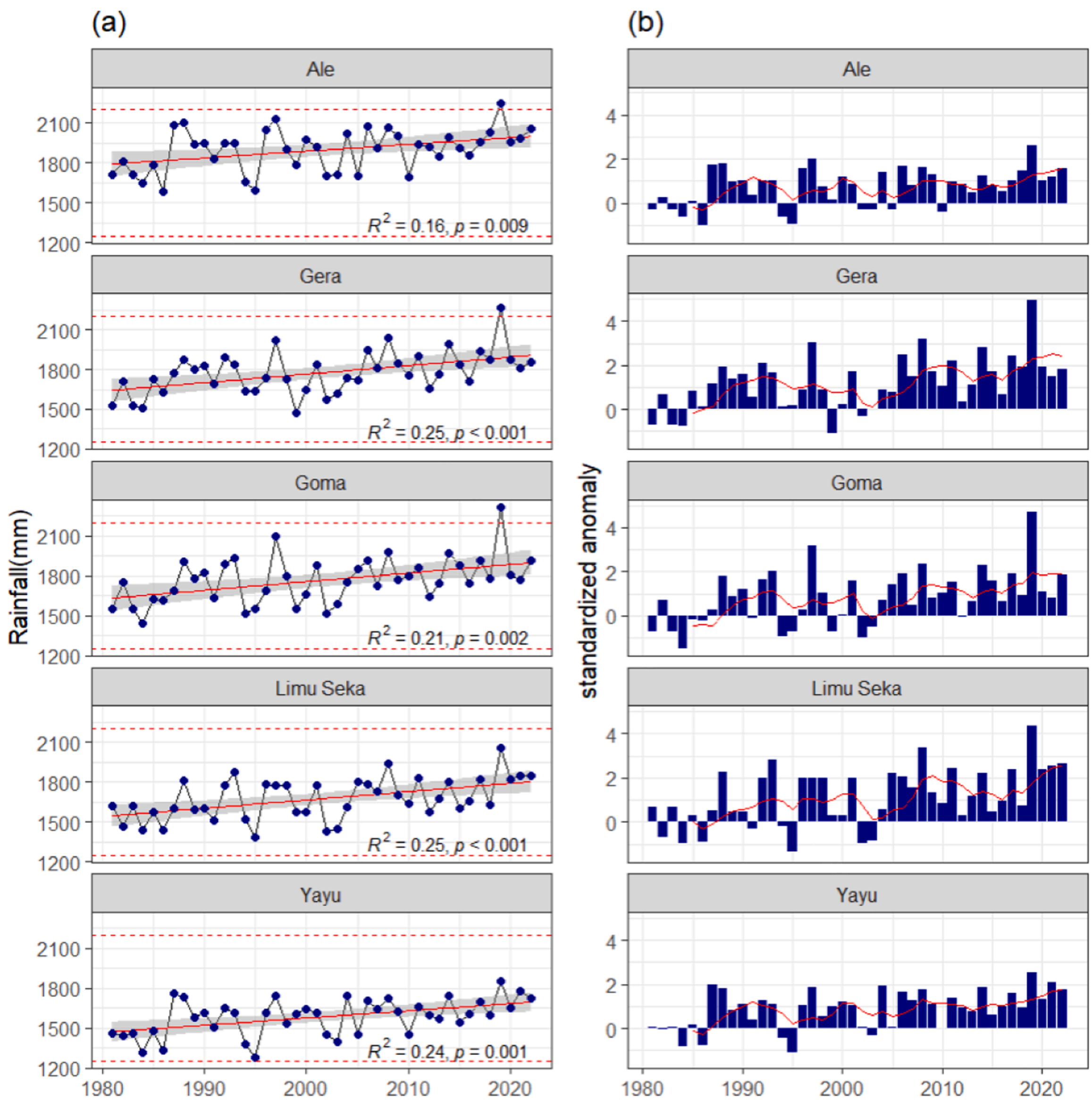

Fig. 2. (a) Mean Annual rainfall trends of the study district (1981–2022). The red dashed line indicates the lower and upper limits of the amount of rainfall suited for Arabica coffee production (Wintgens, 2012). The red regression line indicates the historical trend of rainfall over the study period. 2 (b) indicates annual rainfall anomaly series relative to 1981–1990 mean values (Trenberth, et al., 2007; Guan et al., 2015). The graphs indicate the deviation of rainfall from the mean of the first decade, and the blue bars indicate anomalies.

(Wintgens, 2012) see Fig. 2(a)). One exception is an abrupt increase in mean annual rainfall observed in 2019 in Ale, Gera, and Goma districts, which, combined with the increasing trend of mean rainfall, meant those areas left the optimal envelope for that year. Should annual average rainfall continue to increase, the risk that extreme rainfall years could exit the optimal production range will continue to grow.

Temporal variability and trends of seasonal rainfall

The seasonal rainfall variability analysis showed the highest variability of rainfall in Bega followed by Belg and Kiremt seasons with CV values ranging from 8.2 to 9.6 %, 27.65–42.88 %, and 9.1–21.1 % for Kiremt, Bega and Belg seasons, respectively (Table A1). The standard anomalies of seasonal rainfall also showed both positive and negative anomalies indicating increasing rainfall across all seasons, with varying levels of significance (Fig. 3). Recent studies have also reported a higher variability for Bega rainfall than Kiremt and an increasing trend of variability across time in southwestern Ethiopia (Gemeda et al., 2021).

The amount of seasonal rainfall, including the main rainy season (Kiremt), shows a positive upward trend for all sites, though some are not statistically significant at $p = 0.05$. A significantly increasing rainfall trend was observed in the Kiremt season for the majority of the districts. For Bega season, a significantly increasing trend was observed only in two districts. For the Belg season, a non-significant increasing trend was observed in all districts except for Ale (Table A2). This result shows the heterogenous nature of trends in rainfall, similar to Alemu & Bawoke's (2020) and Bayable et al.'s (2021) findings in other parts of Ethiopia. On the contrary, Gemeda et al. (2021) also reported both significant downward and upward trends in the main rainy season (June to August) in different stations of southwestern Ethiopia. The sea surface temperature anomalies in the Pacific related to ENSO, the complex topography, and sharply elevated mountains in different parts of the country strongly influence the inter-annual and spatial variability of precipitation in Ethiopia (Diro et al., 2011; Ehsan et al., 2021).

Though the existing mean rainfall amount in the Kiremt season is good for coffee production, the standardized rainfall anomaly index indicates both positive and negative deviation of rainfall amount from the long-term average in all seasons, which may negatively affect coffee production (Fig. 3).

The escalating precipitation during the Bega seasons, a critical time for coffee harvesting and processing in southwestern Ethiopia, presents significant ecological and economic risks for farmers (Läderach et al., 2017). Excessive rainfall favors the development of fungal diseases like coffee leaf rust, which affect yield and quality (Jaramillo et al., 2009). High and unexpected rainfall at this time increases the risk of ripe coffee cherries dropping prematurely, as well as increasing decay, cracks on coffee cherries, and other green coffee bean defects (Kath et al., 2021). These issues are a substantial challenge for coffee processing operations in Ethiopia, causing loss of yield and quality more broadly (ECFF and Kew Garden, 2017).

