Environmental Challenges 13 (2023) 100794

Contents lists available at ScienceDirect

Environmental Challenges

journal homepage: www.elsevier.com/locate/envc

Local and regional climate trends and variabilities in Ethiopia: Implications for climate change adaptations

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ARTICLE INFO

Keywords:
Agro-ecological zones
Climate change adaptation
Climate trends
Climate variability
Ethiopia

ABSTRACT

Ethiopia is experiencing considerable impact of climate change and variability in the last five decades. Analyzing climate trends and variability is essential to develop effective adaptation strategies, particularly for countries vulnerable to climate change. This study analyzed trends and variabilities of climate (rainfall, maximum temperature (Tmax), and minimum temperature (Tmin)) at local and regional scales in Ethiopia. The local analysis was carried out considering each meteorological station, while the regional analyses were based on agro-ecological zones (AEZs). This study used observations from 47 rainfall and 37 temperature stations obtained from the Ethiopian Meteorological Institute (EMI) for the period of 1986 to 2020. The Modified Mann-Kendall (MMK) trend test and Theil Sen's slope estimator were used to analyze the trends and magnitudes of change, respectively, in rainfall as well as temperature. The coefficient of variation (CV) and standardized anomaly index (SAI) were also employed to evaluate rainfall and temperature variabilities. The local level analysis revealed that *Bega* (dry season*), Kiremt* (main rainy season), and annual rainfall showed increasing trend, albeit no significant, in most stations, but the rainfall in *Belg* (small rainy*)* season showed a non-significant decreasing trend. The regional levels analysis also indicated an increasing trend of *Bega, Kiremt,* and annual rainfall in most AEZs, while *Belg* rainfall showed a decreasing trend in the greater number of AEZs. The result of both local and regional levels of analysis discerned a spatially and temporally more homogeneous warming trend. Both Tmax and Tmin revealed an increasing trend in annual and seasonal scales at most meteorological stations. Likewise, an increase was recorded for mean Tmax and Tmin in entire/most AEZs. The observed trends and variabilities of rainfall and temperature have several implications for climate change adaptations. For example, the decrease in *Belg* rainfall in most AEZs would have a negative impact on areas that heavily depend on *Belg* season's rainfall for crop production. Some climate adaptation options include identifying short maturing crop varieties, soil moisture conservation, and supplemental irrigation of crops using harvested water during the main rainy season. Conversely, since the first three months of *Bega* season (October to December) are crop harvest season in most parts of Ethiopia, the increase in *Bega* rainfall would increase crop harvest loss, and hence, early planting date

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https://doi.org/10.1016/j.envc.2023.100794
Received 8 September 2023; Received in revised form 5 November 2023; Accepted 12 November 2023
Available online 14 November 2023

and identifying short maturing crops during the main rainy season are some climate adaptation strategies. Because of the increase in temperature, water demand for irrigation during *Bega* season will increase due to increased evapotranspiration. On the other hand, the increase in *Kiremt* rainfall can be harvested and used for supplemental irrigation during *Bega* as well as the small rainy season, particularly for early planting. In view of these findings, it is imperative to develop and implement effective climate-smart agricultural strategies specific to each agro-ecological zone (AEZ) to adapt to rainfall and temperature changes and variabilities.

1. Introduction

Climate change is a global issue with comparatively higher impacts in developing countries (IPCC, 2021; Shibru et al., 2023). The African continent is among the most vulnerable continents to climate variability and climate change because of multiple stresses and low adaptive capacity (Almazroui et al., 2020; Gebrechorkos et al., 2019b; IPCC, 2021). A recent study undertaken using a remote sensing rainfall dataset indicated that areas near the equator received the highest average rainfall (>2000 mm), but 80% of Northern Africa received the lowest rainfall (<250 mm) with a significant increasing trend in rainfall in all African regions (Alahacoon et al., 2021). The Eastern Africa, where Ethiopia is part, contains diverse climatic regions ranging from arid to tropical monsoon conditions with substantial multi-decadal variability in rainfall, but temperature exhibited an average increase of 1.5 °C to 2 °C during 1963 to 2012 periods (Daron, 2014).

Several studies on climate variability and trends over Ethiopia reported spatiotemporal inconsistencies in increasing and decreasing trends as well as warming and cooling conditions. These studies include Abebe et al. (2022) for Tekeze-Atbara River Basin, Alemayehu et al. (2022) for Suha watershed, Dawit et al. (2019) for Guna Tana watershed, Matewos and Tefera (2019) for Sidama Zone, Harka et al. (2021) for Upper Wabe Shebelle River Basin, Lebeza et al. (2023) for Jemma sub-basin, and Tofu and Mengistu (2023) for West Shewa, Ethiopia. For instance, Dawit et al. (2019) reported a significant negative and positive trends in average annual rainfall for the Gunna-Tana watershed of the Upper Blue Nile Basin. However, Mulugeta et al. (2019) and Abebe et al. (2022) found no significant trend in annual rainfall over the Awash Basin (1902–2016) and Tekeze-Atbara River Basin (1960–2019), respectively. Samy et al. (2019) also reported significant increasing and decreasing rainfall trends in the Eastern central part and Southwestern part of the Upper Blue Nile Basin, respectively during 1953–2014. Tofu and Mengistu (2023) also reported the increase of *Kiremt* (main rainy season; June-September) and annual rainfall for west Shewa. Conversely, Teshome and Zhang (2019) reported a decreasing rainfall in the *Kiremt* season and significant variability in the *Belg* season (short rainy season; February-May) rainfall over Ethiopia from 1980 to 2010 with frequent droughts mainly occurring during *Belg* and *Kiremt* seasons. A reduction of *Kiremt* and an increase of *Bega* rainfall in Ethiopia was also reported for 1901–2015 periods (Elzopy et al., 2020).

Likewise, the outputs from studies has shown inconsistence in the directions of temperature changes (Gebrechorkos et al., 2019b; Mohammed et al., 2022; Suryabhagavan, 2017). For example, Suryabhagavan (2017) has reported an increase in maximum, minimum, and mean temperatures during the last three decades. The author also reported that Eastern Ethiopia exhibited more frequent drought, while northern and Southern Ethiopia showed higher magnitude and duration of drought events. Matewos and Tefera (2019) also reported increasing trends in maximum, minimum and mean annual temperatures in the study period in the Central Rift Valley of Ethiopia with higher seasonal rainfall and maximum temperature variability than annual rainfall and minimum temperature, respectively. Ademe et al. (2020) also conducted an agro-ecosystem based trend and variability analysis for the Choke Mountain watershed of the Upper Blue Nile Basin and reported a significant warming trend in all study regions. Gebrechorkos et al. (2019b) also indicated the increase in both maximum temperature (Tmax) and minimum temperature (Tmin) for Ethiopia in particular and East Africa in general, with different magnitudes of changes. However, Alemayehu et al. (2022) reported a decrease and increase in Tmin (0.01 °C per year) and Tmax (0.02 °C per year), respectively for the Suha watershed of the Upper Blue Nile Basin during 1990–2020 periods. Likewise, Berhe et al. (2023) reported a similar directions of Tmax and Tmin changes during the *Kiremt* season for Eastern Zone of Tigray region.

These observed climate variability and extreme events would pose a significant impact on agriculture (both crop and livestock production), economy, biodiversity, and natural resources in Ethiopia (Alemayehu and Bewket, 2016; Araya et al., 2020; Ayal et al., 2023; Demem, 2023; Gashure et al., 2022; Worku et al., 2020). A robust and actionable set of information on climate change and variability is critical for policy-makers and planners to design appropriate adaptation options (Demem, 2023; Gebrechorkos et al., 2019a; Getnet et al., 2023; Hilemelekot et al., 2021). Results from existing research have provided contradictory and inconsistent reports, making it difficult to draw nationwide actionable information. The data type and the temporal and spatial range differences are the most vital causes of these discrepancies. Most of the analyses were performed at the watershed/sub-basin/basin and regional levels and making it challenging to draw country-level climate variability and trend information from these fragmented and spatiotemporally discrete studies. In addition, majority of previous studies for Ethiopia and its watersheds/sub-basins/basins were undertaken either by taking the average values of their study areas (Asfaw et al., 2018; Elzopy et al., 2020) or at the station levels (Lebeza et al., 2023; Mohammed et al., 2022; Worku et al., 2018a), and hence those analyses do not provide relevant information for planning climate-adaptation strategies for a particular region. Nevertheless, evaluating the trends and variabilities of rainfall and temperature at both local and regional levels are vital for developing and implementing suitable climate change adaptation strategies at different scales.

Climate change adaptations are measures implemented at different scales to reduce climate change impacts (Demem, 2023). The number of climate adaptations options can vary from region to region depending on several factors (Ademe et al., 2020; Demem, 2023). For instance, in areas facing reduction in rainfall and increase in temperature, irrigation could be one climate adaptation option depending on water availability (Getachew et al., 2021; Hordofa and Yazew, 2023; Kassie et al., 2013). Soil moisture conservation through appropriate tillage practices and mulching could be also other alternatives. However, in areas where irrigation is not feasible, soil moisture conservation and mulching could be the only remaining climate-adaptation options (Tirfi and Oyekale, 2022). The types of climate change adaptation strategies implemented in a specific season also vary based on the problem. For example, water harvesting from rainwater during the main rainy season could be implemented to reduce climate change induced water scarcity during the dry season (Grum et al., 2016; Worku et al., 2020). On the other hand, riparian buffers and afforestation could be applied for reducing climate change induced flooding during the main rainy season (Gay et al., 2023).

Therefore, the objective of the present study is to analyze climate trends and variabilities both at local and regional scales over Ethiopia to provide a scientific basis for planning climate change adaptation measures. The main reason why this study incorporates the regional level analysis besides to the station level analysis is that the climate elements such as rainfall in Ethiopia varies region to region because of the variations in elevation (Gashaw et al., 2023; Taye et al., 2021). Elevation is also a relevant factor for the variations in temperature (Gashaw et al., 2023; Osima et al., 2018). Our study analyzes the trends and variabilities of primary climate elements since the changes in these climate variables would have a higher impact on human and natural system compared to other climate elements such as wind speed, relative humidity, and solar radiation. Due to this fact, previous studies undertaken in Ethiopia in particular (Alemayehu et al., 2022; Asfaw et al., 2018; Berhe et al., 2023; Tofu and Mengistu, 2023) and in East Africa in general (Gebrechorkos et al., 2019a, 2019b) are also focused on the trends and variabilities of these primary climate variables. This study discusses the implications of the trends and variabilities of climate for climate change adaptation options and hence, the outputs of this study will provide important information for planning local and regional climate change adaptation strategies in Ethiopia.

2. Materials and methods

2.1. Descriptions of the study area

Ethiopia is located in the Eastern Africa region between 3°N-15°N and 33°E-48°E (Fig. 1). The country area occupies approximately 1.2 million km^2, of which water bodies cover about 7444 km^2. The Danakil depression (~120 m below sea level) and Ras Dejen (~ 4620 m above sea level (m a.s.l)) are the lowest points on earth and the highest peak in the country, respectively. Based on altitude and climate, Ethiopia is classified into five traditional AEZs (MoA, 1998). These AEZs are hot arid (<500 m a.s.l), warm semi-arid (500–1500 m a.s.l), cool and humid (1500–2300 m a.s.l), cool sub-humid (2300–3200 m a.s.l), and cool and moist (>3200 m a.s.l) (Fig. 1), which are locally known as *Bereha, Kolla, Weyna Dega, Dega* and *Wurch*, respectively. In Ethiopia, there are three main seasons, such as *Kiremt* (main rainy season), *Bega* (dry season), and *Belg* (small rainy season), which spans from June to September (JJAS), October to January (ONDJ), and February to May (FMAM), respectively. The topographic variations observed in small distance provide diverse climates ranging from semi-arid deserts to humid and temperate climates (Taye et al., 2021). The long term mean annual rainfall of the country during the period 1981–2016 is 620 mm (Gebrechorkos et al., 2019b). The mean annual temperature of the country is 15 °C and 25 °C, observed in the highlands and lowlands, respectively (NMSA, 2001).

2.2. Data types and sources

This study used 35 years (1986–2020) daily data from 47 rainfall and 37 temperature stations (Tables 1-3). The rainfall and temperature (both Tmax and Tmin) data are obtained from the Ethiopian Meteorology Institute (EMI) (http://www.ethiomet.gov.et/). The selection of these stations were based on relative completeness of datasets, data availability and the length of years (at least 30 years of data) for climatological data collection, which is the smallest suggested climate span by the World Meteorological Organization (WMO).

2.3. Filling missed data and quality control

The missing values of the observed rainfall and temperature data were filled using the Multivariate Imputation by Chained Equations (MICE) algorithm (Van Buuren et al., 2015) in R software. The selection of MICE package for filling missing climate data in this study was attributed to its better performance to fill the missing values using other stations data, which is clearly explained in Worku et al. (2018b). Another recent study in Ethiopia have also used MICE package for filling the missing climate data (Gashaw et al., 2023).

The quality of the chosen climate stations were examined using R ClimDex 1.1 (Zhang and Yang, 2004). Errors such as negative rainfall, and Tmin exceeding Tmax were replaced by the values of the closest station. Outliers were detected for daily rainfall, Tmax and Tmin greater than four plus or minus standard deviation, and they are treated according to the World Meteorological Organization (WMO, 2009). Due to its ease of use as a graphical interface and its ability to control the quality of climate data, R ClimDex is also widely used in many other studies undertaken in Ethiopia to control the quality of the climate data (Gashaw et al., 2023; Mohammed et al., 2022; Worku et al., 2018b). The procedures followed for processing the raw climate data, filling the

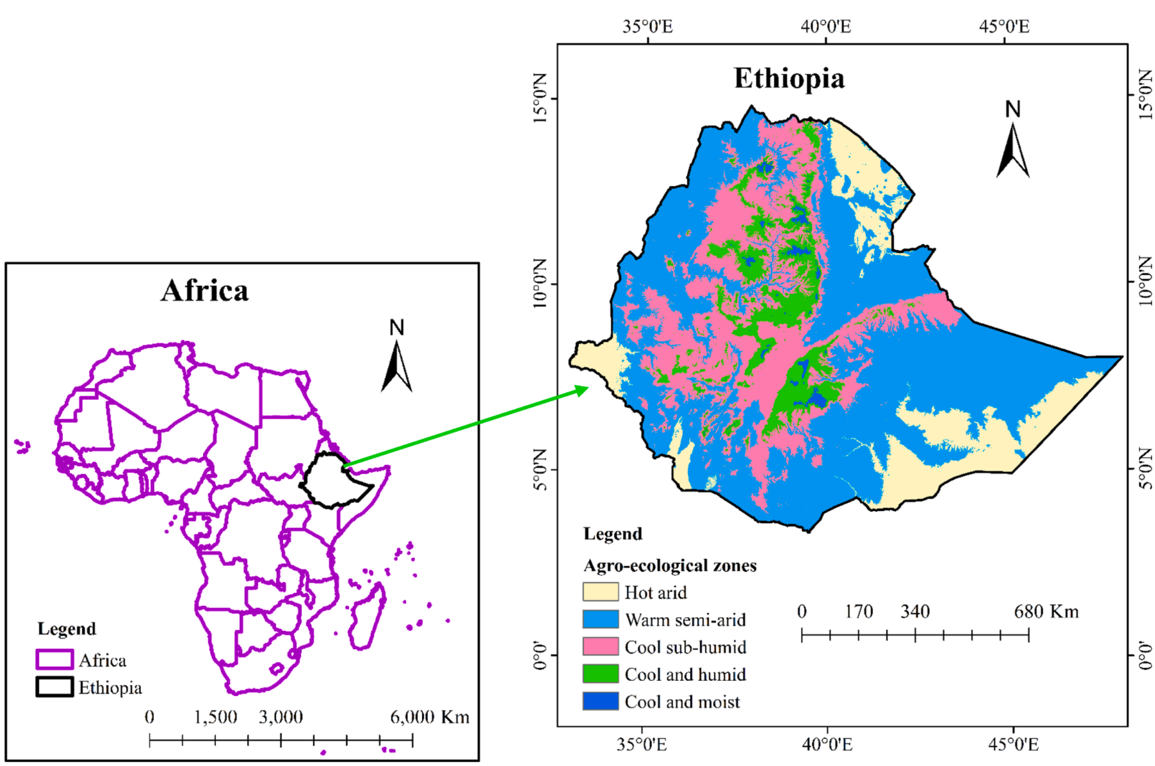

Fig. 1. Location map of the study area with its agro-ecological zones.

Table 1
Trends of seasonal and annual rainfall over Ethiopia (1986–2020).

