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Trends in extreme temperature and rainfall indices in the semi-arid areas of Western Tigray, Ethiopia

Abadi Berhane[1*], Gebre Hadgu[2], Walelign Worku[3] and Berhanu Abrha[4]

Abstract

Background: Africa is the most vulnerable continent in the world; which recurrent droughts, extreme temperature and rainfall affects agriculture and food security. The aim of this study was to analyze the trends in extreme temperature and rainfall in major sesame producing areas in western Tigray using RClimDex software. We selected eight temperature and nine rainfall indices from 27 extreme temperature and rainfall indices, which are recommended by joint CCL/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI). A non-parametric Mann–Kendall test and Sen's slope estimates were used to test the statistical significance and trend of each of the extreme temperature and rainfall indices, respectively.

Results: Number of heavy rainy days, number of very heavy rainy days, very wet days, extremely wet days, and maximum 5 days precipitation showed a negative trend, with significant ($p < 0.05$) decrease throughout the study area. Monthly maximum value of maximum and minimum value of maximum temperature, monthly maximum and minimum value of minimum temperature, hot days and hot nights revealed positive trend throughout the study areas. Total rainfall was decreasing significantly ($p < 0.05$) by 13.34 mm, 13.8 mm, 14.65 mm, 10.9 mm and 8.4 mm/year at Humera and Dansha, Adiremets, Maygaba, Maytsebri and Sheraro, and Adigoshu, respectively. Spatial analysis on extreme temperature also indicated there was relatively lower variability on minimum temperature in Humera, Dansha, Adiremets, and Adigoshu. On average, the western part of Tigray experienced a reduction in total rainfall ranging 8.45 to 14.7 mm/year; and increase in average maximum temperature of 0.04 to 0.051 °C/year since 1983 to 2016. The results also revealed an increase in warm nights and warm days ranging from 0.31 to 0.62 days, and 0.38 to 0.71 days/year, respectively.

Conclusions: Increase in temperature and decrease in amount of rainfall may have a negative impact on crop transpiration, photosynthetic rate and soil water balance; exacerbating distribution and infestation of malaria and leishmaniasis. The results in this study could have an important role in identifying possible present and future production strategies on sesame, cotton, and sorghum crops, which are essential cash crops produced by farmers and investors.

Keywords: Extreme climate indices, Temperature, Rainfall, RClimDex software, Mann–Kendall test, Ethiopia

Background

Africa is one of the most vulnerable continents due to its high exposure and low adaptive capacity (Niang et al. 2014), particularly, East Africa (Haile et al. 2019; Gebrechorkos et al. 2018). East African countries; Ethiopia, Kenya and Tanzania showed an increasing tendency in extreme temperature indices, and irregular rainfall patterns (Gebrechorkos et al. 2018). Compelling evidence revealed that climate change is occurring globally and concerns have arisen about its impact. Global land and ocean surface temperature has increased by 0.85 °C (0.65 to 1.06 °C) from 1880 to 2012; and such warming

*Correspondence: aabay2003@gmail.com
[1] Department of Plant Sciences, Aksum University, Aksum, Ethiopia
Full list of author information is available at the end of the article

of the Earth will continue to cause inter-annual to decadal variability (IPCC 2013). Many of the observed global climate changes are unprecedented in which warming of the atmosphere, decreasing in ice and snow, and rising of sea level have been observed (IPCC 2014). As compared to the disparity in average weather conditions, the frequency of extreme events has a greater environmental and public health impact. Changes in the frequency and severity of extreme climate events and in the variability of weather patterns on Earth will have significant consequences for human and natural systems (Thornton et al. 2014).

Extreme climatic variability on rainfall and temperature variability has been quantified using coherent analytical procedures and significant warming over wider portion of the globe (Frich et al. 2002; Alexander et al. 2006); and the authors discussed that there was no uniform temporal and spatial rainfall pattern. Likewise, Bary et al. (2018), Byakatonda et al. (2018), Labri et al. (2018) and Halimatou et al. (2017) stated that extreme temperature indices over Africa revealed increasing warming trends. Recent studies on extreme temperature and rainfall in Ethiopia indicated that there was a significant increase in warming indicator values and decrease in cold spell indicator values (Gebrechorkos et al. 2018). According to Asfaw et al. (2018), inter and intra-annual rainfall variability was observed in the north central Ethiopia. Similarly, Araya et al. (2011) stated that dry spells, short length of growing period and lack of rainfall result in yield failure in northern Ethiopia. Principally, climate is one of the most important factors among the leading factors for vulnerability, in most parts of Ethiopia (WFP 2014). Hence, Ethiopia has been described as one of the most vulnerable countries to climate change in Africa (Conway et al. 2011).

Ethiopia occupies broad agro-ecological zones (Hurni 1986); for example from the deepest point at the Danakil depression in Afar regional state at about 126 m below sea level, to up to the highest peak at 4562 m above sea level at Ras Dashen in Amhara regional state (MOA 1998). Studies on extreme temperature and rainfall by Addisu et al. (2015), Asfaw et al. (2018), Gebrechorkos et al. (2018), and Mekasha et al. (2014) show that there is significant variability across different agro-ecologies in Ethiopia. Changes in climate extremes are already affecting socio-economic values of the society and natural systems (Karl et al. 2008).