A significant increasing rainfall trend is also observed in Belg for all sites except Goma. Belg is the main period for coffee flowering, fruit initiation, and early development (ECFF and Kew Garden, 2017). The above and below long-term mean of rainfall observed in this season have implications for coffee flowering and development. Changes in climate variables including the amount of rainfall during the vegetative and reproductive phases of the plant would pose a significant impact on coffee yield (Tavares et al., 2018). DaMatta et al. (2018) also reported that too-high and too-low rainfall during coffee's flowering period and later phases of flower bud development lead to unsynchronized fruit

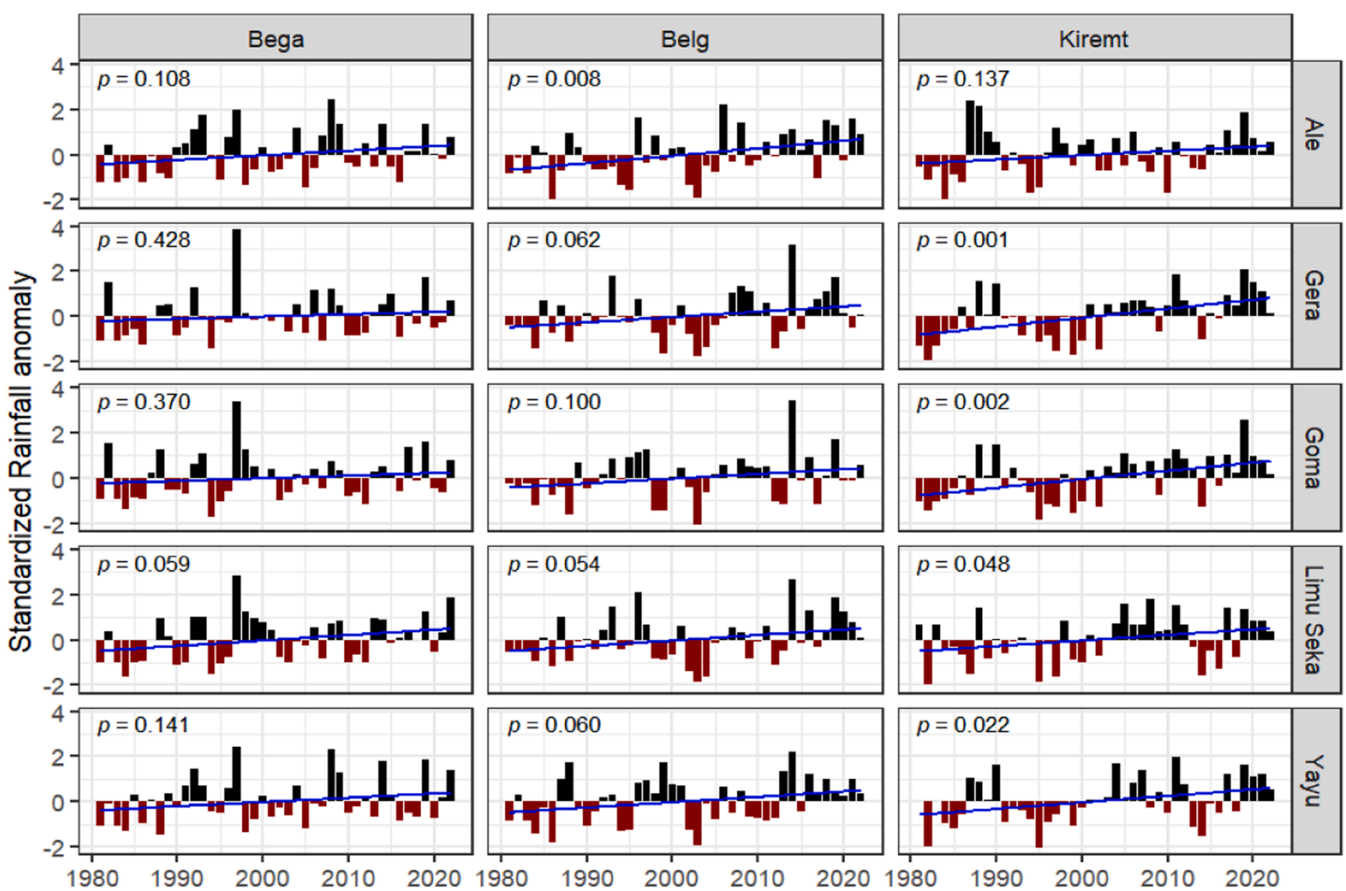

Fig. 3. Standardized seasonal rainfall anomalies for the year 1981–2022 indicate the standard deviation of seasonal rainfall from the long-term mean, the black and red bars indicate positive and negative anomalies respectively.

ripening.

Kiremt, during which coffee fruits develop and ripen, is the wettest season, with a significantly increasing trend of rainfall for all districts except Ale. All sites exhibit both positive and negative deviations from the long-term mean. Which is consistence with the findings of (Bayable et al., 2021; Gashaw et al., 2023). The negative deviations from the long-term mean observed in all districts during Kiremt increase the risk of small-sized coffee beans because of problems caused by small rainfall amount (Kath et al., 2021). High concentrations of rainfall in Kiremt, and unexpected rain in Bega can be major challenges for the small-scale farmers' livelihoods (Ofgeha and Abshire, 2021).

Spatial distribution of rainfall

The spatial distribution of mean annual rainfall is presented in Fig. A1. Statistically significant increasing trends were observed in the three altitude zones (low, mid, and high) of all study sites at $p = 0.05$ level of significance (Fig. 4, Fig. A2). The mean annual amount and the overall trend of rainfall lie within the optimal range (1250–2500 mm/year) of the requirements for Arabica coffee production in the majority of low, mid, and high-altitude areas, except some above-normal rainfall amounts observed at high and mid-altitude zones of Ale, Gera, and Goma. The above and below-normal rainfall amounts may cause some restrictive factors for optimal growth of coffee (Wintgens, 2012). During the last two decades (2000′s and 2010′s) of the study period, the increasing trend in the amount of rainfall has been threatening to exit the optimal range for low, mid, and highland areas of Ale, Goma, and Gera. In addition, there are extreme low and high events of rainfall in the areas that could impact coffee production in different altitudinal zones.

Minimum and maximum temperature trends

The maximum and minimum temperature trends across the study sites are presented in Table A2. All districts have experienced a significantly increasing trend of both Tmax and Tmin, with p-values less than 0.05. Across the observation period, Tmin increased at a quite similar rate (Sen's slope) of 0.02 °C per year in all districts. In Limu Seka the rate is 0.023 °C /year. Tmax has increased at a rate of 0.02 °C/year in Ale and 0.03 °C /year in Gera, Goma, Limu Seka, and Yayu. The highest maximum temperature was recorded in the third and fourth decades of the study period (Fig. 5).

