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ORIGINAL RESEARCH ARTICLE

Spatiotemporal climate trends and policy assessment in Ethiopia's Lake Tana Basin amid global carbon dioxide emissions

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Abstract: Climate change, predominantly driven by escalating global CO_2 emissions, is significantly altering global and regional weather patterns. The Lake Tana Basin, a critical ecological and agricultural zone, exhibits high vulnerability to this climatic variability. This study examined long-term trends in rainfall (1900 – 2023) and temperature (1901 – 2022) using the CenTrends and CRU datasets, along with the spatial variability of rainfall and temperature (1981 – 2022) based on the National Aeronautics and Space Administration data. It also investigated the relationship between climate variables and global CO_2 emissions (using the EDGAR dataset; 1970 – 2022) and assessed the efficacy of local climate policies. The findings revealed pronounced spatiotemporal variability. A significant decrease in crucial summer (Kiremt) rainfall was observed (Sen's slope: −0.335 mm/year; p=0.011), whereas November rainfall displayed a significant increasing trend (Sen's slope: 0.045 mm/month; p=0.04), contributing to rising autumn rainfall. Temperatures are rising unequivocally (p<0.05). Notable spatial variability was also observed across different agroecological zones – for instance, the Gondar station reported an annual rainfall with a coefficient of variation of 32.6% compared to 22.3% at Injibara. A significant decline in rainfall was observed in Woreta and Delgi, with Mann–Kendall trend values of −0.247 (p=0.022) and −0.265 (p=0.014), respectively. A robust, statistically significant positive correlation (r = 0.743; p<0.01) was established between global CO_2 emissions and local temperature changes over 53 years. An in-depth policy review identified substantial challenges that impede effective climate action. These results underscore the urgent need for strengthening policy implementation and promoting targeted, location- and season-specific adaptation and mitigation strategies. These include adopting climate-smart agricultural practices, improving carbon sequestration capacity, and aligning local climate actions with global mitigation efforts. Participation in global climate agreements and initiatives, integrated with local actions that contribute to global emission reduction targets, is essential for ensuring long-term sustainability and enhancing community resilience.

Keywords: Climate change; Inverse distance-weighted; Mann–Kendall test; CenTrends; Climate research unit, Greenhouse gas emissions; Policy analysis; Ethiopia

1. Introduction

Global temperature and precipitation patterns are shifting due to climate change, significantly affecting the Earth's climate system.[1] These changes impact human communities, agriculture, water resources, and ecosystems.[2],[3] Donat *et al*.[4] confirmed that temperature and precipitation patterns exhibit significant variations globally.

Recent research highlights that temperature changes are accompanied by rainfall pattern shifts, characterized by greater fluctuations in frequency and intensity.[5] These changes affect water availability, agriculture, and the frequency of extreme weather events such as floods and droughts.[6] The factors that contribute to these variations in rainfall and temperature are well established. According to Stocker *et al.*,[7] the main cause of climate variability and global warming is greenhouse gas emissions from human activities, such as fossil fuel combustion and deforestation.

Ethiopia, with its reliance on rain-fed agriculture and climate-sensitive ecosystems, is highly vulnerable to climate change.[8],[9] Rapid population growth and limited adaptive capacity exacerbate this vulnerability.[10] Over recent decades, the country has experienced significant changes in rainfall and temperature, affecting food security, water resources, and agricultural productivity.[11] Thus, understanding temporal variability and trends in rainfall and temperature is crucial for designing effective adaptation and mitigation strategies.[12],[13] The Lake Tana Basin, due to its ecological importance and socioeconomic significance, serves as a critical case study for assessing climate variability.[14],[15] The basin has experienced notable shifts in rainfall and temperature patterns, impacting agriculture, livelihoods, and water resources.[16],[17] Studies indicate that temperatures are rising while rainfall is decreasing, thereby affecting evaporation rates, water levels, and rainfall frequency.[13],[18] This variability poses challenges for water management, food security, and agricultural sustainability.[12],[19] Within the Lake Tana Basin, research by Addisu *et al*.[17] and Ayalew *et al*.[12] has revealed warming trends and declining rainfall, highlighting the need for climate-resilient infrastructure and adaptive agricultural strategies. Contrary to this, Tesfaw *et al*.[8] and Weldegerima *et al*.[20] reported increasing amounts of annual rainfall in the Lake Tana Basin, though the rate of increase was not statistically significant during the periods 1981 – 2020 and 1989 – 2015, respectively. This suggests a discrepancy between the findings of different studies conducted in the Lake Tana Basin.

Therefore, the present study aims to address the gap by identifying the relationship between long-term, multi-variable climatic changes and global emission patterns and concurrently evaluating the existing policy framework within the specific context of the Lake Tana Basin. Many studies rely on climatic data from the past few decades. However, there is a need for longer-term, continuous climate datasets with trends in relation to greenhouse gas emissions, along with appropriate climate change adaptation and mitigation policies tailored to the basin. Linking local climate trends to global drivers and analyzing policy responses within the specific context is essential to capture more comprehensive trends in climate variability. This study makes a unique contribution by providing a comprehensive, long-term climatic assessment directly linked to global emission drivers, coupled with policy analysis specific to the basin – addressing a gap in holistic regional climate impact and response studies.

2. Methods

2.1. Study area

The Lake Tana Basin is the second-largest sub-basin of the Blue Nile (Abbay) Basin in Ethiopia and covers an estimated area of 15114 km[2]. Its geographic coordinates range from 11°00'0" N to 12°40'0" N latitude and 36°45'0" E to 38°15'0" E longitude (Figure 1). The basin's highest elevation is ≈4100 m above mean sea level (mamsl), with an average elevation of 2025 mamsl. The Lake Tana Basin has a unimodal rainfall distribution,[18] with a mean annual rainfall estimated at 1280 mm.[16] Most rainfall occurs during the summer season, from mid-June to mid-September. The mean annual temperature of the basin is 21°C.[20],[21]

Summer (Kiremet) is the basin's main rainy season, spanning from mid-June to mid-September, with the basin's climate predominantly characterized as tropical highland monsoon.[22] Air temperature in the basin exhibits strong diurnal variation but small annual and seasonal fluctuations, with a mean annual temperature of about 20°C.[23] The basin has a unimodal rainfall distribution, receiving the majority of rainfall during the summer. Lake Tana has great economic value for Ethiopia, serving as a vital resource for agriculture, water supply, and hydropower production. The basin also presents significant economic potential, particularly in areas such as Fogera, Dembia, and Gilgel Abay River mouth floodplains, which are suitable for irrigation, as well as in hydropower generation through facilities in

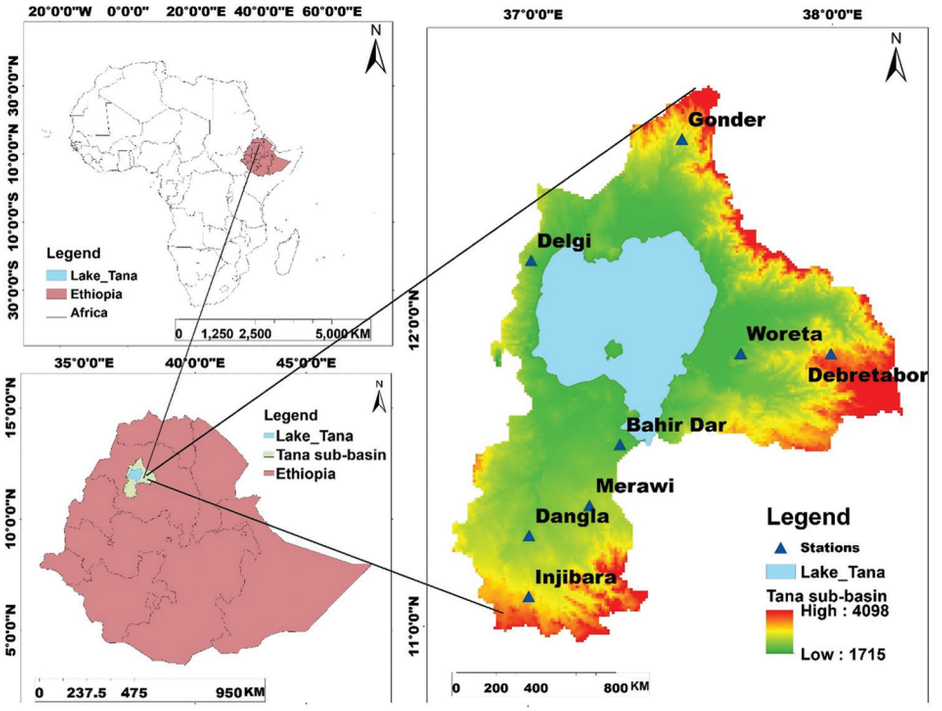

Figure 1. Location of the Lake Tana Basin

Note: The scale bar indicates that a segment of approximately 2 cm (when measured on screen) represents 200 kilometers on the ground. Therefore, the full scale bar represents 800 kilometers.

Tiss Abay and Tana Beles. Rainfall distribution in the region is influenced by the northward and southward movement of the intertropical convergence zone. Based on rainfall variability analysis, 57.5% of the basin experiences low rainfall variability.[13]

The basin comprises three major climatic zones: Wurch (cool climate) at elevations above 3200 m; Dega (cool to humid) at 2300 – 3200 m; and Woina Dega (cool sub-humid) at 1500 – 2300 m.[23] The region experiences four seasons: Kiremt (summer), the main rainy season, lasting from June to August; Meher (autumn), the crop harvesting season, spanning from September to November; Belg (spring), a shorter rainfall season, occurring from March to May; and Bega (winter), the dry and cold season, from December to February.

2.2. Data collection

This study employed a mixed research design that combines quantitative and qualitative approaches. A quantitative design was used for analyzing climatic and greenhouse gas emission data, whereas a qualitative approach was employed to interpret policy-related narratives. The Lake Tana Basin was selected for this study because its largely natural catchment holds high potential for agriculture, livestock, water resources, forestry and wildlife, tourism, and fishery development, in addition to its high biological diversity. The basin is home to numerous animals, plants, fish, wetlands, and forest resources. It also contains fertile soils and cultivable land for intensive agriculture.[24]

The Lake Tana Basin, home to diverse ecosystems and livelihoods, is the largest freshwater lake in Ethiopia and an essential component of the Blue Nile River system.[25] Due to its reliance on rain-fed agriculture, it is highly vulnerable to changes in temperature and rainfall, which directly impact energy production, water resources, and food security.[17],[21],[26] Understanding the region's climate trends is essential given its strategic significance for transboundary water management and hydropower development.[27],[28] Representing Ethiopia's highland agroecological zones, the basin was purposefully selected as the study area to assess the spatiotemporal variability in rainfall and temperature and to inform appropriate climate change adaptation and mitigation strategies.