Recent studies on historical extreme temperature and rainfall variability indicate there is a positive trend in warming indicators in different regions in Ethiopia (Asfaw et al. 2018; Mekasha et al. 2014). Asfaw et al. (2018), Ayalew et al. (2012) and Bewket (2009) also stated there is seasonal and inter-annual rainfall variability across many areas in Ethiopia. Similarly, Tamiru et al. (2015) analyzed that annual rainfall variability was and reported a high coefficient of variability (25%) in Eastern Ethiopia. Trend analysis over Ethiopia in the period 1951-2006 indicated that annual minimum temperature increased by about 0.37 °C every 10 years (NMA 2007). Belg and Kiremt rainfall have decreased by 15–20% across parts of southern, Southeastern, and Southwestern Ethiopia from mid-1970s to late 2000s (Funk et al. 2012).

In Ethiopia, the northern part of the country is affected by climate change and variability (Hadgu et al. 2015; Araya 2011), coupled with high rainfall variability (Araya and Stroosnijder 2011). The region is characterized by erratic rainfall, short length of growing period, where late onset and early cessation of rain frequently occur, affecting crop growth and yield. According to Asaminew et al. (2017), average temperature variability in Dansha and Kebabo experienced increasing trend from 0.5 to 1.65 °C, and 0.5 to 1.5 °C, respectively in western Tigray. The author also found that slight deviation in rainfall was experienced since 1980 to 2010. In addition, Niguse and Araya (2015) found annual rainfall in Humera was decreasing with inter-annual variability of 16.7%, with average minimum and maximum temperature varying between 17.5 °C and 22 °C, and 33 °C and 41.7 °C, respectively.

Although climate change has location specific impact, studies related to extreme rainfall and temperature were concentrated on the highland areas of the country. The lowland semiarid area, where temperature is already marginal for most crops, was not addressed in most studies. Earlier studies also suggested the importance of conducting location specific analysis of weather extremes (Degefu and Bewket 2014). Information related to extreme rainfall and temperature trends in the study area is scanty. In addition, being the major sesame growing area that helps the country to earn hard currency next to coffee, assessing the trend of rainfall and temperature extreme has important implications for an effective management of water resources and climate risk management. Therefore, this study was initiated to analyze the trends in extreme temperature and rainfall indices in major sesame producing districts in the semi-arid areas of western Tigray.

Materials and methods

Area description

This study was conducted in five districts (*Weredas*), namely Tahtay Adiabo, Asgede-tsimbla, Tselemti, Kafta-Humera and Welkait (Fig. 1). It is bordered with Republic of the Sudan in the west, Eritrea in the north (Berhe et al. 2008), central zone of Tigray regional state in the east and Amhara regional state in the south. The study area