In the Gera, Goma, and Yayu districts, the minimum temperature was below the optimal requirement for coffee except during the most recent decade of the study period, meaning that the increasing trend of Tmin is moving these areas into the optimal thermal envelope for coffee production. The lower and upper limits of Tmax for coffee also show that most sites lie within the optimum range, except for Gera district, which was below the mean maximum requirement during the 1980s and 1990s. In the Limu Seka areas, however, a distinct ecological shift has unfolded, as regions previously within the optimal maximum temperature range have begun to exceed these boundaries in some years of the most recent decade (2010s) (Fig. 5). Moat et al. (2017) also reported

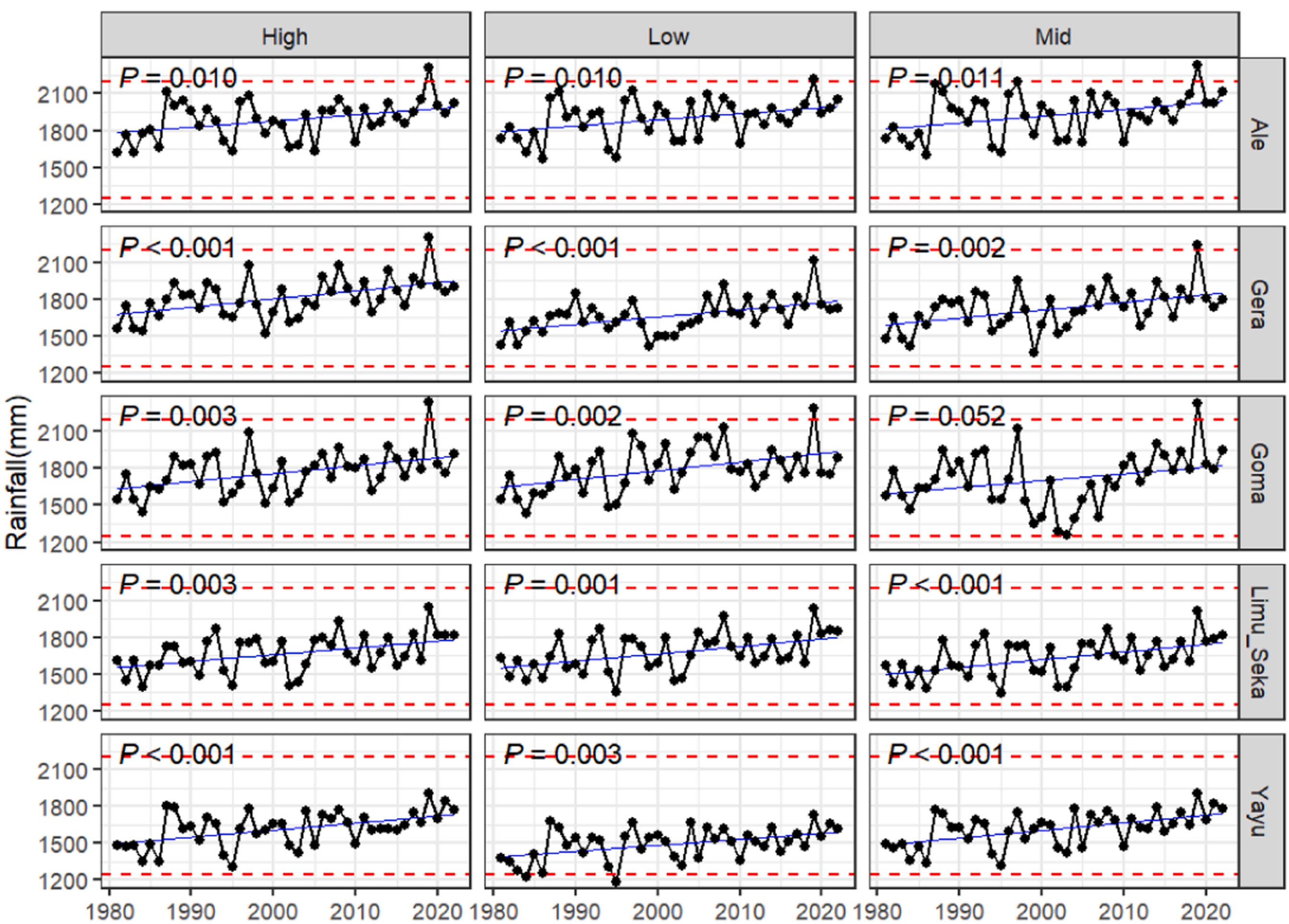

Fig. 4. Annual rainfall trends across altitudinal zones and optimal range of mean annual rainfall (lower limit 1250 mm and upper limit 2500 mm per year) for Arabica coffee production based on Wintgens (2012). The red dashed lines represent upper and lower limits, and the blue lines show the regression line of mean annual rainfall in each altitude zone. The p-value indicates the level of significant increase.

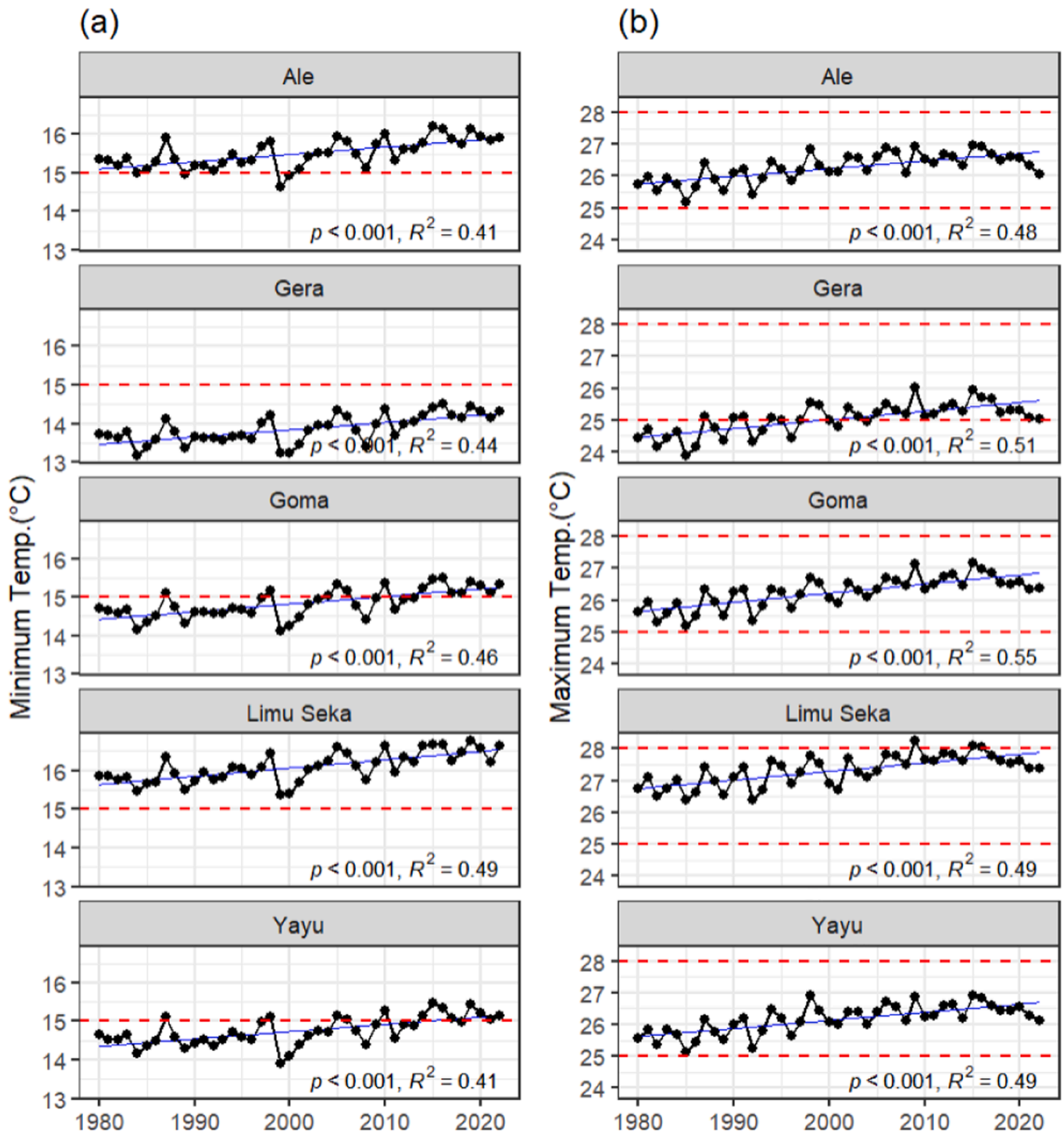

Fig. 5. Mean minimum (a) and mean maximum (b) temperature of the study districts (1981–1982). The red dashed lines in (a) indicate the optimal lower limit of mean minimum temperature, while those in (b) show the upper and lower limits of mean Tmax (Teketay, 1999; Wintgens, 2012; Camargo, 2010; Ademe et al., 2020).

new areas become more suitable for coffee production, and large areas will lose the optimum range of temperature for coffee growth that will pose significant stress on coffee trees in the future because of the influence of increasing temperature in Ethiopia.