The study utilized both primary and secondary data to assess rainfall and temperature variabilities and spatial dynamics. A complete and accurate set of gridded monthly rainfall data was obtained from the CenTrends Greater Horn of Africa precipitation dataset, with a spatial resolution of 0.1° × 0.1°, covering the period

1900 – 2023. Monthly temperature data were sourced from the Climate Research Unit (CRU) Time Series (TS) dataset, with a 0.5° × 0.5° resolution, spanning 1901 – 2022. Both CenTrends and CRU datasets were obtained through the Royal Netherlands Meteorological Institute (*Koninklijk Nederlands Meteorologisch Instituut* [KNMI]) Climate Explorer (https://climexp.knmi.nl/start.cgi).

The two data sources were preferred for their regional focus, frequently updated data quality, and suitability for regional and global climate research. The CenTrends Greater Horn of Africa precipitation dataset has a regional focus on precipitation trends, essential for understanding climate variability in various sectors, such as agriculture and water resources, in the Horn of Africa. The dataset combines satellite data and ground-based observations, updated regularly (monthly or annually) to reflect long-term precipitation trends.[29] The CRU dataset from the University of East Anglia provides long-term global climate data, including temperature and precipitation, which are crucial for studying climate change. The CRU dataset is sourced from a vast network of meteorological stations, with annual updates incorporating new observations and climate models.[30] Both datasets from KNMI offer high-quality, accurate climate data, particularly useful for regional and global climate research. In addition, KNMI data are updated in real-time for immediate applications and revised periodically for long-term studies.[31],[32]

The gridded data are reconstructed datasets based on records from gauge stations and meteorological satellite observations. They are especially useful given the limited number of weather stations, their uneven distribution, frequent missing data, and relatively short observation periods.

To assess the spatiotemporal variability of rainfall and temperature in the Lake Tana sub-basin, data from eight meteorological stations – Debre Tabor, Injibara, Gondar, Merawi, Woreta, Delgi, Bahir Dar, and Dangla – covering 42 years (1981 – 2022) were accessed from the National Aeronautics and Space Administration (NASA's) Climate Data Portal (https://power.larc.nasa.gov/data-access-viewer/websites) (Table 1). We evaluated the association between local climate patterns in the Lake Tana sub-basin and global CO_2 emissions using 53 years (1970 – 2022) of data from the EDGAR 4.3.2 dataset. Known for its consistency and detail, the EDGAR dataset provides national totals and high-resolution global emission maps, allowing researchers to link local climate changes to global emission patterns.[33]

2.3. Data analysis

The collected data were analyzed using various statistical and spatial methods, including the mean, coefficient of variation (CV), the Mann–Kendall (MK) trend test, Sen's slope estimator, and the inverse distance weighting (IDW) method. These methods evaluated the temporal and spatial variability of rainfall and temperature in the Lake Tana Basin, as shown in Figure 2.

The CV measures temporal variability in rainfall – a higher CV indicates greater variability, whereas a lower CV signifies stability or low variability[34] – and is expressed as Equation I:

$$CV = \frac{\sigma}{\overline{X}} \times 100 \quad \text{(I)}$$

Table 1. Description of the study area and selected stations

Stations	Latitude (°)	Longitude (°)	Elevation (m)	Period	Years	Source
Lake Tana Basin	11°00'0" – 12°40'0"N	36°45'0" – 38°45'0"E	2025	1900 – 2023 (rainfall)	124	KNMI[a] ()
				1901 – 2022 (temperature)	123	KNMI[b] ()
Injibara	11.06	36.15	2672	1981 – 2022	42	NASA
Debre Tabor	11.83	37.99	2693	1981 – 2022	42	NASA
Gonder	12.61	37.46	2202	1981 – 2022	42	NASA
Merawi	11.41	37.15	2010	1981 – 2022	42	NASA
Delgi	12.19	37.05	1810	1981 – 2022	42	NASA
Woreta	11.89	37.71	1826	1981 – 2022	42	NASA
Bahir Dar	11.98	37.65	1800	1981 – 2022	42	NASA
Dangla	11.41	37.00	2122	1981 – 2022	42	NASA

Notes: [a]Data refers to the CenTrends Greater Horn of Africa precipitation dataset, Royal Netherlands Meteorological Institute (*Koninklijk Nederlands Meteorologisch Instituut* [KNMI]). [b]Data obtained from the Climate Research Unit (CRU), KNMI.
Abbreviation: NASA: National Aeronautics and Space Administration.

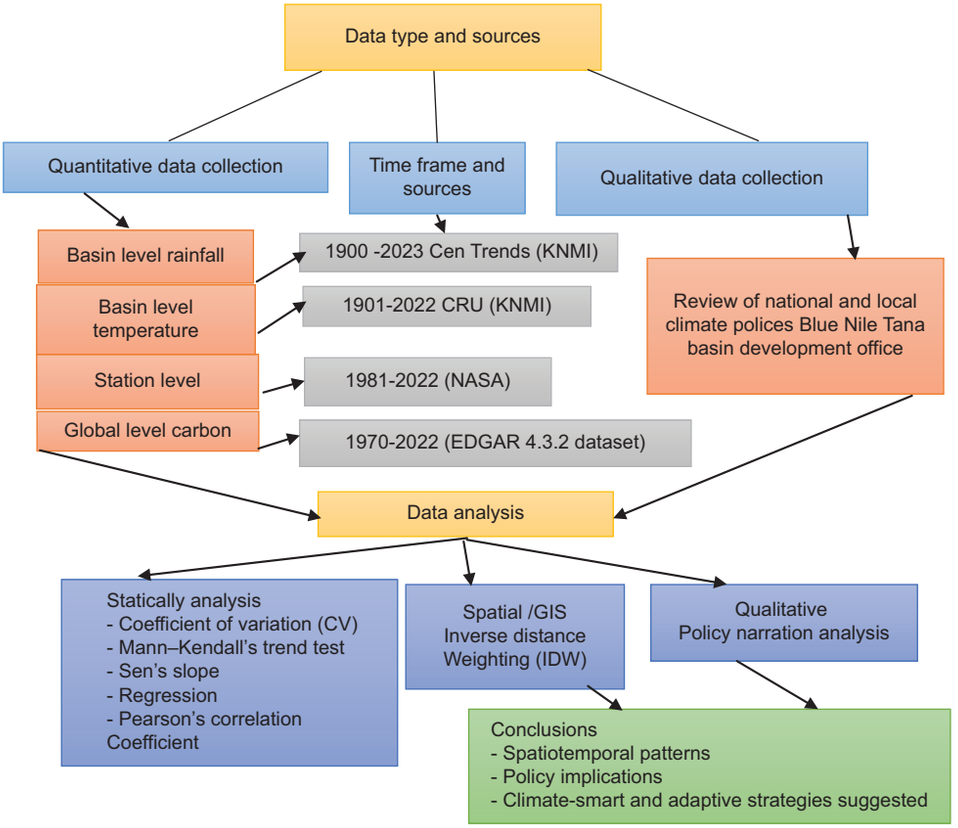

Figure 2. Meteorological flow chart of the study, illustrating the procedures for data collection, processing, and analysis used to evaluate climate trends

Abbreviations: CRU: Climate Research Unit; EDGAR: Emission data base for global atmospheric research; IDW: Inverse distance weighted; GIS: Geographical information system; KNMI: Koninklijk Nederland's Meteorological Institute; NASA: National Aeronautics and Space Administration.

where σ is the standard deviation and $\overline{X}$ is the mean. Accordingly, CV < 20% denotes low variability in rainfall; 20% < CV < 30% denotes moderate variability in rainfall; and CV > 30% indicates high variability in rainfall.

The MK test is a non-parametric method for detecting monotonic trends in TS data without requiring normality or linearity.[35] It is widely used for climatological and hydrological trend detection.[10],[36] It is favored for its robustness against outliers and extremes.[37],[38] As a distribution-free test, the MK test determines whether a statistically significant trend exists in rainfall and temperature variability.[39],[40] A positive value indicates an increasing trend, whereas a negative value indicates a decreasing trend over time.[41] The statistic S is calculated as follows:

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \mathrm{sgn}(X_j - X_i) \quad \text{(II)}$$

where N is the number of data points and X_i and X_j are the TS observations. Assuming $(X_j - X_i) = \theta$, the value of sgn (θ) is computed from:

$$gn(\theta) = \begin{cases} +1 \ldots\ldots\ldots \theta > 0 \\ 0 \ldots\ldots\ldots \theta = 0 \\ -1 \ldots\ldots\ldots \theta < 0 \end{cases} \quad \text{(III)}$$

with positive S values indicating increasing trends and negative S values indicating decreasing trends. Under the hypothesis that the observations are independent and randomly distributed, for large samples ($n \geq 10$, though some studies use $n \geq 8$), the variance statistic σ is approximately normally distributed with zero mean and is calculated as follows:

$$\sigma^2 = \frac{n(n-1)(2n+5)}{18} \quad \text{(IV)}$$

The standardized normal deviate (Z-statistic) distribution is then calculated as:

$$Z = \begin{cases} \dfrac{S-1}{\sigma} & if\ S > 0 \\ 0 & if\ S = 0 \\ \dfrac{S+1}{\sigma} & if\ S < 0 \end{cases} \quad \text{(V)}$$

with positive *Z*-values indicating increasing trends and negative *Z*-values indicating decreasing trends.

Sen's slope estimator is used to quantify the magnitude of trends detected by the MK test in TS data through non-parametric methods,[42] Notable, t is commonly applied in meteorological studies due to its robustness and relative insensitivity to extreme values.[40],[43] To derive an estimate of the slope b_i, the slopes of all the data pairs are computed as follows:[34]

$$b_i = \frac{X_j - X_i}{j - i},\ i = 1, 2, 3\ldots,\ N,\ \ j > i \quad \text{(VI)}$$

where xj and xi are data values at times j and i, respectively, and j > i. Sen's slope estimator is the median of N values of bi:

$$b = \begin{cases} b_{\frac{(N+1)}{2}} & \text{if N is odd} \\ 0.5[b_{\frac{N}{2}} + b_{\frac{(N+2)}{2}}] & \text{if N is even} \end{cases} \quad \text{(VII)}$$

A positive value of b indicates an increasing value with time, whereas a negative value of b indicates a decreasing value with time.