No.	Stations	*Bega* Z	Bsen	*Belg* Z	βsen	*Kiremt* Z	Bsen	Annual Z	βsen
1	Abomsa	1.63	3.00	−0.51	−1.16	−0.48	−0.80	0.03	0.13
2	Adama	1.02	0.64	0.43	0.70	1.36	3.31	1.25	4.03
3	Addis Ababa	0.45	0.38	−1.25	−2.72	1.48	3.29	0.06	0.34
4	Ambo	−0.43	−0.37	−0.60	−1.00	0.00	−0.01	−1.02	−2.49
5	Arba minch	1.60	2.70	−0.21	−0.33	1.09	1.75	1.51	5.14
6	Asebe Teferi	0.34	0.48	−0.11	−0.25	0.03	0.12	0.23	0.89
7	Asela	0.04	0.08	−0.14	−0.67	1.05	1.54	0.65	2.24
8	Asgori	3.45*	3.94	1.14	1.99	−3.49*	−8.52	−0.31	−0.68
9	Asossa	1.70	2.51	−0.82	−1.65	2.73*	7.15	2.36^{+}	8.22
10	Bahir Dar	−0.77	−1.10	2.74*	6.95	−0.45	−1.18	2.19^{+}	8.30
11	Boditi	1.02	1.59	−1.16	−3.06	0.00	−0.07	−0.37	−1.43
12	Bonga	1.89	3.90	1.69	3.88	2.56*	8.04	3.45*	15.32
13	Butajira	0.18	0.27	−3.01*	−11.05	0.23	1.08	−1.28	−9.02
14	Dangila	1.45	2.35	0.06	0.14	0.65	1.46	1.59	7.29
15	Debre Birhan	0.11	0.03	−0.75	−0.62	2.39	4.48	2.22^{+}	4.08
16	Debre Markos	−0.14	−0.25	1.02	2.07	−0.09	−0.16	0.54	1.39
17	Debre Tabor	0.61	0.80	−0.43	−1.09	1.56	7.94	1.70	8.06
18	Degehabur	1.79	1.27	−1.93^{+}	−3.16	2.68*	1.88	0.00	−0.08
19	Dilla	1.16	2.27	−0.06	−0.20	0.28	1.03	0.57	2.30
20	Dire Dawa	0.23	0.18	−2.64*	−5.31	1.76	3.26	−0.78	−2.15
21	Dubity	1.28	0.23	−2.27	−1.83	0.54	0.49	−0.92	−1.18
22	Fiche	1.26	0.90	−1.68	−2.21	1.93^{+}	4.90	2.03^{+}	4.07
23	Gimbi	1.55	3.06	2.13^{+}	4.66	−0.99	−3.88	1.33	5.87
24	Gonder	0.65	0.60	0.60	0.84	0.94	2.56	1.48	4.10
25	Gore	0.38	0.45	1.55	3.70	−1.46	−4.57	0.31	0.96
26	Haramaya	0.26	0.26	−0.62	−1.16	2.44*	3.97	0.14	0.23
27	Hawassa	0.51	0.70	0.85	1.80	0.67	1.05	0.77	2.37
28	Hosanna	0.20	0.29	−0.41	−1.27	1.33	2.53	0.04	0.16
29	Jijiga	0.40	0.44	−0.34	−0.44	−1.14	−1.28	−0.82	−1.83
30	Jimma	0.71	0.77	1.53	2.76	0.72	1.49	1.70	6.38
31	Kombolcha	0.06	0.02	−1.87	−2.76	0.94	2.45	−0.60	−1.65
32	Konso	−0.03	−0.09	−0.26	−0.84	1.92	2.43	0.77	2.04
33	Lalibela	−0.07	−0.09	−1.05	−1.37	−0.51	−1.35	−0.57	−1.08
34	Mekele	−1.28	−0.35	−0.62	−0.53	0.26	0.47	−1.33	−2.65
35	Metema	−0.51	−0.41	−1.80	−1.72	0.80	2.03	0.21	0.59
36	Mizan Teferi	0.68	1.36	−0.88	−1.82	−1.14	−4.38	−0.82	−3.90
37	Mojo	2.60*	2.20	1.33	2.66	0.06	0.20	1.70	6.81
38	Moyale	0.82	1.60	−0.47	−1.06	0.71	0.26	0.43	1.68
39	Negele	1.82	2.06	−2.05^{+}	−5.01	0.74	0.51	−0.81	−1.67
40	Nekemte	1.82	3.32	0.67	1.89	0.23	1.22	0.99	5.57
41	Pawe	4.71*	38.11	3.32*	10.07	−5.14*	−47.46	0.54	2.50
42	Robe	0.91	1.23	0.00	−0.05	1.76	2.87	1.90	4.54
43	Teppi	1.05	2.53	1.96^{+}	2.74	−0.34	−0.85	0.65	3.24
44	Tulu bolo	2.88*	2.73	−2.27^{+}	−3.76	−2.19	−14.38	0.03	0.29
45	Wolaita	0.82	1.66	0.60	2.11	2.36	7.07	1.90	9.80
46	Yirgachefe	0.55	1.23	−0.20	−0.73	1.96	5.69	1.70	7.68
47	Yirgalem	−0.68	−1.40	−0.23	−0.71	0.26	0.66	−0.62	−1.99

* and + are significant trend at α 0.01 and α 0.05 respectively.

missing values as well as quality control of the data are detailed in Wubaye et al. (2023).

2.4. Methods of data analysis

Trend analysis was conducted using the modified Mann-Kendall (MMK) trend test and Sen's slope estimator (Mann, 1945; Sen, 1968). The MMK and its preceding version, and Sen's slope are among the widely statistical analysis applied to study the trends of climate variables in different studies undertaken in Ethiopia (Abebe et al., 2022; Lebeza et al., 2023; Mohammed et al., 2022; Shibru et al., 2023; Worku et al., 2018a). The non-parametric model MMK test and Sen's slope have been applied to the seasonal and annual rainfall and temperature series to investigate the rainfall and temperature trends. For making a statistical decision, the test statistics were evaluated at the 1% ($\alpha < 0.01$) and 5% ($\alpha < 0.05$) levels of significance.

The interannual variability of annual and seasonal rainfall was calculated as Eq. (1).

$$CV\ (\%) = \frac{SD}{M} \times \ 100 \qquad (1)$$

Where, CV=the coefficient of variation, SD=the standard deviation, and *M*=the mean. According to Hare (2003), the CV result <20%, 20%–30%, and >30% are less variable, moderately variable and highly variable, respectively.

The frequency of dry and wet years over 1986–2020 periods were computed using the standardized anomaly index (SAI). The average index of all meteorological stations was used to estimate the country-wide trend of indices. The standardized anomaly of each index at the country level was calculated following Eq. (2).

$$SAIi = \frac{(Xt - Xmean)}{\mu} \qquad (2)$$

Where, SAIi is the standardized anomaly index in the year i, Xt is the annual index value in year t, Xmean is the long-term mean annual index over a period of observation, and μ is the standard deviation of the annual index over the period of observation. The 5-year moving average was also used to show the annual variation of extremes within the period. McKee et al. (1993) indicated that the SAI result 2 and above, 1.5 to 1.99, 1 to 1.49, −0.99 to 0.99, −1 to −1.499, −1.5 to −1.99 and −2

Table 2
Trends of seasonal and annual mean Tmax over Ethiopia (1986–2020).

No.	Stations	*Bega*		*Belg*		*Kiremt*		Annual	
		Z	βsen	Z	βsen	Z	βsen	Z	βsen
1	Adama	0.84	0.01	1.99+	0.03	2.37+	0.04	2.06+	0.03
2	Addis Ababa	3.89*	0.05	4.09*	0.06	2.71*	0.02	4.69*	0.04
3	Ambo	2.85*	0.02	3.24*	0.05	3.04*	0.03	3.47*	0.03
4	Asbe Teferi	−2.05+	−0.04	−0.27	0.00	−1.35	−0.02	−1.48	−0.02
5	Assela	−1.21	−0.02	−0.20	0.00	0.09	0.00	−0.40	−0.01
6	Bahir Dar	4.62*	0.04	2.34+	0.05	5.35*	0.06	4.50*	0.05
7	Boditi	2.78*	0.03	3.85*	0.07	2.05+	0.02	3.32*	0.04
8	Bonga	1.39	0.01	1.49	0.02	0.99	0.01	1.45	0.01
9	Dangila	2.53*	0.02	2.71*	0.05	2.74*	0.03	2.66*	0.03
10	Debre Birhan	3.89*	0.04	3.31*	0.04	2.71*	0.02	4.96*	0.03
11	Debre markos	2.30+	0.02	1.95+	0.03	4.43*	0.04	3.79*	0.03
12	Debre Tabor	1.85	0.02	2.41*	0.04	3.07*	0.04	3.01*	0.03
13	Dire Dawa	5.17*	0.05	4.80*	0.09	3.55*	0.04	5.72*	0.06
14	Dubity	5.47*	0.08	4.43*	0.08	3.01*	0.04	5.41*	0.06
15	Fiche	3.25*	0.03	3.75*	0.04	2.83*	0.03	4.13*	0.04
16	Gewane	4.32*	0.08	3.93*	0.14	3.64*	0.07	4.00*	0.09
17	Gondar	4.02*	0.04	3.35*	0.05	4.96*	0.05	4.69*	0.05
18	Gore	3.41*	0.03	2.73*	0.03	4.12*	0.03	4.57*	0.03
19	Haramaya	2.90*	0.02	3.81*	0.05	2.76*	0.03	4.50*	0.03
20	Hawassa	0.34	0.00	3.34*	0.05	3.65*	0.03	3.42*	0.02
21	Hosanna	4.50*	0.04	4.02*	0.06	4.99*	0.04	5.55*	0.04
22	Jijiga	−1.22	−0.01	1.29	0.02	0.53	0.01	0.50	0.00
23	Kombolcha	5.27*	0.05	4.73*	0.07	3.96*	0.04	5.58*	0.05
24	Konso	3.10*	0.03	4.50*	0.08	3.40*	0.04	5.28*	0.05
25	Lalibela	1.83	0.02	2.51*	0.03	2.61*	0.03	3.28*	0.03
26	Mekelle	3.72*	0.03	3.41*	0.05	3.93*	0.04	4.19*	0.04
27	Mojo	5.17*	0.08	3.01*	0.05	3.95*	0.08	5.18*	0.07
28	Moyale	−0.87	−0.01	1.90	0.04	3.17*	0.04	2.34*	0.03
29	Negele	4.36*	0.04	5.48*	0.08	4.84*	0.07	5.84*	0.07
30	Nekemte	1.93+	0.01	2.47*	0.03	3.53*	0.03	3.88*	0.02
31	Pawe	−4.50*	−0.10	−4.26*	−0.17	4.63*	0.32	2.34+	0.02
32	Robe	3.10*	0.03	3.92*	0.05	2.54*	0.02	4.37*	0.03
33	Teppi	0.28	0.00	2.30+	0.02	1.26	0.01	2.26*	0.01
34	Tulu Bolo	0.54	0.01	2.44*	0.05	2.36*	0.04	1.93+	0.03
35	Wolayata	1.89	0.02	2.56*	0.04	1.97+	0.02	2.56*	0.02
36	Yirgacheffe	0.50	0.01	2.44*	0.04	2.85*	0.04	2.66*	0.03
37	Yirgalem	1.22	0.02	3.10*	0.04	1.51	0.02	2.68*	0.02

* and + are significant trend at α 0.01 and α 0.05 respectively.

and less are classified as more extreme wet, very wet, moderately wet, normal, moderately dry, very dry and extreme dry, respectively.

Analysis of trends and variabilities of rainfall, Tmax and Tmin in this study were undertaken at the local and regional levels. The study employed the local level analysis using the 47 rainfall and 37 temperature meteorological stations, which are represent local climates. On the other hand, the regional analysis were made at the five AEZs levels, such as hot arid, warm semi-arid, cool sub-humid, cool and humid, and cool and moist AEZs. Hence, the regional analysis were carried out by taking the average values of those meteorological stations found in the same AEZs. Wubaye et al. (2023) have also used this approach for analyzing the climate extremes in different AEZs. This approach was also employed in another study for evaluating performances of rainfall and temperature products against observed data (Gashaw et al., 2023) as well as for planning climate change adaptation strategies following agro-ecosystem approach (Ademe et al., 2020). The analysis of trends and variabilities of climate were undertaken at the *Bega* (October-January), *Belg* (February-May), *Kiremt* (June-September), and annual temporal scales. *Belg* and *Kiremt* are known as small and main rainy seasons in Ethiopia, respectively (Wubaye et al., 2023).

3. Results and discussion

3.1. Trends of rainfall and temperature at local and regional levels

Tables 1, 2 and 3 present the seasonal (*Bega, Belg and Kiremt* seasons) as well as the annual trends of rainfall, Tmax, and Tmin over Ethiopia between 1986 and 2020 at the local level. Table 4 provides a summary of the trends of all stations of these climate variables.

3.1.1. Trends of seasonal and annual rainfall at local level

The results of seasonal and annual rainfall trends over Ethiopia for 47 meteorological stations are presented in Table 1. The table shows 83% of the stations showed an increase in *Bega* (dry season) rainfall, while the remaining 17% of the stations exhibited a declining trend (Table 4). Out of the stations that displayed an increase, Asgori, Mojo, Pawe, and Tulu bolo meteorological stations showed a significant ($\alpha<0.01$) increasing trend, while the others showed an insignificant increase in *Bega* season rainfall. This result is consistent with the study conducted by Alemayehu et al. (2020) in Alwero watershed (Western Ethiopia) who also reported an increasing trend in *Bega* season rainfall. Similarly, Bayable et al. (2021) also found an increase in *Bega* rainfall in the West Harerge Zone (Eastern Ethiopia).

In contrast to the *Bega* season rainfall, 63.9% of meteorological stations in Ethiopia displayed a downward trend, while 34% had an increasing trend in the *Belg* season rainfall (Table 4). Among the meteorological stations, Bahir Dar and Pawe showed a significant ($\alpha<0.01$) increasing trend, whereas Butajira and Dire Dawa displayed a significant ($\alpha<0.01$) downward trend in the *Belg* season. These findings are consistent with the results of Belay et al. (2021) who reported that *Belg* rainfall, which is vital for farmers for land preparation and planting activities, showed a significant decreasing trend in Southern Ethiopia. Alemayehu and Bewket (2016) also reported the reductions of *Belg* rainfall in their three studied districts of the North Shewa Administrative Zone. Moreover, a decreasing trend of *Belg* season rainfall was also reported in Eastern Zone of Tigray region (Berhe et al., 2023) and Central

Table 3
Trends of seasonal and annual mean Tmin over Ethiopia during 1986–2020 periods.