The annual Tmax and Tmin anomaly relative to the mean values of the first decades of the study period showed that more positive anomalies occurred than negative anomalies indicating more warming years for both Tmin and Tmax (Fig. 6(a) & 6(b)). In all districts, the majority of the study periods exhibited more temperature than the first decade (1981–1990).

Our findings indicated strong increases in Tmax after the early 1990′s, consistent with other work documenting positively increasing trends of both Tmax and Tmin in different parts of Ethiopia (NMA, 2007; Alemayehu and Bewket, 2017; Suryabhagavan, 2017; Gebremeskel et al., 2019; Matewos and Tefera, 2020: Gemeda et al., 2021). The rate of Tmax increase in our study sites is quite consistent with documented Tmax change in Ethiopia of about 0.2 °C per decade over the past 50 years (WBG, 2020), which might be a potential challenge for coffee production at lower and mid-altitude ranges (Zullo et al., 2011; Davis et al., 2012; Wintgens, 2012).

Seasonal trends of maximum and minimum temperature (1981–2022)

The highest mean Tmax during Belg season was recorded for Gera, at 28.82 °C, and the lowest mean Tmax was recorded in Ale, at 24.61 °C. Bega is the hottest season in Ale, Gera, and Goma, while Belg is the hottest in Limu Seka and Yayu, with mean Tmax values of 30.01, 29.32, 30.01, 30.58, and 29.33 in Limu Seka, Goma, Gera, Yayu, and Ale districts, respectively. Mean Tmin ranges from 12.69 °C (Gera) in Bega season to 16.56 °C (Limu Seka) in the Kiremt season. In all districts, Bega and Belg seasons registered the highest, and Kiremt the lowest, Tmin values (Fig. 7).

Tmax shows significant increasing trends in all seasons at $p = 0.05$ for all districts, except for Yayu, which shows a non-significant increasing trend in Kiremt and Belg seasons. A significant increasing trend of Tmin was also observed in all seasons in Goma, Gera, Yayu, and

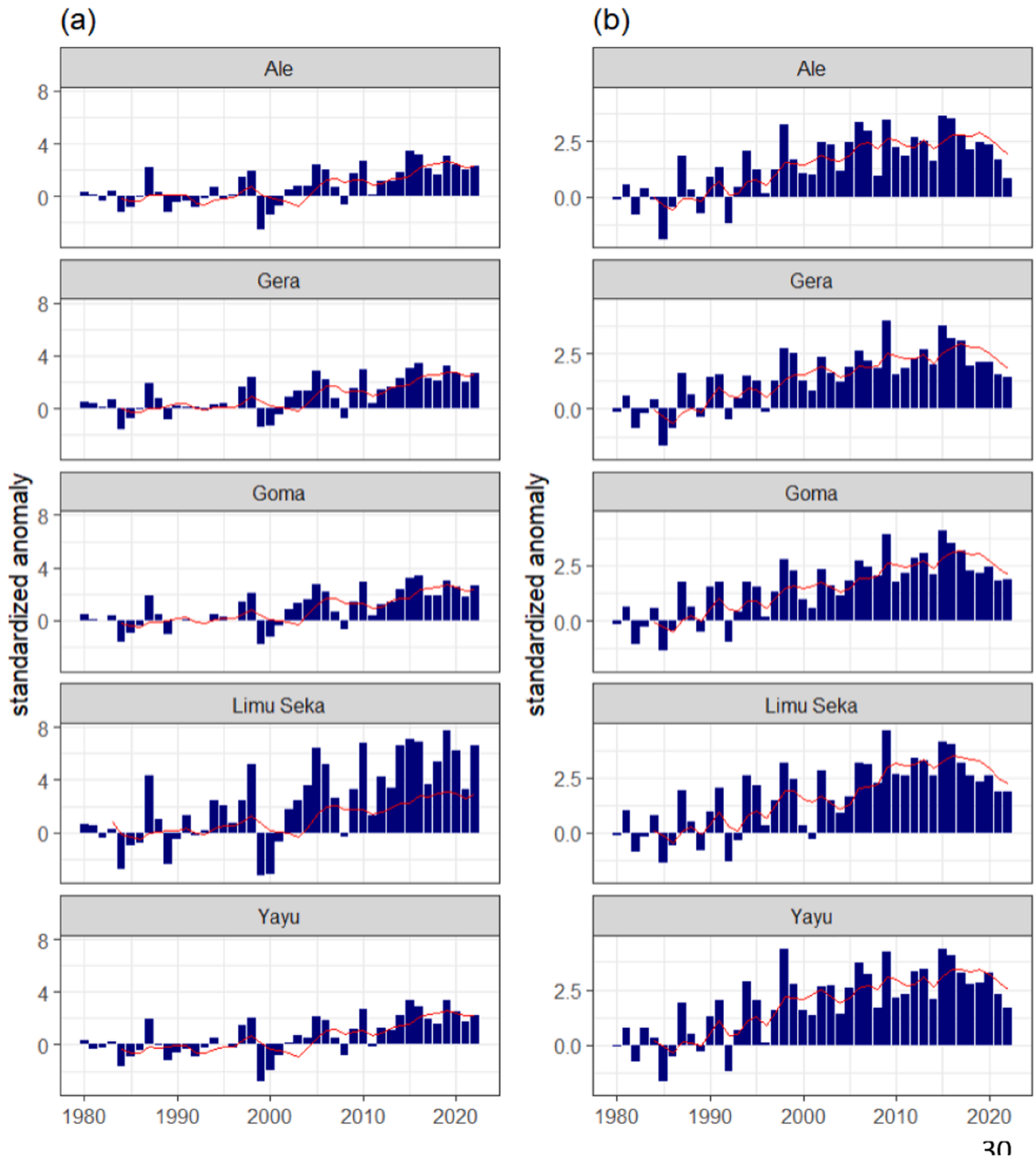

Fig. 6. Annual anomaly series relative to 1981–1990 mean values for Tmin (a) and Tmax (b) during 1981–2022. The blue bars indicate anomalies, and the red line indicate trends of variability.

Ale districts. Limu Seka shows a non-significant increasing trend in the Kiremt and Bega seasons, whereas Belg seasons show a significantly increasing trend (Table A3). The rate of increase in Tmax for Belg ranges from 0.02 to 0.04 °C/year across the study sites. Tmin increased in a higher rate during Kiremt season with Sen's slope value ranging from 0.001 to 0.03 °C/year.