IDW is a spatial analysis tool used to illustrate spatial trends in observed rainfall and temperature data. It measures the relationship between neighboring stations over time and is particularly robust in mountainous terrains where complex rain orography interactions occur.[44] IDW interpolation is applied to map annual and seasonal (winter, spring, summer, and autumn) spatial distributions of rainfall and temperature. The method assumes that nearby points exert a greater influence on the interpolated surface than distant points.[45],[46] IDW is a flexible and widely available interpolation method in GIS software, particularly effective in relatively flat zones.[46]

Pearson's correlation coefficient was employed to determine the relationship between temperature and global CO_2 emissions, as well as between CO_2 emissions and rainfall. It is the most popular method for calculating the direction and degree of association between variables to understand the effects of temperature and rainfall on global CO_2 emissions. The relationships between the variables were calculated using a previously reported formula:[47]

$$r = \frac{\sum(X - \bar{X})(Y - \bar{Y})}{\sqrt{\sum(X - \bar{X})^2 \sqrt{(Y - \bar{Y})^2}}} \quad \text{(VIII)}$$

where X = Cumulative CO_2; Y = Annual temperature; $\bar{X}$ = Mean of cumulative CO_2; and $= \bar{Y}$ Mean of temperature. The value of r is always between −1 and +1: $-1 \leq r \leq 1$. If r = −1, then it is a perfect negative relationship between X and Y. If $-0.99 < r < -0.5$, then it is a moderately negative relationship. If $-0.49 < r > 0$, it is a weak negative relationship. If r = 0, then it means there is no relationship between the two variables. If $0 < r < 0.49$, then it is a weak positive relationship. If $0.5 < r > 0.99$, the relationship is moderately positive, and if r = +1, it is a perfect positive relationship between X and Y variables.

For detecting and estimating variability and trends in annual and seasonal rainfall and temperature, and greenhouse gas emissions in a TS, XLSTAT 2024 (Addinsoft, France), Microsoft Excel (Microsoft Corporation, USA), and R Studio (Posit PBC, USA) were utilized. In addition, GIS (version 10.7; Esri, USA) was also used for mapping and spatial trend analysis of the rainfall and temperature data.

3. Results and discussion

3.1. Temporal variability and trends in rainfall and air temperature

3.1.1. Temporal rainfall variability

Rainfall is crucial for agriculture, especially in rain-fed systems, as it maintains soil moisture for crop growth and food security.[48] As displayed in Table 2, the long-term mean annual rainfall of the study area was 1164 ± 80.7 mm, indicating relatively stable rainfall in the study area. Likewise, the CV of 6.94% suggests low annual rainfall variability in the Lake Tana sub-basin over 104 years. Similarly, a low CV (*i.e.*, < 20%) was previously reported for the Lake Tana sub-basin as well, validating the lower variability in rainfall.[8] The mean decadal rainfall over 124 years was 1165.12 ± 23.62 mm, with a CV of 2.03%, collectively indicating consistent and stable rainfall over the 124 years.

In the Lake Tana sub-basin, the Kiremt[1] (summer) season contributed 67% of the total annual rainfall, whereas the Meher[2] (autumn) months contributed 20% of the total annual rainfall (Table 2). Conversely, the

[1] Kiremt (summer) is the rainy season in Ethiopia, lasting from June to August.

[2] Meher (autumn) is the crop harvesting season in Ethiopia, spanning September to November.

Table 2. Statistical analyses of rainfall (1900 – 2023)

Time series	Min	Max	Mean	SD	CV%	% of total mean	MK trend test	*p*	Sen's slope
Month									
January	0.5	29.4	5.1	4.7	91.7	0	0.033	0.585	0.004
February	1.3	29.9	7.6	5.8	76.3	1	−0.102	0.092	−0.017
March	3.8	82.8	18.3	12.1	66.1	1	0.014	0.817	0.004
April	8.1	98.0	35.9	17.5	48.6	3	−0.007	0.905	−0.004
May	12.6	157.5	77.2	27.6	35.8	7	−0.014	0.824	−0.02
June	95.5	230.4	160.3	25.1	15.7	14	−0.014	0.821	−0.015
July	195.8	401.9	305.1	34.0	11.2	26	−0.084	0.166	−0.113
August	210.2	379.8	313.1	29.6	9.5	27	−0.185**	0.002	−0.225
September	91.0	236.6	158.4	25.5	16.1	14	−0.053	0.386	−0.054
October	19.3	140.4	61.7	23.2	37.5	5	0.006	0.926	0.005
November	0.5	54.0	14.0	11.6	82.8	1	0.125*	0.04	0.045
December	1.2	30.6	7.2	5.9	81.1	1	−0.002	0.974	0
Season									
Winter	3.8	56.1	19.9	9.9	49.9	2	−0.012	0.848	−0.005
Spring	51.3	241.4	131.5	37.5	28.5	11	−0.007	0.916	−0.009
Summer	567.5	934.8	778.4	61.0	7.8	67	−0.154*	0.011	−0.335
Autumn	142.7	374.3	234.2	37.0	15.8	20	0.022	0.718	0.031
Annual	919.8	1367.9	1164.0	80.7	6.9	100	−0.081	0.181	−0.291
Decadal	1114.5	1195.1	1165.1	23.6	2.0	100	−0.359	0.1	−0.373

Notes: *p<0.05; **p<0.01. Abbreviations: CV: Coefficient of variation; MK: Mann–Kendall; SD: Standard deviation.

Belg[3] (spring) and Bega[4] (winter) seasons contributed only 11% and 2%, respectively, of the annual total rainfall at the Lake Tana sub-basin during the indicated period (1900 – 2023). These findings imply that the bulk of the mean annual rainfall in the Lake Tana sub-basin occurs during the summer months, whereas shorter rainfalls occur during the autumn and spring months. Winter is almost dry and does not often contribute to rain-fed agriculture in the basin or the rest of Ethiopia. These seasonal rainfall variations are almost comparable to those reported by Mekonen and Berlie,[10] who found that summer and autumn accounted for 68.4 – 74.4% and 13 – 23% of the annual rainfall, respectively, in the North Wollo Zone of north-eastern Ethiopia. In addition, Weldegerima *et al.*[20] reported that Kiremt and Meher accounted for 78% of total annual rainfall in the Lake Tana sub-basin, while Bega and Belg accounted for 9.4% and 12.5%, respectively.

As displayed in Table 2, the highest monthly rainfall was recorded in August (27%) and July (26%), consistent with the findings by Setegn *et al.*[16] and Weldegerima *et al.*,[20] who also reported the highest rainfall in July/August, reaching 250 – 330 mm/month. Rainfall from both July and August accounted for over 50% of the total annual precipitation in the study area, indicating a distinct wet season compared to other months. In contrast, June and September each contributed 14% of the total mean annual rainfall, with a significantly lower combined total rainfall compared to that of July and August. These 4 months together collectively define the primary wet season for the basin. Shekuru *et al.*[49] and Mekonen and Berlie[10] also reported that a significant proportion of the mean total annual rainfall (81.6%) in the North Shewa Zone is concentrated in the 4 months (June–September).

With respect to the monthly trends and variability, June to September experienced less variable rainfall, with respective CVs of 15.68% (June), 11.15% (July), 9.46% (August), and 16.11% (September). The remaining months, however, presented greater rainfall variability (Table 2).

[3] Belg (spring) is the short rainfall season in Ethiopia, spanning March to May.

[4] Bega (winter) is the dry and cold season in Ethiopia, occurring from December to February.

The MK trend test (Table 2) revealed that the monthly rainfall trends in January, March, and October were 0.033, 0.014, and 0.006, respectively, indicating a non-significant upward rainfall trend. The MK trend test for August yielded −0.185 (p=0.002), with Sen's slope of −0.225, indicating a significantly downward rainfall trend. Conversely, the rainfall trend in November was significantly upward (MK test: 0.125, p=0.04; Sen's slope: 0.045). The remaining months experienced non-significant downward rainfall trends with negative Sen's slope values. Shekuru *et al.*[49] reported statistically significant decreasing rainfall trends for only 2 months (February and June). Likewise, Mekonen and Berlie[10] revealed a statistically non significant decreasing rainfall trend in February, May, and September. However, these reports are contrary to the case in the Lake Tana sub-basin, likely due to differences in the physical attributes of the studied sites or the magnitude of the data used by these studies.

The CVs presented in Table 2 validated the variability of seasonal rainfall in the Lake Tana sub-basin, ranging from 7.8% in summer (low variability) to 49.9% in winter (high variability). Addisu *et al.*[17] and Mekonen and Berlie[10] consistently reported much higher CVs for spring and comparatively less variable rainfall during the summer season in the Lake Tana sub-basin and South Wollo, respectively. Other comparative studies conducted in the Amhara region of Ethiopia have also reported similar results.[50] The seasonal MK trend test revealed that summer presented the highest seasonal mean rainfall (≈778.4 mm), but exhibited a downward trend, as indicated by Kendall's tau of −0.154, a significant p-value of 0.011, and a Sen's slope of −0.335. This implies that rainfall during the summer season in the Lake Tana sub-basin is high but significantly decreases over time. Climate change significantly affects livelihoods, food production, and the overall economy, particularly agriculture-based economies (*e.g.*, crop production, livestock production, horticultural crops, aquaculture [fish production], and apiculture) in developing nations. In addition, ongoing climate change is expected to exacerbate desertification and disrupt crop-growing seasons.

The significantly downward trend in summer rainfall has also been reported across different parts of Ethiopia.[51] Gemeda *et al.*[52] and Asfaw *et al.*[53] observed decreasing Kiremt rainfall in different parts of Ethiopia, including the central highlands. Contrary to this, Mekonen and Berlie[10] highlighted non significant decreasing trend in summer rainfall for the Wollo Zone of north-eastern Ethiopia; they also revealed that autumn experienced moderate mean rainfall (≈234.2 mm), with a positive MK trend (Kendall's tau: 0.022), p-value of 0.718 and a Sen's slope of 0.031. The difference in results is likely due to the geographical location of the study sites. Gebremichael *et al.*[54] indicated that the spatial variability of rainfall in the Lake Tana Basin is highly influenced by terrain orientation in the region and other geographical factors, including altitude, slope, and the associated diurnal wind direction. However, large-scale spatial patterns demonstrate that annual rainfall decreases from the south (ca. 1600 mm) to the north (ca. 1200 mm). Therefore, the southern part of the basin has higher precipitation than both the western and northern parts.[55] South Wollo is located in the rain shadow area of Ethiopia, in contrast to the Lake Tana Basin, which is situated on the windward side of the country's central highlands.