No.	Stations	*Bega* Z	βsen	*Belg* Z	βsen	*Kiremt* Z	βsen	Annual Z	βsen
1	Adama	−3.69*	−0.32	−3.85*	−0.38	−3.65*	−0.24	−4.08*	−0.29
2	Addis Ababa	1.72	0.02	2.53*	0.03	3.24*	0.03	2.76*	0.02
3	Ambo	3.10*	0.04	4.03*	0.05	4.01*	0.04	4.46*	0.04
4	Asbe Teferi	3.29*	0.11	4.90*	0.15	4.09*	0.12	4.30*	0.14
5	Assela	1.51	0.02	−2.10^{+}	−0.03	−0.53	−0.01	−0.81	−0.01
6	Bahir Dar	−1.58	−0.02	−1.92	−0.04	−2.33^{+}	−0.02	−1.46	−0.02
7	Boditi	4.80*	0.06	4.90*	0.06	5.64*	0.06	5.67*	0.06
8	Bonga	0.27	0.01	0.41	0.01	−0.37	−0.01	0.27	0.0033
9	Dangila	4.66*	0.09	4.23*	0.07	2.76*	0.03	4.83*	0.06
10	Debre Birhan	0.77	0.01	−0.16	0.00	0.38	0.004	0.44	0.0036
11	Debre markos	3.67*	0.03	3.96*	0.04	5.55*	0.03	5.27*	0.03
12	Debre Tabor	1.02	0.01	−0.68	−0.01	−0.37	−0.003	0.14	0.0006
13	Dire Dawa	0.10	0.00	1.86	0.02	1.78	0.02	1.28	0.01
14	Dubity	−0.82	−0.02	−0.78	−0.02	0.30	0.004	−0.47	−0.0089
15	Fiche	−0.60	−0.01	1.99^{+}	0.02	4.43*	0.03	1.99^{+}	0.014
16	Gewane	2.20^{+}	0.05	3.07*	0.07	2.83*	0.05	2.67*	0.05
17	Gondar	2.95*	0.03	3.47*	0.04	3.95*	0.03	3.75*	0.03
18	Gore	1.21	0.01	2.12^{+}	0.03	4.06*	0.02	2.60*	0.02
19	Haramaya	0.97	0.02	0.34	0.01	4.23*	0.03	1.79	0.01
20	Hawassa	4.97*	0.09	3.93*	0.05	6.02*	0.05	5.85*	0.07
21	Hosanna	0.55	0.01	0.97	0.01	2.78*	0.02	1.61	0.02
22	Jijiga	−1.49	−0.03	−1.09	−0.03	0.71	0.01	−1.29	−0.02
23	Kombolcha	0.37	0.0034	−0.62	−0.01	1.95^{+}	0.01	0.30	0.0021
24	Konso	2.57*	0.02	2.84*	0.05	3.34*	0.04	3.17*	0.034
25	Lalibela	0.99	0.0063	1.53	0.019	1.73	0.01	2.19^{+}	0.0127
26	Mekelle	0.72	0.011	2.12^{+}	0.020	2.49*	0.021	1.78	0.016
27	Mojo	−1.79	−0.03	−1.97^{+}	−0.03	−1.48	−0.02	−2.23^{+}	−0.03
28	Moyale	−2.09^{+}	−0.05	0.68	0.01	1.65	0.02	−0.21	−0.0040
29	Negele	4.33*	0.04	4.46*	0.06	4.77*	0.06	5.31*	0.05
30	Nekemte	2.22^{+}	0.02	3.84*	0.04	5.14*	0.03	4.29*	0.03
31	Pawe	5.74*	0.18	−3.14*	−0.07	−2.78*	−0.04	2.80*	0.02
32	Robe	3.34*	0.04	2.86*	0.03	5.54*	0.05	4.94*	0.04
33	Teppi	0.92	0.01	0.97	0.01	1.96^{+}	0.02	1.52	0.01
34	Tulu Bolo	0.62	0.01	2.02^{+}	0.05	2.34^{+}	0.06	2.22^{+}	0.03
35	Wolayata	3.61*	0.03	4.37*	0.05	5.17*	0.04	4.77*	0.04
36	Yirgacheffe	3.55*	0.06	2.50*	0.03	2.16^{+}	0.02	3.69*	0.04
37	Yirgalem	−1.49	−0.02	−1.24	−0.03	1.09	0.01	−0.62	−0.01

* and + are significant trend at α 0.01 and α 0.05, respectively.

Table 4
Summary of the seasonal and annual rainfall, mean Tmax and mean Tmin trends over Ethiopia (1986–2020).

	Rainfall				Tmax				Tmin			
	Bega	*Belg*	*Kiremt*	Annual	*Bega*	*Belg*	*Kiremt*	Annual	*Bega*	*Belg*	*Kiremt*	Annual
%↑	83	34	70.3	70.3	86.5	91.8	97.3	94.6	78.4	70.3	81.1	78.4
%↓	17	63.9	25.5	27.6	13.5	8.2	2.7	5.4	21.6	29.7	18.9	21.6
%ns	0	2.1	4.2	2.1	0	0	0	0	0	0	0	0
↑%*	8.5	4.3	8.8	2.1	54	73	75.7	81.1	35.1	40.5	51.4	45.9
%↓*	0	4.3	4.4	0	2.7	2.7	0	0	2.7	5.4	5.4	2.7
%↑$^{+}$	0	4.3	2.2	8.5	5.4	10.8	8.1	8.1	2.7	5.4	10.8	8.1
%↓$^{+}$	0	6.5	0	0	2.7	0	0	0	2.7	2.7	2.7	2.7

%↑ = Percent of stations with an increasing trend,%↓= Percent of stations with a decreasing trend, ↑%* = Percent of stations with a significant increasing trend at α 0.01,%↓*= Percent of stations with a significantly decreasing trend at α 0.01,%↑+ = Percent of stations with the significant increasing trend at α 0.05,%↓+ = Percent of stations with the significant decreasing trend at α =0.05, and%ns percent of stations with no trend change.

and Northwest parts of the country (Tirfi and Oyekale, 2022). Regarding this, Asfaw et al. (2018) suggested that the dynamics of global warming caused by El-Nino Southern Oscillation (ENSO) have led to a significant decreasing and increasing trend in rainfall and temperature, respectively, in East Africa.

The *Kiremt* (main rainy season) seasonal rainfall tended to be similar to that of the *Bega* seasonal rainfall. Most stations showed an increasing trend in *Kiremt* rainfall, with 70.3% of them demonstrating an increase. This is consistent with the findings of Belay et al. (2021), who also observed a non-significant increasing trend. The increase in *Kiremt* rainfall was also observed in West Shewa (Tofu and Mengistu, 2023) and Central and Northwest parts of Ethiopia (Tirfi and Oyekale, 2022). At Asosa, Bonga, Degehabur, Fiche, and Haramaya meteorological stations, significant increase (α<0.05) in *Kiremt* rainfall was observed. However, Asgori and Pawe meteorological stations showed a significant (α<0.01) decreasing trend. In contrast of the increase of *Kiremt* rainfall in the majority of the studied climate stations, Mekonen and Berlie (2019) found that *Kiremt* season rainfall was declining in the South Wello Zone, though the reported change was not significant.

Similar to the trend of *Kiremt* season rainfall, 70.3% of the analyzed stations had an increasing trend in annual rainfall, while 27.6% of the stations reported a decline in annual rainfall (Table 4). Among these stations, Assosa, Bahir Dar, Debre Birhan, and Fiche meteorological stations demonstrated a significant (α <0.05) increasing trend. These findings are consistent with research conducted by Mohammed et al. (2022) who also reported a significant increase at the Debre Birhan meteorological station. Additionally, Alemayehu et al. (2020) in Alwero watershed (Western Ethiopia), Tofu and Mengistu (2023) in West Shewa, and Lebeza et al. (2023) in Jemma sub-basin (Upper Blue Nile Basin) have also reported an upward trend in annual rainfall. However, Bayable et al. (2021) reported a non-significant decreasing trend in annual rainfall in West Harerge Zone (Eastern Ethiopia). Similarly, Mulugeta et al. (2019) investigated a non-significant decreasing trend in annual rainfall in Awash River Basin, Ethiopia. These differences in rainfall trends show that the study area experiences high spatial and temporal variability in rainfall.

Over the last 30 years, the trend analysis of rainfall shows that the amount of rainfall has been decreasing at the Butajira station in *Belg* (−11.05 mm/decade) and annual (−9.02 mm/decade) at its maximum magnitude. The highest increasing trend was observed at Bonga station in the annual (15.32 mm/decade) and *Kiremt* (8.04 mm/decade) temporal scales. Additionally, Pawe meteorological station also recorded a maximum increasing trend in the *Bega* (38.11 mm/decade) and *Belg* (10.07 mm/decade) seasons. On the other hand, the Pawe station showed the highest magnitude of decreasing trend during the *Kiremt* season (−47.46 mm/decade). During the *Bega* season, the Yirgalem station exhibited the highest decreasing trend (−1.4 mm/decade).

3.1.2. Trends of seasonal and annual rainfall at regional level

The rainfall trends observed at the station level are reflected in the seasonal and annual rainfall trends at regional levels. In hot arid agro-ecological zone (AEZ), rainfall has experienced an insignificant increasing trend during *Bega* and *Kiremt* seasons while *Belg*, and annual rainfall showed a non-significant decreasing trend (Table 5). The warm semi-arid AEZ showed increasing trends in *Bega, Kiremt* and annual rainfall at 80%, 70% and 70% of the stations, respectively. However, the *Belg* season showed decreasing trends in 80% of the stations. At 10% of stations in warm semi-arid AEZ, the *Bega, Belg*, and *Kiremt* seasons rainfall showed a significant ($\alpha<0.01$) increasing trend. Meanwhile, 10% of stations for the *Belg* and *Kiremt* seasons showed a significant decreasing trend. This result is consistent with Etana et al. (2020), who reported an increase in annual rainfall in midland (warm semi-arid) zone.

Similar to the warm semi-arid zone, the cool sub-humid AEZ showed an increasing trend in *Bega, Kiremt*, and annual rainfall at most stations. Over the cool sub-humid AEZ, 52% and 48% of meteorological stations exhibited increasing and decreasing trends, respectively in the *Belg* rainfall (Table 5). In the cool and humid AEZ, a downward trend was observed in the majority (90%) of the stations during the *Belg* season's rainfall. On the other hand, an upward trend was observed in the *Bega,* and *Kiremt* seasons, as well as in the annual rainfall at most of the stations in the cool and humid AEZ. A significant ($\alpha<0.05$) increasing trend was observed in *Kiremt* and annual rainfall. Similarly, an increasing trend in *Bega, Kiremt* and annual rainfall and a decreasing trend in *Belg* rainfall was observed in cool and moist AEZ.

In general, an increasing trend for *Bega, Kiremt*, and annual rainfall was observed in all AEZs, except the decreasing trend in annual rainfall in hot arid AEZ. Whereas, decreasing trends in *Belg* rainfall were observed in most/entire stations of the cool and moist, hot arid, warm semi-arid, and cool and humid AEZs, but the cool sub-humid AEZ exhibited an increasing and decreasing trend in 52% and 48% of the stations, respectively.

3.1.3. Trends of seasonal and annual temperatures at local level

Similar to the analysis of rainfall, the trend of *Bega, Belg, Kiremt,* and the annual average Tmax, as well as Tmin of 37 meteorological stations in Ethiopia was analyzed. Tables 2-4 present the trend of mean Tmax and Tmin for seasonal and annual timescales. Most of the stations located throughout the country show an increasing trend in mean Tmax and Tmin at seasonal and annual time scales.

Table 5

Summary of the seasonal and annual rainfall, mean Tmax and Tmin trends in different AEZs of Ethiopia (1986–2020).

		Rainfall				Tmax				Tmin			
		Bega	*Belg*	*Kiremt*	Annual	*Bega*	*Belg*	*Kiremt*	Annual	*Bega*	*Belg*	*Kiremt*	Annual
Hot arid	%↑	100	0	100	0	100	100	100	100	0	0	100	0
	%↓	0	100	0	100	0	0	0	0	100	100	0	100
	↑%*	0	0	0	0	100	100	100	100	0	0	0	0
	%↓*	0	0	0	0	0	0	0	0	0	0	0	0
	%↑+	0	0	0	0	0	0	0	0	0	0	0	0
	%↓+	0	0	0	0	0	0	0	0	0	0	0	0
Warm semi-arid	%↑	80	20	70	70	71.4	85.7	100	100	85.7	85.7	85.7	85.7
	%↓	20	80	30	30	28.6	14.3	0	0	14.3	14.3	14.3	14.3
	↑%*	10	10	10	0	57.1	57.1	85.7	85.7	42.9	42.9	42.9	57.2
	%↓*	0	10	10	0	14.3	14.3	0	0	0	14.3	14.3	0
	%↑+	0	10	0	0	0	14.3	0	14.3	14.3	0	14.3	0
	%↓+	0	20	0	0	0	0	0	0	14.3	0	0	0
Cool sub-humid	%↑	88	52	68	72	89.5	94.7	94.7	94.7	73.7	68.4	79.0	73.6
	%↓	12	48	32	28	10.5	5.3	5.3	5.3	26.3	31.6	21.0	26.4
	↑%*	12	4	12	4	47.4	73.6	63.0	73.7	42.1	47.4	52.6	52.6
	%↓*	0	4	4	0	0	0	0	0	5.3	5.3	5.3	5.3
	%↑+	0	4	0	8	5.2	10.5	15.8	10.5	5.3	10.5	15.8	5.3
	%↓+	0	4	0	0	5.2	0	0	0	0	5.3	5.3	5.3
Cool and humid	%↑	70	10	70	80	88.9	88.9	100	88.9	88.9	77.8	77.8	88.9
	%↓	30	90	30	20	11.1	11.1	0	11.1	11.1	22.2	22.2	11.1
	↑%*	0	0	0	0	55.5	77.7	88.8	88.8	22.2	33.3	66.6	33.3
	%↓*	0	0	0	0	0	0	0	0	0	0	0	0
	%↑+	0	0	10	10	11.1	11.1	0	0	0	22.2	0	22.2
	%↓+	0	0	0	0	0	0	0	0	0	11.2	0	0
Cool and moist	%↑	100	0	100	100	100	100	100	100	100	0	100	100
	%↓	0	100	0	0	0	0	0	0	0	100	0	0
	↑%*	0	0	0	0	100	100	100	100	0	0	0	0
	%↓*	0	0	0	0	0	0	0	0	0	0	0	0
	%↑+	0	0	0	100	0	0	0	0	0	0	0	0
	%↓+	0	0	0	0	0	0	0	0	0	0	0	0

%↑ = Percent of stations with an increasing trend,%↓= Percent of stations with a decreasing trend, ↑%* = Percent of stations with a significant increasing trend at α 0.01,%↓*= Percent of stations with a significantly decreasing trend at α 0.01,%↑+ = Percent of stations with the significant increasing trend at α 0.05, and%↓+ = Percent of stations with the significant decreasing trend at α 0.05%.

A warming trend has been observed in most meteorological stations for both seasonal and annual timescales for average Tmax. Only the Asbe Teferi meteorological station exhibits an insignificant decreasing trend in mean Tmax in the *Kiremt* season (Table 2). Out of all the analyzed stations, 28 meteorological stations showed a significantly ($\alpha < 0.01$) increasing trend in average Tmax. These results are concurrent with Mohammed et al. (2022), who reported a significant increase in the average Tmax on the annual and seasonal time scale in most meteorological stations. A significant ($\alpha < 0.01$) increasing trend was observed in 54%, 73%, 75.7%, and 81.1% of the stations in the *Bega, Belg, Kiremt,* and annual time scales, respectively (Table 4). On the other hand, a significant decreasing ($\alpha < 0.01$) trend was found at Pawe meteorological station on *Belg* and *Bega* seasons. The MMK trend test confirmed that in the *Bega* season, a decreasing trend was observed at Asebe Teferi, Assela, Jijiga, Moyale, and Pawe meteorological stations. Furthermore, Asebe Teferi and Assela meteorological stations indicated a downward trend in mean annual Tmax. The warming trend of mean Tmax ranges from 0.002 to 0.08, 0.02- 0.14, 0.001- 0.32, and 0.004- 0.09 °C for *Bega, Belg, Kiremt*, and annual time scales, respectively. The results are similar to those reported by Ademe et al. (2020) for Choke Mountain. Similar to the significantly ($\alpha < 0.01$) increasing trend in average Tmax of most stations in this study, several studies (Gebrechorkos et al., 2019b; Jury and Funk, 2013) conducted in different places and timeframes have also reported a warming trend.

Similar to the mean Tmax, the mean Tmin also showed a positive trend on both seasonal and annual timescales at most meteorological stations (Table 3). Out of all meteorological stations, 21.6%, 29.7%, 18.9%, and 21.6% showed negative trends in *Bega, Belg, Kiremt*, and annual timescale, respectively (Table 4). The *Bega, Belg, Kiremt*, and annual Tmin trends show a significant increase ($\alpha < 0.01$) trend at 35.1%, 40.5%, 51.4%, and 45.9% of the stations, respectively. This result coincides with previous findings of Matewos and Tefera (2019) in Sidama Zone and Suryabhagavan (2017) in Ethiopia. For instance, Matewos and Tefera (2019) reported Tmin and Tmax has shown an increasing trend over time in the Central Rift Valley region of Ethiopia. An increasing trend in Tmax and Tmin was observed in most meteorological stations of Ethiopia (Suryabhagavan, 2017), and the Jemma sub-basin of Ethiopia (Worku et al., 2018a). Other studies conducted in different parts of Ethiopia (Asfaw et al., 2018; Shekuru et al., 2022) and East Africa (Gebrechorkos et al., 2019b) also assert an increasing trend of Tmax and Tmin with a difference in magnitude and spatial variation. Conversely, Alemayehu et al. (2022) reported a decrease in Tmin and an increase in Tmax in Suha watershed of the Upper Blue Nile Basin during the *Kiremt* season. Berhe et al. (2023) also found a non-significant increasing trend of Tmax and a decreasing trend of Tmin, respectively during the *Kiremt* season in the Eastern Zone Tigray region.

In the current study, it was observed that there is a difference in the extent of change in Tmax and Tmin. For instance, at the Asebe Teferi meteorological station, the increase in Tmin was higher than the increase in Tmax. Concurrently, Mengistu et al. (2014) reported that the positive trend of Tmin was higher than the Tmax in the Upper Blue Nile Basin, Ethiopia. Additionally, a study by Tirfi and Oyekale (2022b) showed a higher increase in minimum temperature (0.15 °C) than in maximum temperature (0.13 °C) in the Teff growing belts of Ethiopia from 1981 to 2018. Comparable to the trend of temperature in Ethiopia, an increase in annual Tmax and Tmin by 0.141 °C/decade and 0.204 °C/decade, respectively, was observed in the globe from 1950 to 2004 (Vose et al., 2005).