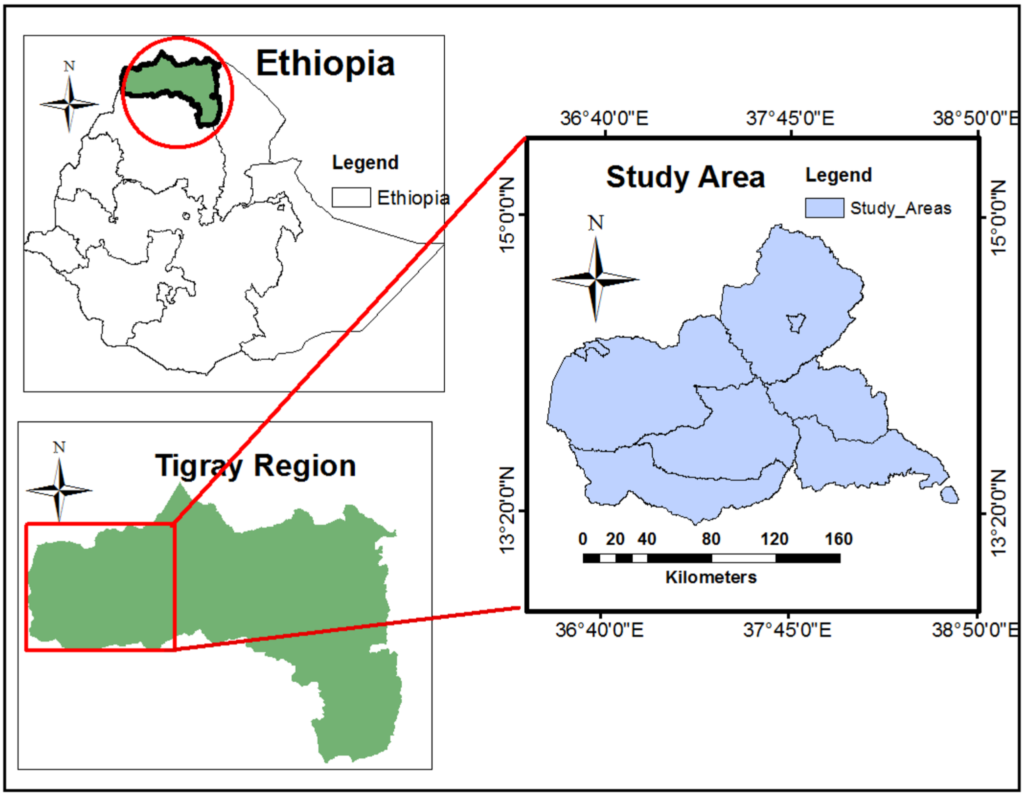

Fig. 1 Location map of the study area

covers 13°37′ North latitude and 36°37′ longitude East at Humera, 14°43′ latitude North and 37°4′ longitude East at Badme, and 13°35′ North latitude and 38°43′ East longitude at Maytsebri; with elevation ranging from 600 m above sea level at Humera to 1300 m above sea level at Maytsebri. The area is characterized as hot to warm semi-arid agro-ecology with high rainfall variability ranging 300 mm to 800 mm (MOA 1998), and short length of growing period, erratic rainfall and, high daily maximum and minimum temperature variability. The maximum temperature of the study area reaches up to 42 °C from April to June, and declines 25–35 °C from late June to February. The average maximum and minimum temperature of the area is 37 and 20 °C, respectively. In this particular study nine observational stations; Adigoshu, Adiremets, Badme, Dansha, Dedebit, Humera, Maygaba, Maytsebri and Sheraro (Table 1) were considered due to the suitability of the areas for sesame production in

Table 1 Geographical locations, data type, and database availability of nine stations used in the study

Weather station	Elevation (m)	Latitude (Decimal)	Longitude (Decimal)	Data availability	Data type Rainfall	temperature
Sheraro	1031	14.240	37.555	1983–2016	Yes	Yes
Badme	1080	14.725	37.804	1983–2016	Yes	Yes
Humera	600	14.580	36.62	1983–2016	Yes	Yes
Adiremets	2014	13.751	37.324	1983–2016	Yes	Yes
Dansha	780	13.540	36.969	1983–2016	Yes	Yes
Adigoshu	1115	14.167	37.306	1984–2016	Yes	Yes
Dedebit	897	14.068	37.760	1983–2015	Yes	Yes
Maytsebri	1350	13.586	38.143	1983–2015	Yes	Yes
Maygaba	914	13.793	37.690	1983–2015	Yes	Yes

western Tigray, which is an important cash crop in the area. Mixed crop-livestock agriculture is the dominant practice in the study area with sesame as dominant cash crop, and cattle and goats as major livestock production activities (Medhin 2011).

Methodology

Climate data source

Long-term observed climate data of some stations was not available, and for some stations there are no complete set of data. To complement the ground data and fill missing data of the stations, climate data were obtained from National Aeronautic Space Administration (NASA) [http://power.larc.nasa.gov/common/AgroclimatologyMethodology/]. Previous study based on NASA/POWER datasets and observed data in US Cooperative Observer Program (COOP) were evaluated, and the results showed a good agreement between the two datasets (White et al. 2008). Wart et al. (2015), White et al. (2008), and Bai et al. (2010) have also validated NASA/POWER climate datasets. Therefore, a database on historical climate data for each station was prepared. Accuracy and agreement of NASA climate data parameters (1° latitude and 1° longitude spatial resolution) with observed climate data are archived in the Agro-climatology Archive (Stackhouse et al. 2017), hence these data can be used for crop modeling application and climate change and variability analysis.

Data quality control

Before analysis of extreme temperature and rainfall indices, daily rainfall and temperature data were inspected and detected for outliers and missing data to avoid erroneous data that can cause changes in the seasonal cycle or variance of the data (Abbas 2013).

For further quality control of the data, the procedure in RClimDex 1.10 software was applied (Zhang and Yang 2004). RClimDex was developed by the Expert Team on Climate Change Detection Monitoring and Indices (ETCCDMI) at the Climate Research Branch of the Meteorological Service of Canada. Daily rainfall amounts less than 0 were removed, and both daily maximum and minimum temperatures were set to a missing value, if daily maximum temperature is less than the respective daily minimum temperature. Outliers in daily maximum and minimum temperature were also assessed as values outside of four standard deviations of the climatologically mean of the value for the day (Zhang and Yang 2004).

Outliers are values that are outside of a region defined by the user, which is the mean plus or minus n times the standard deviation of the value for the day, that is (mean-n*std, or mean + n*std). Standard deviation (std) represents the standard deviation of the day and n is an input value selected by the user, and mean is the computed value from the climate data of the day (Zhang and Yang 2004). Therefore, the number of standard deviations was set to be four, as the software identifies the values that lie outside four standard deviations of the mean of the time series.