The annual CV (Table 2) exhibited a less variable trend (CV: 6.49%), and the MK test results (Kendall's tau: −0.081; p=0.181) revealed a non-significant downward trend, with a Sen's slope of −0.291, consistent with a previous report.[17] However, Tesfaw *et al.*[8] and Weldegerima *et al.*[20] noted that the annual rainfall in the Lake Tana Basin is trending upward, though not statistically significant.

The decadal rainfall (Table 2) displayed less variability and a non-significant downward trend (Kendall's tau: −0.359; p=0.100; Sen's slope: −0.373). The overall rainfall analysis highlights significant seasonal and monthly variations, with particular concern for summer (August), where significant downward trends could impact water availability. Although the annual and decadal trends suggest a general decline, most of these trends are statistically non-significant downward trends, except in certain months such as November. As November is one of the crop-harvesting months in the northwestern highlands of Ethiopia, continuous monitoring and analysis are warranted. However, our results, consistent with the findings by Suryabhagavan,[56] Esayas *et al.,*[57] and Shekuru *et al.*,[49] indicate a statistically non-significant downward rainfall trend.

The observed variability in rainfall could have significant consequences for smallholder farmers, affecting their agricultural practices and crop production. Having adequate and timely rainfall during the cropping seasons (Belg and Kiremt) is critical for farming practices. However, the short growing season caused by the variability and inconsistency of rainfall during cropping seasons, as well as the inadequacy of soil moisture to support crop production for most of

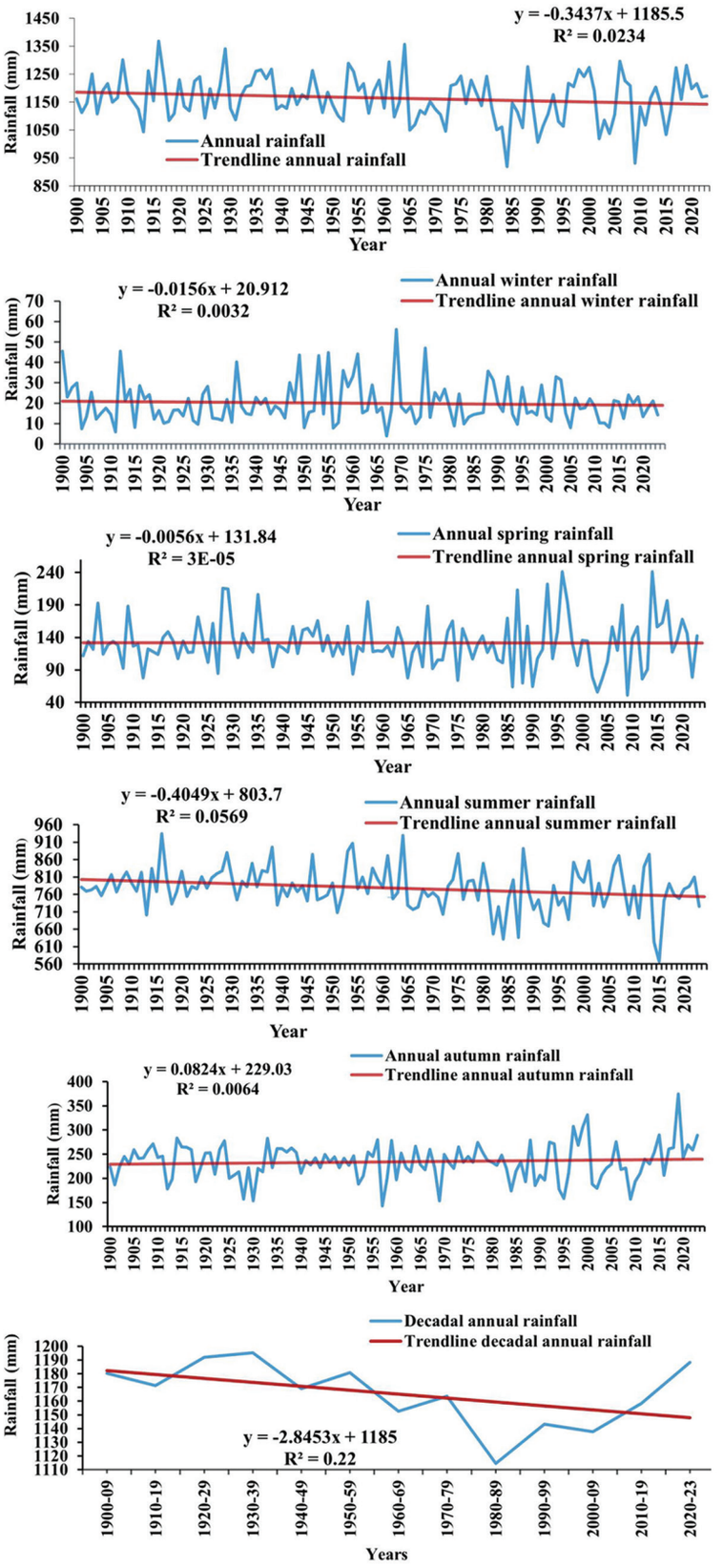

Figure 3. Annual, annual winter, annual spring, annual summer, annual autumn, and decadal rainfall trends (1900 – 2023)

the year, discourages agricultural practices and reduces crop production across the region.[57] Variability in the onset and cessation of rainfall affects the length of the growing period, as well as planting and harvesting times. This uncertainty in the cropping calendar has a direct impact on agricultural production.[52]

As shown in Figure 3, the regression coefficients illustrated downward rainfall trends with rates of −0.343, −0.015, −0.005, and −0.404 mm/year for the annual, winter, spring, and summer scales, respectively, as well as a declining decadal rainfall trend (≈−2.845 mm/decade). In this case, the summer rainfall exhibits a significant downward trend. However, in autumn, the regression coefficient displays a non-significant upward trend at a rate of 0.082 mm/year. The decrease in summer rainfall (≈−0.404 mm/year) suggests the prevalence of potential challenges in sustaining rain-fed agriculture and replenishing water resources during the main crop-growing season. On the other hand, the non-significant increasing trend in autumn (0.082 mm/year) affected the crop harvesting conditions. Overall, the reduction in rainfall during summer and spring could lead to lower crop yields and reduced agricultural productivity, affecting livelihoods in rain-dependent farming systems. A declining trend in annual and seasonal rainfall stresses the need for improved water harvesting, conservation, and irrigation systems to adapt to reduced water availability. Similarly, Wakjira *et al.*[58] reported that the amount of rainfall received and its seasonal distribution in the Lake Tana sub-basin significantly affect its agricultural activity, natural vegetation, and regional humidity.

In a study by Mekonen and Berlie[10] in North Wollo, Northeast Ethiopia, regression coefficients exhibited successive decreasing trends at rates of −0.432, −0.335, and −0.595 mm/year for summer, spring, and annual rainfall, respectively, and −6.537 mm/decade rainfall. Similarly, Shekuru *et al.*[49] reported that the regression coefficients for annual, summer, and spring rainfall exhibited decreasing trends at rates of 3.104, 1.707, and 1.431 mm/year, respectively, in the North Shewa Zone, Central Ethiopia. Wagesho *et al.*[51] reported a significant downward trend in summer rainfall in the Tekeze River basin in northern Ethiopia. Conversely, Suryabhagavan[56] and Esayas *et al.*[57] identified statistically significant and non-significant rainfall trends in the Wolaita Zone in southern Ethiopia and Ethiopia, respectively.

The observed temporal variability in rainfall within the Lake Tana Basin carries significant implications for its predominantly rain-fed agricultural systems. The long-term mean annual rainfall of 1164 mm indicates low overall inter-annual variability (CV: 6.94%) over 124 years, suggesting a generally stable annual water income historically. However, this masks critical seasonal and monthly shifts.

The pronounced seasonality, with summer (Kiremt) rainfall contributing 67% of the annual total, underscores the region's dependence on this single rainy season for agricultural productivity. The statistically significant decrease in summer rainfall, evidenced by a Sen's slope of −0.335 mm/year (p=0.011) and a regression coefficient indicating a decline of −0.404 mm/year, is a major concern. This reduction during the primary crop-growing season can lead to moisture stress, reduced crop yields, and increased food insecurity, consistent with findings by Deressa *et al.*,[59] who noted that Ethiopian agriculture is highly sensitive to rainfall variability. The significant declining trend in August rainfall (Sen's slope: −0.225; p=0.002), a peak rainfall month, further exacerbates this vulnerability. For instance, staple crops, such as teff and maize, are crucial for local livelihoods, but they are highly dependent on consistent Kiremt rains. Hence, decreased rainfall can delay planting, stunt growth, and diminish harvest volumes.[60]

Conversely, the significant increase in November rainfall (Sen's slope: 0.045; p=0.04), while seemingly minor, occurs during the harvesting period for many crops in the northwestern highlands. Increased moisture at this time can lead to post-harvest losses due to rotting, spoilage, and difficulties in drying grains, as highlighted by Wossen *et al.*[61] in similar Ethiopian contexts. The high CV (49.9%) in winter rainfall (Bega), though contributing little to annual totals (2%), indicates unpredictability that can affect dry season cultivation or perennial crops.