These findings are consistent with previous studies (Ademe et al., 2020; Gemeda et al., 2021) that indicated increasing Tmax and Tmin in different seasons of the year based on meteorological station data in south and southwestern Ethiopia. Other regional studies have also shown Ethiopia's maximum and minimum temperatures to be increasing (Abebe, 2017; Asfaw et al., 2018; Benti and Abara, 2019).

Increasing temperatures across seasons can have substantial impacts on coffee yield and quality. Kath et al. (2021), for instance, link above-average Tmin and Tmax during Bega, the harvest season, with coffee bean defects, and high average temperatures in Kiremt, early in the growing season to insect damage and changes in bean color. Consistent Tmax above 22 °C for Arabica coffee can reduce crop growth and damage the crop physiology, especially during flower bud development in Belg (Carr, 2001; Zullo et al., 2011; Bracken et al., 2023). In addition, high Tmax was associated with an increased risk of changes in coffee bean color in different growing seasons. In Ale, Goma, Limu Seka, and Yayu, Tmax has increased to already exceed 28 °C in the Bega and Belg seasons, when high temperatures during these seasons lead to coffee bean defects and loss of coffee beverage quality (Camargo, 2010), and appear set to continue rising. On the other hand, rising minimum temperatures in Kiremt, when low temperatures can depress coffee plant growth (DaMatta et al., 2018), may be moving Gera, Goma, and Yayu more comfortably into the optimal minimum temperature envelope.

Fig. 7. Trends of Tmax and Tmin, by season (1981–2022) in different districts. p indicates the level of significant increase.

Spatial analysis of maximum and minimum temperature

The spatial distribution and trends in mean maximum and minimum temperature were presented in Figs. A3 & A4. Consistently with Asfaw et al. (2018) and Shekuru et al. (2020), we find important temperature differences across elevation zones, despite that all areas are experiencing rising temperatures in both Tmax and Tmin (Fig. 8(a) and (b)). The annual temperature anomalies relative to the first decade showed that all altitude zones have experienced more positive maximum and minimum temperatures in the majority of the years relative to the first decade. More than 78 % of the years for Tmin and >85 % of the years for Tmax across all altitude zones experienced high temperatures above the mean value of 1981–1990 (Fig. 8(c) and (d)).

Tmin is above the lower bound of the optimal envelope in the majority of low and mid-altitude areas of all districts, except in Gera during the 1980s and 1990s of the study periods. In the highland areas, Tmin was below the optimal limit in all areas and has been above the limit line since 2010′s in Ale, Limu Seka, and Yayu. The mean Tmax of mid and high-altitude zones in Limu Seka, Goma, Yayu, and Ale are within the envelope of temperature requirements for Arabica coffee production (Teketay, 1999; Wintgens, 2012; Ademe et al., 2020). Most of the high-altitude areas of Gera district are below the lower Tmax limit for optimum Arabica coffee growth, whereas low-altitude areas of Limu Seka, Goma, and Yayu districts are beginning to exceed the optimum range in some years (Fig 8(b)). The increasing trend of temperature coupled with increasing variability at different elevation zones, indicates that coffee production is under threat in low and mid-altitude areas. Other studies also indicated that coffee is negatively influenced by increasing temperature in low-altitude areas of Ethiopia (Sisay, 2018). In their study Zullo et al. (2011) and Davis et al. (2012) also found that the increasing temperature above the optimal requirement at lower altitude areas is negatively affecting coffee cultivation.

Conclusions

This study involves the analysis of climatic variables, i.e. rainfall, minimum and maximum temperature spatio-temporal trend as well as its implications for coffee production in selected coffee-growing districts of Southwest Ethiopia from 1981 to 2022. A statistically significant increasing trend of mean annual rainfall was observed at a rate of 5.09, 5.43, 6.44, 6.49, and 6.26 mm/year for Ale, Yayu, Gera, Goma, and Limu Seka districts respectively, with both negative and positive anomalies, indicating the occurrence of both below and above-normal rains. This study concludes that the amount of rainfall in all seasons and altitude zones is increasing with varying levels of significance, with year-to-year variability. Currently, the areas remain within the envelope of optimal requirements for coffee production (1250–2200 mm), and should annual average rainfall continue to increase, there will be a higher risk that it could exceed optimal rates in the future in selected elevations. Moreover, the increasing trend of variability, above and below normal rainfalls in different seasons has substantial implications for coffee at different phenological stages.

The mean Tmin and Tmax at annual and seasonal scales showed a positive upward trend in all districts and altitude zones. Tmin increased with a rate of 0.023 °C /year in Limu Seka and by 0.02 °C/year in other districts Tmax was increased by 0.2 °C/decade for Ale and 0.3 °C /decade in Gera, Goma, Limu Seka, and Yayu. Continuously increasing temperatures, together with the variability and fluctuation in different seasons,