However, it was observed that some meteorological stations in Ethiopia have experienced a decrease in temperature. Specifically, the Pawe meteorological station showed a decreasing trend in Tmin during the *Kiremt* and *Belg* seasons from 1986 to 2020. The warming trend of mean Tmin ranged from 0.0005 to 0.18, 0.005 –0.15, 0.004–0.12, and 0.0006–0.14 °C for the *Bega, Belg, Kiremt*, and annual time scales, respectively. Additionally, a significant ($\alpha < 0.05$) decreasing trend of Tmin was observed at Bahir Dar (*Kiremt* season), Moyale (*Bega* season), Assela (*Belg* season), and Mojo (*Belg* season) meteorological stations.

3.1.4. Trends of seasonal and annual temperature at regional levels

Table 5 displays the trends of Tmax and Tmin over the five AEZs of the country. The result revealed an increasing trend in mean Tmax in *Bega, Belg* and *Kiremt* seasons as well as annual timescale in most/entire stations located in all AEZs. The trends in Tmin, however, is not similar in all AEZs. For example, in the hot arid AEZ, an insignificant decreasing trend in *Bega, Belg*, and annual timescales and an insignificant increasing trend in *Kiremt* season were observed in most of the stations. In warm semi-arid, cool sub-humid, and cool humid AEZs, a warming trend in Tmin were observed at seasonal and annual temporal scales in the greater number of the stations. At the cool and moist AEZ, a warming trend in Tmin was recorded in *Bega, Kiremt,* and annual time scales, while decreasing trend in Tmin was observed in the *Belg* season (Table 5). Similar to this result, Ademe et al. (2020) reported an increasing trend of Tmax in warm semi-arid (upper *Kolla*), cool sub-humid (upper *Weyna Dega*), and cool and humid (upper *Dega*) AEZs.

3.2. Spatiotemporal variability of rainfall and temperature at local and regional levels

3.2.1. Spatiotemporal variability of rainfall at local level

Ethiopia has experienced high spatial and temporal heterogeneity in the long-term seasonal and annual rainfall from 1986 to 2020 (Tables 6, 7 and 8). The meteorological stations in the study had an average annual rainfall ranging from 223.03 mm to 2109.64 mm, with a coefficient of variation (CV) of rainfall ranging from 11.18% to 40.71%. The *Kiremt* season rainfall contributed about 56.71% of total annual rainfall, while the *Belg* and *Bega* seasons contributed 27.73% and 15.56% of the total annual rainfall, respectively. Concurrent with these results, there are many studies (Abebe et al., 2022; Alemayehu et al., 2020; Worku et al., 2018a) that have investigated the *Kiremt* season is the main rainfall season followed by the *Belg* season. For instance, Alemayehu et al. (2020) disclosed that *Kiremt* rainfall contributes the highest rainfall (56%) followed by *Belg* rainfall (25%) and *Bega* rainfall (19%). Taye et al. (2021) also mentioned that July to September are the main rainy months over the Upper Awash Basin of Ethiopia, with June being the driest month in the Basin.

Belg season rainfall in Ethiopia is known for its high variability (>30%) in most of the meteorological stations. However, in the meteorological stations located in the Southwestern part of Ethiopia, *Belg* season rainfall variability is medium and low. For instance, the Teppi meteorological station of Southwestern Ethiopia showed less than 20% variability in *Belg* season rainfall. The *Kiremt* season rainfall showed low variability (8.5%) followed by *Belg* season rainfall (18.86%) across all stations. On the other hand, *Bega* season rainfall showed high coefficient variation (33.83%) implying more interannual variability than *Belg* and *Kiremt* seasons rainfall. In the *Belg* season, total rainfall varies from 70.19 mm (Dubity) to 606.64 mm (Yirgachefe) (CV% 17.66 to 124.18). The *Bega* season total rainfall varies from 20.08 mm (Dubity) to 689.76 mm (Pawe) (CV% 30.32 to 191.42). This result agrees with the findings of Asfaw et al. (2018) in the Woleka sub-basin, Ademe et al. (2020) in Choke Mountain, Alemayehu et al. (2020) in Alwero watershed (Western Ethiopia) and Worku et al. (2018a) in Jemma sub-basin, which detect low rainfall variability in the *Kiremt* season than in the *Belg* season rainfall over their respective study areas.

The spatial distribution of annual rainfall over the study area ranges from 223.03 mm in Dubity to 2109.64 mm in Nekemte. Eleven stations in the Southwestern and Western part of Ethiopia (Nekemte, Mizan Teferi, Gore, Gimbi, Bonga, Pawe, Teppi, Dangila, Jimma, Bahir Dar, and Debre Tabor) receive high annual rainfall, ranging from 2109.64 mm and 1506.37 mm. Conversely, the Eastern part of Ethiopia, including Jijiga, Degehabur, and Dubiety, receives low annual rainfall ranging from 595.17 mm to 223.03 mm. The spatial distribution of rainfall also varies with the season, with *Belg* rainfall ranging from

Table 6
Seasonal and annual rainfall (mm) and coefficient of variations (CV%) for the studied stations over Ethiopia (1986–2020).

No.	Stations	*Bega* Mean	CV	*Belg* Mean	CV	*Kiremt* Mean	CV	Annual Mean	CV
1	Abomsa	167.88	76.65	286.34	43.78	501.89	19.44	956.11	19.21
2	Adama	67.99	82.30	196.08	48.67	639.22	21.23	903.29	17.69
3	Addis Ababa	64.53	70.53	269.73	41.89	891.69	13.87	1225.94	13.46
4	Ambo	106.30	98.00	262.85	34.03	695.52	23.02	1064.67	22.13
5	Arba minch	273.35	44.42	403.63	23.27	269.22	58.63	946.21	24.27
6	Asebe Teferi	111.82	86.40	299.15	49.71	491.36	30.89	902.32	26.11
7	Asela	110.71	63.89	360.34	37.58	608.75	13.95	1079.79	14.66
8	Asgori	98.14	124.18	271.97	36.57	689.48	20.27	1059.59	17.28
9	Asosa	230.48	46.66	187.64	50.95	787.24	31.81	1205.35	27.47
10	Bahir Dar	112.30	120.85	231.49	64.90	1181.64	16.88	1525.42	15.91
11	Boditi	203.44	48.48	465.56	29.86	565.11	22.39	1234.11	15.67
12	Bonga	359.25	34.07	566.47	22.24	870.54	25.00	1796.26	15.59
13	Butajira	111.31	78.7	384.01	53.61	606.98	36.32	1102.31	34.04
14	Dangila	167.51	66.24	249.83	60.05	1204.66	13.98	1622.00	15.16
15	Debre Birhan	41.37	80.67	164.75	31.44	737.53	16.99	943.65	12.90
16	Debre Markos	126.26	57.14	258.27	42.17	964.35	12.62	1348.88	11.18
17	Debre Tabor	139.42	87.72	230.09	51.10	1136.85	19.59	1506.37	16.23
18	Degehabur	82.04	86.81	197.76	58.80	75.77	62.82	355.56	40.71
19	Dilla	336.55	38.40	597.86	37.46	506.15	25.72	1440.55	23.97
20	Dire Dawa	78.59	91.20	254.28	47.55	308.87	30.46	641.74	22.05
21	Dubity	20.08	126.20	70.19	80.48	132.76	41.73	223.03	31.46
22	Fiche	77.66	139.37	209.29	43.19	887.60	16.35	1174.55	13.42
23	Gimbi	191.38	64.65	339.97	40.80	1323.80	13.51	1855.15	11.89
24	Gonder	114.41	72.45	152.67	50.86	911.28	21.52	1178.37	20.38
25	Gore	321.13	31.53	450.33	29.80	1107.76	15.09	1879.22	14.01
26	Haramaya	102.68	80.46	290.19	33.79	449.57	18.52	842.44	17.55
27	Hawassa	157.67	43.92	356.91	28.93	471.72	23.77	986.30	15.44
28	Hosanna	150.59	70.61	448.44	28.97	615.65	15.19	1214.68	14.19
29	Jijiga	74.59	80.47	237.40	43.22	283.19	21.97	595.17	19.10
30	Jimma	256.81	42.14	472.05	21.18	861.01	14.19	1589.86	12.82
31	Kombolcha	98.70	66.05	242.31	41.43	691.28	18.19	1032.29	13.13
32	Konso	247.63	54.16	398.73	32.55	173.12	47.26	819.48	20.79
33	Lalibela	71.17	97.39	154.44	52.13	582.24	23.01	807.85	15.26
34	Mekelle	25.09	101.02	100.94	63.26	477.80	25.29	603.83	22.63
35	Metema	74.79	65.36	117.61	61.79	849.29	17.61	1041.69	15.34
36	Mizan Teferi	483.60	30.32	595.81	20.84	994.22	24.23	2073.63	18.48
37	Mojo	76.77	132.12	213.19	63.41	692.23	26.88	982.19	25.78
38	Moyale	255.79	71.31	294.67	46.81	53.59	76.89	604.05	34.68
39	Negele	205.76	38.29	386.04	35.41	59.51	55.06	651.31	20.11
40	Nekemte	238.40	40.93	429.65	30.68	1441.59	13.20	2109.64	12.01
41	Pawe	689.76	78.41	433.53	109.26	647.62	93.85	1770.92	29.02
42	Robe	164.25	47.94	293.66	33.06	412.82	22.12	870.73	14.78
43	Teppi	356.38	30.39	520.80	17.66	755.34	22.27	1632.52	15.70
44	Tulu bolo	159.29	191.42	225.79	42.04	784.19	46.19	1169.27	26.51
45	Wolaita	230.47	54.59	458.88	32.25	613.75	29.65	1303.09	22.14
46	Yirgachefe	368.11	41.37	606.64	25.96	459.81	36.62	1410.90	23.15
47	Yirgalem	263.32	46.95	468.19	28.05	521.64	30.67	1253.14	22.74

Table 7
Summary of the stations seasonal and annual rainfall coefficient of variations (CV%) over Ethiopia (1986–2020).

	Percent of variability Less	Moderate	High
Bega	0	0	100
Belg	2.1	21.3	76.6
Kiremt	34	36.2	29.8
Annual	55.3	36.2	8.5

Table 8
Seasonal and annual rainfall (mm) and coefficient of variations (CV%) over Ethiopia (1986–2020).

No.	Time scales	Mean	CV	Annual rainfall%
1	*Bega*	180.98	33.83	15.56
2	*Belg*	322.32	18.86	27.73
3	*Kiremt*	659.30	8.50	56.71
4	Annual	1162.60	8.23	100

70.19 mm in Dubity to 606.64 mm in Yirgachefe. The Eastern part of Ethiopia experiences the lowest amount of *Belg* and *Bega* rainfall was 70.19 mm and 20.08 mm, respectively.

On the contrary, the highest amount of annual, *Belg, Bega*, and *Kiremt* rainfall was observed in Western, Southern, Northern, and Western parts of Ethiopia, respectively. The highest CV of annual rainfall was observed at Degehabur (40.71%), Moyale (34.68%), Butajira (34.04%), and Dubity (31.46%) meteorological stations (Table 6). On the other hand, the lowest CV of annual rainfall was observed in Debre Markos, Gimbi, Nekemte, and Jimma meteorological stations. The CV of *Kiremt* season rainfall ranges from 12.62% (Debre Markos) to 93.85% (Pawe). Out of all meteorological stations, 76.6% of stations are characterized by a high CV of *Belg* season rainfall. The results of this study are consistence with the findings of Zegeye et al. (2022) in Northwestern Ethiopia, and Anose et al. (2021) in the Omo-Gibe River Basin in Ethiopia, who reported there was a spatial and temporal variation of the seasonal and annual rainfall. Such spatial variation of annual and seasonal rainfall is mainly attributed to the complex topography of Ethiopia, with elevations ranging from −110 m below sea level to 4620 m a.s.l. Other studies (Bayable et al., 2021; Gebrechorkos et al., 2019a; Taye et al., 2021) have also shown that local scale climatic controls such as local topography and global factors such as ENSO are important drivers of spatial variation of climate in Ethiopia (Bayable et al., 2021; Gebrechorkos et al., 2019a; Taye et al., 2021).

The spatial distributions of annual and seasonal rainfall trend results are presented in Fig. 2. Stations located in the Eastern, Central, and Southern parts of the country have an insignificant increasing trend in the *Bega* season (Fig. 2A). Meanwhile, there was an insignificant downward trend in the northern parts of the country during the *Bega* season, which is Ethiopia's dry season. The northern, Central, Southern, and Eastern parts of the country showed a significant decreasing trend in the *Belg* season's rainfall. However, some stations (Pawe, Teppi, Bahir Dar, and Gimibi) located in Central and Southern parts of Ethiopia showed a significant (α<0.01and α <0.05) increasing trend (Fig. 2B). Additionally, there is also an increasing trend in *Kiremt* season rainfall in the northern part of the country (Fig. 2C). Several stations located in Northeastern and Central Ethiopia show a decreasing trend in annual rainfall (Fig. 2D), whereas stations located in Northwestern and Southwestern Ethiopia exhibit an increasing trend. Similarly, a study conducted in southwest Ethiopia also asserts the decreasing trend of *Belg* rainfall from the period 1983 to 2016 (Habte et al., 2021). In this regard, the Southeastern, Eastern, and Rift Valley regions of Ethiopia could be highly impacted by the decrease of *Belg* season rainfall where *Belg* is the main rainfall season in these regions. Our findings are consistent with the findings of Brown et al. (2017), who reported increased rainfall in northern Ethiopia during the *Kiremt* season. It has also been reported that annual rainfall decreased insignificantly in Central Ethiopia (Mekuyie and Mulu, 2021).

Fig. 3 discloses a positive and negative anomaly of standardized annual rainfall. Extreme wet years (2019 and 2020) and very wet year (2006) were observed in annual rainfall. In contrast, 2002, 2009, and 2015 were very dry years, while 1986, 1991, and 1995 were recorded as moderately dry years in the country. The findings of this study coincide with Alemayehu et al. (2020), which reported 2006 was the wettest year while 1984 was the driest year in the Alwero watershed of Western Ethiopia. In addition, Mengistu et al. (2014) identified 2002 and 2009 as the driest years while 2006 was the wettest year in the Upper Blue Nile Basin. Additionally, NMA (2007) also disclosed that 1994, 1999, and 2002 were dry years while 1998 and 2006 were wet years.

The highest anomaly (3) and lowest anomaly (−1.6) on the annual timescale were observed in the 2020 and 2002 years, respectively. In the annual base, the rainfall of 17 years showed a negative anomaly while the rainfall of the remaining 18 years showed a positive anomaly. In the *Kiremt* season, very wet years (1988, 2007, and 2019), moderately wet years (1994, 1996, 1998, 2001, and 2002), very dry years (1987,2009 and 2015), and moderately dry years (1986,1995 and 2002) were identified. In the *Kiremt* season, 20 years showed a positive anomaly while 15 years showed a negative anomaly. In the *Bega* season, rainfall of 19 years out of 35 years showed negative anomaly rainfall.