3.1.2. Temporal variability and trends in air temperature

The mean monthly minimum, maximum, average, and decadal air temperature data from 1901 to 2022 were assessed to examine the temporal variability and trends in air temperature (Table 3 and Figure 4). Accordingly, the minimum air temperature of the study area (Lake Tana sub-basin) was found to be 7.99°C, with a maximum air temperature of 34.10°C and an annual average air temperature of 21.17°C (Table 3). The regression coefficients for the minimum, annual average, and maximum air temperatures tended to increase at rates of 0.011, 0.008, and 0.010°C/year, respectively (Figure 4). The decadal air temperature regression coefficient results revealed that the average, maximum, and minimum air temperatures experienced

Table 3. Mann–Kendall (MK) trend test results for different air temperatures (1901 – 2022)

Month	Mean minimum air temperature				Mean maximum air temperature				Average air temperature			
	Mean	MKT	*p*	Slope	Mean	MKT	*p*	Slope	Mean	MKT	*p*	Slope
Jan	10.6	0.255***	<0.0001	0.011	28.4	0.039	0.521	0.002	19.5	0.175**	0.004	0.007
Feb	12.1	0.297***	<0.0001	0.016	29.7	0.106	0.084	0.005	20.9	0.211**	0.001	0.011
Mar	14.2	0.379***	<0.0001	0.016	30.9	0.209**	0.001	0.01	22.5	0.317***	<0.0001	0.013
Apr	15.7	0.382***	<0.0001	0.015	31.4	0.232***	0	0.01	23.5	0.343***	<0.0001	0.013
May	16.4	0.498***	<0.0001	0.017	30.7	0.149*	0.015	0.006	23.5	0.35***	<0.0001	0.011
Jun	15.8	0.291***	<0.0001	0.009	28.8	0.006	0.926	0	22.3	0.15*	0.014	0.005
Jul	15.3	0.163**	0.008	0.005	25.8	0.067	0.276	0.003	20.5	0.122*	0.047	0.004
Aug	14.9	0.216***	0	0.007	25.3	0.106	0.083	0.005	20.1	0.162**	0.008	0.006
Sep	14.3	0.31***	<0.0001	0.008	26.8	0.144*	0.019	0.005	20.5	0.238***	0	0.007
Oct	13.9	0.384***	<0.0001	0.011	27.9	0.179**	0.004	0.006	20.9	0.309***	<0.0001	0.008
Nov	12.6	0.304***	<0.0001	0.009	28.2	0.203**	0.001	0.007	20.4	0.279***	<0.0001	0.008
Dec	10.9	0.354***	<0.0001	0.014	27.9	0.121*	0.049	0.005	19.4	0.261***	<0.0001	0.01
Average	10.3	0.339***	<0.0001	0.013	31.7	0.251***	< 0.0001	0.01	21.2	0.378***	<0.0001	0.008
Decadal	10.4	0.692**	0.001	0.015	31.8	0.41	0.059	0.011	21.2	0.538*	0.012	0.009

Notes: *p<0.05; **p<0.01; ***p<0.001.
Abbreviation: MKT: Mann–Kendall trend.

increasing trends at rates of 0.083, 0.0113, and 0.149°C/decade, respectively (Figure 5). Specifically, an abrupt increase in air temperature has been observed since 2000. Mohamed and El-Mahdy[11] indicated that annual maximum and minimum air temperatures were increasing at a rate of 0.037 and 0.025°C/decade, respectively, from 1950 to 2018 in the Lake Tana sub-basin. Abegaz *et al.*[62] highlighted that an increase in air temperature and a decrease in rainfall may impact crop production and soil water balance. According to Tabari,[6] the variability and trends in temperature and rainfall in Ethiopia's Nile Basin are increasing and are expected to continue rising in the future, which hinders agricultural production. This implies that the country whose mainstay depends on agriculture must adapt to further warming, reduced and erratic rainfall, and more frequent climatic extremes.

In addition, the change in air temperature trends and variability is statistically significant in most stations.[63] Birara *et al.*[64] reported that air temperatures in the Lake Tana sub-basin have increased from 1980 to 2015. Studies across different parts of Ethiopia have revealed increasing trends in long-term mean annual maximum, minimum, and average air temperatures.[9],[10],[49],[50],[57] These studies concluded that increasing rates of annual, maximum, and minimum air temperatures were observed in many parts of Ethiopia, significantly impacting smallholder farmers' crop production processes by reducing soil moisture availability and cropland productivity.

The MK trend test results indicate that the monthly minimum air temperature displays a significant upward trend (Table 3). Similarly, Mekonen and Berlie[10] noted that the monthly minimum air temperature significantly trended upwards, except for July, in the South Wollo Zone, north-eastern Ethiopia. Dawit *et al.*,[63] reported significant upward and downward trends in average minimum air temperatures across different stations in the Guna-Tana watershed, in north-central Ethiopia. Likewise, significant upward trends were observed for maximum air temperature in most months, except for January, February, June, July, and August. The monthly mean air temperature also displayed a significant upward trend for all months (Table 3). These findings are consistent with previous reports by Mekonen and Berlie,[10] who reported significant upward trends in mean monthly air temperature, except for January, June, July, and December. Similarly, Shekuru *et al.*[49] revealed a statistically significant upward trend for all long-term monthly average air temperatures in the North Shewa Zone, Central Ethiopia.

The consistent and significant upward trends in minimum, maximum, and average air temperatures are critical factors affecting agriculture. Rising air temperatures can increase evapotranspiration rates, thereby reducing soil moisture availability – even if rainfall levels remain constant.[65] This can shorten

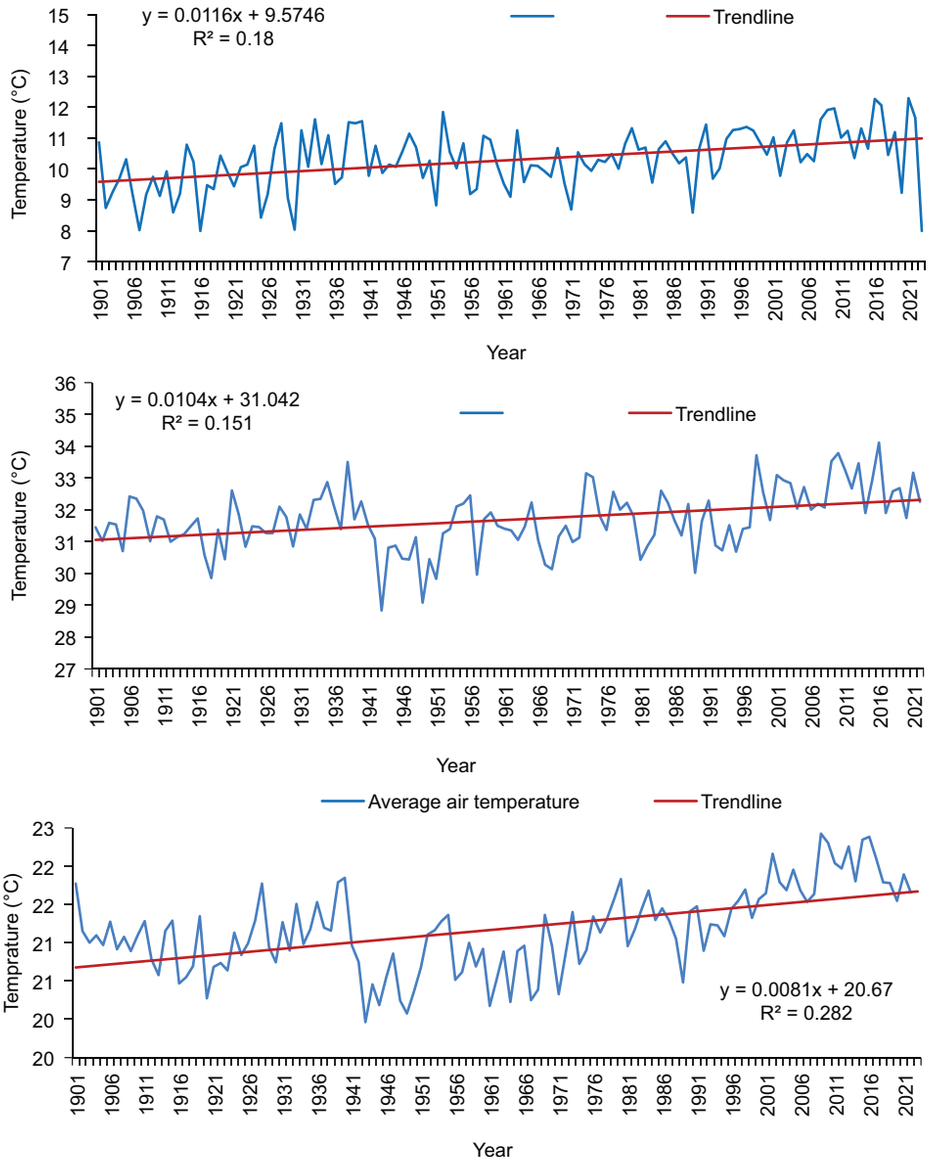

Figure 4. Temporal trends of mean minimum, mean maximum, and average air temperature (1900 – 2022)

the growing period for crops and increase the water requirements for irrigation, where available. Specific agricultural impacts include heat stress on crops, potentially reducing yields of air temperature-sensitive crops (*e.g.*, coffee) at lower altitudes within the basin. Furthermore, warmer air temperatures can alter the lifecycle of agricultural pests and diseases, potentially leading to new or more severe outbreaks.

3.2. Spatial variability and trends of rainfall and air temperature

3.2.1. Spatial variability and trends in rainfall

Table 4 provides an analysis of annual rainfall across different stations in the Lake Tana Basin based on data spanning 1981 – 2022. The analysis included the mean annual rainfall, CV, MK trend test results, *p*-values, and Sen's slope for each location, offering insights into the temporal and spatial variability of rainfall in the basin.