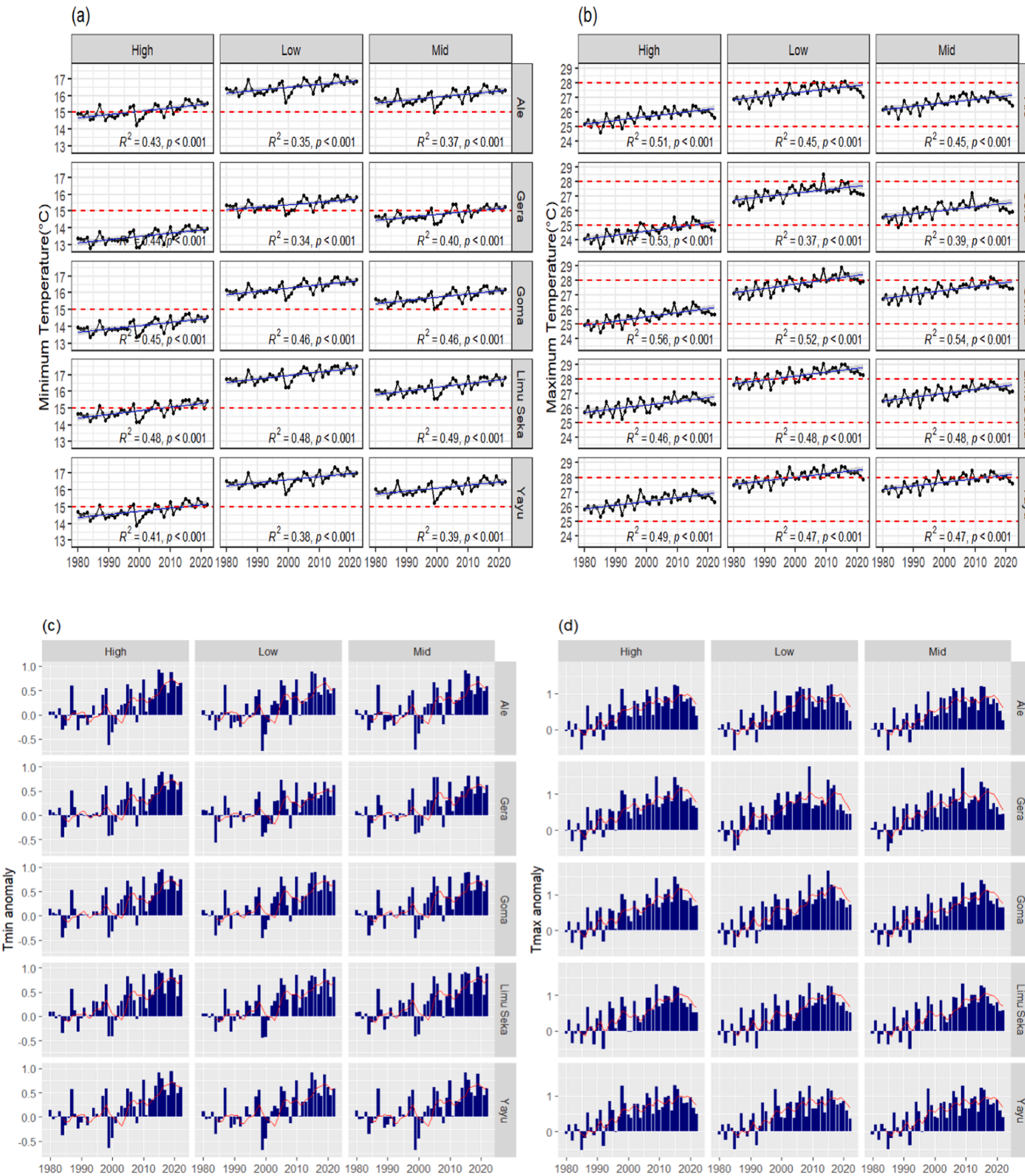

Fig. 8. (a) Minimum Temperature trends, (b) Maximum temperature trends (1981–2022) for different altitude zones and districts. The red dashed lines indicate the optimal lower limit of average Tmin across the years (15 °C), and the upper and lower limits of Average Tmax that range from 25 to 28 °C (Ademe et al., 2020; Camargo, 2010; Teketay, 1999; Wintgens, 2012). (c) Tmin anomalies and, (d) Tmax anomaly relative to the mean Temperature of the first decade (1981–1990). The blue bars are the positive and negative anomalies.

are significant challenges for coffee production in certain elevations. While the mean Tmax of mid and high-altitude zones remain within optimal limits for maximum temperature requirements (25–28 °C) for coffee production in selected sites, low-altitude areas have begun exceeding the optimum range (> 28 °C). Some areas in the high-altitude range might become more suitable with the increasing temperature trend, and low and mid-land areas might lose suitability because of increasing temperatures above the optimum range, though even highland areas might be at risk from excessive precipitation if current trends continue.

Overall, the findings of this study are beneficial for assessing the impacts of the changing climate on the coffee sector as the area is one of the major hubs for coffee production. As variability and trends of climate variables are influenced by locations, analyses of climate variables are crucial for planning and decision of adaptation interventions for continued coffee viability in the study region. Furthermore, the evidence presented here suggests that climate adaptation for coffee farmers in the region is not just a matter for future consideration, rather several parts of the study area are already feeling its effects.

CRediT authorship contribution statement

Melkamu Mamuye: Conceptualization, Data curation, Writing – review & editing, Formal analysis, Methodology, Validation, Visualization, Writing – original draft. **Caleb Gallemore:** Conceptualization, Data curation, Investigation, Methodology, Supervision, Visualization, Writing – review & editing. **Kristjan Jespersen:** Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing, Conceptualization. **Ng'winamila Kasongi:** Conceptualization, Formal analysis, Methodology, Validation, Visualization, Writing – review & editing. **Gezahegn Berecha:** Formal analysis, Methodology, Resources, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Kristjan Jespersen reports financial support was provided by Copenhagen Business School. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix

Table A1
Long-term Seasonal trend of rainfall (3 main seasons per year).

Season	Tests	Ale	Yayu	Gera	Goma	Limu Seka
Kiremt (JJAS)	CV (%)	9.33	8.2	9.6	8.2	9.11
mm	MK	1.77	2.33	3.31	3.04	2.005
	P	0.08	0.12	**0.0009**	**0.002**	**0.05**
	Sen`s slope	2.43↑	2.64↑	3.74↑	3.92↑	2.89↑
Bega (ONDJ)	CV (%)	17.3	10.3	17.5	15.3	10.1
mm	MK	1.94	1.11	1.25	1.38	2.01
	P	**0.05**	0.27	0.213	0.168	**0.05**
	Seńs slope	1.65↑	0.896↑	1.41↑	1.447↑	1.78↑
Belg (FMAM)	CV (%)	9.1	21.1	14.84	17.04	9.11
mm	MK	2.65	1.77	1.77	1.64	1.89
	P	**0.008**	0.08	0.08	0.102	0.06
	Sen's slope	1.73↑	2.23↑	1.68↑	1.56↑	1.977↑

Bolded values are statistically significant at $Zs > 1.96$ ($\alpha = 0.05$) at 5 % level of significance, ↑ = positively Increasing trend.

Table A2
Mean maximum and minimum temperature trend (1980–2022).

Attribute	Test	Limu Seka	Goma	Gera	Yayu	Ale
Tmax	Z_s	4.46	5.15	4.69	4.73	4.5
	Sen's	0.03	0.03	0.03	0.03	0.02
	P	**8.262e-06**	**2.619e-07**	**2.752e-06**	**2.241e-06**	**6.791e-06**
Tmin	Z_s	5.0	4.5	4.44	4.46	4.35
	Sen's	0.023	0.02	0.02	0.02	0.02
	P	**5.66e-07**	**6.791e-06**	**9.108e-06**	**8.262e-06**	**1.339e-05**

Bolded values are significantly different.

Table A3
Mean maximum and minimum temperature trends of different seasons (1980–2022).

Site name		Kiremt (JJAS)			Bega (ONDJ)			Belg (FMAM)		
		Zs	*P*	Sen's	Zs	*P*	Sen's	Zs	*P*	Sen's
Tmax	LS	3.39	**0.01**	0.03	3.66	**0.0003**	0.02	4.37	**1.217e-05**	0.04
	GM	3.119	**0.002**	0.02	4.668	**3.1e-06**	0.03	4.35	**1.339e-05**	0.04
	GR	3.244	**0.001**	0.02	3.265	**0.001**	0.013	4.19	**2.837e-05**	0.03
	YY	1.486	0.245	0.02	5.02	**5.1e-07**	0.025	1.55	0.06	0.02
	AL	2.218	**0.03**	0.02	5.04	**4.5e-07**	0.03	3.47	**0.0005**	0.03
Tmin	LS	1.0	0.226	0.001	4.1	0.276	0.01	6.6	0.601	0.06
	GM	5.1	**3.27e-07**	0.03	3.1	**0.002**	0.02	2.5	**0.011**	0.013
	GR	4.9	**8.71e-07**	0.03	3.2	**0.002**	0.015	2.8	**0.005**	0.02
	YY	4.3	**1.54e-05**	0.024	2.9	**0.004**	0.014	2.5	**0.013**	0.013
	AL	4.6	**4.57e-06**	0.03	3.3	**0.001**	0.014	2.8	**0.006**	0.014

Bolded values indicate statistically significant results, LS=Limu Seka, GM=Goma, GR=Gera, YY=Yayu, AL=Ale.