Trend analysis

The Mann–Kendal's test was applied to detect the temperature and precipitation indices (Table 2). The Mann–Kendal's test is a non-parametric test, with no requirement the data to be normal (Yue and Wang 2004). The Mann–Kendal statistic (S) measures the time series trend of the different temperature and rainfall extreme indices. The Mann-Kendal test statistic (S) is calculated by computing the difference between the later measured value and all earlier measured values following Eq. 1 (Yue and Wang 2004).

$$\boldsymbol{S} = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \boldsymbol{Sign(Yj - Yi)} \tag{1}$$

where sign (Yj–Yi) is equal to +1, 0 or −1. When the magnitude of the S is large positive number, the later measured values tend to be larger than earlier one, and an upward trend is indicated. Whereas, when the S is large negative number, the later measured values tend to be smaller than the earlier ones and the trend will be a downward one.

$$\text{Sign}\left(\text{Xj} - \text{Xi}\right) \left\{ \begin{array}{l} \mathbf{1\ if\ Xj - Xi > 0} \\ \mathbf{0\ if\ Xj - Xi = 0} \\ \mathbf{-1\ if\ Xj - Xi < 0} \end{array} \right\} \tag{2}$$

(Yj–Yi), where j > I, and assign the integer 1, 0 or −1 to positive difference, no difference, and negative differences, respectively. The S test statistic is computed as the sum of the integers (Eq. 1). The magnitude of the slope of the trends from temperature and rainfall extremes was calculated using the Sen's slope estimator (ß) (Sen 1968); which is the median of set of slopes using Eq. 3 that j > 1.

$$\upbeta = \frac{\mathbf{Y_j - Y_i}}{\mathbf{tj - ti}} \tag{3}$$

The Z statistic is also another important parameter to measure significance of the trend for each parameter. The variance of S, for the situation where there may be ties (i.e., equal values) in the x values, is given by;

$$\boldsymbol{Var(S)} = \frac{1}{18}\left[\boldsymbol{N(N-1)(2N+5)} - \sum_{i=1}^{m} \boldsymbol{ti(ti-1)(2ti+5)}\right] \tag{4}$$

Table 2 List of temperature and rainfall indices

ID	Indicator name	Definition	Units
Temperature indices			
TXx	Max Tmax	Monthly maximum value of daily maximum temperature	°C
TNx	Max Tmin	Monthly maximum value of daily minimum temperature	°C
TXn	Min Tmax	Monthly minimum value of daily maximum temperature	°C
TNn	Min Tmin	Monthly minimum value of daily minimum temperature	°C
TN10p	Cool nights	Percentage of days when TN < 10th percentile	Day
TX10p	Cool days	Percentage of days when TX < 10th percentile	Day
TN90p	Warm nights	Percentage of days when TN > 90th percentile	Day
TX90P	Warm days	Percentage of days when TX > 90th percentile	Day
WSDI	Warm spell duration indicator	Annual count of days with at least 6 consecutive days when TX > 90th percentile	Day
DTD	Diurnal temperature range	Monthly mean difference between the maximum and minimum temperatures	°C
CSDI	Cold spell duration indicator	Annual count of days with at least 6 consecutive days when TN < 10th percentile	Day
Rainfall indices			
RX1day	Max 1-day precipitation amount	Monthly maximum 1-day precipitation	mm
RX5day	Max-5day precipitation amount	Monthly maximum consecutive 5-day precipitation	mm
R10mm	Number of heavy precipitation days	Annual count of days when PRCP = 10mm	Day
R20mm	Number of very heavy precipitation days	Annual count of days when PRCP = 20mm	Day
CDD	Consecutive dry days	Maximum number of consecutive days with RR ≥ 1 mm	Day
CWD	Consecutive wet days	Maximum number of days with RR ≥ 1 mm	Day
R95p	Very wet days	Annual total PRCP when RR > 95th percentile	Day
R99p	Extremely wet days	Annual total PRCP when RR > 99th percentile	Day
PRCPTOT	Total precipitation	Annual total PRCP in wet days (RR ≥ 1 mm)	mm

where, m is the number of tied groups in the data set and t_i is the number of data points in the ith tied group. For n larger than 10, Z_{MK} approximates the standard normal distribution (Partal and Kahya 2006; Yenigun and Mulut 2008) and computed as follows.

$$Z_{MK} = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & if\ S < 0 \end{cases}. \quad (5)$$

The presence of a statistically significant trend is evaluated using the Z_{MK} value. In a two-sided test for trend, the null hypothesis Ho should be accepted if $|Z_{MK}| < Z_{1-\alpha/2}$ at a given level of significance. $Z_{1-\alpha/2}$ is the critical value of Z_{MK} from the standard normal table. Example for 5% significance level, the value of $Z_{1-\alpha/2}$ is 1.96.

If there is a linear trend a time series, then the slope can be estimated using a simple non-parametric procedure developed by Sen (1968) known as Sen's estimator. The slope estimates of N pairs of data are first computed by;

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

where x_j and x_k are data values at times j and k ($j > k$) respectively. The median of these N values of Q_i is Sen's estimator of slope. If N is odd, then Sen's estimator is computed by $Q_{med} = Q_{(N+1)/2}$ and if N is even, then Sen's estimator is computed by $Q_{med} = \left[Q_{N/2} + Q_{(N+2)/2}\right]/2$. Finally, Q_{med} is tested by a two-sided test at the 100(1-α)% confidence interval and the true slope may be obtained by the non-parametric test.

Results

Extreme temperature indices

In this study, monthly maximum value of daily maximum temperature, monthly minimum value of daily maximum temperature, monthly maximum value of daily minimum temperature, monthly minimum value of daily minimum temperature, number of cool nights and cool days, number of warm nights, and warm days, are considered. Summary of trend analysis on extreme temperature indices form nine stations selected in this study are presented in Table 3.