The mean annual rainfall for the Debre Tabor, Injibara, Gondar, Merawi, Woreta, Delgi, Bahir Dar, and Dangla stations is 1090.5, 2079.9, 1589.8, 1862.6, 1531.1, 1603.1, 1603.1, and 1862.6 mm, respectively (Table 4). Rainfall variability appears moderate at all stations, except the Gondar station, which experienced high variability (CV: 32.6) in the Woina Dega (subtropical) climatic zone. The results revealed differences in rainfall variability among stations within the same agroecological zone. At these stations,

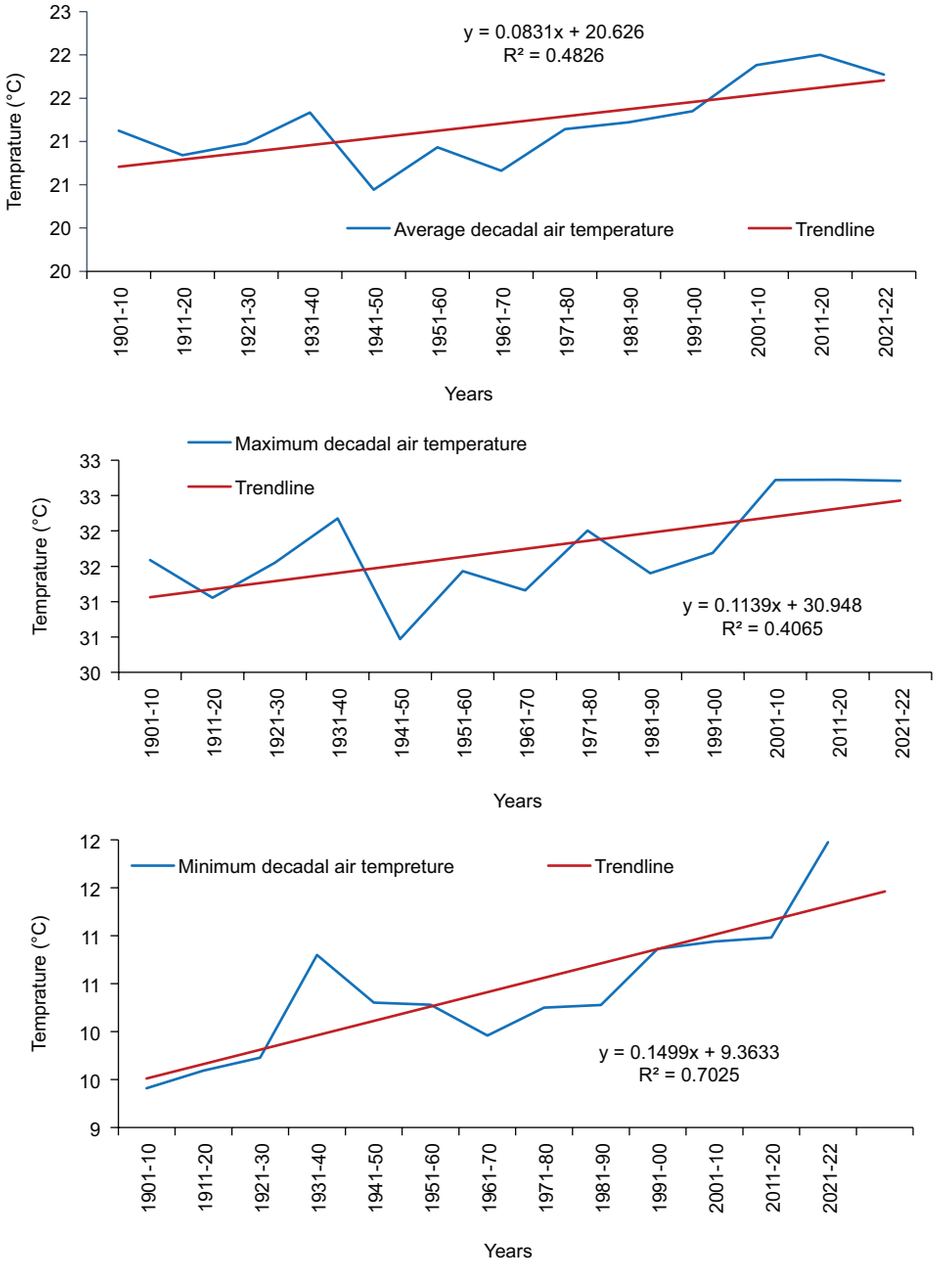

Figure 5. Decadal trends of average, maximum, and minimum air temperature (1901 – 2022)

annual rainfall displayed a significant downward trend, with MKT values of −0.247 at the Woreta station (p=0.022) and −0.265 at the Delgi station (p=0.014) (Figure 6 and Table 4).

In contrast, rainfall variability in areas with the Dega climate (temperate climate type) remains relatively low (CV: 26.0% [Debre Tabor]; 22.3% [Injibara]). This finding indicates that the amount of rainfall is highly variable in Woina-Dega climatic areas compared to Dega-type climates, suggesting rainfall variability within the same basin between different agroecosystems. Similarly, Shekuru *et al.*[49] reported CVs of 15.9% for Dega and 20.8% for Kolla. Comparative results were also reported across different parts of the country.[9],[10],[69] Therefore, it is necessary to investigate rainfall variability in different climatic zones to establish mitigation and adaptation strategies for better and more sustainable livelihoods.

Seasonally, all stations experienced the highest amount of rainfall during Kiremt and the lowest amount

Table 4. Spatial rainfall variability (1981 – 2022)

Season	Statistic	Station							
		Debre Tabor	Injibara	Gondar	Merawi	Woreta	Delgi	Bahir Dar	Dangla
Annual	Mean	1090.5	2079.9	1589.8	1862.6	1531.1	1626.9	1603.1	1862.6
	CV (%)	26.000	22.3	32.6	20.7	23.6	22.8	20.2	20.7
	MKT	−0.146	0.141	−0.001	−0.128	−0.247*	−0.265*	−0.081	−0.128
	p	0.175	0.193	1.000	0.237	0.022	0.014	0.455	0.237
	Sen's slope	−5.274	7.485	0.000	−5.802	−9.703	−11.400	−2.511	−5.802
Winter	Mean	30.1	22.0	12.4	13.2	22.3	14.5	23.6	13.3
	CV (%)	172	146	224	147	185	191.0	143	146
	MKT	−0.087	0.036	−0.101	−0.029	−0.194	−0.105	−0.093	−0.030
	p	0.441	0.740	0.399	0.810	0.088	0.369	0.383	0.775
	Sen's slope	0.000	0.000	0.000[1]	0.000	−0.273	0.000	0.000	0.000
Spring	Mean	138.5	281.1	172.2	228.4	205.6	201.6	219.6	228.4
	CV (%)	60.1	49.8	63.3	48.7	50.0	47.4	48.1	48.7
	MKT	−0.159	0.138	0.080	0.051	−0.137	−0.038	0.024	0.051
	p	0.143	0.201	0.461	0.641	0.205	0.729	0.828	0.641
	Sen's slope	−1.438	1.758	0.895[1]	0.608	−1.319	−0.330	0.293	0.608
Summer	Mean	764.5	1317.1	1104.0	1220.5	1040.4	1095.5	1068.0	1220.5
	CV (%)	27.0	19.3	32.1[2]	19.3	23.9	22.7	19.8	19.3
	MKT	−0.101	0.037	−0.040	−0.186	−0.214*	−0.234*	−0.108	−0.186
	p	0.351	0.737	0.721[3]	0.085	0.047	0.030	0.319	0.085
	Sen's slope	−2.614	1.506	−1.217	−5.022	−5.679	−7.302	−2.636	−5.022
Autumn	Mean	157.4	459.7	301.2	400.3	262.8	315.3	291.9	400.3
	CV (%)	42.0	35.6	39.2[2]	32.9	38.1	35.5	34.8	32.9
	MKT	−0.019	0.118	−0.021	−0.061	−0.142	−0.212*	0.064	−0.060
	p	0.871	0.274	0.854[4]	0.580	0.190	0.050	0.558	0.580
	Sen's slope	−0.005	2.914	−0.510	−0.608	−1.758	−2.637	0.586	−0.608

Note: [1]Sen Slope 0.000 in winter and 0.895 in spring describes no trend and an insignificant increasing trend in winter and spring rainfall, respectively, in Gonder; [2]Coefficient of variation 32.1 in summer and 39.2 in autumn, which describes high rainfall variability in Gonder station; [3]Gonder station with *p*-values of 0.721 for summer rainfall, which indicates a non significant decreasing trend; [4]*p*-values of 0.854 represents non significant declining trend of autumn rainfall at Gonder station;*$p<0.05$.
Abbreviations: CV: Coefficient of variation; MKT: Mann–Kendall trend.

of rainfall during Bega (Table 4 and Figure 6). During winter, all stations, except the Injibara station, exhibited a non-significant downward trend. During spring, Woreta and Delgi presented non-significant downward trends, but the other stations presented non-significant upward trends. In summer, Woreta and Delgi presented significant downward trends, but the remaining stations presented non-significant downward trends, except for the Injibara station, which presented a non-significant upward trend. In autumn, the Delgi station presented a significant decreasing trend, but Injibara and Bahir Dar presented a non-significant upward trend; the remaining stations presented a non-significant downward trend (Figure 6). In contrast to the findings of Weldegerima *et al.*,[20] spatial annual rainfall exhibited downward trends in all stations, except Injibara station; the difference in findings may be due to the short data period analyzed in the study. Nonetheless, the spatial seasonal analysis results validated the decreasing annual and summer rainfall at the Lake Tana sub-basin, similar to that in Woreta and Delgi. These results, particularly the significant downward trends in annual rainfall at

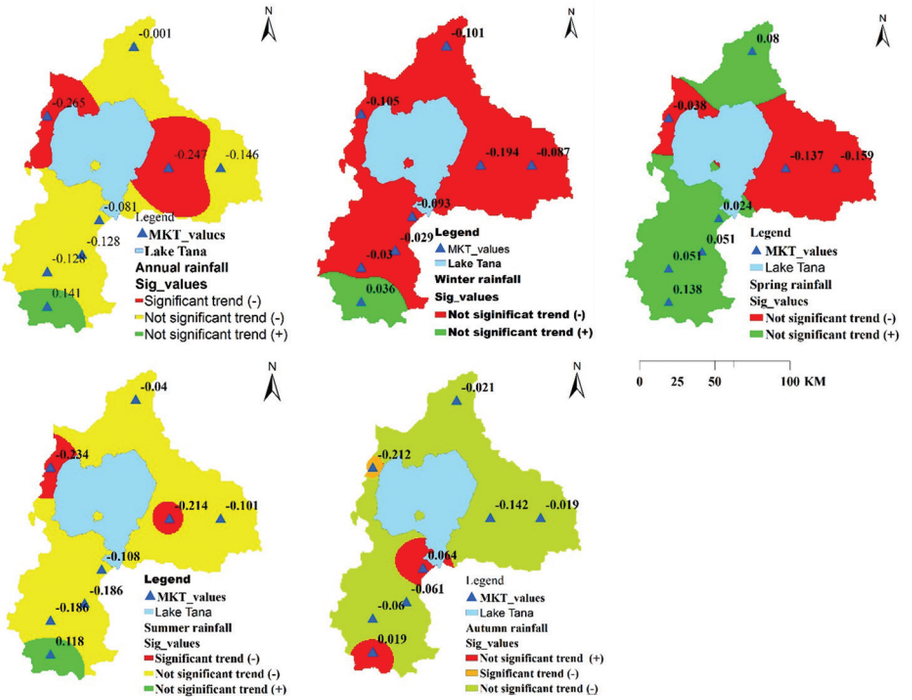

Figure 6. Trends of annual and seasonal rainfall (1981 – 2022). MKTV_values represent the Mann–Kendall trend test values; sig_value indicates significant values represented on the maps.

