**ORIGINAL PAPER**

# Analysis of climatic trends in the upper Blue Nile basin based on homogenized data

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## Abstract

The headwater region of the upper Blue Nile is the main source of the Nile water for the three Eastern Nile countries, namely Ethiopia, Sudan, and Egypt. Climate-related studies for the region is thus paramount. However, previous studies for the region used non-homogenous data, and did not remove all the significant autocorrelations in trend analysis. Therefore, this study analyzed the trend using gap-filled and homogenized meteorological data over the period $1980-2017$. Using the non-parametric Mann–Kendall test adjusted by effective sample size, the influence of all significant positive and negative autocorrelations on the trend was removed. Sen's slope was used to determine the magnitude of trends. The tests were applied to minimum and maximum temperatures, mean temperature, diurnal temperature range (DTR), and total precipitation as well as seasonal and annual extreme climate indices. In general, the climate in the study region has become wetter and warmer. As for extreme temperature, the hot ends of the daily temperature distribution have altered more rapidly than the cold ends. Accordingly, the DTR exhibited a consistent increasing trend across the stations. The rainfall showed increases in maximum $1-$day precipitation amount, maximum $5-$day precipitation amount, number of heavy precipitation days, total annual rainfall, and extremely wet days. As trend magnitudes of the homogenized series differed from those of the original series, the results that emerged from the previous hydroclimate-related studies for the region using non-homogenized data should be revised. This study has significant implications for water use efficiency and adaptation to climate risk in the three riparian countries, given the recently commenced water resources projects.

## 1 Introduction

Detection of long-term trends in climatic variables is a vital task in climate change studies. Knowledge about past and recent climate changes has received substantial attention across the globe (Hegerl et al. 2019). Climate change is directly linked to temperature and precipitation. These parameters determine the environmental condition, which affects the agricultural productivity (Worku et al. 2019).

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Increasing temperatures and changes in rainfall pattern resulting from global climate change have serious effects on water resources availability and surface energy budgets, along with the danger of increasing occurrences of droughts and floods (Tesfamariam et al. 2019).

One of the effects of global warming might be an increase in climate extremes (Alexander et al. 2006; Aguilar et al. 2009; Gummadi et al. 2017; Manikandan et al. 2018; Rai et al. 2019; Lionello and Scarascia 2020). Not only the detection of changes in mean values, but also in extremes, of temperature and rainfall are vital for implementing climate change adaptation and mitigation measures. Extremes in a changing climate are more important than averages (Katz and Brown 1992) because these events might cause property damage, loss of life, and threat to the existence of society. Changes in natural and human systems emanate from extreme climate events much more than from their average counterparts (Perera et al. 2020). Therefore, climate extremes and their impacts have been investigated by many scholars (e.g., Seleshi and Camberlin 2004; Shang et al. 2010; Degefu and Bewket 2014; Gummadi et al. 2017;

IPCC 2012; Gebrechorkos et al. 2018; Berhane et al. 2020; Shawul and Chakma 2020). Some near-global analyses of changing climate extremes indicated widespread and significant warming trends related to temperature extremes (Alexander et al. 2006; Donat et al. 2013). They also reported that changes in precipitation extremes were spatially more complex. As changes in extreme precipitation will have substantial consequences on water, food, and energy nexus (WMO 2009; Degefu and Bewket 2014; Elagib et al 2021), assessing the trends of mean and extreme rainfall is crucial to understand flooding and drought consequences in the framework of climate change and the nexus system.

The Intergovernmental Panel on Climate Change (IPCC) Special Report on Extremes (SREX) provided the most comprehensive global review and assessment on the relation between climate extremes, their impacts, and the strategies to manage the associated threats (IPCC 2012). However, lack of long-term and homogenized climate data hinders the investigations of climate extremes particularly in data-scarce areas like the Horn of Africa. When analyzing changes in indices of climate extremes, studies in Africa reported increases in warm extremes and decreases in cold extremes (Alexander et al. 2006; Aguilar et al. 2009; Collins 2011; Kruger and Sekele, 2013; Nashwan and Shahid 2019; Berhane et al. 2020). These studies also reported both an increase and a decrease in rainfall amount and an increase in heavy precipitation. East African countries (Ethiopia, Kenya, and Tanzania) witnessed an increasing tendency in extreme temperature indices, and uneven rainfall patterns (Gebrechorkos et al. 2018).

Several studies have been undertaken in Ethiopia in order to assess trends in mean temperatures and total rainfall using non-homogenous climatological dataset (e.g., Conway et al. 2004; Cheung et al. 2008; Tessema et al. 2010; Gebremicael et al. 2013; Tekleab et al. 2013; Viste et al. 2013; Tabari et al. 2015; Asfaw et al. 2018; Jaweso et al. 2019). Most of the above studies have found positive trends in temperature indices and mixed trends in precipitation. Past climatic studies in Ethiopia are summarized in Table S1. Findings from these studies indicated that trends in rainfall-related indices are highly influenced by local and large-scale climate conditions. Conclusions drawn from previous trend detection studies for the upper Blue Nile basin are contradictory. Reasons for this contradiction might be the difference in length of the study periods, data inhomogeneity, dissimilar classifications of the major rainy season, and variation in trend assessment approaches. For instance, Cheung et al. (2008) used a parametric t-test whereas Mengistu et al. (2014) applied F-tests for trend detection. Parametric tests are applicable for normally distributed data, which are not usually the case with rainfall time series. Some investigations that applied a non-parametric approach, such as the Mann–Kendall technique, overlooked the influence of serial correlation in data (e.g.

Seleshi and Zanke 2004; Viste et al. 2013). In addition, some studies applied the trend-free pre-whitening approach to remove the influence of serial correlation on the Mann–Kendall trend test (e.g. Tessema et al. 2010; Tekleab et al. 2013). This method, however, eliminates the serial correlation in the data only at the first lag while serial correlations in other time lags are ignored. A more recent study applied non-parametric trend detection approach, which considered all the significant serial correlations (e.g. Tabari et al. 2015), paid less attention to data homogenization. It is generally recognized that only by using homogenized data series can the long-term climatic trends be accurately detected (Zahng et al. 2014). Studies should therefore examine and adjust the non-homogeneities before analyzing long-term trends in climatological data (Meshram et al. 2020).

Quantifiable information describing how weather and climate extremes are changing using homogenized climate data over the upper Blue Nile basin in Ethiopia has until now been very limited. Climatic studies for the upper Blue Nile basin are crucial for water provisioning of the downstream riparian countries in general and the study region in particular. In this paper, therefore, we attempt to detect trends in precipitation, diurnal temperature range, and minimum, maximum, and mean temperatures on seasonal and annual scales. The study includes (1) identification of trends using the Mann–Kendall trend test, adjusted with the effective sample size (ESS) technique to take all significant serial correlations into account; (2) detecting the trend magnitude and slope by applying the non-parametric Sen's slope approach; and (3) analyzing trends on extreme temperature and rainfall indices as defined by the joint World Meteorological Organization Commission for Climatology (CCL)/ Climate Variability and Predictability (CLIVAR) Expert Team for Climate Change Detection Monitoring and Indices (ETCCDMI).

## 2 Description of the study area

The study region—the upper Blue Nile—is characterized by tropical climate, influenced by high altitude. Tana and Beles watersheds are the main contributors of flow to the upper Blue Nile (Fig. 1). The combined surface area of both watersheds is 28,900 km$^2$. Four rivers (Gilgel Abbay, Ribb, Megech, and Gummara) contribute the flow to Lake Tana. The hydrological year in the study area is divided into three seasons. Kiremt is the main rainy season, which refers to the months from June to September, Belg is a small rainy season that lasts from March to May, and Bega is the dry season, which lasts from October to February (NMA 1996). Based on Shuttle Radar Topography Mission (SRTM) 90 m digital elevation model, the altitude of the two sub-basins