3.2.2. Spatiotemporal variability of rainfall at regional level

Spatial distribution of annual rainfall showed variation, which ranges from 223.03 mm to 1282.66 mm over hot arid, and cool sub-humid AEZs, respectively. The highest rainfall seasons are different among different AEZs. For instance, the warm semi-arid AEZ receives the highest rainfall (274.77 mm) during the *Bega* season, the cool sub-humid AEZ receives the highest rainfall during *Belg* (360.29 mm), and

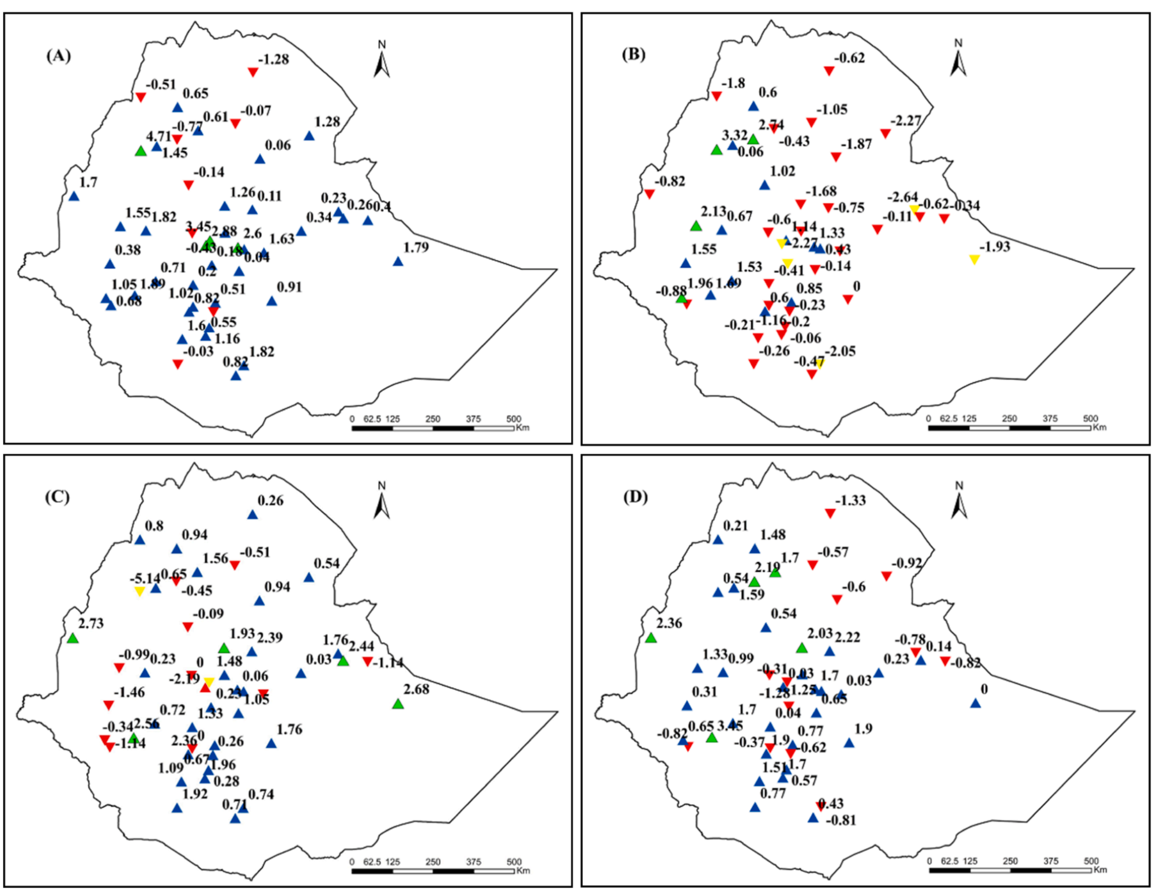

Fig. 2. Spatial distribution of rainfall trends over Ethiopia (1986–2020) during *Bega* (A), *Belg* (B), *Kiremt* (C), and Annual (D) temporal scales. Upright triangle filled with blue and inverted triangle filled with red indicate increasing and decreasing trends, respectively. Upright triangle filled with green and the inverted triangle filled with yellow color represents significant increasing and decreasing trends, respectively. Insignificant trends are represented by filled upright and inverted triangles.

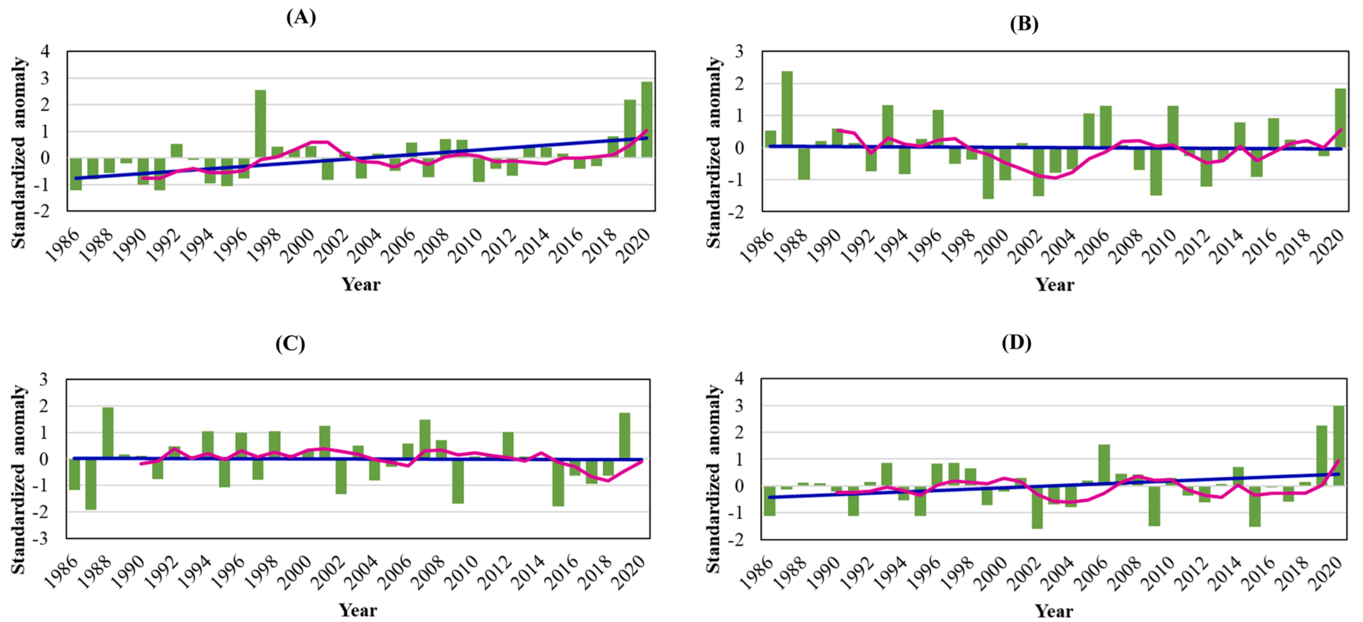

Fig. 3. Temporal average rainfall anomaly over Ethiopia (1986–2020) during *Bega* (A), *Belg* (B), *Kiremt* (C), and Annual (D) time scales. Blue color straight line and curved violet line represent linear trend and the five-year moving average of average rainfall, respectively.

Kiremt (754.03 mm). Mean rainfall in the *Kiremt* season varies from 53.59 mm (in the warm semiarid) to 1441.59 mm (cool sub-humid). In addition, the mean *Bega* rainfall varies from 20.08 mm (in the hot arid) to 274.77 mm (in the warm semi-arid). Similarly, Addisu et al. (2015) investigated that mean annual rainfall in Lake Tana sub-basin ranges from 2000 mm in the southwest highlands and less than 250 mm in the Eastern and Southeastern lowland parts.

The CV ranges from 8.43% in the cool sub-humid to 126.2% in the hot arid AEZ (Table 9). Hot arid AEZ exhibits high variability of annual rainfall (31.46%) and *Bega* season rainfall (126.2%). All AEZs showed high rainfall variability in the *Bega* season (Table 9) except the warm semi-arid AEZ, which showed medium rainfall variability. While less variability is detected in semi-arid (annual and *Kiremt* season rainfall) and cool sub-humid (annual, *Belg*, and *Bega* seasons rainfall) AEZs. Furthermore, the cool and humid AEZ is characterized by moderate and less variability of rainfall during the *Bega* and *Kiremt* seasons, respectively.

3.2.3. Spatiotemporal variability of temperature at local level

The mean annual Tmax during the last 35 years of the study period showed spatial variation ranging from 37.87 °C in Dubity (2015) and 19.97 °C (1989) in Debre Birhan with a CV of 2.14% and 2.19%, respectively (Table 10). Dubity is the hottest meteorological station, which showed Tmax of 34.95 °C, 37.63 °C, and 41.01 °C during the *Bega, Belg*, and *Kiremt* seasons, respectively followed by Gewane meteorological station. In contrast, Debre Birhan and Fiche meteorological stations show the lowest Tmax. In the *Kiremt* season, Tmax varies from 19.32 °C (Fiche) to 41.01 °C (Dubity) over the study period, while Tmin varies from 8.06 °C in Debre Birhan to 26.07 °C in Dubity meteorological station (Tables 10 and 11). In the *Bega* season, Tmax varies from 19.31 °C (Debre Birhan) to 34.95 °C (Dubity). Annual Tmin varies from Debre Birhan (6.32 °C) to 22.76 °C (Dubity).

Kiremt is the warmest season in the study area with a Tmax of 41.01 °C whereas the *Bega* season is characterized by the lowest Tmax (19.31 °C). There is a 17.9 °C difference between the maximum and minimum values of Tmax over the study period. On the other hand, there is a 16.88 °C difference between highest and lowest values of Tmin. This implies that relatively high variability is revealed for Tmax than Tmin.

The highest Tmax was observed on *Bega* in 2020 (26.72 °C) and *Belg* in 2015 (28.69 °C), and on *Kiremt* season in 2015 (26.46 °C). While the lowest Tmax was observed on the *Bega* in 1989 (25.4 °C), in the *Belg* in 1989 (26.41 °C) and during the *Kiremt* season in 1988 (24.33 °C). On the other hand, the highest Tmin was observed during the *Bega* season in 1997 (12.02 °C), in *Belg* in 2016 (14.23 °C), and in the *Kiremt* season in 2017 (14.15 °C). The lowest Tmin was recorded in the *Bega* season in 1999 (10.57 °C), in *Belg* in 1989 (12.43 °C) and in *Kiremt* season in 1986 (13.01 °C). Tmax and Tmin showed less seasonal and annual variability over the study period. High annual Tmax and Tmin (Figs. 4 and 6) characterize the Eastern part of Ethiopia.

Figs. 4 and 6 present the spatial distributions of annual and seasonal Tmax and Tmin trends. As illustrated in these figures, in most parts of the country, a significant increasing trend was detected in *Bega* season for Tmax (Fig. 4A). Some meteorological stations which are located in the Southern (Moyale), and northern (Pawe) parts of the country showed a decreasing trend in Tmax during the *Bega* season (Fig. 4A). Similarly, in most parts of the country, significant increasing trends were detected in annual Tmax (Fig. 4D). On the other hand, an increasing

Table 9
The AEZ wise seasonal and annual rainfall coefficient of variation (CV%) over Ethiopia (1986–2020).

No.	AEZs	*Bega*		*Belg*		*Kiremt*		Annual	
		Mean	CV	Mean	CV	Mean	CV	Mean	CV
1	Hot arid	20.08	126.2	70.19	80.48	132.76	41.73	223.03	31.46
2	Warm semi-arid	274.77	30.04	360.29	20.52	418.66	18.34	1053.71	9.37
3	Cool sub-humid	180.64	39.76	348	18.66	754.03	8.43	1282.66	8.82
4	Cool and humid	109.76	56.28	26.12	29.61	707.91	10.22	1078.87	9.58
5	Cool and moist	41.37	80.67	164.75	31.44	737.53	16.99	943.65	12.9

Table 10
Seasonal and annual mean Tmax variability (coefficient of variations, CV%) of stations over Ethiopia (1986–2020).

No.	Stations	*Bega* Mean	CV	*Belg* Mean	CV	*Kiremt* Mean	CV	Annual Mean	CV
1	Adama	27.165	2.91	29.951	3.53	27.473	3.02	28.197	2.70
2	Addis Ababa	23.66	2.91	25.35	3.47	22.01	2.29	23.67	2.41
3	Ambo	26.50	1.92	27.98	3.07	23.53	2.73	26.00	1.98
4	Asbe Teferi	27.12	4.07	28.49	3.04	28.11	3.53	27.91	3.11
5	Assela	21.74	4.26	23.48	5.35	20.98	4.76	22.07	4.05
6	Bahir Dar	27.65	2.64	30.52	3.43	25.91	2.99	28.02	2.64
7	Boditi	25.64	2.52	26.07	4.09	22.07	3.11	24.59	2.77
8	Bonga	27.88	2.35	28.03	3.26	26.03	2.36	27.31	1.98
9	Dangila	25.19	2.58	27.46	3.55	22.84	3.31	25.16	2.39
10	Debre Birhan	19.31	2.96	21.12	3.26	19.47	2.59	19.97	2.19
11	Debre markos	23.16	2.36	25.20	3.09	20.01	2.55	22.79	2.00
12	Debre Tabor	22.24	2.77	24.40	3.68	20.34	3.85	22.33	2.51
13	Dire Dawa	30.51	2.25	32.79	3.72	33.94	1.96	32.42	2.22
14	Dubity	34.95	2.86	37.63	2.57	41.01	2.22	37.87	2.14
15	Fiche	19.91	3.37	22.20	3.34	19.32	3.73	20.48	2.82
16	Gewane	34.65	4.10	37.22	6.77	38.31	4.14	36.73	4.57
17	Gondar	27.47	2.33	29.70	3.15	24.39	2.61	27.18	2.23
18	Gore	24.54	1.96	26.06	2.68	21.91	1.94	24.17	1.75
19	Haramaya	23.36	1.97	25.23	2.93	23.89	2.56	24.16	1.92
20	Hawassa	28.15	1.83	28.97	2.67	25.28	2.33	27.47	1.70
21	Hosanna	23.56	2.48	24.22	3.73	20.52	2.81	22.77	2.57
22	Jijiga	27.89	2.15	29.38	2.00	27.67	2.42	28.32	1.51
23	Kombolcha	25.21	2.78	27.47	3.77	28.09	2.15	26.92	2.42
24	Konso	28.89	2.18	29.09	3.76	26.69	2.76	28.22	2.24
25	Lalibela	25.15	2.38	26.75	2.88	22.21	3.48	24.70	2.01
26	Mekelle	22.92	2.52	25.49	3.57	24.28	2.66	24.23	2.49
27	Mojo	28.67	3.30	30.58	3.28	27.42	4.38	28.89	3.07
28	Moyale	28.36	2.47	29.13	3.57	25.41	2.66	27.63	2.29
29	Negele	27.51	2.61	28.15	3.94	25.04	4.30	26.90	3.24
30	Nekemte	24.83	1.61	26.70	2.92	21.69	2.37	24.41	1.79
31	Pawe	31.29	3.96	33.76	6.73	32.65	12.60	32.57	1.96
32	Robe	21.34	2.33	22.93	3.15	21.84	2.06	22.04	1.85
33	Teppi	30.45	1.67	31.37	1.97	27.95	1.43	29.93	1.18
34	Tulu Bolo	24.59	6.41	26.13	7.13	24.15	6.55	24.96	6.24
35	Wolayata	26.39	2.19	26.91	3.37	22.92	2.29	25.40	1.85
36	Yirgacheffe	26.22	3.08	26.74	3.23	24.14	3.56	25.69	2.46
37	Yirgalem	27.13	2.05	27.84	2.72	24.56	2.68	26.50	1.83

trend was observed in different parts of the country in *Bega* Tmin (Fig. 6A). While some stations located in the northern (Bahir Dar), Eastern (Dubity and Jijiga), and Southern (Moyale) parts displayed decreasing trend during the *Bega* season in Tmin (Fig. 6A).

Figs. 5 and 7 describe the annual and seasonal Tmax and Tmin anomalies that occurred in Ethiopia from 1986 to 2020. At the annual scale, Tmax showed a negative anomaly from 1986 to 2001 and a consistent positive anomaly from 2001 to 2020 (Fig. 5D). Annual Tmax anomaly also showed a negative anomaly from 1986 to 2001 (Fig. 7D). Furthermore, in 2004, 2005, 2007, 2008, 2011, and 2012 negative anomaly in Tmin was observed. In general, Tmax and Tmin anomaly trends indicate increasing warming conditions in the seasonal annual timescales.

3.2.4. Spatiotemporal variability of temperature at regional level

The regional level analysis of temperature discloses the hot arid AEZ has the highest Tmax and Tmin in the study area. On the other hand, the cool and moist AEZ showed the lowest Tmax and Tmin (Tables 12). In the cool and moist AEZ, Tmax ranges from 19.3 °C to 21.1 °C during the *Bega* and *Belg* seasons, respectively. Similarly, in the warm semi-arid AEZ, the highest Tmax was observed in the *Belg* season (31.65 °C) with a 2.29% CV, while the lowest Tmax was detected in the *Kiremt* season with a 3.5% CV (Table 12). The annual Tmax is in the order of 19.97 °C in a cool and moist AEZ to 37.87 °C in the hot arid AEZ, with a low CV (Table 12).

In the cool and humid AEZ, Tmin is between 9.01 °C (*Bega*) and 11.13 °C (*Belg*). In the cool and moist AEZ, Tmin ranges from 3.52 °C (*Bega* season) to 8.06 °C (*Kiremt* season). Furthermore, in cool sub-humid AEZ, annual Tmin is between 11.82 °C and 12.85 °C. The cool and moist, and warm semi-arid AEZs had the highest and lowest Tmin variability, respectively. As shown in Tables 12, the highest Tmin and Tmax were observed in lower elevation areas (hot arid, and warm semi-arid AEZs). While in areas at high elevations, such as cool and moist AEZ, a lower temperature was observed. Such elevation-dependent variation of temperature is also investigated by Osima et al. (2018), who conclude elevation is an important determinant in the distribution of temperature in Ethiopia.