Woreta and Delgi stations and the decreasing summer rainfall in these locations, indicate emerging hotspots of water stress. Agricultural communities in these areas will likely face more frequent crop failures or be forced to shift to more drought-tolerant crops or livelihoods.

These findings also emphasize the importance of considering local climate trends in agricultural planning, water resource management, and adaptation strategies, as certain areas within the basin are experiencing notable changes in rainfall patterns, potentially impacting water availability and agricultural productivity, which are the main livelihoods of the local community. Moreover, these findings partly coincide with previous reports.[49],[57] Bewket[67] also emphasized the micro-climatic variations in the Ethiopian highlands and their impact on agricultural planning.

3.2.2. Spatial variability and trends in air temperature

The spatial variability of air temperature refers to differences in air temperature across geographic regions due to various factors, including altitude, latitude, proximity to water bodies, urbanization, and land cover.

The long-term average air temperature distribution varied spatially, ranging from 17.21°C in Injibara to 20.8°C in Delgi (Table 5 and Figure 7). MK trend analysis of the mean, maximum, and minimum air temperatures among the stations revealed a statistically significant upward trend (p<0.05), except for the Injibara station, where the maximum air temperature displayed a non-significant upward trend. This observation highlights increasing air temperature variability and warming trends in the Lake Tana sub-basin. The average mean air temperature at the Lake Tana sub-basin from 1981 to 2022 exhibited a significant upward trend (MK test: 0.526; p<0.0001) for almost all the stations, suggesting rising air temperatures over time (Table 5). As a result, certain areas with more rapid warming might experience faster degradation of soil organic matter or increased heat stress on livestock.

These results are consistent with the reports by Mekonen and Berlie[10] and Suryabhagavan,[56] where the average, minimum, and maximum air temperatures exhibited spatially significant upward and downward trends over time across various parts of Ethiopia. Dawit *et al.*[63] reported significant upward and downward trends in average minimum air temperatures across different stations in the Guna-Tana watershed. Moreover, Mengistu *et al.*[50] and Shekuru *et al.*[49] reported increasing air temperature in highland and lowland agroecological zones of 1.28°C and 0.64°C, respectively, over three decades, negatively affecting the livelihood of smallholder farmers.

Table 5. Spatial trends of minimum, maximum, and mean air temperatures (1981 – 2022)

Air temperature	Statistic	Station							
		Debre Tabor	Injibara	Gondar	Merawi	Woreta	Delgi	Bahir Dar	Dangla
Average	Mean	18.364	17.209	19.6	19.3	21.1	20.8	18.9	19.4
	MKT	0.468***	0.282**	0.343**	0.396***	0.468***	0.389***	0.419***	0.396***
	p	<0.0001	0.009	0.001	0.000	<0.0001	0.000	0.000	0.000
	Sen's slope	0.020	0.011	0.019	0.018	0.017	0.020	0.016	0.018
Minimum	Mean	11.9	9.57	12.5	11.6	15.8	13.7	11.38	11.56
	MKT	0.443***	0.275*	0.396***	0.372**	0.382***	0.358***	0.389***	0.371***
	p	<0.0001	0.010	0.000	0.001	0.000	0.001	0.0002	0.0005
	Sen's slope	0.020	0.011	0.019	0.017	0.016	0.016	0.020	0.016
Maximum	Mean	25.3	25.99	27.8	19.3	26.8	29.2	27.31	28.25
	MKT	0.422***	0.117	0.308**	0.396***	0.454***	0.410***	0.338**	0.349**
	p	<0.0001	0.278	0.004	0.000	<0.0001	0.000	0.001	0.001
	Sen's slope	0.024	0.009	0.021	0.018	0.022	0.026	0.021	0.021

Notes: **p*<0.05; ***p*<0.01; ****p*<0.001.
Abbreviation: MKT: Mann–Kendall trend.

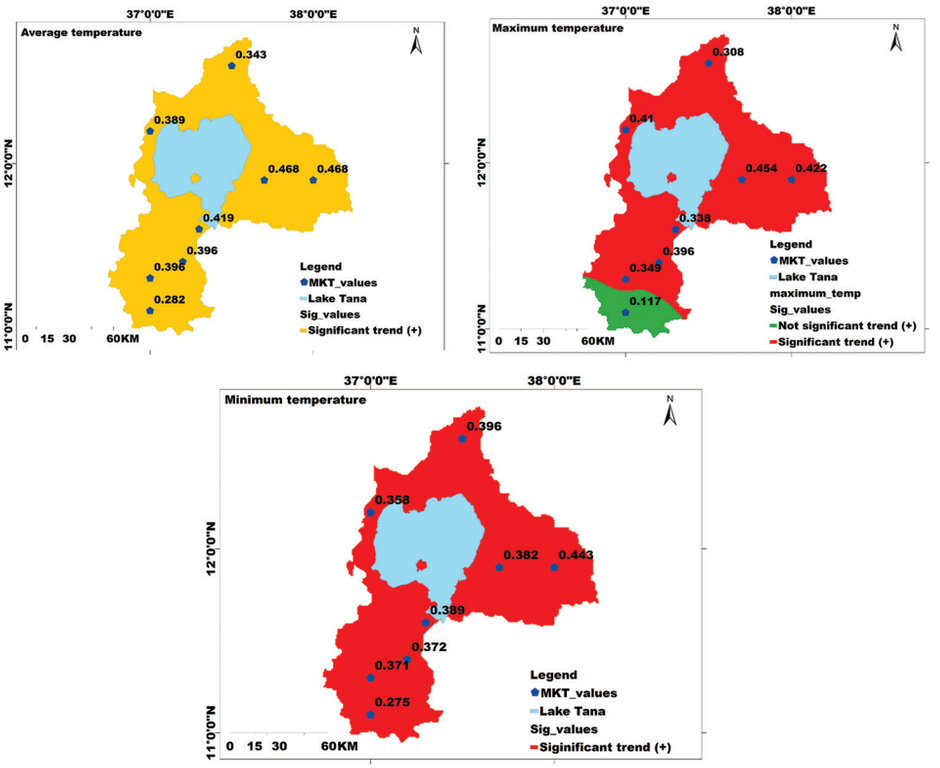

Figure 7. Trends of average, maximum, and minimum air temperatures (1981 – 2022). MKT_values represent the Mann–Kendall trend test values; sig_value indicates significant values represented on the maps.

3.2.3. Station-based seasonal and spatial trends in air temperature at the Lake Tana sub-basin

The station-based trend of air temperature in the Lake Tana sub-basin (1981 – 2022) is displayed in Table 6. During winter, there were significant upward air temperature trends at the Debre Tabor, Gondar, Woreta, and Delgi stations, with MK trend values of 0.243, 0.216, 0.278, and 0.271, respectively (p<0.05). The

Table 6. Seasonal station-based spatial trends in air temperature (1981 – 2022)

Season	Statistic	Station						
	Debre Tabor	Injibara	Gondar	Merawi	Woreta	Delgi	Bahir Dar	Dangla
Winter								
Mean	18.18	16.89	19.47	18.89	20.89	20.78	19.00	22.4
MKT	0.243*	0.049	0.216*	0.177	0.278*	0.271*	0.1777	0.2846**
p	0.024	0.657	0.045	0.102	0.01	0.012	0.099	0.008
Sen's slope	0.015	0.003	0.014	0.016	0.016	0.021	0.011	0.031
Spring								
Mean	20.50	19.86	22.36	22.36	23.39	23.78	21.70	22.36
MKT	0.379***	0.199***	0.278*	0.285**	0.346**	0.329**	0.288**	0.285**
p	0	0.0654	0.01	0.008	0.001	0.002	0.007	0.008
Sen's slope	0.034	0.020	0.028	0.031	0.032	0.033	0.028	0.031
Summer								
Mean	17.68	16.19	18.51	18.13	19.81	19.08	17.8735	18.13
MKT	0.072	0.113	0.057	0.171	0.006	0.129	0.112	0.171
p	0.508	0.298	0.603	0.114	0.965	0.233	0.303	0.114
Sen's slope	0.005	0.005	0.003	0.008	0	0.006	0.005	0.008
Autumn								
Mean	17.09	15.89	18.21	17.98	20.28	19.51	17.59	17.98
MKT	0.35**	0.448***	0.363**	0.409	0.359**	0.351**	0.384***	0.408***
p	0.001	0.0000	0.001	0	0.001	0.001	0.0003	0.0001
Sen's slope	0.021	0.014	0.022	0.015	0.018	0.016	0.017	0.015

Notes: *p<0.05; **p<0.01; ***p<0.001.
Abbreviation: MKT: Mann–Kendall trend.

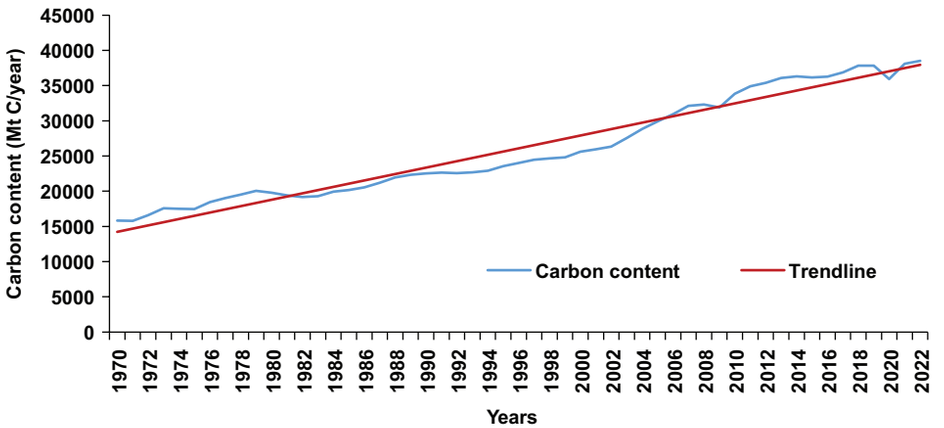

Figure 8. Trends of global CO_2 emissions (1970 – 2022) based on the EDGAR Report 2023

remaining stations displayed non-significant upward trends. During spring, there was a significant upward trend for all stations (p<0.05), except the Injibara station, which experienced a non-significant upward trend. During summer, air temperatures exhibited non-significant upward trends at all stations. The autumn season experienced a statistically significant warming or upward trend across all stations.