**Fig. 1** Hydro-meteorological stations under consideration
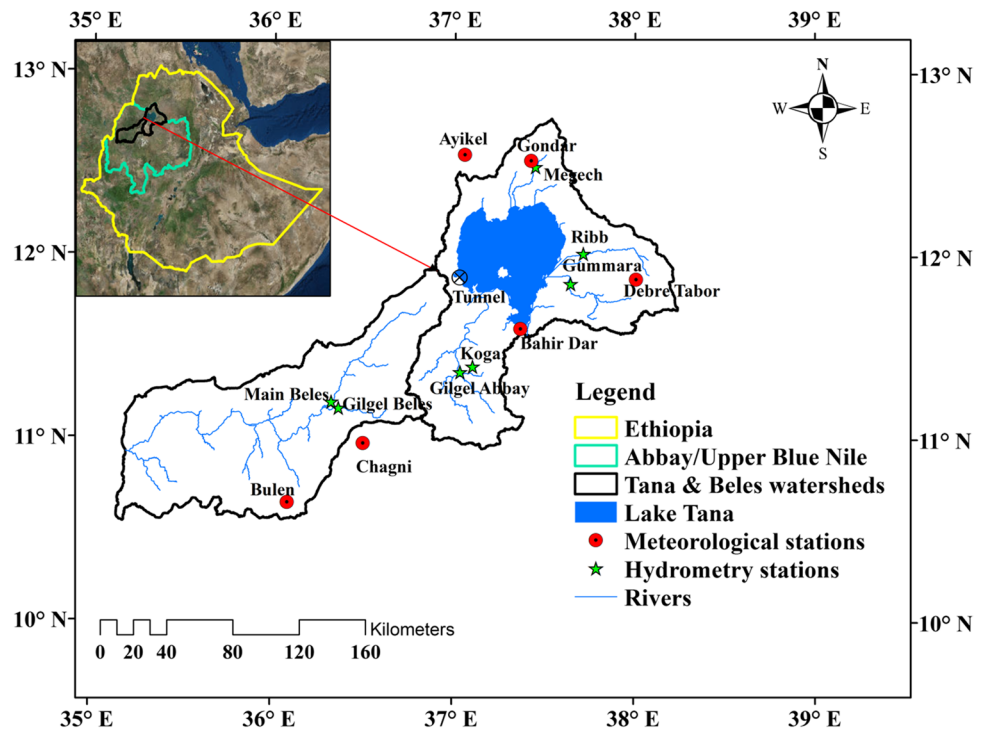
ranges from 435 to 4090 m a.m.s.l. Rainfed agriculture or cultivation and forestation are the dominant land uses and land covers in the Tana and Beles sub-basins (Woldesenbet et al. 2017a).

# 3 Data and methodology

The overall data and methodology used in the current study are overviewed in Table 1 and Fig. 2.

## 3.1 Data

The climate data, including daily precipitation and maximum and minimum temperatures, for the period extending

from 1980 to 2017 for Lake Tana and Beles sub-basins were obtained from the National Meteorological Agency of Ethiopia for six stations. In general, the spatial coverage of the climatic data is meager in the sub-basins, and had many data gaps. Accurate detection of climatic trends requires quality-controlled, gap-filled, and homogenized time series (Cannarozza et al. 2006; Zhang et al. 2014) prior to trend detection. Therefore, the missing records of precipitation and temperature from the six meteorological stations were interpolated based on the coefficient of correlation weighting method then homogenized using the Multiple Analysis of Series for Homogenization (MASH) (Szentimrey 2011; Woldesenbet et al. 2017b).

MASH is an automatic homogenization algorithm based on relative homogeneity test procedure that does not assume

**Table 1** Description of meteorological stations for daily rainfall and temperature in the study area

| No | Station name | Latitude (°N) | Longitude (°E) | Elevation (m) | Period of records | Average | | |
|----|--------------|---------------|----------------|---------------|-------------------|---------|---|---|
| | | | | | | Rainfall (mm) | Temperature (°C) | |
| | | | | | | | Maximum | Minimum |
| 1 | Ayikel | 12.32 | 37.03 | 2150 | 1980 − 2017 | 1247.3 | 24.0 | 13.4 |
| 2 | Bahir Dar | 11.36 | 37.25 | 1770 | 1980 − 2017 | 1495.1 | 26.9 | 11.9 |
| 3 | Bulen | 10.41 | 36.06 | 1450 | 1980 − 2017 | 1476.8 | 28.0 | 14.5 |
| 4 | Chagni | 10.57 | 36.30 | 1620 | 1980 − 2017 | 1584.2 | 28.3 | 13.4 |
| 5 | Debre Tabor | 11.53 | 38.02 | 2690 | 1980 − 2017 | 1421.4 | 22.1 | 9.2 |
| 6 | Gondar | 12.33 | 37.25 | 1967 | 1980 − 2017 | 1156.4 | 27.0 | 13.7 |
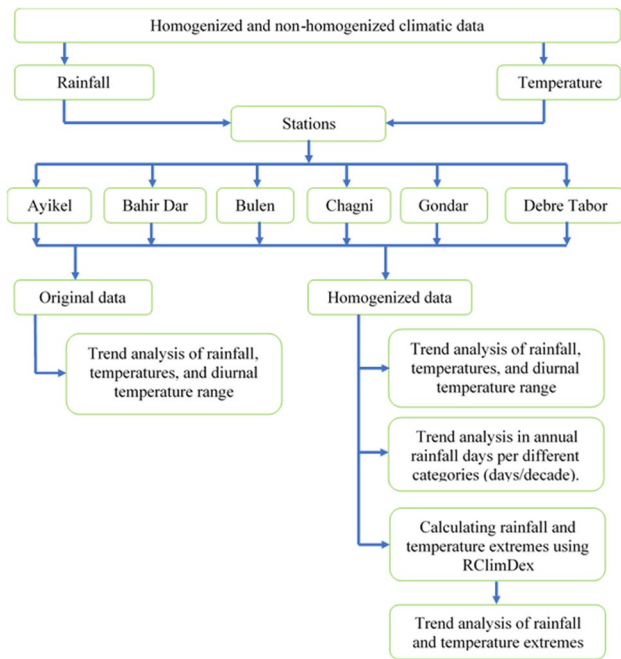
**Fig. 2** Data, stations used, and methodology employed in the current study considering original data and homogenized climate data from Woldesenbet et al. (2017b)

the reference series to be homogeneous. It uses a multiple breakpoint approach. The function of reference and target series changes step by step in the course of the procedure. MASH uses additive model for temperature and cumulative model for precipitation. Monthly homogeneity was estimated without metadata, and was transferred to daily series. New monthly series were calculated from the adjusted daily time series, and their homogeneities were checked. As MASH has an automatic algorithm for the homogenization of daily data, daily series were automatically corrected, and automatic quality control was applied for homogenized daily data (Szentimrey 2011; Woldesenbet et al. 2017b).

## 3.2 Extreme climate indices

For extreme climate indices, the data were analyzed using the RClimDex package. The software and documentation are available for download from the Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) website (http://etccdi.pacificclimate.org). As the data were already gap-filled and homogenized, RClimDex was used to calculate climate indices from the daily data. RClimDex has become a common tool for analyzing climate change indices, and has been implemented by various studies (e.g., Easterling et al. 2003; Alexander et al. 2006; New et al. 2006; Aguilar et al. 2009; Caesar et al. 2011; Sun et al. 2016; Saddique et al. 2020; van der Walt and Fitchett 2020; Zuo et al 2021). Anomalies in percentile indices were calculated relative to $1981-2010$ base

period. Since all the indices are basically anomalies from the same reference period, arithmetic averages of the indices from all the stations were calculated (Aguilar et al. 2009).

The indices considered in this study were categorized into four groups: (1) absolute indices like the hottest day and coldest night in the year or the annual daily and 5-day maximum precipitation; (2) threshold indices, which count the number of days exceeding a fixed threshold, such as tropical nights and summer days, (3) percentile-based threshold indices, which refer to the exceedance rates below 10th percentile or above 90th percentile derived from the 1981–2010 base period; and (4) duration indices, which represent the lengths of warm and cold spells based on percentile thresholds or dry and wet spell based on absolute threshold.

## 3.3 Monotonic trends

One of the commonly used trend detection approach in climate data is the original non-parametric Mann–Kendall (Mann, 1945; Kendall, 1975) trend test, which assumes no significant serial autocorrelation among the data records. The existence of long-term persistence in climate time series influences the determination of their trends. Mann–Kendall trend detection method by considering Hurst coefficient (Hamed, 2008) was attempted to check whether a significant autocorrelation at long lags exists. However, the approach is applicable when Hurst coefficient (H) is statistically significant for the existence of long-term persistence.