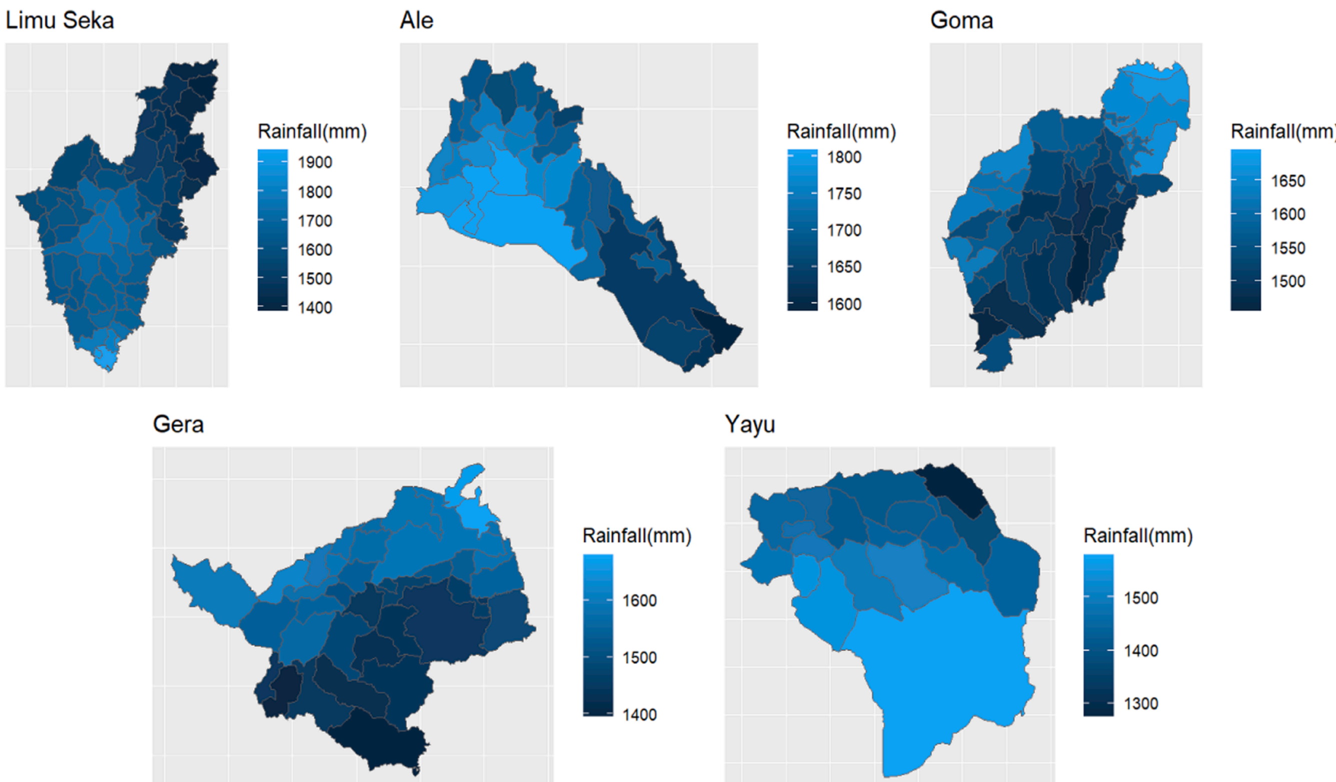

Fig. A1. Spatial distribution of mean annual rainfall (42 years average) of the study districts.

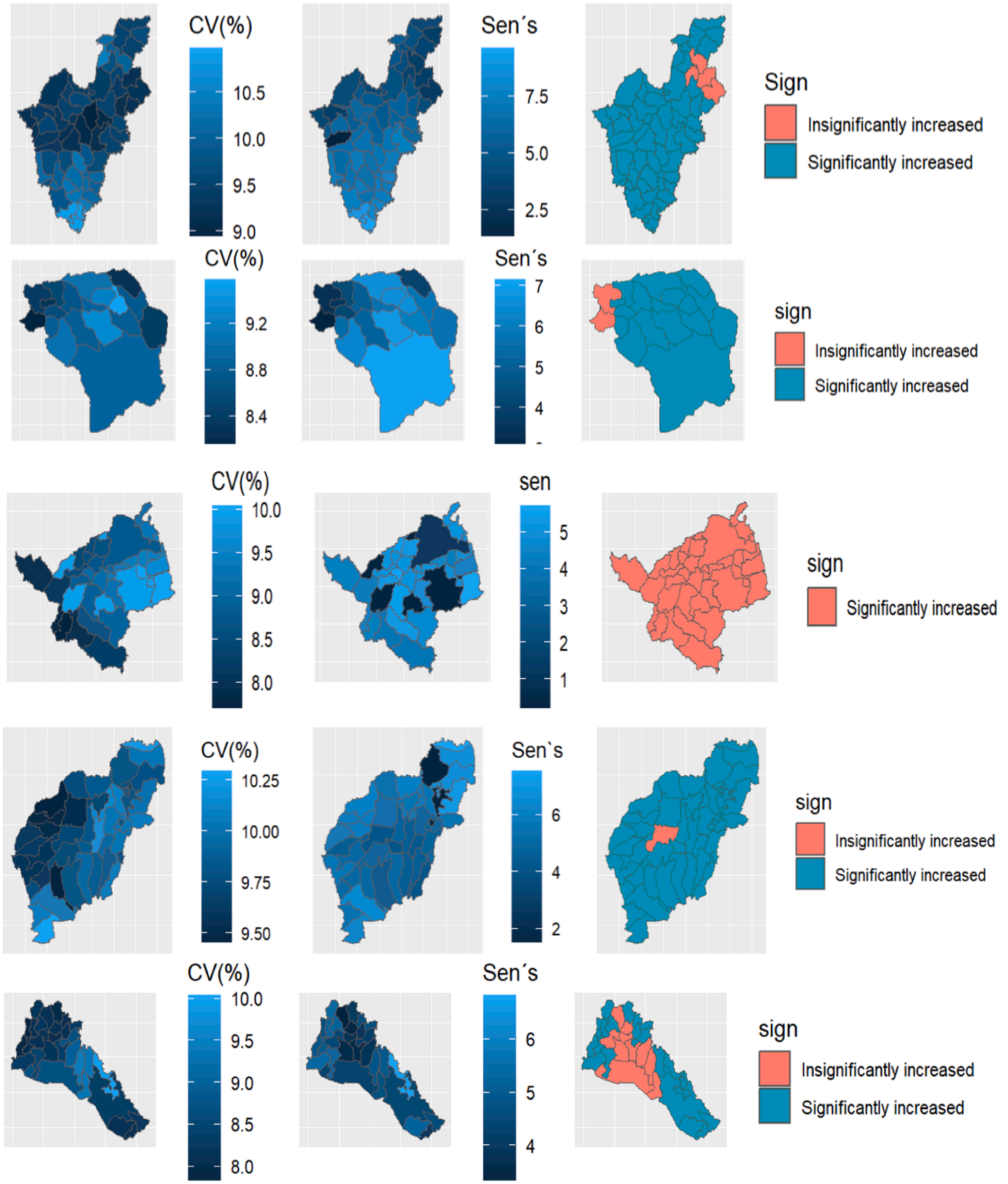

Fig. A2. Map showing CV, Sen's slope value, and level of significant increase in mean annual rainfall (42 years average) in different parts of the study districts