Monthly maximum value of daily maximum temperature (TXx) and monthly minimum value of daily maximum temperature (TXn)

Results from the trend analysis revealed that there was a positive trend across all study areas. There was statistically highly significant ($p < 0.01$) increase in TXx at Badme and Sheraro, and statistically significant ($p < 0.05$) increase at Adigoshu, Dedebit, Humera, and Maygaba.

Table 3 Trend analysis on extreme temperature indices from 1983 to 2016 for nine stations

Station	TXx	TNx	TXn	TNn	TN10P	TX10P	TN90P	TX90P
Adigoshu	0.03	0.026	−0.01	−0.004	−0.29	−0.23	0.33	0.43
Adiremets	0.03	0.026	−0.003	0.02	−0.31	−0.41	0.56	0.64
Badme	0.04	0.024	−0.01	0.036	−0.36	−0.44	0.61	0.57
Dansha	0.03	0.015	−0.003	0.004	−0.33	−0.39	0.59	0.65
Dedebit	0.03	0.022	−0.007	0.026	−0.38	−0.45	0.59	0.67
Humera	0.03	0.015	−0.003	0.005	−0.38	−0.37	0.62	0.71
Maygaba	0.03	0.024	−0.007	0.036	−0.35	−0.46	0.61	0.68
Maytsebri	0.03	0.022	−0.007	0.026	−0.38	−0.46	0.59	0.67
Sheraro	0.03	0.021	−0.014	0.02	−0.44	−0.32	0.31	0.38

There results also showed that there was no significant ($p<0.05$) increase in TXx at Adiremets and Dansha in the western part of the study area. TXx varied from 0.03 to 0.04 °C throughout all stations, with relatively smaller deviations 0.004 and 0.007 °C/year in Humera and Maytsebri, respectively. Overall, the changes in TXx at all the stations in the study areas tend to be similar, except Badme station with 0.04 °C. The linear regression analysis also revealed that changes in TXx varied with the coefficient of determination (R^2) from 0.15 to 0.20; which implying about 15% to 20% was expressed by the linear regression of TXx and year in the time series (Fig. 2).

On the other hand, TXn (Fig. 3) revealed that there was a negative trend with no statistical significance ($p<0.05$) variability throughout the study area. Maximum variability on TXn was observed at Sheraro with −0.014 °C, Adigoshu and Badme with −0.01 °C in the time series. Relatively smaller variability was observed on TXn ranging from −0.003 °C at Adiremets, Dansha, and Humera, to −0.007 °C in Dedebit, Maygaba, and Maytsebri. The highest inter-annual TXn value at all stations was indicated from March to June; whereas, TXn at Humera during July, August and September varies from 23 °C to 27 °C, and 27 °C to 37 °C during March, April, May and June (data not presented in this report). The monthly minimum value of the daily maximum temperature at Sheraro during July, August and September varied from 21 to 26 °C, while the minimum

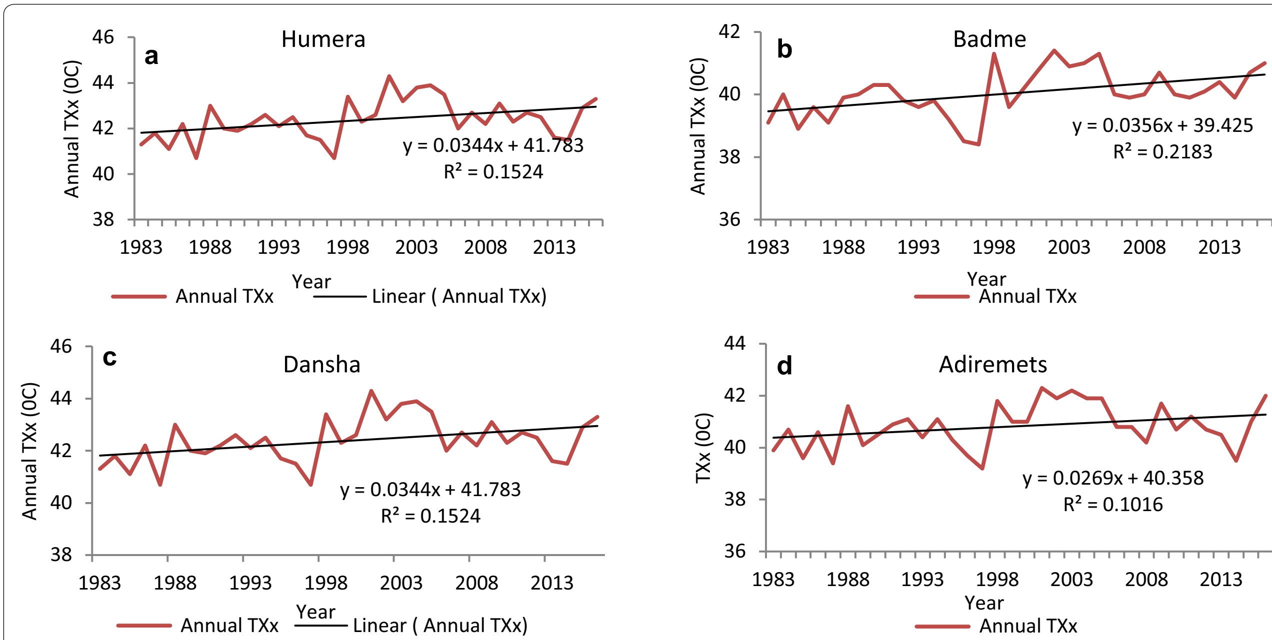

Fig. 2 Annual monthly maximum value of daily maximum temperature (TXx) at **a** Humera, **b** Badme, **c** Dansha, **d** Adiremets, **e** Sheraro and **f** Maytsebri