Numerous approaches have been applied in the literature to eliminate the influence of serial correlations on the Mann–Kendall trend test. Prior to the trend test, approaches like pre-whitening (von Storch, 1999) and trend-free pre-whitening (Yue et al. 2002) adjust the data depending on significant autocorrelation at lag 1. Others adjust the variance considered in the trend analyses, for example by using an effective sample size (Bayley and Hammersley, 1946) relating to the significant autocorrelation at any specific lag time. The current study used the Mann–Kendall trend test with the effective sample size approach, and removed all the significant autocorrelations at the 95% confidence level. The variance of the Mann–Kendall trend test was adjusted as (Yue and Wang, 2004):

$$Variance^*(S) = Variance(S)\frac{m}{n^*} \tag{1}$$

where *Variance\*(S)* is the adjusted variance, *Variance (S)* is the variance of the Mann–Kendall statistic before the adjustment, *m* is the actual sample size of the sample time series, and *n\** is the effective sample size which is computed using the following formula:

$$n^* = \frac{n}{1 + 2.\sum_{k=1}^{n-1}\left(1 - \frac{k}{n}\right).R_k} \tag{2}$$

where $R_k$ is the significant lag-$k$ serial correlation coefficient computed as follows (Yue and Wang, 2004):

$$r_k = \frac{\frac{1}{n-k} \sum_{t=1}^{n-k} \left\{ X_t - \left[ \frac{1}{n} \sum_{t=1}^{n} X_t \right] \right\} \left\{ X_{t+k} - \left[ \frac{1}{n} \sum_{t=1}^{n} X_t \right] \right\}}{\frac{1}{n} \sum_{t=1}^{n} \left\{ X_t - \left[ \frac{1}{n} \sum_{t=1}^{n} X_t \right] \right\}^2}$$

(3)

In the current study, monotonic trends in monthly, seasonal, and annual precipitation, temperature (mean, maximum, and minimum), and diurnal temperature range were assessed by applying the Yue and Wang (2004) approach, which has been extensively utilized in hydro-climatic trend analysis in different regions of the world (Tabari et al. 2015; Berhane et al 2020).

## 3.4 Trend magnitude

Once there is a trend in a data, the change per unit time (slope) can be determined by applying a non-parametric method (Sen, 1968). The Sen's slope method provides a strong estimate of the magnitude of a trend (Yue et al. 2002) and is computed as follows:

$$Q_i = \frac{x_j - x_k}{j - k} \text{ for i } = 1, \dots, N,$$

(4)

where $x_j$ and $x_k$ are the data values at times j and k (j > k), respectively. If there is only one datum in each time period; then, $N = \frac{n(n-1)}{2}$, where $n$ is the number of time periods. If there are multiple observations in one or more time periods; then, $N < \frac{n(n-1)}{2}$, where $n$ is the total number of observations. The $N$ values of $Q_i$ are ranked from smallest to largest, and the median of slope or Sen's slope estimator is computed as:

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

(5)

The $Q_{med}$ sign reflects data trend while its value indicates the steepness of the trend.

# 4 Results

## 4.1 Trends in climate elements

Since the Hurst coefficient was found to be statistically insignificant for all the climatic parameters at all the stations on annual and seasonal scales (Table S2), the modified Mann–Kendall trend analysis with Hurst coefficient (Hamed, 2008) was not considered for further discussion in the subsequent sections.

### 4.1.1 Rainfall

Trends in seasonal and annual rainfall obtained by the modified Mann–Kendall test and Sen's slope estimator are summarized in Table 2. The main rainy season rainfall showed both increasing and decreasing trends. Similarly, Belg rainfall exhibited increasing trends at two of the stations and a decreasing trend at one station. Annual precipitation increased at all the stations located in the Lake Tana sub-basin (Fig. 3) except Ayikel, which indicated a decreasing trend.

The effect of data homogenization manifested in the magnitude of the rainfall trends (*e.g.*, in the form of decreased trend magnitude of the annual rainfall at four out of six stations, and of the main rainy season rainfall at half of the stations). Data homogenization changed the trend magnitude and statistical significance simultaneously (*e.g.*, the small rainy season at Bahir Dar). Overall, because most of the original rainfall time series were already homogenous, the effect of homogenization on the trends was small.

### 4.1.2 Mean temperature (Tmean)

The seasonal and annual trends in mean temperature are shown in Table 3. Homogenization increased or decreased the trend magnitudes and the number of significant trends at most of the stations. In the main rainy season and the dry period, increasing trends manifested at all the stations.

**Table 2** Mann − Kendall trend considering effective sample size (ESS) for original and homogenized seasonal and annual total rainfall (mm/decade, Sen's slope) for stations in and around Tana and Beles sub-basins

| Time/station | Ayikel | | Bahir Dar | | Bulen | | Chagni | | Debre Tabor | | Gondar | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rainfall | O | H | O | H | O | H | O | H | O | H | O | H |
| Main rainy season (JJAS) | *−22.3* | *−22.3* | *55.4* | **31.4** | *−39.9* | *−39.9* | *27.7* | **21.2** | 5.6 | 5.6 | *43.2* | 28.8 |
| Small rainy period (MAM) | −6.3 | −6.3 | −4.1 | *−20.1* | 23.9 | 23.9 | *21.0* | *21.0* | **15.1** | 7.6 | 6.5 | 6.5 |
| Dry period (ONDJF) | *−24.6* | **−7.5** | *11.5* | 12.1 | 2.3 | 2.3 | *13.4* | *13.4* | *−21.1* | *−21.1* | 4.1 | 4.5 |
| Annual precipitation | *−49.6* | **−33.8** | *66.0* | 21.8 | −26.0 | −26.0 | *68.9* | *59.6* | −8.6 | −11.7 | *56.5* | **39.6** |

O stands for original and H stands for homogenized datasets. Significant trends ($p \leq 0.05$) are indicated in bold and highly significant trends ($p \leq 0.001$) are indicated in bold and italics

**Fig. 3** Sample time series for selected annual total and extreme rainfall parameters at Ayikel and Gondar stations
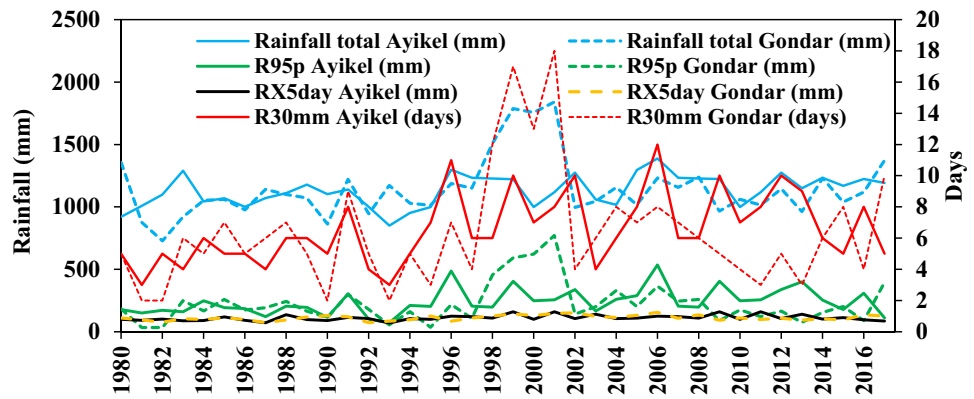


**Table 3** Mann–Kendall trend considering effective sample size (ESS) for original and homogenized seasonal and annual Tmean, Tmax, Tmin, and DTR for stations in and around Tana and Beles sub-basins (°C/decade)

| Variables | Season/stations | Ayikel | | Bahir Dar | | Bulen | | Chagni | | Debre Tabor | | Gondar | | Average | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | O | H | O | H | O | H | O | H | O | H | O | H | O | H |
| Tmean | Annual | *0.12* | *0.13* | *0.12* | *0.25* | *0.18* | *0.15* | *0.21* | *0.16* | *0.15* | *0.18* | *0.36* | *0.27* | *0.15* | *0.17* |
| | Main rainy season | *0.07* | *0.14* | *0.15* | *0.27* | *0.22* | *0.19* | *0.25* | *0.15* | *0.24* | *0.20* | *0.38* | *0.33* | *0.22* | *0.22* |
| | Small rainy period | *0.42* | *0.13* | 0.06 | *0.32* | **0.12** | 0.05 | *0.75* | 0.15 | 0.06 | *0.22* | *0.33* | *0.28* | *0.29* | *0.19* |
| | Dry period | − 0.06 | *0.10* | **0.11** | *0.20* | *0.23* | *0.22* | −0.14 | *0.17* | *0.10* | *0.19* | *0.40* | *0.25* | *0.17* | *0.18* |
| Tmax | Annual | *0.11* | *0.17* | *0.46* | *0.47* | *0.14* | *0.19* | *0.27* | *0.33* | *0.50* | *0.36* | *0.41* | *0.38* | *0.28* | *0.31* |
| | Main rainy season | *0.15* | *0.31* | *0.36* | *0.48* | *0.20* | *0.23* | *0.25* | *0.29* | *0.34* | *0.27* | *0.35* | *0.43* | *0.29* | *0.33* |
| | Small rainy period | *0.13* | *0.25* | *0.42* | *0.44* | 0.05 | 0.00 | 0.15 | **0.19** | *0.46* | *0.32* | *0.28* | *0.28* | *0.33* | *0.25* |
| | Dry period | *0.10* | **0.07** | *0.50* | *0.50* | *0.22* | *0.26* | *0.17* | *0.41* | *0.56* | *0.48* | *0.25* | *0.43* | *0.27* | *0.36* |
| Tmin | Annual | *0.10* | **0.06** | − 0.02 | 0.00 | *0.21* | **0.10** | *0.18* | 0.00 | *−0.17* | 0.00 | *0.29* | *0.14* | **0.04** | **0.03** |
| | Main rainy season | 0.00 | 0.00 | − 0.08 | 0.03 | *0.18* | **0.09** | *0.23* | 0.00 | *0.11* | *0.11* | *0.31* | *0.14* | **0.14** | **0.08** |
| | Small rainy period | *0.13* | 0.00 | − 0.32 | *0.16* | *0.29* | 0.08 | *1.00* | 0.27 | *−0.24* | *0.19* | *0.30* | *0.25* | *0.27* | *0.12* |
| | Dry period | *0.09* | **0.09** | −0.18 | −0.07 | *0.26* | *0.18* | −0.48 | −0.06 | *−0.39* | −0.18 | *0.28* | 0.08 | **0.04** | 0.00 |
| DTR | Annual | 0.00 | *0.10* | *0.67* | *0.50* | −0.06 | **0.06** | 0.06 | *0.29* | *0.71* | *0.38* | 0.08 | *0.24* | *0.22* | *0.25* |
| | Main rainy season | *0.10* | *0.25* | *0.48* | *0.43* | −0.06 | **0.11** | 0.00 | *0.19* | *0.24* | *0.14* | 0.00 | *0.25* | *0.13* | *0.23* |
| | Small rainy period | *0.41* | *0.15* | *0.80* | *0.33* | −0.31 | −0.07 | *−1.15* | 0.04 | *0.78* | *0.13* | *0.14* | *0.14* | *0.09* | *0.11* |
| | Dry period | *−0.33* | 0.00 | *0.67* | *0.55* | −0.04 | **0.07** | *0.81* | *0.47* | *1.00* | *0.67* | *0.15* | *0.33* | *0.21* | *0.33* |