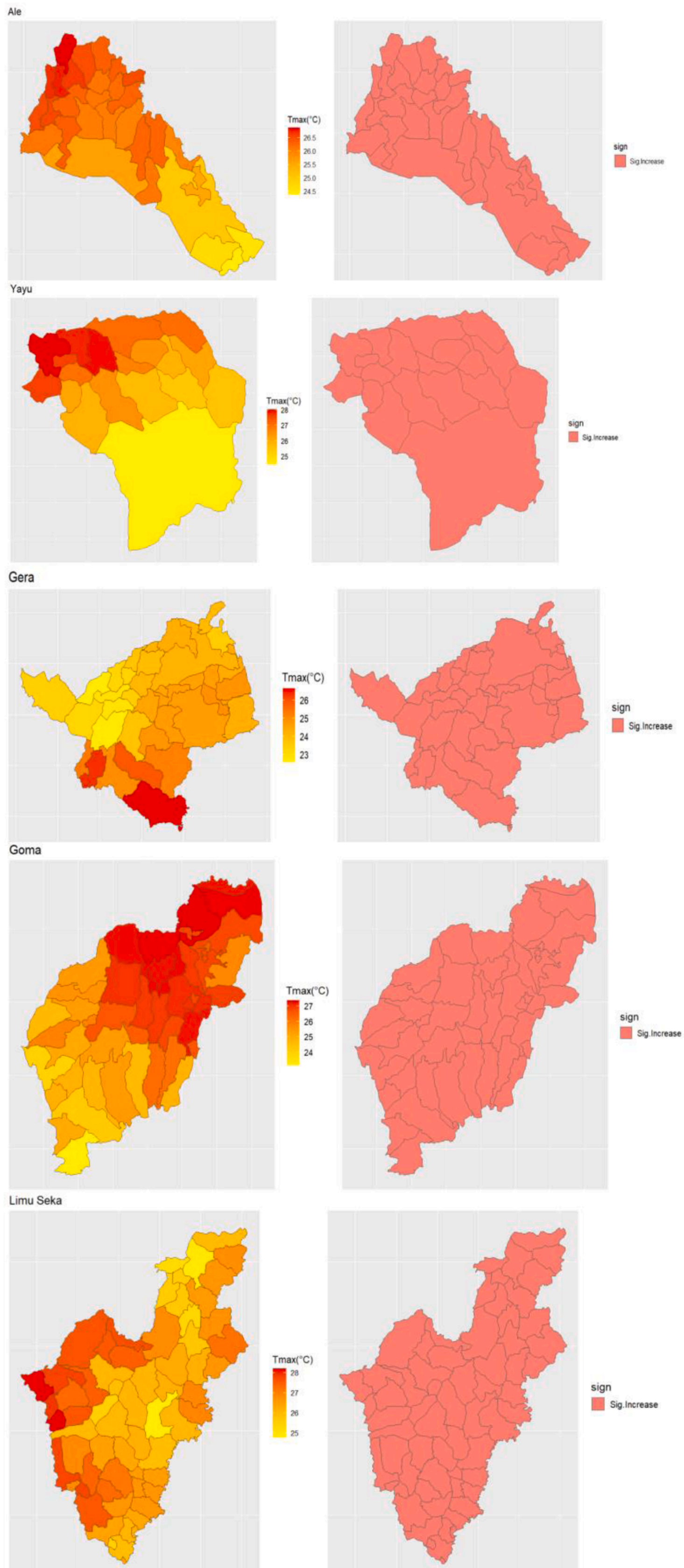

Fig. A3. Map showing the spatial distribution of mean Tmax, and the level of significant increase over the 42 year average in different parts of the study districts.

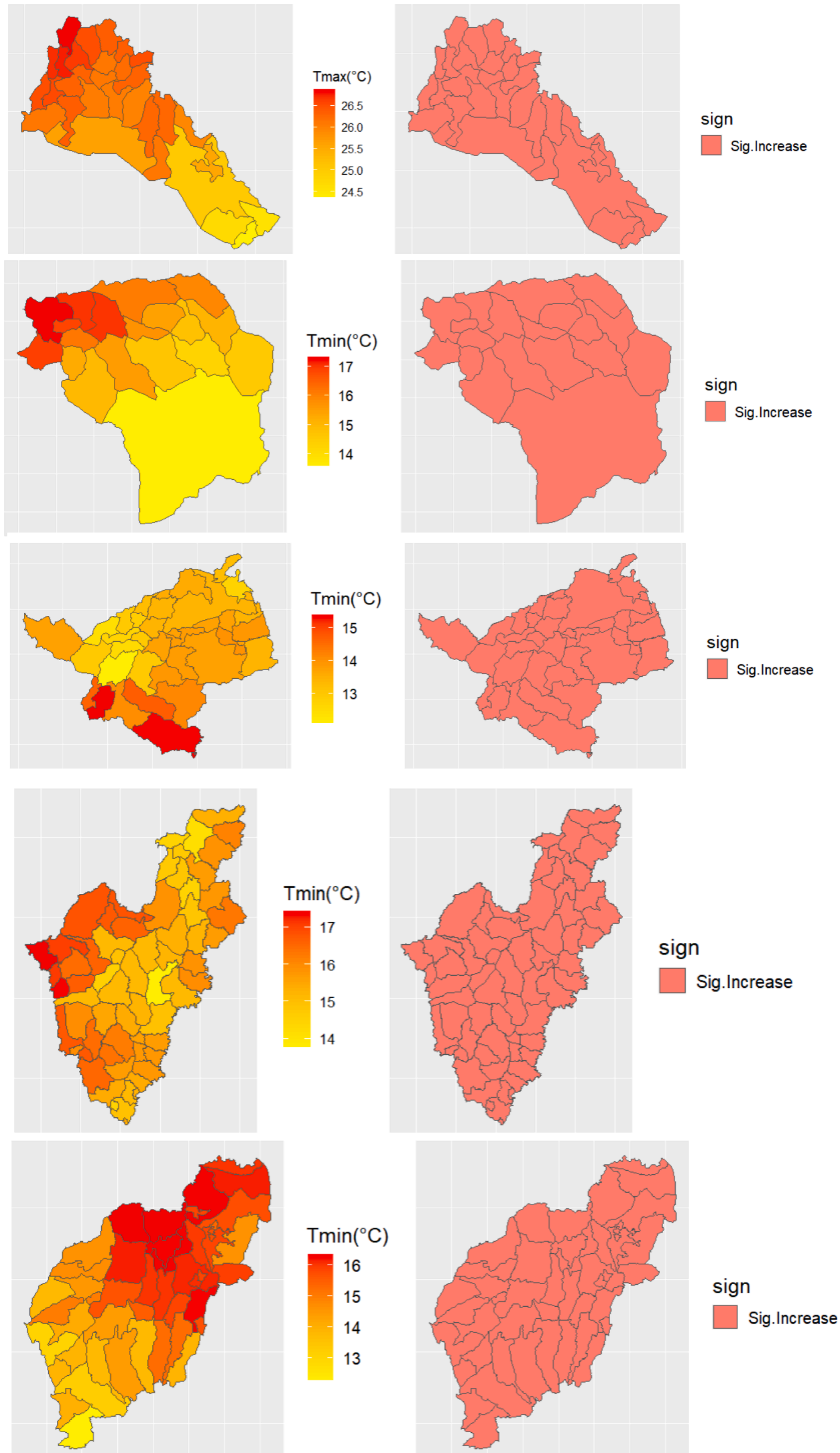

Fig. A4. Map showing the spatial distribution of mean Tmin, and the level of significant increase over the 42 years average in different parts of the study districts.

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