3.3. Causes and trends of global carbon dioxide emissions

According to the EDGAR Report 2023, the major

causes of CO_2 emissions were industrial combustion, transport, agriculture, fuel exploitation, waste, land use, and land-use changes.[35]

Global CO_2 emissions have steadily increased from 15000 to over 38000 Mt CO_2/year, making it the primary greenhouse gas (Figure 8). The trendline (red; R^2 = 0.9554) indicates a significant and steady growth over time, emphasizing the critical need for emission-reduction initiatives to combat climate change.[68]

From 1970 to 2022, global CO_2 emissions observed a significant sharp increase (Kendall's tau: 0.956; Sen's slope: 448.260; p<0.0001) (Table 7), primarily driven by fossil fuel use. These findings emphasize the need for comprehensive mitigation efforts targeting CO_2 emissions. The continued rise of CO_2 reflects heavy reliance on fossil fuels.[69],[70] Continued greenhouse gas emissions can cause long-term changes in the climate system and increase the likelihood of widespread climatic extremes.[71]

3.4. Relationship between climate parameters and cumulative global carbon dioxide emissions

The Pearson correlation matrix revealed a significant relationship for both variables, rainfall (p=0.0004) and air temperature (p=0.0006), with carbon dioxide emission. There is a weak positive correlation between rainfall and carbon dioxide emission (r = 0.144; p<0.0001). The strong positive correlation (r = 0.743) between carbon dioxide emissions and air temperature suggests that carbon dioxide emissions significantly influence air temperature patterns, whereby 55.2% of the variation in air temperature (r^2 = 0.552) is associated with carbon dioxide emission levels.

This result is similar to the study conducted by Benti and Abara[72] in southern Ethiopia. The study reported coefficients of determination between global CO_2 concentrations and climatic variables, with values of 0.308 for air temperature and 0.204 for rainfall. This indicates that carbon dioxide emissions are a key driver of climate change. Therefore, reducing carbon dioxide emissions through effective climate policies is essential for limiting climate change and mitigating its adverse effects (*e.g*., global warming).[65]

3.5. Climate-related policies and strategies in the Lake Tana Basin

To support development in the basin and the nation, Ethiopia has implemented a wide range of laws, proclamations, regulations, programs, and action plans, many of which are highlighted by the Blue Nile and Lake Tana Basin Development Office. These instruments frequently emphasize climate change adaptation, natural

Table 7. Correlation result of climate parameters and global carbon emissions

Variable	Coefficients of determination (Pearson)			*p*-values (Pearson)			Correlation matrix (Pearson)		
	Carbon	Rainfall	Temperature	Carbon rainfall	Rainfall	Temperature	Carbon	Rainfall	Temperature
Carbon	1	0.020	0.553	0	0.307	<0.0001	1	0.143	0.743
Rain fall	0.020	1	0.008	0.307	0	0.525	0.143	1	-0.089
Temperature	0.553	0.008	1	<0.0001	0.525	0	0.743	-0.089	1

resource management, and sustainable development.

Ethiopia's Environmental Policy (EPE, 1999) promotes conservation, efficient water use, sustainable watershed management, and ecosystem restoration to enhance climate resilience. The country's Ten-Year Development Plan (2021 – 2030) and Agricultural Policy (1995) prioritize agricultural modernization while addressing land degradation and climate change. [73]

The Lake Tana Basin is recognized as a crucial area under the Environmental Water Management Policy (EWM, 1999). In addition, the Ethiopian Water Resources Management Proclamation (No. 197/2000) ensures the protection and sustainable utilization of water resources for both social and economic benefits. The Environmental Impact Assessment Proclamation (No. 299/2002) mandates the assessment of potential environmental effects before project implementation.[74]

To safeguard biodiversity, public health, and environmental esthetics, the Environmental Pollution Control Proclamation (No. 300/2002) requires effective pollution mitigation measures. The Fisheries Development and Utilization Proclamation (No. 315/2003) emphasizes sustainable management of wetlands and the development of fishery resources. [75] Forest resources are supported indirectly through the Proclamation for the Development, Conservation, and Sustainable Utilization of Forests (No. 542/2004). Furthermore, the River Basin Councils and Authorities Proclamation (No. 534/2007) promotes the integrated management of water resources for sustainable and balanced development.[76]

Among the supporting regulations is the Council of Ministers Regulation No. 115/2005, which enforces the obligations of the Water Resources Management Proclamation, commonly referred to as the Ethiopian Water Resources Management Regulations. Finally, the Lake Tana Biosphere Reserve Regulation (No. 125/2014) provides a framework for the sustainable management of the Lake Tana Basin.[77]

With a focus on agriculture, forestry, renewable energy, and energy efficiency, Ethiopia's Climate Resilient Green Economy (CRGE) Strategy (2011) aims to achieve middle-income status by 2025 through climate-resilient, green development. The National Adaptation Programme of Action (NAPA, 2007) seeks to reduce the country's vulnerability to climate change impacts. The Green Legacy Initiative (2019) promotes ecological restoration and environmental awareness by encouraging large-scale tree planting to mitigate climate change and support sustainable environmental management.[78]

3.6. Policy implementation and its effectiveness for climate change adaptation and mitigation

According to the Blue Nile and Lake Tana sub-basin Administration Office Report 2025,[79] several initiatives have been implemented to mitigate the impacts of climate change in the Lake Tana sub-basin: K

(i) Adaptation initiatives include conducting vulnerability assessments, installing 17 early warning telemetry stations, supporting climate-resilient infrastructure (*e.g.*, irrigation and dams), creating a 20-year water allocation strategy, increasing community awareness and training, and restoring ecosystems, Ribb and Megech.
(ii) Mitigation measures include increasing renewable energy and energy efficiency, and encouraging appropriate land management to reduce carbon dioxide emissions.
(iii) Agroecological practices include agroforestry in highlands, which improves soil and sequesters carbon, and conservation agriculture (*e.g.*, Fogera Plain) to reduce erosion.
(iv) Water harvesting to increase water availability.

According to the report,[79] most of the initiatives have been effective, but several limitations remain, including insufficient funding, weak coordination, data gaps, and community resistance. Therefore, for Ethiopia to convert its policy commitments into real environmental and developmental benefits, it is imperative to strengthen institutional capacity, improve coordination, raise public awareness, ensure political prioritization, and create strong monitoring and evaluation systems.

In general, linking local climate change to global emissions and policy responses is supported by the strong positive correlation (Pearson's $r = 0.743$, $p<0.01$) between global CO_2 emissions and local temperature trends in the Lake Tana sub-basin. This provides clear evidence of the local manifestation of global climate change. This finding is consistent with the broader scientific consensus articulated by Masson *et al.*[65] that anthropogenic greenhouse gas emissions are the primary driver of observed warming trends.

Ethiopia has diverse policies and strategies aimed at addressing climate change, such as CRGE and NAPA. [80],[81] However, this study identified significant gaps in their implementation within the Lake Tana sub-basin, including weak enforcement, limited financial resources, coordination issues, and community resistance. This

reflects broader challenges in translating national climate policies into effective local action in many developing countries. The effectiveness of agroecological practices, such as conservation agriculture in the Fogera Plain and water-harvesting initiatives, is acknowledged, but these are often hampered by the identified systemic limitations.

4. Conclusion

A comprehensive analysis of over a century of rainfall (1900 – 2023) and temperature (1901 – 2022) data for the Lake Tana sub-basin in Ethiopia revealed significant climatic trends. The study identified notable annual, seasonal, and decadal rainfall variations, with a clear decreasing trend in summer rainfall, which is critical for crop production and poses challenges to agriculture, water availability, and environmental stability. Conversely, November rainfall displayed a significant positive trend. These findings challenge some previous studies and refine others conducted in the Lake Tana sub-basin. High rainfall variability was observed across different agroecological zones, which is higher in Woina-Dega than in Dega climates and among meteorological stations, such as the Gondar station (CV: 32.6%). The air temperature analysis indicated a significant overall upward trend in minimum, maximum, and average air temperatures. Spatially, Injibara recorded the lowest average air temperature, whereas Woreta recorded the highest. A strong positive correlation (r = 0.743; p<0.01) between global CO_2 emissions and local air temperature trends underscores the influence of global climate drivers.

Despite existing policies and strategies implemented by the Blue Nile and Lake Tana sub-basin development office, weak enforcement due to limited funds, poor coordination, data gaps, and community resistance has impeded progress in addressing climate change. The observed air temperature and rainfall variability could significantly impact agriculture and water resources, which are vital for local livelihoods. Therefore, there is a pressing need to invest in and scale up the adoption of climate-smart agricultural practices that enhance resilience to changing rainfall patterns and rising air temperatures. These practices can also contribute to climate change mitigation by reducing agricultural emissions and enhancing soil carbon sequestration. Key strategies include providing training and technical assistance to farmers on conservation agriculture, agroforestry, drought-resistant crop varieties, water-efficient irrigation techniques, and water harvesting methods.

Diversifying livelihoods is essential to reduce dependence on climate-sensitive sectors such as rain-fed agriculture and to strengthen the adaptive capacity of local communities. This can be achieved by supporting the development of alternative income-generating activities such as sustainable tourism, aquaculture, and value-added processing of agricultural products, as well as by improving access to credit and market information.

In addition, aligning local climate actions with global mitigation efforts is crucial. This includes active participation in global climate agreements and initiatives and the implementation of local actions that contribute to global emission reduction targets. Strengthening and integrating national frameworks, such as NAPA, CRGE strategy, and the Green Legacy Initiative – while addressing local adaptation needs using station-specific climate data – can ensure both global and local climate goals are met.

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Conflict of interest

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Ethics approval and consent to participate

The study has been ethically approved by the ethical committee of Department of Geography and

Environmental Studies, Faculty of Social Sciences, Bahir Dar University (Ref No.: 109/2024).

Consent for publication

Not applicable.

Availability of data

Data on rainfall (1900 – 2023) and temperature (1901 – 2022) can be obtained from KNMI Climate Explorer (https://climexp.knmi.nl/start.cgi). Station data (1981 – 2022) can be obtained from NASA POWER Data Access Viewer (DAV) (https://power.larc.nasa.gov/data-access-viewer/). Data on greenhouse gas emissions (1970 – 2022) can be obtained from the EDGAR 4.3.2 dataset.

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