O stands for original and H stands for homogenized datasetsSignificant trends (*p* ≤ 0.05) are indicated in bold and highly significant trends (*p* ≤ 0.001) are indicated in bold and italics

Similar to the main rainy season, Tmean in the small rainy season revealed an increasing trend at most of the stations. The annual Tmean revealed an increasing trend (Fig. 4). The trend in Tmean indicated a clear warming in the study region over the period 1980–2017. Tmean trends showed increasing trend after homogenization (Table 3).

### 4.1.3 Maximum temperature (Tmax)

The results of applying statistical tests for the seasonal and annual Tmax over the period 1980–2017 are presented in Table 3. As shown, Tmax revealed increasing trends on the annual and seasonal scales at almost all of the stations. It is clearly noted that no decreasing trend was detected on seasonal and annual Tmax series. The effect of data homogenization on the trend magnitude and significance was not uniform among the stations and seasons for daytime temperature (Table 3). Trend magnitudes for annual Tmax were higher for homogenized series than that of the original series at most of the stations. In the dry period and the main rainy season, only the trend magnitude changed but the numbers of significant trends due to homogenization remained unchanged. Both the number of significant trends and the trend magnitude changed for the small rainy season.

**Fig. 4** Time series of mean annual maximum temperature (Tmax), minimum temperature (Tmin), mean temperature (Tmean), and diurnal temperature range (DTR)
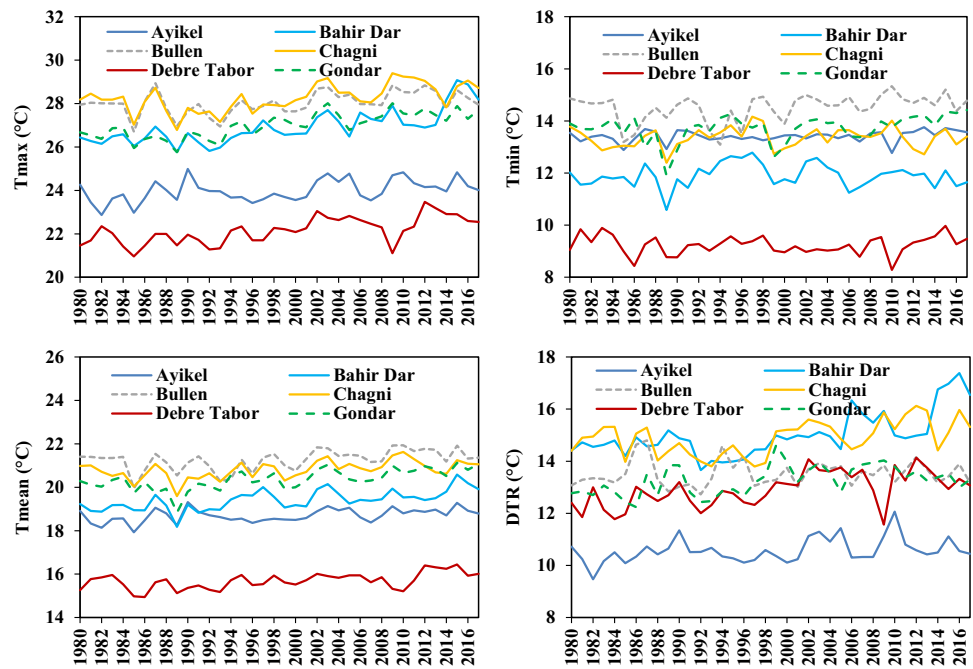


### 4.1.4 Minimum temperature (Tmin)

Table 3 summarizes the trends in seasonal and annual minimum temperatures. During the dry period, both increasing and declining trends were manifested. The majority of the stations indicated increasing trends during the main and small rainy seasons. In general, the annual and seasonal minimum temperatures demonstrated increasing trends at most of the stations. Homogenization affected the Tmin in the trend magnitude, the direction of trends, and the number of significant trends between the homogenized and the original time series (Table 3). The number of significant trends following homogenization reduced drastically on the annual and seasonal scales together from 25 to 15.

### 4.1.5 Diurnal temperature range (DTR)

On the seasonal and annual scales, most of the stations portrayed increasing trends in DTR (Table 3). These trends partly indicated that the rate of increase in the minimum temperature was less than that in the maximum temperature in the study region. No significant decreasing trend in DTR was observed on the annual and seasonal time scales. The number of significant trends for both the seasonal and annual DTR increased due to homogenization (Table 3). In general, the declining trends of DTR before homogenization converted into positive or weak trends after homogenization.

### 4.2 Trends in climate extremes

The trends in all climate extreme indices are summarized for all the stations in Table 4, showing stations with magnitude of trends that are significant at ≤ 5% level.

### 4.2.1 Cold extremes

Three to five stations showed decreasing trends in all the indices of cold extremes, except the cold spell duration indicator (CSDI) trend, which was statistically insignificant at all the stations (Table 4). The percentage of days when maximum temperature is less than the 10th percentile (TX10p) for the period 1981−2010 indicated that the number of cold days has declined, with about 83% of the stations having statistically significant trends. Significant trends in TX10p ranged from − 3.50 to 0.76% per decade at Bahir Dar and Chagni, respectively. These percentages correspond to trends of − 12.8 days/decade to − 2.8 days/decade, respectively. Similarly, the minimum of the minimum temperature (TNn) decreased at the stations of Bulen, Debre Tabor, and Gondar at rates of 0.20, 0.75, and 0.29 °C/decade, respectively.

### 4.2.2 Hot extremes

One to four stations showed increasing trend in hot extremes except in TR20 and TNx (Table 4). TNx showed both increasing and decreasing trends. In particular, TX90p indicated an increase in the number of warm days, with all the stations having statistically significant trends. The

**Table 4** Trends in the temperature and precipitation indices recommended by the ETCCDI. Percentile values used as a thresholds for some of the indices were calculated for the base period 1981−2010