3.3. Implications of climate trends and variabilities for climate change adaptations

Our finding indicated an increasing trend in *Bega, Kiremt*, and annual rainfall in all AEZs (except the decreasing trend in annual rainfall in hot arid AEZ) and decreasing trends in *Belg* rainfall in most/entire stations of the cool and moist, cool and humid, warm semi-arid, and hot arid AEZs. *Belg* season rainfall in cool sub-humid AEZ exhibited an increasing and decreasing trend in 52% and 48% of the stations, respectively. The study also indicated an increasing trend in Tmax over the entire AEZs, most/entire meteorological stations, and all temporal scales. A warming trend in Tmin were also observed at seasonal and annual temporal scales in the greater number of the stations found in warm semi-arid, cool sub-humid, cool humid, and cool and moist AEZs, except the decreasing trend in Tmin during *Belg* season at cool and moist AEZ. In the hot arid AEZ, an insignificant decreasing trend in *Bega, Belg*, and annual timescales and an insignificant increasing trend in *Kiremt* season were observed. To support climate change adaptation planning, we have discussed implications of trends and variabilities of rainfall and temperature for climate change adaptations here below.

Table 11
Seasonal and annual mean Tmin variability (coefficient of variations, CV%) of the studied stations over Ethiopia (1986–2020).

No.	Stations	*Bega* Mean	CV	*Belg* Mean	CV	*Kiremt* Mean	CV	Annual Mean	CV
1	Adama	9.43	9.61	12.01	7.82	14.01	5.92	11.82	5.48
2	Addis Ababa	9.15	6.50	11.82	5.84	11.59	4.56	10.85	4.54
3	Ambo	11.08	7.94	13.02	5.70	12.28	6.57	12.13	5.87
4	Asbe Teferi	12.26	15.00	13.99	15.27	14.53	14.90	13.60	14.11
5	Assela	8.42	10.67	10.15	7.35	10.71	6.38	9.76	5.27
6	Bahir Dar	9.52	9.48	12.08	8.52	13.77	2.83	11.79	4.97
7	Boditi	12.02	15.87	13.58	14.30	12.59	16.80	12.73	15.48
8	Bonga	11.14	8.93	12.38	6.66	12.63	7.38	12.05	5.96
9	Dangila	6.98	14.8	9.53	11.3	11.74	8.8	9.42	10.0
10	Debre Birhan	3.52	29.63	7.37	14.05	8.06	6.18	6.32	9.96
11	Debre markos	9.18	5.93	11.59	6.52	10.86	4.63	10.54	5.18
12	Debre Tabor	10.42	4.75	8.20	6.15	10.02	3.71	9.55	3.47
13	Dire Dawa	16.27	3.27	19.60	3.28	21.51	2.57	19.13	2.21
14	Dubity	19.449	5.60	22.776	4.23	26.074	2.76	22.767	2.57
15	Fiche	6.62	9.53	9.19	6.59	9.30	4.24	8.37	4.51
16	Gewane	19.01	8.05	22.04	6.02	24.06	4.88	21.70	5.36
17	Gondar	12.36	5.63	15.01	5.95	13.77	5.71	13.71	5.31
18	Gore	13.94	3.46	14.73	4.41	13.27	2.80	13.98	3.06
19	Haramaya	5.40	25.84	10.90	9.15	13.41	7.04	9.90	8.54
20	Hawassa	11.41	10.00	13.63	6.34	14.40	4.32	13.15	5.79
21	Hosanna	10.01	6.63	11.75	5.46	11.28	4.44	11.01	4.79
22	Jijiga	9.12	15.58	12.40	12.30	15.45	6.91	12.32	6.74
23	Kombolcha	9.82	7.89	13.20	6.29	14.93	2.68	12.65	3.61
24	Konso	17.09	6.15	18.05	5.58	16.69	6.29	17.27	5.34
25	Lalibela	12.78	2.86	14.39	4.10	12.87	3.01	13.34	2.43
26	Mekelle	9.76	8.98	12.12	7.00	12.64	4.51	11.51	5.76
27	Mojo	9.48	11.33	12.67	7.21	12.95	12.91	11.70	9.04
28	Moyale	17.61	7.61	18.41	6.02	16.47	4.46	17.49	4.63
29	Negele	15.66	6.54	16.65	7.37	15.23	6.18	15.85	6.28
30	Nekemte	12.38	3.61	13.76	4.71	12.69	4.61	12.94	3.90
31	Pawe	16.27	13.79	16.67	7.98	17.43	5.33	16.79	2.77
32	Robe	6.96	10.86	8.74	7.35	9.28	6.61	8.33	6.74
33	Teppi	14.28	5.51	15.84	4.44	15.87	4.05	15.33	4.06
34	Tulu Bolo	8.44	18.42	9.98	16.33	10.04	17.89	9.49	15.82
35	Wolayata	14.31	3.74	15.30	5.23	14.25	4.16	14.62	4.06
36	Yirgacheffe	9.62	10.39	11.08	9.33	12.02	6.19	10.92	6.92
37	Yirgalem	10.47	12.48	11.58	11.72	12.43	7.61	11.49	7.36

The lessening in *Belg* rainfall in most meteorological stations and AEZs would have a higher influence on *Belg* season rain-fed crop producing areas and those that are using this rainfall to supplement irrigation. Thus, climate adaptation strategies such as water harvesting techniques during the main rainy season and soil and water management practices are imperative in those areas (Abebe et al., 2022; Alemayehu et al., 2022; Usmail et al., 2023; Worku et al., 2020). In addition, conserving soil moisture (Yang et al., 2021), changing planting date (Getachew et al., 2021; Kassie et al., 2014; Tirfi and Oyekale, 2022), improving irrigation water-use efficiency (Grum et al., 2016; Tirfi and Oyekale, 2022) and identifying drought-tolerant crop varieties (Getachew et al., 2023; Guodaar and Appiah, 2022; Usmail et al., 2023) are other climate adaptation options.

The reduction of rainfall during the *Belg* season, mainly in hot arid and warm semi-arid AEZs, also intensifies the existing severe droughts in Eastern and Southeastern Ethiopia. Hence, it will introduce additional challenges for the pastoralist communities (Shibru et al., 2023). Thus, selling livestock before the occurrence of drought, buying livestock after the drought, and livestock mobility (Demem, 2023) are climate change adaptation options. The reduction of rainfall coupled with the increase in Tmax in all parts of the highlands (>1500 m a.s.l) and Tmin in most parts of the highlands during the *Belg* season will also affect cattle production. Hence, drought-resistant livestock such as camel and goat (Demem, 2023; Habte et al., 2022), livestock diversification and off-farm income diversification (Naod et al., 2020; Usmail et al., 2023) are some climate adaptations.

On the other hand, since the first three months of the *Bega* season (October to December) are the harvest period in most parts of the country, the increase in *Bega* rainfall would increase crop harvest loss. Early planting date and identifying short maturing crops during the main rainy season are some climate adaptation options (Tirfi and Oyekale, 2022). The increase in temperature during the *Bega* season will also introduce a challenge for using irrigation during this season since higher evapotranspiration leads to higher crop water requirements. Identifying crops that have lower water requirements, finding short maturity crops, and adjusting planting dates are among the potential climate adaptation alternatives (Demem, 2023; Tirfi and Oyekale, 2022). Soil moisture conservation practices and improving irrigation water-use efficiency would be other possible adaptation options during the dry season (Gurara et al., 2021; Tirfi and Oyekale, 2022).

The increased rainfall in *Kiremt* can be harvested to supplement irrigation during the dry and short rainy seasons, mainly for early planting (Grum et al., 2016; Hordofa and Yazew, 2023). In contrast, the increase of *Kiremt* rainfall would increase flooding mainly in those areas that are already experiencing flooding, such as the Awash River (Haile et al., 2023), the flood plains surrounding Lake Tana (Alaminie et al., 2023), the Wabi Shebele River (Merga et al., 2023; Wudineh et al., 2021), the Genale-Dawa River (Mengistu et al., 2022), the Baro-Akobo Rivers (Tamiru and Dinka, 2021), and the Nile River riparian downstream countries (Elsafi, 2014). Therefore, riparian buffers, as well as agroforestry and afforestation programs in the upper catchments, can be good adaptation options to reduce flooding in those areas (Gay et al., 2023; Tirfi and Oyekale, 2022). Since foot slope settlements are often affected by floods, settlement planning should be also cognizant of the severity of floods that would happened as a result of the increasing trend of rainfall. Adjusting water releases from reservoirs and dams such as the Grand Ethiopian Renaissance Dam (GERD), which releases more water before the start of the main rainy season (Lazin et al., 2023), is also

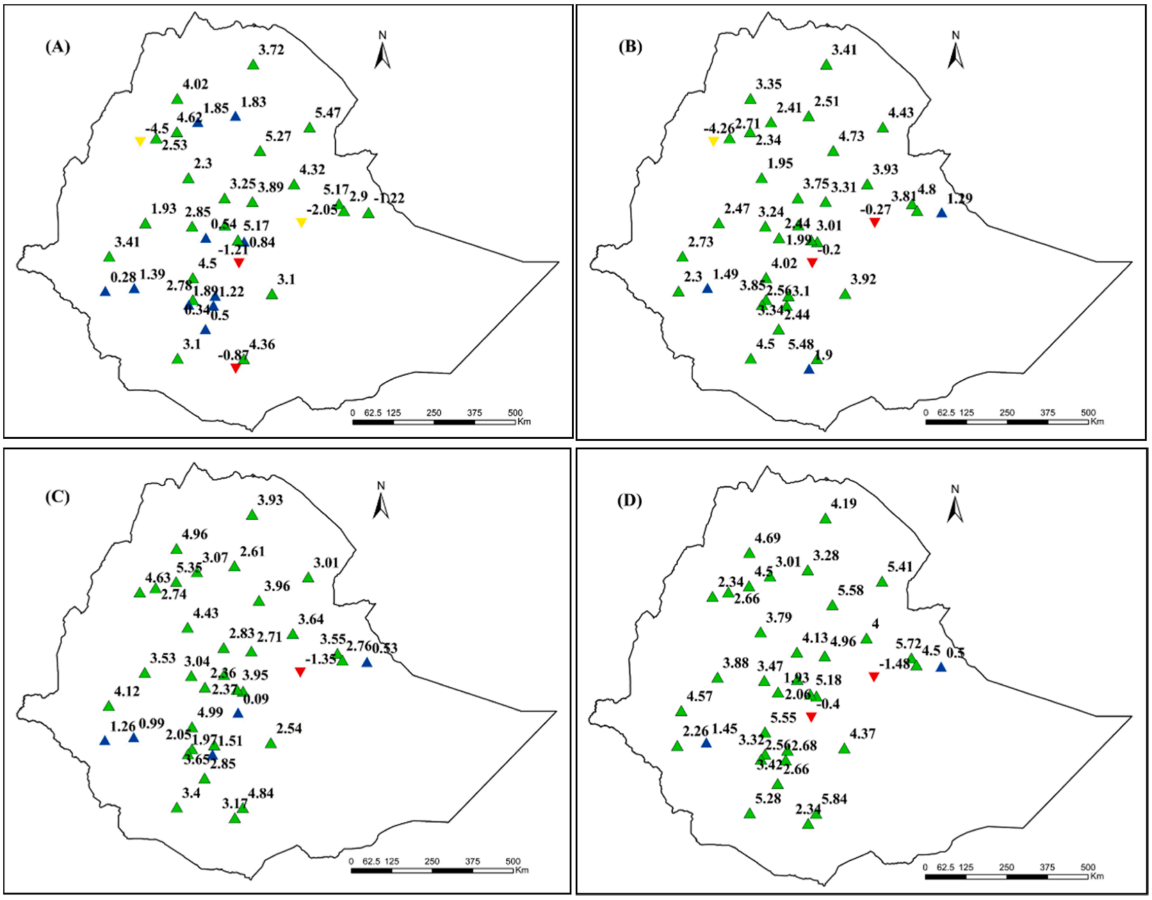

Fig. 4. Spatial distribution of mean Tmax trends over Ethiopia (1986–2020) for *Bega* (A), *Belg* (B), *Kiremt* (C), and Annual (D) temporal periods. Upright triangle filled with blue and inverted triangle filed with red indicates increasing and decreasing trends, respectively. Upright triangle filled with green and the inverted triangle filled with yellow color represent a significant increasing and decreasing trends, respectively. Insignificant trends are represented by filled upright and inverted triangles.

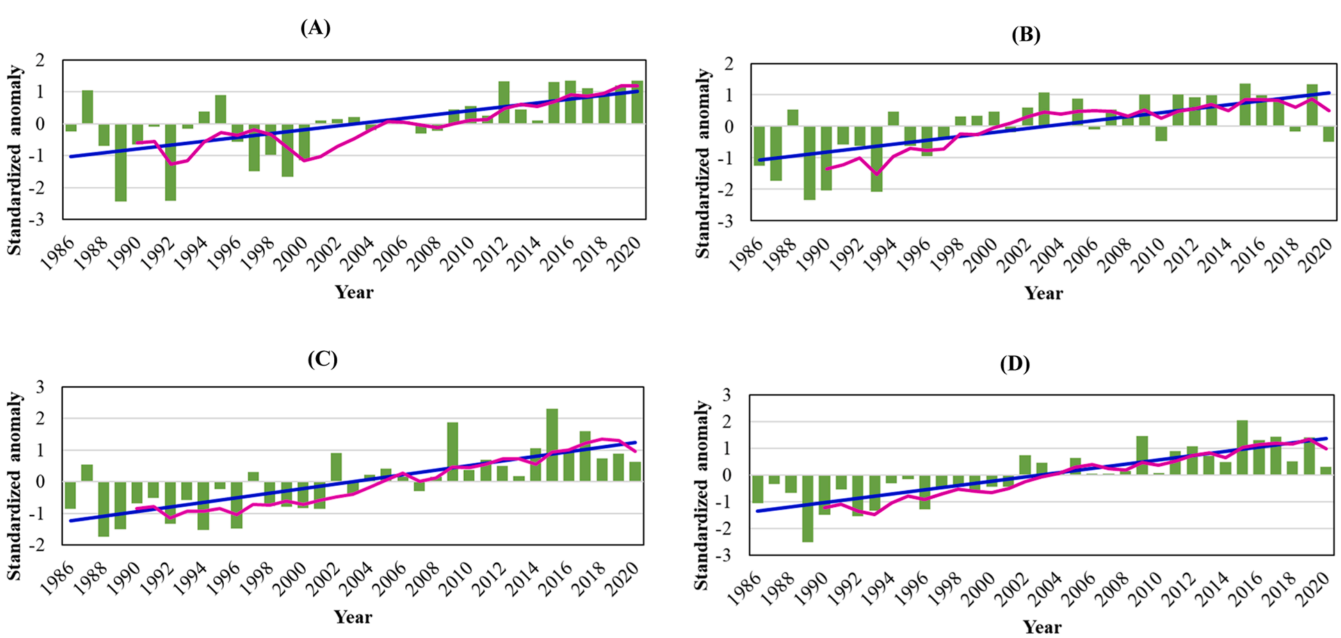

Fig. 5. Temporal mean Tmax anomaly over Ethiopia (1986–2020) for *Bega* (A), *Belg* (B), *Kiremt* (C), and Annual (D) time scales. Blue color straight line and curved violet line represent linear trend and the five-year moving average of mean Tmax, respectively.