value of the daily maximum temperature during March, April, May and June ranged between 26 and 36 °C from 1983 to 2016. Similarly, the highest monthly minimum value of the daily maximum temperature at Adiremets, Dansha, Maygaba, Maytsebri, and Dedebit was observed during February, March and April. Whereas the smallest monthly minimum value of the daily maximum temperature was observed during the main rainy season from July to September (data not shown).

Monthly maximum (TNx) and monthly minimum (TNn) values of daily minimum temperature

Results on monthly minimum value of daily minimum temperature revealed a positive trend, except at Adigoshu where, a negative trend was observed. Trend analysis for TNx (Fig. 4) for the nine stations showed a positive trend varying from 0.015 to 0.09 °C/year (Table 3). Monthly maximum value of daily minimum temperature was lower in January and December at all meteorological stations with higher monthly values observed during April, May and June. Based on the results from the trend analysis, TNn (Fig. 5) across the study areas vary from 0.003 to 0.036 °C. The highest TNn record was observed in April, May, June, and July in majority of stations, with the lowest TNn variability occurring during October, November, December and January.

Cool nights (TN10p) and cool days (TX10p)

Results on number of cool nights (TN10p) (Fig. 6) revealed a statistically highly significant ($p < 0.01$) negative trend throughout the study area. The number of cool nights was decreasing from 2.9 to 4.4 days/year in the time series (Table 3). Number of cool nights was highly decreasing at Badme and Sheraro as compared to Adigoshu and Adiremets. Similarly, the number of cool days (TX10P) (Fig. 7) in the study area was statistically significantly ($p < 0.01$) decreased, with the highest reduction recorded at Badme, Dedebit, and Maygaba, comparing to that of at Adigoshu and Sheraro. The coefficient of determination (R^2) in the regression analysis ranges from 0.37 to 0.43, which indicate that number of cool nights decreased considerably with time in the time series span. Similarly, the coefficient of determination (R^2) for the number of cool days varied from 0.146 to 0.253. Generally, number of cool nights and cool days were considerably affected by number of years in the time span.

Warm nights (TN90p) and warm days (TX90p)

There was a positive trend on warm nights (TN90p), with highly significant ($p < 0.01$) increase observed at Adiremets, Badme, Dansha, Dedebit, Humera, Maygaba, and Maytsebri (Fig. 8). The changes in TN90p in the study area vary from 0.3 to 0.61 days (Table 3). Similarly, there was a significant ($p < 0.05$) positive trend on warm days (TX90p) (Table 3) throughout