| Indices definition | Ayikel | Bahir Dar | Bulen | Chagni | Debre Tabor | Gondar | Unit |
|---|---|---|---|---|---|---|---|
| Summer days (SU25) | 0.00 | *23.06* | *3.75* | *5.00* | *14.74* | *8.33* | days/decade |
| Tropical nights (TR20) | 0.00 | 0.00 | 0.00 | − 1.67 | 0.00 | 0.00 | days/decade |
| Max Tmax (TXx) | − 0.11 | *0.60* | 0.00 | 0.00 | **0.29** | *0.69* | °C/decade |
| Min Tmax (TXn) | **0.06** | *0.19* | − 0.12 | 0.11 | − 0.08 | **0.18** | °C/decade |
| Max Tmin (TNx) | − 0.05 | − 0.06 | *− 0.21* | *− 0.95* | 0.47 | *0.15* | °C/decade |
| Min Tmin (TNn) | 0.00 | − 0.38 | **− 0.20** | 0.00 | *− 0.75* | **− 0.29** | °C/decade |
| Cool days (TX10p) | 0.31 | *− 3.50* | *− 1.14* | *− 0.76* | *− 3.28* | *− 2.43* | %/decade |
| Warm days (TX90p) | **0.56** | 5.44 | *1.16* | *2.22* | *5.50* | *4.88* | %/decade |
| Cool nights (TN10p) | *0.42* | 0.77 | − 0.42 | 0.10 | **0.92** | *− 0.75* | %/decade |
| Warm nights (TN90p) | − 0.40 | *0.83* | *1.59* | − 0.15 | *2.19* | *1.64* | %/decade |
| Warm spell duration indicator (WSDI) | 0.00 | 0.00 | 0.00 | 0.00 | *0.59* | *2.69* | days/decade |
| Cold spell duration indicator (CSDI) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | days/decade |
| Diurnal temperature range (DTR) | 0.00 | *0.45* | 0.00 | *0.13* | *0.37* | *0.24* | °C/decade |
| Max 1-day precipitation amount (RX1day) | 1.17 | − 1.22 | 0.73 | *− 2.28* | 2.00 | **2.59** | mm/decade |
| Max 5-day precipitation amount (RX5day) | *5.55* | − 1.00 | 0.22 | − 0.89 | 2.81 | **6.30** | mm/decade |
| Simple daily intensity index (SDII) | *0.43* | 0.07 | *− 0.31* | *− 0.40* | − 0.20 | **0.25** | mm/day/decade |
| Number of heavy precipitation days (R10mm) | *1.15* | **1.36** | − 0.63 | 0.00 | **− 1.25** | *2.00* | days/decade |
| Number of very heavy precipitation days (R20mm) | *0.97* | **0.83** | 0.00 | 0.53 | 0.00 | **0.71** | days/decade |
| Number of days above 30 mm (R30mm) | *0.91* | 0.00 | 0.00 | 0.00 | **− 0.54** | 0.36 | days/decade |
| Consecutive dry days (CDD) | *− 6.84* | *11.94* | 0.00 | 2.00 | 2.27 | − 3.75 | days/decade |
| Consecutive wet days (CWD) | 0.00 | 0.48 | *− 0.34* | *1.61* | − 0.86 | 0.00 | days/decade |
| Very wet days (R95p) | *33.48* | − 3.00 | − 1.69 | − 8.79 | − 20.61 | 7.87 | mm/decade |
| Extremely wet days (R99p) | *12.46* | 0.00 | 0.00 | − 1.86 | 0.00 | 0.00 | mm/decade |
| Annual total wet-day precipitation (PRCPTOT) | *49.38* | **42.36** | 3.00 | *32.55* | − 4.68 | **44.50** | mm/decade |
| Extreme temperature range (ETR) | 0.00 | *0.89* | **0.29** | 0.13 | *0.89* | *0.94* | °C/decade |

Significant trends ($p \leq 0.05$, Mann–Kendall test) are indicated in bold. Highly significant trends ($p \leq 0.001$, Mann–Kendall test) are indicated in bold and italics.

significant trends in TX90p ranged from 0.56 to 5.50% per decade. These percentages correspond to trends of 2.0 to 20.1 days/decade, respectively. The number of warm nights increased at four stations. In the case of TX90p and TN90p, approximately five stations had greater magnitude in TX90p trends. The number of stations with significant trend in TNx was higher than that in TXx. Five out of six stations showed increasing trend in SU25 ranging from 3.75 to 23.06 days/decade. Warm spell duration indicator (WSDI) increased at two out of six stations.

### 4.2.3 Comparison of hot and cold extremes

It is practical to contrast trends in hot and cold indices, as this helps to understand the relative changes in the extremities of the daily temperature distributions. During the study period, the number of stations with increasing trends in TX90p was six while that with decreasing trends in TX10p was five (Fig. 5). But the trend magnitude was higher for TX90p than for TX10p (Table 4).

As for TXx, the trend magnitude ranged from 0.29 to 0.69 °C/decade while TXn showed a range of trend magnitude of 0.06 to 0.19 °C/decade. In general, the trends in the hot tails of the maximum temperature distribution were of higher magnitude compared to their cold counterparts. There was an increase in the absolute annual maximum of both daily maximum and minimum temperatures in common with the global picture.

The trends in warm extremes, such as TX90p, TN90p, and WSDI, showed greater magnitudes than those for cold extremes like TX10p, TN10p, and CSDI. With increasing occurrences of warm extremes and decreasing number of cold extremes, the temperature series clearly indicated warming in the study region. Across the entire region, the frequency of warm days increased whereas that of cold days decreased.

Not only the number of stations with significant trends was greater for WSDI during the study period, but also the trend magnitudes were higher than that of CSDI (Table 4).

**Fig. 5** Number of stations with significant trends in daily extreme temperature
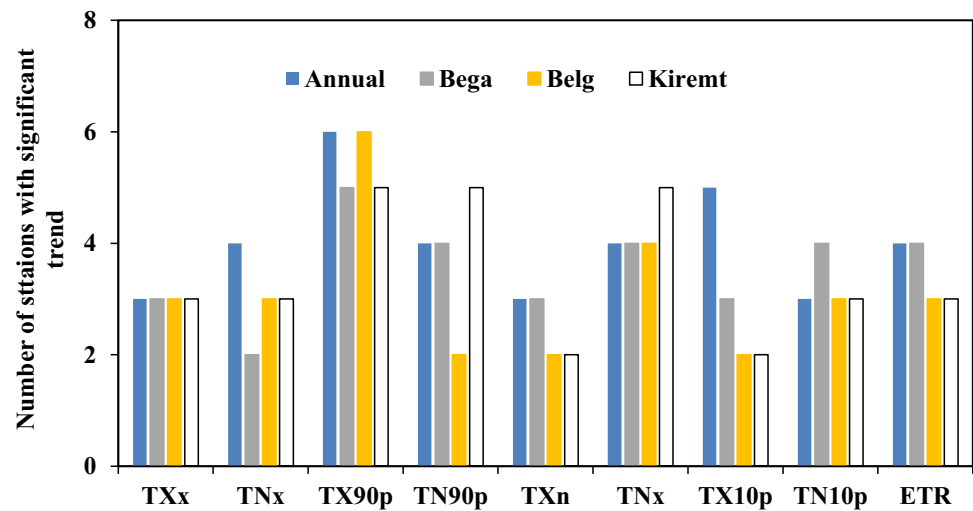


### 4.2.4 Precipitation extremes

The significance of trends in precipitation extremes during the period $1980-2017$ was much lower compared to that of temperature extremes (Table 4). Most precipitation indices exhibited both increasing and decreasing trends though the increasing trend was slightly dominant. However, only few trends were statistically significant for any index. More than half of the extreme precipitation indices at Ayikel and Gondar showed increasing trends.

Increase of extremely wet days (R99p) and very wet days (R95p) manifested only at Ayikel station. As the study region has high spatio-temporal variability of rainfall, the discrepancy might have arisen due to the scale of spatial extent used to calculate the regional average and the period of trends.

The majority of the stations showed increasing trends (4 statistically significant) in the annual total wet-day precipitation (PRCPTOT). Likely associated with increase in total precipitation, the length of the maximum number of consecutive dry days decreased in the source region of the Blue Nile. The simple daily intensity index, which measures the average amount of rainfall per day, showed mixed trends. The trends in the contribution of monthly and seasonal rainfall to the annual total rainfall varied among the stations. In general, the contribution of the main rainy season rainfall to the annual total rainfall increased but that of the small rainy season decreased.

## 5 Discussion

This section discusses and places the results in the context of existing literature regionally and worldwide.

### 5.1 Rainfall trends

In general, the main rainy season and annual precipitation got wetter for most of the stations while the small rainy season got relatively drier in the study region during the period $1980-2017$. This result is in agreement with results obtained by Maidment et al. (2015), who noted decreases in March–May East African rainfall using multiple observational data sets for $1983-2014$. However, Meze-Hausken (2004) indicated the absence of decreasing trends in rainfall in the northern and northeastern highlands. Cheung et al. (2008), Gebremichael et al. (2013), Gummadi et al. (2017), Mengistu et al. (2014), Seleshi and Zanke (2004), and Viste et al. (2013) also reported the absence of significant trends in rainfall in different parts of the upper Blue Nile, thus contradicting the outcome of the current study. The main reason for this discrepancy might be the differences in the length of the data record, data homogenization, and/or differences in trend detection approaches (Table S1). Our result also disagrees with results presented by Tabari et al. (2015) due to differences in the length of records and homogenization. The increase in rainfall during the main rainy season observed in the current study might lead to excess soil moisture and ultimately result in flooding, soil erosion, and/or siltation of water structures.