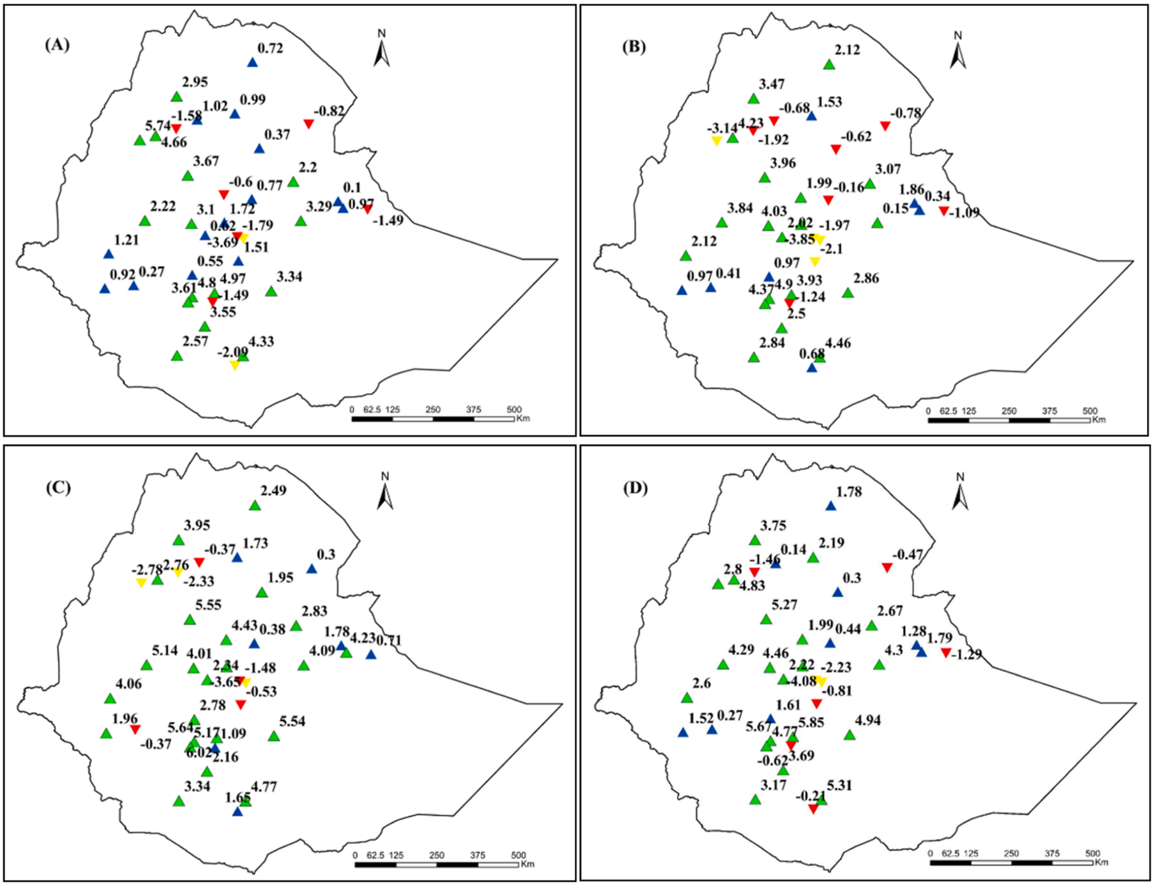

Fig. 6. Spatial distribution of mean Tmin trends over Ethiopia (1986–2020) for *Bega* (A), *Belg* (B), *Kiremt* (C), and Annual (D) temporal scales. Upright triangle filled with blue and inverted triangle filed with red indicate increasing and decreasing trends, respectively. Upright triangle filled with green and inverted triangle filled with yellow color represent a significant increasing and decreasing trends, respectively. Insignificant trends are represented by filled upright and inverted triangles.

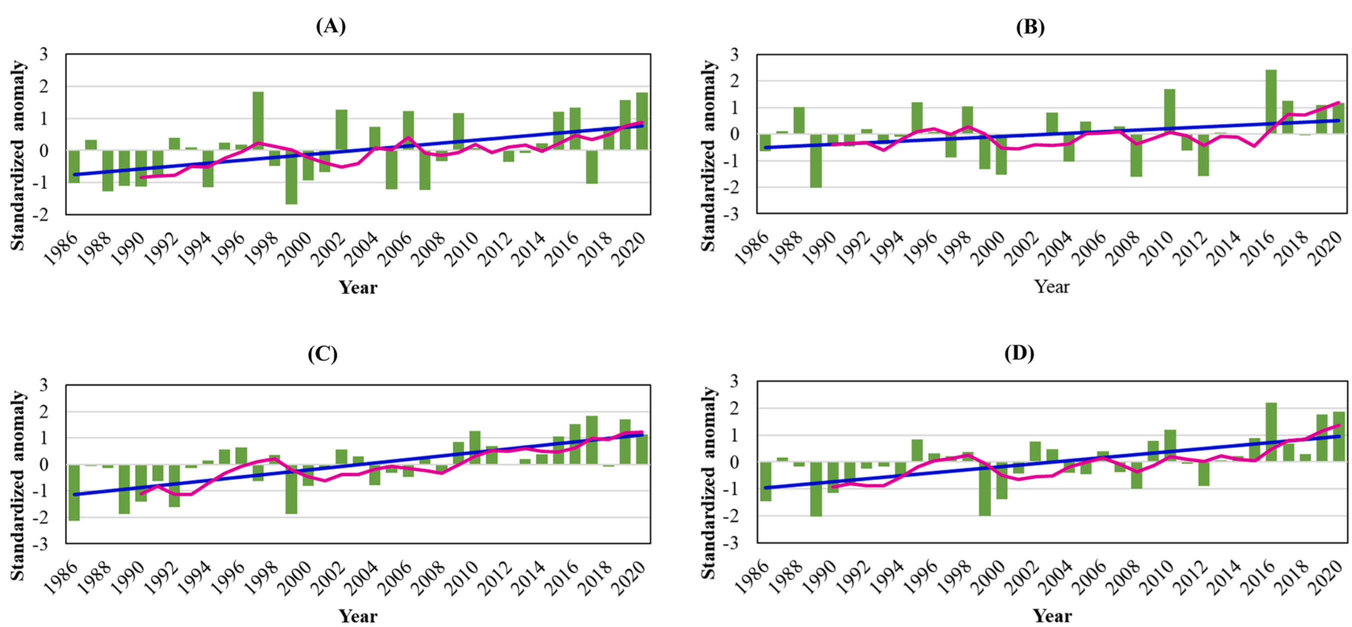

Fig. 7. Temporal mean Tmin anomaly over Ethiopia (1986–2020) for *Bega* (A), *Belg* (B), *Kiremt* (C), and Annual (D) temporal periods. Blue color straight line and curved violet line represent linear trend and the five-year moving average of mean Tmin, respectively.

another climate adaptation option to reduce flooding in the Nile River riparian downstream countries. The increase in *Kiremt* rainfall also amplifies the ongoing severe soil erosion in the Ethiopian highlands, mainly in areas with low vegetation cover. Hence, it increases the sedimentation of reservoirs. The increase in *Kiremt* season rainfall will also increase nutrient losses from agricultural fields, affecting crop

Table 12
Seasonal and annual mean Tmax and Tmin variability (coefficient of variation, CV%) in AEZs of Ethiopia (1986–2020).

Climate variables	AEZs	*Bega* Mean	CV	*Belg* Mean	CV	*Kiremt* Mean	CV	Annual Mean	CV
Tmax									
	Hot arid	34.95	2.86	37.64	2.57	41.01	2.22	37.87	2.14
	Warm semi-arid	30.24	1.19	31.65	2.29	30	3.50	30.63	1.90
	Cool sub-humid	24.85	1.78	27.91	2.16	24.85	1.78	26.38	1.43
	Cool and humid	22.63	1.82	24.45	2.78	21.28	2.20	22.79	1.75
	Cool and moist	19.31	2.96	21.12	3.26	19.47	2.58	19.97	2.19
Tmin									
	Hot arid	19.45	5.60	22.78	4.23	26.07	2.76	22.77	2.57
	Warm semi-arid	16.60	3.89	18.18	2.87	18.18	2.16	17.65	2.53
	Cool sub-humid	12.36	3.68	12.36	3.68	12.85	2.72	11.82	2.91
	Cool and humid	9.01	4.33	11.13	4.1	10.95	2.86	10.36	2.86
	Cool and moist	3.52	29.64	7.37	13.84	8.06	6.18	6.32	9.96

production (Kassie et al., 2013) and intensifying water hyacinth expansion (Goshu et al., 2020). Therefore, identifying effective riparian buffer widths (Lee et al., 2020; Sirabahenda et al., 2020) and other best management practices are among the climate change adaptation options (Gashaw et al., 2021). In addition, the observed high variability in *Kiremt* season rainfall will cause variability in crop yields due to the removal of soil nutrients because of the increase in rainfall (Tirfi and Oyekale, 2022). Thus, implementations of agroforestry and terracing will be potentially effective climate-adaptation options (Do et al., 2023; Vancampenhout et al., 2006).

The overall increase in *Kiremt* season rainfall could increase crop yields. However, the increase in temperature in most meteorological and AEZs would intensify crop pest damages. Hence, crop diversification, planting pest resistant crops and improving pest management are some strategies for adapting the changes (Demem, 2023; Hordofa and Yazew, 2023). Apart from pests, although the increase in *Kiremt* rainfall could potentially increase crop yield, the increases in temperature can reduce crop production in important cereal producing areas of the country due to temperature stresses. In line with this, a study undertaken in the upper west region of Ghana reported that maize and rice are particularly vulnerable and sensitive to extreme temperatures (Derbile et al., 2022). Since maize in the entire country and rice in Northwestern Ethiopia are the dominant crops, the adverse effects of extreme temperatures on these crops have implications on food security. Thus, identifying new crop varieties that have a better resistance to the increases in temperature could be an effective adaptation strategy. In addition, since the increase in temperature would have impact on the fertilization and plant growth, identifying appropriate fertilizer rates and application dates are another alternative for adapting to the changes (Ademe et al., 2020; Demem, 2023; Guodaar and Appiah, 2022; Kassie et al., 2015).

The temperature increase in most high-elevation areas of the country will also change the types of crops produced in these region, which means there could be a shift from the current barley production to maize production or to other crops in these areas. The increase in temperature in higher-elevation areas mainly in cool and moist AEZ, which have not been previously used for crop production, may become suitable for crop production. In contrast, the increased temperature in cool sub-humid AEZ, in which crop production currently takes place, may result in some of the areas becoming unfavorable for crop production. Moreover, the increase in temperature in most high-elevation areas may create a conducive environment for the incidence of malaria and hence, malaria intervention would become relevant (Filho et al., 2023; Nigussie et al., 2023).

4. Conclusions

This study evaluated the trends and variability of rainfall and temperature at local and regional levels in Ethiopia from 1986 to 2020. Stations and AEZs levels are used to make the local and regional levels of analysis, respectively. The local levels analysis indicates an insignificant increasing trend of annual, *Bega*, and *Kiremt* seasons' rainfall in most meteorological stations, but a decreasing trend of *Belg* season rainfall was observed in most stations. Regional levels analysis discerns an increasing trend of annual, *Bega*, and *Kiremt* rainfall in greatest number of AEZs and a decreasing trend in *Belg* rainfall in most AEZs. A spatially and temporally more homogeneous warming trend was observed at local and regional levels. Both Tmax and Tmin revealed an increasing trend of annual and seasonal scales at most meteorological stations. Similarly, increasing trends of annual and seasonal Tmax and Tmin were observed in entire/most AEZs. Tmax and Tmin showed less variability (<20%) in seasonal and annual time scales. Overall, the variability of rainfall and temperature could cause repercussions on natural and human systems. Several potential climate adaptation strategies are available for various sectors to reduce climate risks. However, further research would be required to identify effective climate change adaptation strategies from the available options.

Declaration of Competing Interest

The authors 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

The authors do not have permission to share data.

Acknowledgments

The climate data used in this study are obtained free of cost from the Ethiopian Meteorology Institute (EMI). The through revision of this paper was undertaken during the One Planet Fellowship Program (OPFP), which is the joint program of Agropolis Foundation (France) and African Women in Agricultural Research (AWARD, Kenya), of the first author at Wageningen University and Research, the Netherlands. Hence, the authors greatly acknowledge the three institutions. The authors also extend their gratitude to the editor of the journal and the anonymous reviewer for providing constructive comments, which helped us to greatly improve the quality of the paper.

References

Abebe, B.A., Grum, B., Degu, A.M., Goitom, H., 2022. Spatio-temporal rainfall variability and trend analysis in the Tekeze-Atbara river basin, northwestern Ethiopia. Meteorol. Appl. 29.
Addisu, S., Selassie, Y.G., Fissha, G., Gedif, B., 2015. Time series trend analysis of temperature and rainfall in lake Tana Sub-basin, Ethiopia. Environ. Syst. Res. 4.
Ademe, D., Zaitchik, B.F., Tesfaye, K., Simane, B., Alemayehu, G., Adgo, E., 2020. Climate trends and variability at adaptation scale: patterns and perceptions in an agricultural region of the Ethiopian Highlands. Weather Clim. Extrem. 29.

Alahacoon, N., Edirisinghe, M., Simwanda, M., Perera, E.N.C., Nyirenda, V.R., Ranagalage, M., 2021. Rainfall variability and trends over the African continent using TAMSAT Data (1983–2020): towards climate change resilience and adaptation. Remote Sens. (Basel) 14.

Alaminie, A.A., Amarnath, G., Padhee, S.K., Ghosh, S., Tilahun, S.A., Mekonnen, M.A., Assefa, G., Seid, A., Zimale, F.A., Jury, M.R., 2023. Nested hydrological modeling for flood prediction using CMIP6 inputs around Lake Tana, Ethiopia. J. Hydrol.: Reg. Stud. 46.

Alemayehu, A., Bewket, W., 2016. Local climate variability and crop production in the central highlands of Ethiopia. Environ. Dev. 19, 36–48.

Alemayehu, A., Maru, M., Bewket, W., Assen, M., 2020. Spatiotemporal variability and trends in rainfall and temperature in Alwero watershed, western Ethiopia. Environ. Syst. Res. 9.

Alemayehu, Z.Y., Minale, A.S., Legesse, S.A., 2022. Spatiotemporal rainfall and temperature variability in Suha watershed, Upper Blue Nile Basin, Northwest Ethiopia. Environ. Monit. Assess. 194, 538.

Almazroui, M., Saeed, F., Saeed, S., Nazrul Islam, M., Ismail, M., Klutse, N.A.B., Siddiqui, M.H., 2020. Projected change in temperature and precipitation over Africa from CMIP6. Earth Syst. Environ. 4, 455–475.

Anose, F.A., Beketie, K.T., Terefe Zeleke, T., Yayeh Ayal, D., Legese Feyisa, G., 2021. Spatio-temporal hydro-climate variability in Omo-Gibe river Basin, Ethiopia. Climate Serv. 24.

Araya, A., Prasad, P.V.V., Gowda, P.H., Djanaguiraman, M., Kassa, A.H., 2020. Potential impacts of climate change factors and agronomic adaptation strategies on wheat yields in central highlands of Ethiopia. Clim. Change 159, 461–479.

Asfaw, A., Simane, B., Hassen, A., Bantider, A., 2018. Variability and time series trend analysis of rainfall and temperature in northcentral Ethiopia: a case study in Woleka sub-basin. Weather Clim. Extrem. 19, 29–41.

Ayal, D.Y., W/Michael, T., Getahun, A.B., Ture, K., Zeleke, T.T., Tesfaye, B., 2023. Climate variability induced household food insecurity coping strategy in Gambella Zuria Woreda, Southwestern, Ethiopia. Climate Serv. 30.

Bayable, G., Amare, G., Alemu, G., Gashaw, T., 2021. Spatiotemporal variability and trends of rainfall and its association with Pacific Ocean Sea surface temperature in West Harerge Zone, Eastern Ethiopia. Environ. Syst. Res. 10.

Belay, A., Demissie, T., Recha, J.W., Oludhe, C., Osano, P.M., Olaka, L.A., Solomon, D., Berhane, Z., 2021. Analysis of climate variability and trends in Southern Ethiopia. Climate 9.

Berhe, A.G., Misgna, S.H., Abraha, G.G.-S., Abraha, A.Z., 2023. Variability and trend analysis of temperatures, rainfall, and characteristics of crop-growing season in the eastern zone of Tigray region, northern Ethiopia. Theor. Appl. Climatol. 152, 25–43.

Brown, M.E., Funk, C., Pedreros, D., Korecha, D., Lemma, M., Rowland, J., Williams, E., Verdin, J., 2017. A climate trend analysis of Ethiopia: examining subseasonal climate impacts on crops and pasture conditions. Clim. Change 142, 169–182.

Daron, J.D., 2014. Regional Climate Messages: east Africa. Scientific report from the CARIAA Adaptation at Scale in Semi-Arid Regions (ASSAR) Project. In: Collaborative Adaptation Research Initiative in Africa and Asia Ottawa, ON.

Dawit, M., Halefom, A., Teshome, A., Sisay, E., Shewayirga, B., Dananto, M., 2019. Changes and variability of precipitation and temperature in the Guna Tana watershed, Upper Blue Nile Basin, Ethiopia. Model Earth Syst. Environ. 5, 1395–1404.

Demem, M.S., 2023. Impact and adaptation of climate variability and change on small-holders and agriculture in Ethiopia: a review. Heliyon 9, e18972.

Derbile, E.K., Bonye, S.Z., Yiridomoh, G.Y., 2022. Mapping vulnerability of smallholder agriculture in Africa: vulnerability assessment of food crop farming and climate change adaptation in Ghana. Environ. Challenges 8.

Do, V.H., La, N., Bergkvist, G., Dahlin, A.S., Mulia, R., Nguyen, V.T., Öborn, I., 2023. Agroforestry with contour planting of grass contributes to terrace formation and conservation of soil and nutrients on sloping land. Agric. Ecosyst. Environ. 345.

Elsafi, S.H., 2014. Artificial Neural Networks (ANNs) for flood forecasting at Dongola Station in the River Nile. Sudan. Alexandria Eng. J. 53, 655–662.