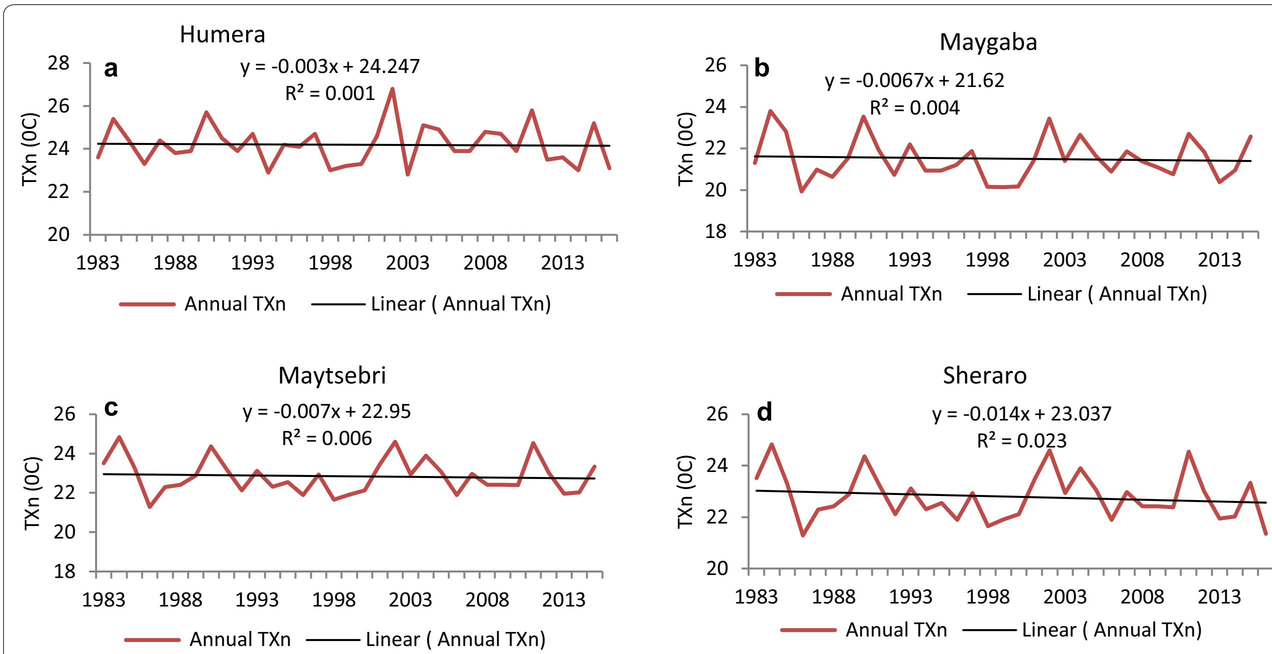

Fig. 3 Trends in annual monthly value of the minimum value of the daily maximum temperature (TXn) at **a** Humera, **b** Maygaba, **c** Maytsebri, **d** Sheraro

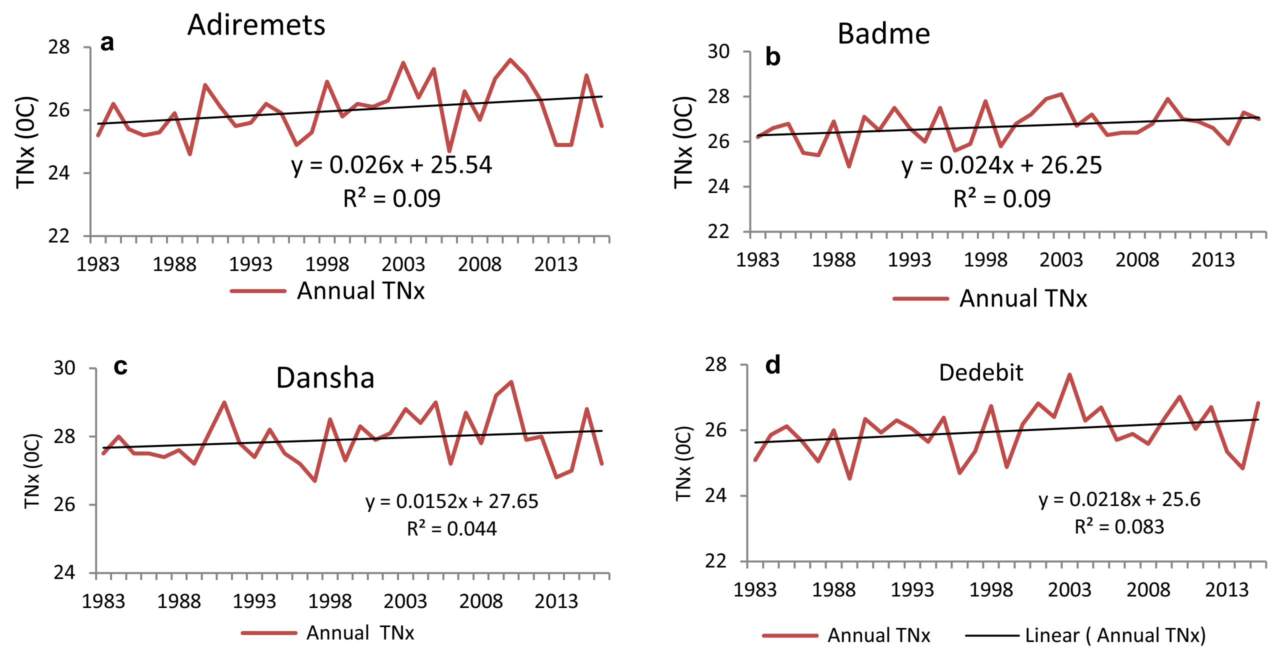

Fig. 4 Monthly maximum value of daily minimum temperature (TNx) **a** Adiremets, **b** Badme, **c** Dansha, **d** Dedebit