### 5.2 Temperatures trends

In the study area, warming of air indicated by increasing mean annual temperature in the main rainy season was significantly higher than that of the small rainy season. Hulme et al. (2001) and Collins (2011) also noted that significantly larger warming was observed for June, July, and August in Africa and across Central Africa, respectively. Elagib and Mansell (2000) also indicated higher and more significant trends in the wet-season series than in the hot and dry seasons at Sudanese stations located south of latitude 16°N during the period extending from the 1940s to 1996. The rise in mean temperature might increase the

potential evapotranspiration, speed the rate of growth of plants, and shift agroecology zones (Hatfield and Prueger 2015). It might also increase water evaporation from natural and man-made surface reservoirs.

In general, the day temperature rose in the upper Blue Nile at a higher rate in the main rainy season than in the small rainy season. During the dry period, the day temperature rose at the highest rate. Christy et al. (2009), Collins et al. (2011), Shawul and Chakma (2020), and Worku et al. (2019) also reported warming trends in maximum temperature in the eastern part of Africa, the whole Africa, Beressa, and Upper Awash River basins in Ethiopia, respectively.

As a whole, the nighttime temperatures revealed dominantly increasing trends in the current study area. In line with these results, Conway et al. (2004) reported increasing trends in minimum temperature at Addis Ababa although they cautioned about the results due to data inhomogeneity. Mengistu et al. (2014) also indicated a significant increasing trend in minimum temperature in northern, central, southern, and southeastern parts of the basin in all seasons. Tekleab et al. (2013) also reported increasing trends in minimum temperatures at the majority of the stations they considered. In their study, station-specific trends in minimum temperature were not reported. As a result, it is not possible to compare their results with ours. Trends in minimum temperature are mainly heterogeneous, partly due to their significant relationship with the altitude of the station location (Woldesenbet et al. 2017a). The higher warming rate in minimum temperature compared to that of maximum temperature (Tekleab et al. 2013; Mengistu et al. 2014) is not noticeable in this study. The increase of daytime temperature at a rate greater than that of the nighttime temperature is in accord with findings by Elagib (2010), Sulieman and Elagib, (2012), Meehl et al. (2009), and Trewin and Vermont (2010), who indicated that Tmax is warming at a higher rate than that revealed by Tmin in Sudan, El-Gedaref in the eastern Sudan, the USA, and Australia, respectively. In eastern Africa, including Ethiopia, King'uyu et al. (2000) also studied data from 71 weather stations from 1939 to 1992 and concluded that the nighttime air was warming, but the trend was not spatially constant over the given study area.

The magnitude of trends in DTR during the main rainy season was higher than that of the small rainy season at all the stations under consideration. These trends can be explained by the higher rate of warming during the daytime over that observed during the nighttime. Elagib and Abdu (2010) indicated that increasing cloud amount and rainfall and declining sunshine played a significant role in the changes in DTR in the Kingdom of Bahrain. Besides, they speculated that the diminished levels of atmospheric moisture increased the DTR. Wang et al. (2014) also identified a negative correlation between DTR and the precipitation value in north east China. The diurnal temperature range, which is decreasing globally (*e.g.*, Karl et al. 1993), is slightly increasing in the current study region. Aguliar et al. (2009) also reported similar results for Zimbabwe and Guinea. The somewhat universal consensus that DTR is declining partly due to a higher rate of increase in minimum temperature than in maximum temperature is unnoticeable in this study. Although literature for cities around the study region showed that most of the minimum temperature records might be affected by urban heat islands (Elagib 2011; Teferi and Abraha 2017), the extent of urbanization in the current study region is minimal.

## 5.3 Trends in extreme temperature and precipitation indices

Statistically significant trends in cold extremes are decreasing, meaning that cold nights and cold days are decreasing in the study region. This result is consistent with global and regional trends (Alexander et al. 2006; New et al. 2006; Aguilar et al. 2009; Funk et al. 2015; Asfaw et al. 2018; Gebrechorkos et al. 2018). The magnitudes of trends at distinct stations are normally higher for TX10p than TN10p and for TNn than TXn. Warm spells (WSDI) increased consistently across the stations. These results are partly in agreement with that found by Brown et al. (2008), who indicated that extreme daily temperatures have increased for most regions of the globe since 1950. Berhane et al. (2020) also indicated significant increasing trends in temperature extremes for stations in western Tigray, Ethiopia.

The trends in the hot tails of the maximum temperature distribution are on average of higher magnitude that those observed in their cold counterparts. This result is in agreement with that obtained using EURO-CORDEX by Rey et al. (2020), who indicated that the warm ends of the daily temperature distribution are varying more rapidly than the cold tails. There is an increase in the absolute annual maximum of both daily maximum and minimum temperatures, again in common with the global picture.

The significant trends in warm extremes, such as TX90p, TN90p, and WSDI, showed greater magnitudes than those in cold extremes like TX10p, TN10p, and CSDI. This finding is in accord with global results (*e.g.*, Alexander et al. 2006; Donat et al. 2013), indicating that warming since 1980s is somewhat shaped by the rise of warm extremes than by the decline of cold extremes. With increasing occurrence of warm extremes and decreasing frequencies of cold extremes, the temperature series clearly indicated significant warming in the upper Blue Nile. Over the entire region, the frequency of warm days seems to be increasing whereas the frequency of cold days appears to be decreasing. These trends agree with trends observed across different parts of the world (Caesar et al. 2011). Periods of extreme temperature values might be hazardous to crop development and growth (Das et al. 2003).

The warmest day and night of the year is warming at a rate approximately comparable to the global average. The coldest day and night of the year are cooling slower than the global average rate although the planetary trend in the coldest day is insignificant. Hulme et al. (2001) stated that during the twentieth century, temperature in Africa increased at a rate of 0.5 °C century$^{-1}$ from 1987 to 1998. They also indicated that the June − August and September − November seasons showed moderately warmer conditions than in December − February and March − May. Kruger and Shongwe (2004) found for Africa that the days and nights with high temperatures have risen while those with low temperatures have declined.

Most precipitation indices for the study area exhibited both increasing and decreasing trends though the increasing trend is slightly dominant. However, only few trends are statistically significant for any index. The study region has high intra- and inter-annual variability of rainfall (Seleshi and Zanke, 2004), thus making the trends problematic to identify. The majority of the stations showed increasing trends in annual total wet day precipitation (PRCPTOT). This observation goes parallel to the global results (Alexander et al. 2006; New et al. 2006), indicating consistent trends towards wetter conditions. Assessments of rainfall extreme events are useful for understanding the influences of climate extremes on soil erosion and sedimentation in the source region of the upper Blue Nile basin. Soil erosion and sedimentation in the Blue Nile river has increased (Gebremicael et al. 2013), which is likely partly associated with the increasing trends of daily rainfall intensity and amount.

Variability in rainfall during the main rainy season in the study region is regulated by large-scale climate forcings and changes in sea surface temperatures, such as El Niño–Southern Oscillation (ENSO) and Indian Ocean Dipole (Degefu et al. 2016; Gebrechorkos et al. 2019; Mpelasoka et al. 2018). The equatorial central Pacific, the tropical and South Atlantic, and the South West Indian Ocean influence the main rainy season rainfall anomaly, with the equatorial Pacific sea surface temperatures (SSTs) variability playing the greatest role (Diro et al. 2011; Gleixner et al. 2016; Omondi et al. 2013).

Changes in the frequency of climate extreme indices can often have a greater unfavorable impact on rain-fed agriculture and agroecology than a change in mean climate condition. The current study also gives useful information for climate risk management in water, energy, and food security nexus from the viewpoint of climate change.

# 6 Conclusions

The trend analysis was carried out for homogenized precipitation and temperature time series within or near the Tana and Beles sub-basins over the period 1980–2017. In general, the results indicated significant warming apparent by increasing trends in maximum temperature, mixed significant trends in minimum (or night) temperature, and significant increasing trends in annual and main rainy-season precipitation.

The rate of change in Tmin for most of the stations considered herein was lower than that for Tmax. On one hand, the warming trend indicated by temperature could increase crop water demand and water evaporation from reservoirs in the sub-basins. On the other hand, the increase in rainfall may raise effective rainfall amounts to compensate for crop water demand. It may also increase the input to reservoirs as direct rainfall. Therefore, the effect of higher temperature level and rainfall volume on net crop water demand and net reservoir losses might offset each other in the study region.

The study provides evidence that during the last 38 years, the source region of the Blue Nile was particularly affected by warming indicated by daytime extremes rather than cooling manifested by nighttime extremes. As the trend direction and magnitude depend on the length of the records, the trend values in the current study might change when considering longer-term climate data. It should be noted, however, that the trends detected in the present study must be considered an investigative evaluation due to the short period (38 years) covered in the analysis.