Elzopy, K.A., Chaturvedi, A.K., Chandran, K.M., Gopinath, G., K, N., Surendran, U., 2020. Trend analysis of long-term rainfall and temperature data for Ethiopia. South African Geogr. J. 103, 381–394.

Etana, D., Snelder, D.J.R.M., van Wesenbeeck, C.F.A., de Cock Buning, T., 2020. Trends of climate change and variability in three agro-ecological settings in central Ethiopia: contrasts of meteorological data and farmers' perceptions. Climate 8.

Filho, W.L., May, J., May, M., Nagy, G.J., 2023. Climate change and malaria: some recent trends of malaria incidence rates and average annual temperature in selected sub-Saharan African countries from 2000 to 2018. Malar. J. 22, 248.

Gashaw, T., Dile, Y.T., Worqlul, A.W., Bantider, A., Zeleke, G., Bewket, W., Alamirew, T., 2021. Evaluating the effectiveness of best management practices on soil erosion reduction using the SWAT model: for the case of Gumara Watershed, Abbay (Upper Blue Nile) Basin. Environ. Manage. 68, 240–261.

Gashaw, T., Worqlul, W., Lakew, A., Teferi Taye, H., Seid, M., Haileslassie, A., 2023. Evaluations of satellite/reanalysis rainfall and temperature products in the Bale Eco-Region (Southern Ethiopia) to enhance the quality of input data for hydro-climate studies. Remote Sens. Appl. 31.

Gashure, S., Wana, D., Samimi, C., 2022. Impacts of climate variability and climate-smart agricultural practices on crop production in UNESCO designated cultural landscapes of Konso, Ethiopia. Theoret. Appl. Climatol. 150, 1495–1511.

Gay, E.T., Martin, K.L., Caldwell, P.V., Emanuel, R.E., Sanchez, G.M., Suttles, K.M., 2023. Riparian buffers increase future baseflow and reduce peakflows in a developing watershed. Sci. Total Environ. 862, 160834.

Gebrechorkos, S.H., Hulsmann, S., Bernhofer, C., 2019a. Long-term trends in rainfall and temperature using high-resolution climate datasets in East. Sci. Rep. 9, 11376.

Gebrechorkos, S.H., Hülsmann, S., Bernhofer, C., 2019b. Changes in temperature and precipitation extremes in Ethiopia, Kenya, and Tanzania. Int. J. Climatol. 39, 18–30.

Getachew, F., Bayabil, H.K., Hoogenboom, G., Kiker, G.A., Yu, Z., Li, Y., 2023. Development of climate-smart sorghum ideotype for climate resilience in Ethiopia. Field Crops Res. 303.

Getachew, F., Bayabil, H.K., Hoogenboom, G., Teshome, F.T., Zewdu, E., 2021. Irrigation and shifting planting date as climate change adaptation strategies for sorghum. Agric. Water Manage. 255.

Getnet, G.T., Bantider Dagnew, A., Ayal, D.Y., 2023. Spatiotemporal variability and trends of rainfall and temperature in the tropical moist montane ecosystem: implications to climate-smart agriculture in Geshy watershed, Southwest Ethiopia. Climate Serv. 30.

Goshu, G., Strokal, M., Kroeze, C., Koelmans, A.A., de Klein, J.J.M., 2020. Assessing seasonal nitrogen export to large tropical lakes. Sci. Total Environ. 731, 139199.

Grum, B., Hessel, R., Kessler, A., Woldearegay, K., Yazew, E., Ritsema, C., Geissen, V., 2016. A decision support approach for the selection and implementation of water harvesting techniques in arid and semi-arid regions. Agric. Water Manage. 173, 35–47.

Guodaar, L., Appiah, D.O., 2022. Evolving farm-level adaptation to climate variability and change risks in the forest-savanna transitional zone of Ghana. Environ. Challenges 9.

Gurara, M.A., Jilo, N.B., Tolche, A.D., 2021. Impact of climate change on potential evapotranspiration and crop water requirement in Upper Wabe Bridge watershed, Wabe Shebele River Basin, Ethiopia. J. Afr. Earth Sci. 180.

Habte, A., Mamo, G., Worku, W., Ayalew, D., Gayler, S., Diaz, J., 2021. Spatial variability and temporal trends of climate change in Southwest Ethiopia: association with farmers' perception and their adaptation strategies. Adv. Meteorol. 2021, 1–13.

Habte, M., Eshetu, M., Maryo, M., Andualem, D., Legesse, A., 2022. Effects of climate variability on livestock productivity and pastoralists perception: the case of drought resilience in Southeastern Ethiopia. Vet. Anim. Sci. 16, 100240.

Haile, A.T., Worku Bekele, T., Rientjes, T., 2023. Interannual comparison of historical floods through flood detection using multi-temporal Sentinel-1 SAR images, Awash River Basin, Ethiopia. Int. J. Appl. Earth Obs. Geoinf. 124.

Hare, W., 2003. Assessment of Knowledge on Impacts of Climate Change–Contribution. arct. 100 (6).

Harka, A.E., Jilo, N.B., Behulu, F., 2021. Spatial-temporal rainfall trend and variability assessment in the Upper Wabe Shebelle River Basin, Ethiopia: application of innovative trend analysis method. J. Hydrol. Reg. Stud. 37.

Hilemelekot, F., Ayal, D.Y., Ture, K., Terefe Zeleke, T., 2021. Climate change and variability adaptation strategies and their implications for household food Security: the case of Basona Worena District, North Shewa zone, Ethiopia. Climate Serv. 24.

Hordofa, L., Yazew, T., 2023. Evaluating impacts of climate variability on smallholder livelihoods and adaptation practices in the western Shewa Zone, Oromia, Ethiopia. Front. Climate 5.

IPCC, 2021. Summary for Policymakers. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel On Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3–32. https://doi.org/10.1017/9781009157896.001.

Jury, M.R., Funk, C., 2013. Climatic trends over Ethiopia: regional signals and drivers. Int. J. Climatol. 33, 1924–1935.

Kassie, B.T., Asseng, S., Rotter, R.P., Hengsdijk, H., Ruane, A.C., Van Ittersum, M.K., 2015. Exploring climate change impacts and adaptation options for maize production in the Central Rift Valley of Ethiopia using different climate change scenarios and crop models. Clim. Change 129, 145–158.

Kassie, B.T., RÖTter, R.P., Hengsdijk, H., Asseng, S., Van Ittersum, M.K., Kahiluoto, H., Van Keulen, H., 2013. Climate variability and change in the Central Rift Valley of Ethiopia: challenges for rainfed crop production. J. Agric. Sci. 152, 58–74.

Kassie, B.T., Van Ittersum, M.K., Hengsdijk, H., Asseng, S., Wolf, J., Rötter, R.P., 2014. Climate-induced yield variability and yield gaps of maize (Zea mays L.) in the Central Rift Valley of Ethiopia. Field Crops Res. 160, 41–53.

Lazin, R., Shen, X., Moges, S., Anagnostou, E., 2023. The role of Renaissance dam in reducing hydrological extremes in the Upper Blue Nile Basin: current and future climate scenarios. J. Hydrol. (Amst.) 616.

Lebeza, T.M., Gashaw, T., Tefera, G.W., Mohammed, J.A., 2023. Trend analysis of hydro-climate variables in the Jemma sub-basin of Upper Blue Nile (Abbay) Basin, Ethiopia. SN Appl. Sci. 5.

Lee, S., McCarty, G.W., Moglen, G.E., Li, X., Wallace, C.W., 2020. Assessing the effectiveness of riparian buffers for reducing organic nitrogen loads in the Coastal Plain of the Chesapeake Bay watershed using a watershed model. J. Hydrol. (Amst.) 585.

Mann, H.B., 1945. Nonparametric tests against trend. Econometrica 245–259.

Matewos, T., Tefera, T., 2019. Local level rainfall and temperature variability in drought-prone districts of rural Sidama, central rift valley region of Ethiopia. Phys. Geogr. 41, 36–53.

McKee, T.B., Doesken, N.J., Kleist, J., 1993. The relationship of drought frequency and duration to time scales, Proceedings of the 8th Conference on Applied Climatology. Boston, MA, USA, pp. 179–183.

Mekonen, A.A., Berlie, A.B., 2019. Spatiotemporal variability and trends of rainfall and temperature in the Northeastern Highlands of Ethiopia. Model Earth Syst. Environ. 6, 285–300.

Mekuyie, M., Mulu, D., 2021. Perception of impacts of climate variability on pastoralists and their adaptation/coping strategies in fentale district of Oromia Region, Ethiopia. Environ. Syst. Res. 10.

Mengistu, D., Bewket, W., Lal, R., 2014. Recent spatiotemporal temperature and rainfall variability and trends over the Upper Blue Nile River Basin. Ethiopia. Int. J. Climatol. 34, 2278–2292.

Mengistu, T.D., Feyissa, T.A., Chung, I.M., Chang, S.W., Yesuf, M.B., Alemayehu, E., 2022. Regional flood frequency analysis for sustainable water resources management of Genale–Dawa River Basin, Ethiopia. Water (Basel) 14.

Merga, B.B., Mamo, F.L., Moisa, M.B., Tiye, F.S., Gemeda, D.O., 2023. Assessment of flood risk by using geospatial techniques in Wabi Shebele River Sub-basin, West Hararghe Zone, southeastern Ethiopia. Appl. Water Sci. 13.

MoA, 1998. Agro-ecological Zones of Ethiopia. Natural Resources Management and Regulatory Department. With support of German Agency for Technical Cooperation (GTZ).

Mohammed, J.A., Gashaw, T., Worku Tefera, G., Dile, Y.T., Worqlul, A.W., Addisu, S., 2022. Changes in observed rainfall and temperature extremes in the Upper Blue Nile Basin of Ethiopia. Weather Clim. Extrem. 37.

Mulugeta, S., Fedler, C., Ayana, M., 2019. Analysis of long-term trends of annual and seasonal rainfall in the Awash River Basin, Ethiopia. Water (Basel) 11.

Naod, E., Addisu Legesse, S., Tegegne, F., 2020. Livestock diversification prospects for climate change adaptation in Dangila district. Trop. Anim. Health Prod. 52, 1435–1446.

Nigussie, T.Z., Zewotir, T.T., Muluneh, E.K., 2023. Seasonal and spatial variations of malaria transmissions in northwest Ethiopia: evaluating climate and environmental effects using generalized additive model. Heliyon 9, e15252.

NMA, 2007. Climate change national adaptation programme of action (Napa) of Ethiopia. National Meteorological Services Agency, Ministry of Water Resources, Federal Democratic Republic of Ethiopia, Addis Ababa.

NMSA, 2001. Federal Democratic Republic of Ethiopia Ministry of Water Resources National Meteorological Services Agency, Initial National Communication of Ethiopia to the United Nations Framework Convention on Climate Change (UNFCCC); NMSA: Addis Ababa, Ethiopia.

Osima, S., Indasi, V.S., Zaroug, M., Endris, H.S., Gudoshava, M., Misiani, H.O., Nimusiima, A., Anyah, R.O., Otieno, G., Ogwang, B.A., Jain, S., Kondowe, A.L., Mwangi, E., Lennard, C., Nikulin, G., Dosio, A., 2018. Projected climate over the Greater Horn of Africa under 1.5 °C and 2 °C global warming. Environ. Res. Lett. 13.

Samy, A., Ibrahim, M.G., Mahmod, W.E., Fujii, M., Eltawil, A., Daoud, W., 2019. Statistical assessment of rainfall characteristics in upper Blue Nile Basin over the Period from 1953 to 2014. Water (Basel) 11.

Sen, P.K., 1968. Estimates of the regression coefficient based on Kendall's tau. J. Am. Stat. Assoc. 63, 1379–1389.

Shekuru, A.H., Berlie, A.B., Bizuneh, Y.K., 2022. Variability and trends of temperature and rainfall over three agro-ecological zones in North Shewa. Central Ethiopia. Arabian J. Geosci. 15.

Shibru, M., Opere, A., Omondi, P., Gichaba, M., 2023. Understanding physical climate risks and their implication for community adaptation in the borana zone of southern Ethiopia using mixed-methods research. Sci. Rep. 13, 6916.

Sirabahenda, Z., St-Hilaire, A., Courtenay, S.C., van den Heuvel, M.R., 2020. Assessment of the effective width of riparian buffer strips to reduce suspended sediment in an agricultural landscape using ANFIS and SWAT models. Catena 195.

Suryabhagavan, K.V., 2017. GIS-based climate variability and drought characterization in Ethiopia over three decades. Weather Clim. Extrem. 15, 11–23.

Tamiru, H., Dinka, M.O., 2021. Application of ANN and HEC-RAS model for flood inundation mapping in lower Baro Akobo River Basin. Ethiopia. J. Hydrol.: Reg. Stud. 36.

Taye, M.T., Dyer, E., Charles, K.J., Hirons, L.C., 2021. Potential predictability of the Ethiopian summer rains: understanding local variations and their implications for water management decisions. Sci. Total Environ. 755, 142604.

Teshome, A., Zhang, J., 2019. Increase of extreme drought over Ethiopia under climate warming. Adv. Meteorol. 2019, 1–18.

Tirfi, A.G., Oyekale, A.S., 2022. Analysis of trends and variability of climatic parameters in Teff growing belts of Ethiopia. Open Agric. J. 7, 541–553.

Tofu, D.A., Mengistu, M., 2023. Observed time series trend analysis of climate variability and smallholder adoption of new agricultural technologies in west Shewa. Ethiopia. Scientific African 19.

Usmail, A.J., Maja, M.M., Lakew, A.A., 2023. Farmers' perceptions of climate variability and adaptation strategies in the rural areas of Dire Dawa administration, eastern Ethiopia. Heliyon 9, e15868.

Van Buuren, S., Groothuis-Oudshoorn, K., Robitzsch, A., Vink, G., Doove, L., Jolani, S., Schouten, R., Gaffert, P., Meinfelder, F., Gray, B., 2015. MICE: Multivariate Imputation by Chained Equations. 2017. URL https://CRAN.R-project.org/package=mice. R package version 2, 15.

Vancampenhout, K., Nyssen, J., Gebremichael, D., Deckers, J., Poesen, J., Haile, M., Moeyersons, J., 2006. Stone bunds for soil conservation in the northern Ethiopian highlands: impacts on soil fertility and crop yield. Soil Tillage Res. 90, 1–15.

Vose, R.S., Easterling, D.R., Gleason, B., 2005. Maximum and minimum temperature trends for the globe: an update through 2004. Geophys. Res. Lett. 32.

WMO, 2009. Guidelines on analysis of extremes in a changing climate in support of informed decisions for adaptation 55.

Worku, G., Teferi, E., Bantider, A., Dile, Y.T., 2018a. Observed changes in extremes of daily rainfall and temperature in Jemma Sub-Basin, Upper Blue Nile Basin, Ethiopia. Theoret. Appl. Climatol. 135, 839–854.

Worku, G., Teferi, E., Bantider, A., Dile, Y.T., 2020. Prioritization of watershed management scenarios under climate change in the Jemma sub-basin of the Upper Blue Nile Basin, Ethiopia. J. Hydrol.: Reg. Stud. 31.

Worku, G., Teferi, E., Bantider, A., Dile, Y.T., Taye, M.T., 2018b. Evaluation of regional climate models performance in simulating rainfall climatology of Jemma sub-basin, Upper Blue Nile Basin, Ethiopia. Dyn. Atmos. Oceans 83, 53–63.

Wubaye, G.B., Gashaw, T., Worqlul, A.W., Dile, Y.T., Taye, M.T., Haileslassie, A., Zaitchik, B., Birhan, D.A., Adgo, E., Mohammed, J.A., Lebeza, T.M., Bantider, A., Seid, A., Srinivasan, R., 2023. Trends in rainfall and temperature extremes in Ethiopia: station and agro-ecological zone levels of analysis. Atmosphere (Basel) 14.

Wudineh, F.A., Moges, S.A., Kidanewold, B.B., 2021. Flood change detection and attribution using simulation approach in data-scarce watersheds: a case of Wabi Shebele River Basin. Ethiopia. J. Water Resour. Protect. 13, 362–393.

Yang, M., Wang, G., Lazin, R., Shen, X., Anagnostou, E., 2021. Impact of planting time soil moisture on cereal crop yield in the Upper Blue Nile Basin: a novel insight towards agricultural water management. Agric. Water Manage. 243.

Zegeye, M.K., Bekitie, K.T., Hailu, D.N., 2022. Spatio-temporal variability and trends of hydroclimatic variables at Zarima Sub-Basin North Western Ethiopia. Environ. Syst. Res. 11.

Zhang, X., Yang, F., 2004. RClimDex (1.0) user manual. Climate Res. Branch Environ. Canada 22.