Attention must be paid to data homogenization prior to trend detection and climatic related studies. It is recommended that the previous climate-related studies, which overlooked this pivotal issue in the analysis, should be revisited. Furthermore, a robust approach to removing significant serial correlation in climatic data should be emphasized before a trend detection is carried out. The outcomes of the current study offer crucial information on the recent trends of mean and extreme rainfall and temperature in the headwater region of the upper Blue Nile basin, where many water resource developments projects have been undertaken by the Government of Ethiopia for food and energy security. The study also gives useful information to consider while managing the water, energy, and food security nexus of the region in the context of climate change.

**Data availability** Not applicable.

**Code availability** Not applicable.

## Declarations

**Ethics approval** For this type of study, formal consent is not required.

**Consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.

## References

Aguilar AE, Barry AA, Brunet M, Ekang L, Fernandes A, Massoukina M, Mbah J, Mhanda A, do Nascimento DJ, Peterson TC, ThambaUmba O, Tomou M, Zhang X (2009) Changes in temperature and precipitation extremes in western central Africa, Guinea Conakry, and Zimbabwe, 1955–2006. J Geophys Res 114:DO2115. https://doi.org/10.1029/2008JD011010

Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Klein Tank AMG, Haylock M, Collins D, Trewin B, Rahimzadeh F, Tagipour A, Rupa Kumar K, Revadekar J, Griffiths G, Vincent L, Stephenson DB, Burn J, Aguilar E, Brunet M, Taylor M, New M, Zhai P, Rusticucci M, Vazquez-Aguirre JL (2006) Global observed changes in daily climate extremes of temperature and precipitation. J Geophys Res 111:D05109

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

Bayley GV, Hammersley JM (1946) The "effective" number of independent observations in an autocorrelated time series. J R Stat Soc B8:184–197

Berhane A, Hadgu G, Worku W, Abrha B (2020) Trends in extreme temperature and rainfall indices in the semi-arid areas of Western Tigray. Ethiopia Environ Systems Res 9(1):1–20

Brown SJ, Caesar J, Ferro CAT (2008) Global changes in extreme daily temperature since 1950. J Geophys Res 113:D05115. https://doi.org/10.1029/2006JD008091

Caesar J, Alexander LV, Trewin B, Tsering K, Sorany L, Vuniyayawa V, Keosavang N, Shimana A, Htay MM, Karmacharya J, Jayasinghearachchi DA, Sakkamart J, Soares E, Hung LT, Thuong LT, Hue CT, Dung NTT, Hung PV, Cuong HD, Cuong NM, Sirabaha S (2011) Changes in temperature and precipitation extremes over the Indo-Pacific region from 1971–2005. Int J Climatol 31:791–801

Cheung WH, Senay GB, Singh A (2008) Trends and spatial distribution of annual and seasonal rainfall in Ethiopia. Int J Climatol 28:1723–1734

Christy JR, Norris WB, McNider RT (2009) Surface temperature variations in east Africa and possible causes. J Climate 22:3342–3356

Collins JM (2011) Temperature Variability over Africa. J Climate 24:3649–3666. https://doi.org/10.1175/2011JCLI3753.1

Conway D, Mould C, Bewket W (2004) Over one century of rainfall and temperature in Addis Ababa, Ethiopia. Int J Climatol 24:77–91. https://doi.org/10.1002/joc.989

Das HP, Adamenko TI, Anaman KA, Gommes RG, Johnson G (2003). Agrometeorology related to extreme events. World Meteorological Organization, Technical Note No. 201.

Degefu MA, Bewket W (2014) Variability and trends in rainfall amount and extreme event indices in the Omo-Ghibe River Basin, Ethiopia. Reg Environ Change 14:799–810. https://doi.org/10.1007/s10113-013-0538-z

Degefu MA, Rowell DP, Bewket W (2016) Teleconnections between Ethiopian rainfall variability and global SSTs: observations and methods for model evaluation. Meteorol Atmos Phys 129(2):173–186. https://doi.org/10.1007/s00703-016-0466-9

Diro GT, Grimes DIF, Black E (2011) Teleconnections between Ethiopian summer rainfall and sea surface temperature: part I-observation and modelling. Clim Dyn 37(1):103–119. https://doi.org/10.1007/s00382-010-0837-8

Donat MG, Alexander LV, Yang H, Durre I, Vose R, Caesar J (2013) Global land-based datasets for monitoring climatic extremes. Bull Am Meteorol Soc 96:997–1006. https://doi.org/10.1175/BAMS-D-12-00109.1

Easterling DR, Alexander L, Mokssit A, Detemmerman V (2003) CCl/CLIVAR workshop to develop priority climate indices. Bull Amer Meteor Soc 84:1403–1407

Elagib NA (2010) Trends in intra- and inter-annual temperature variabilities across Sudan. Ambio 39:413–429. https://doi.org/10.1007/s13280-010-0042-3

Elagib NA (2011) Evolution of urban heat island in Khartoum. Int J Climatol 31(9):1377–1388. https://doi.org/10.1002/joc.2159

Elagib NA, Abdu ASA (2010) Development of temperatures in the Kingdom of Bahrain from 1947 to 2005. Theor Appl Climatol 101:269–279. https://doi.org/10.1007/s00704-009-0205-y

Elagib NA, Mansell MG (2000) Recent trends and anomalies in mean seasonal and annual temperatures over Sudan. J Arid Environ 45(3):263–288

Elagib NA, Saad SAG, Basheer M, Rahma AE, Gore EDL (2021) Exploring the urban water-energy-food nexus under environmental hazards within the Nile. Stoch Environ Res Risk Assess 35:21–41

Funk C, Nicholson SE, Landsfeld M, Klotter D, Peterson P, Harrison L (2015) The Centennial Trends Greater Horn of Africa precipitation dataset. Scientific Data 2:150050. https://doi.org/10.1038/sdata.2015.50

Gebrechorkos SH, Hülsmann S, Bernhofer C (2019). Long-term trends in rainfall and temperature using high-resolution climate datasets in East Africa. *Scientific Reports*, 9(1). doi:https://doi.org/10.1038/s41598-019-47933-8

Gebrechorkos SH, Hülsmann S, Bernhofer C (2018) Changes in temperature and precipitation extremes in Ethiopia, Kenya, and Tanzania. Int J Climatol 39(1):18–30. https://doi.org/10.1002/joc.5777

Gebremicael TG, Mohamed YA, Betrie GD, van der Zaag P, Teferi E (2013) Trend analysis of runoff and sediment fluxes in the Upper Blue Nile basin: a combined analysis of statistical tests, physically-based models and landuse maps. J Hydrol 482:57–68

Gleixner S, Keenlyside N, Viste E, Korecha D (2016) The El Niño effect on Ethiopian summer rainfall. Clim Dyn 49(5–6):1865–1883. https://doi.org/10.1007/s00382-016-3421-z

Gummadi S, Rao KPC, Seid J, Legesse G, Kadiyala MDM, Takele R, Amede T, Anthony Whitbread A (2017) Spatio-temporal variability and trends of precipitation and extreme rainfall events in Ethiopia in 1980–2010. Theor Appl Climatol 134:1315–1328. https://doi.org/10.1007/s00704-017-2340-1

Hamed KH (2008) Trend detection in hydrologic data: the Mann-Kendall trend test under the scaling hypothesis. J Hydrol 349(3–4):350–363

Hatfield JL, Prueger JH (2015) Temperature extremes: effect on plant growth and development. Weather Clim Extremes 10:4–10

Hegerl GC, Brönnimann S, Cowan T, Friedman AR, Hawkins E, Iles C, Müller W, Schurer A, Undorf S (2019) Causes of climate

change over the historical record. Environ Res Lett 14:123006. https://doi.org/10.1088/1748-9326/ab4557

Hulme M, Doherty R, Ngara T, New M, Lister D (2001) African climate change: 1900–2100. Climate Res 17:145–168

IPCC (2012). Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. http://ipcc-wg2.gov/SREX/report/full-report/.

Jaweso D, Abate B, Bauwe A, Lennartz B (2019) Hydro-meteorological trends in the upper Omo-Ghibe river basin. Ethiopia Water 11(9):1951

Karl TR, Knight RW, Gallo KP, Peterson TC (1993) A new perspective on recent global warming: asymmetric trends of daily maximum and minimum temperature. Bull Amer Meteor Soc 74(6):1007–1023

Katz RW, Brown BG (1992) Extreme events in a changing climate: variability is more important than averages. Clim Change 21(3):289–302

Kendall MG (1975) Rank Correlation Methods. Charles Griffin, London

King'uyu SM, Ogallo LA, Anyamba EK, (2000) Recent trends on minimum and maximum surface temperatures over eastern Africa. J Climate 13:2876–2886

Kruger AC, Shongwe S (2004) Temperature trends in South Africa: 1960–2003. Int J Climatol 24:1929–1945. https://doi.org/10.1002/joc.1096

Kruger AC, Sekele SS (2013) Trends in extreme temperature indices in South Africa: 1962–2009. Int J Climatol 33(3):661–676

Lionello P, Scarascia L (2020) The relation of climate extremes with global warming in the Mediterranean region and its north versus south contrast. Reg Environ Change 20:31. https://doi.org/10.1007/s10113-020-01610-z

Maidment RI, Allan RP, Black E (2015) Recent observed and simulated changes in precipitation over Africa. Geophys Res Lett 42:8155–8164. https://doi.org/10.1002/2015GL065765

Manikandan N, Das DK, Mukherjee J, Sehgal VK, Krishnan P (2018) Extreme temperature and rainfall events in National Capital Region of India (New Delhi) in the recent decades and its possible impacts. Theor Appl Climatol. https://doi.org/10.1007/s00704-018-2652-9

Mann HB (1945) Nonparametric tests against trend. Econometrica 13:245–259

Meehl GA, Tebaldi C, Walton G, Easterling D, McDaniel L (2009) Relative increase of record high maximum temperatures compared with record low minimum temperatures in the U.S. Geophys Res Lett 36:L23701. https://doi.org/10.1029/2009GL040736

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

Meshram SG, Kahya E, Meshram C, Ghorbani MA, Ambade B, Mirabbasi R (2020) Long-term temperature trend analysis associated with agriculture crops. Theor Appl Climatol 140:1139–1159. https://doi.org/10.1007/s00704-020-03137-z

Mpelasoka F, Awange JL, Zerihun A (2018) Influence of coupled ocean-atmosphere phenomena on the Greater Horn of Africa droughts and their implications. Sci Total Environ 610–611:691–702

Nashwan MS, Shahid S (2019) Spatial distribution of unidirectional trends in climate and weather extremes in Nile river basin. Theor Appl Climatol 137:1181–1199. https://doi.org/10.1007/s00704-018-2664-5

New M, Hewitson B, Stephenson DA, Tsiga A, Kruger A, Manhique A, Gomez B, Coelho CAS, Masisi DN, Kululanga E, Mbambalala E, Adesina F, Saleh H, Kanyanga J, Adosi J, Bulane L, Fortunata L, Mdoka ML, Lajoie R (2006) Evidence of trends in daily climate extremes over Southern and West Africa. J Geophys Res 111:D14102. https://doi.org/10.1029/2005JD006289

NMA (National Meteorological Agency) (1996) Climatic and agro-climatic resources of Ethiopia. NMSA Meteorological Research Report Series. V1, No. 1, Addis Ababa, 137p

Omondi P, Ogallo LA, Anyah RO, Muthama JM, Ininda J (2013) Linkages between global sea surface temperatures and decadal rainfall variability over Eastern Africa region. Int J Climatol 33(8):2082–2104. https://doi.org/10.1002/joc.3578

Perera ATD, Nik VM, Chen D, Scartezzini J-L, Hong T (2020) Quantifying the impacts of climate change and extreme climate events on energy systems. Nat Energy 5:150–159. https://doi.org/10.1038/s41560-020-0558-0

Rai P, Choudhary A, Dimri AP (2019) Future precipitation extremes over India from the CORDEX-South Asia experiments. Theor Appl Climatol. https://doi.org/10.1007/s00704-019-02784-1

Rey J, Rohat G, Perroud M, Goyette S, Kasparian J (2020). Shifting velocity of temperature extremes under climate change. *Environ. Res. Lett.* 15(3) 034027.

Saddique N, Khaliq A, Bernhofer C (2020) Trends in temperature and precipitation extremes in historical (1961–1990) and projected (2061–2090) periods in a data scarce mountain basin, northern Pakistan. Stoch Environ Res Risk Assess 34:1441–1455

Seleshi Y, Zanke U (2004) Recent changes in rainfall and rainy days in Ethiopia. Int J Climatol 24:973–983

Sen PK (1968) Estimates of the regression coefficient based on Kendall's tau. J Amer Statist Assoc 63:1379–1389

Shang H, Yan J, Gebremichael M, Ayalew SM (2010) Trend analysis of extreme precipitation in the northwestern Highlands of Ethiopia with a case study of Debre Markos. Hydrol Earth Syst Sci 7:8587–8605. https://doi.org/10.5194/hess-15-1937-2011

Shawul AA, Chakma S (2020) Trend of extreme precipitation indices and analysis of long-term climate variability in the Upper Awash basin, Ethiopia. Theor Appl Climatol 140:635–652. https://doi.org/10.1007/s00704-020-03112-8

Sulieman HM, Elagib NA (2012) Implications of climate, land-use and land-cover changes for pastoralism in Eastern Sudan. J Arid Environ 85:132–141. https://doi.org/10.1016/j.jaridenv.2012.05.001

Sun W, Mu X, Song X, Wu D, Cheng A, Qiu B (2016) Changes in extreme temperature and precipitation events in the Loess Plateau (China) during 1960–2013 under global warming. Atmos Res 168:33–48

Szentimrey T (2011). Manual of Homogenization Software MASHv3.03. Hungarian Meteorological Service, Budapest, Hungary.

Tabari H, Taye MT, Willems P (2015) Statistical assessment of precipitation trends in the upper Blue Nile River basin. Stoch Env Res Risk A 29(7):1751–1761

Teferi E, Abraha H (2017). Urban heat island effect of Addis Ababa city: implications of urban green spaces for climate change adaptation. In: Leal Filho W, Belay S, Kalangu J, Menas W, Munishi P, Musiyiwa K (eds) Climate Change Adaptation in Africa. Climate Change Management. Springer, Cham. https://doi.org/10.1007/978-3-319-49520-0_33

Tekleab S, Mohamed Y, Uhlenbrook S (2013) Hydro-climatic trends in the Abay/Upper Blue Nile basin, Ethiopia. Hydrology, land-use and climate in the Nile Basin: recent modelling experiences. Phys Chem Earth Parts a/b/c 61–62:32–42

Tesfamariam BG, Gessesse B, Melgani F (2019) Characterizing the spatiotemporal distribution of meteorological drought as a response to climate variability: the case of rift valley lakes basin of Ethiopia. Weather and Climate Extremes 26:100237. https://doi.org/10.1016/j.wace.2019.100237

Trewin B, Vermont H (2010) Changes in the frequency of record temperatures in Australia, 1957–2009. Austr Meteor Oceanogr J 60:113–119

van der Walt A, Fitchett JM (2020) Trend analysis of cold extremes in South Africa: 1960–2016. Int J Climatol 41(3):2060–2081. https://doi.org/10.1002/joc.6947

Viste E, Korecha D, Sorteberg A (2013) Recent drought and precipitation tendencies in Ethiopia. Theor Appl Climatol 112(3–4):535–551. https://doi.org/10.1007/s00704-012-0746-3

von Storch H (1999). Misuses of statistical analysis in climate research. In: von Storch H., Navarra A. (eds) Analysis of Climate Variability. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-03744-7_2

Wang F, Zhang C, Peng Y, Zhou H (2014) Diurnal temperature range variation and its causes in a semiarid region from 1957 to 2006. Int J Climatol 34(2):343–354. https://doi.org/10.1002/joc.3690

WMO (World Meteorological Organization) (2009) Guidelines on: analysis of extremes in a changing climate in support of informed decisions for adaptation. Climate Data and Monitoring WCDMP-No. 72. Geneva, Switzerland

Woldesenbet TA, Elagib NA, Ribbe L, Heinrich J (2017a) Hydrological responses to land use/cover changes in the source region of the Upper Blue Nile Basin. Ethiopia Sci Total Environ 575:724–741

Woldesenbet TA, Elagib NA, Ribbe L, Heinrich J (2017b) Gap-filling and homogenization of climatological datasets in the headwater region of the Upper Blue Nile Basin, Ethiopia. Int J Climatol 37:2122–2140

Worku T, Khare D, Tripathi SK (2019) Spatiotemporal trend analysis of rainfall and temperature, and its implications for crop production. J Water Clim Chang 10(4):799–817

Yue S, Pilon P, Phinney B, Cavadias G (2002) The influence of autocorrelation on the ability to detect trend in hydrological series. Hydrol Process 16:1807–1829. https://doi.org/10.1002/hyp.1095

Yue S, Wang CY (2004) The Mann-Kendall test modified by effective sample size to detect trend in serially correlated hydrological series. Water Resour Manag 18(3):201–218

Zhang L, Ren GY, Ren YY, Zhang AY, Chu ZY, Zhou YQ (2014) Effect of data homogenization on estimate of temperature trend: a case of Huairou station in Beijing Municipality. Theor Appl Climatol 115(3):365–373. https://doi.org/10.1007/s00704-013-0894-0

Zuo Q, Song Y, Wang H, Li J, Han C (2021) Spatial variations of extreme precipitation events and attribution analysis in the main water resource area of the Belt and Road Initiative. Theor Appl Climatol 144:535–554

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