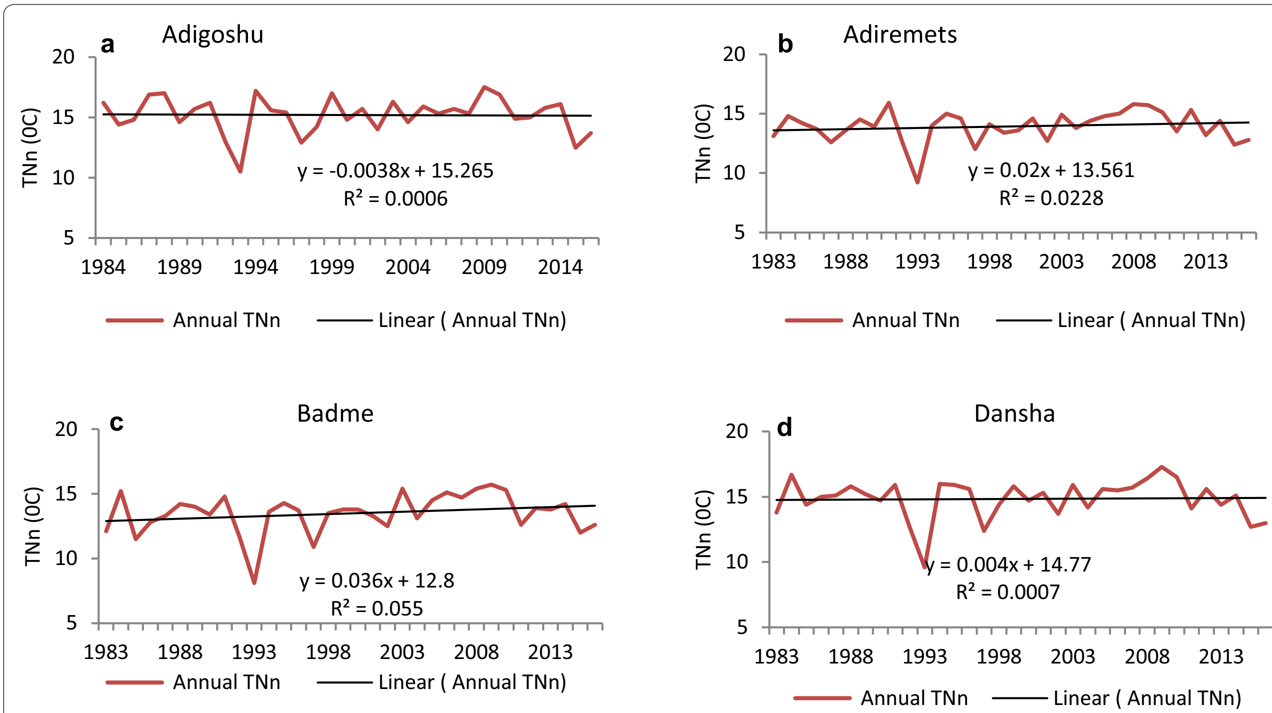

Fig. 5 Monthly minimum value of daily minimum temperature at (TNn), **a** Adigoshu, **b** Adiremets, **c** Badme, **d** Dansha, **e** Humera and **f** Sheraro

the study area. Warm days at Adigoshu, Adiremets, Badme, Dansha, Dedebit, Humera, Maygaba, Maytsebri, and Sheraro, was significantly increasing with 0.43, 0.64, 0.57, 0.65, 0.67, 0.7, 0.68, 0.67, and 0.38 days/year, respectively. The smallest change on TX90p since 1983 was observed at Adigoshu and Sheraro, whereas,

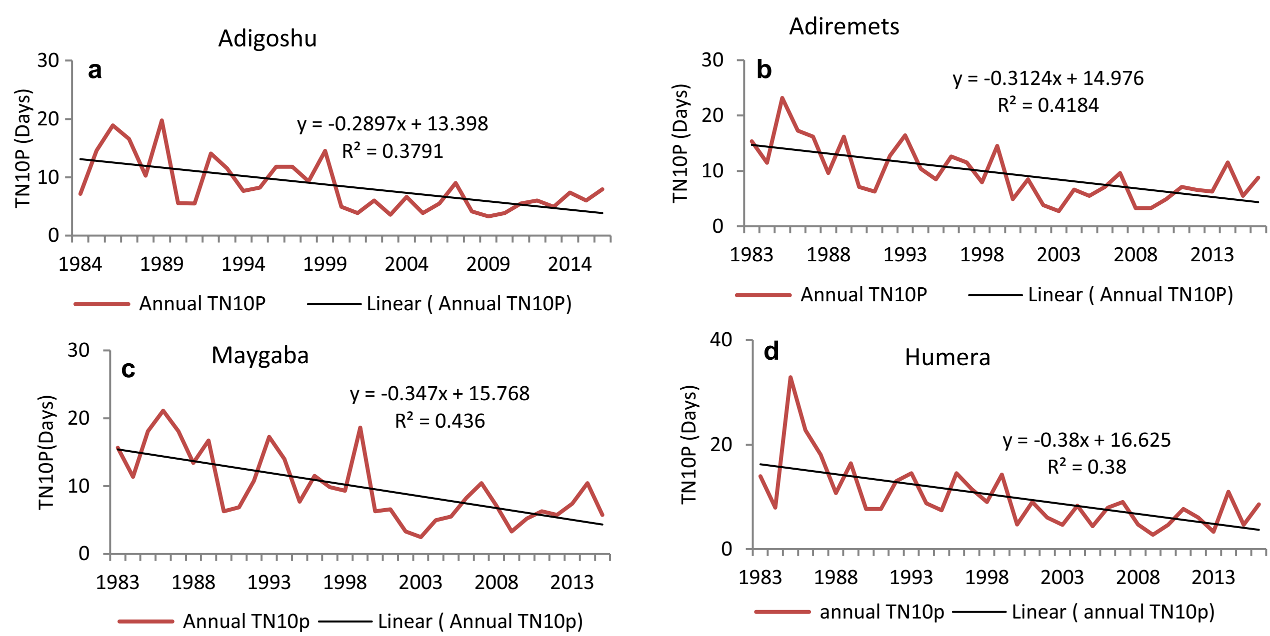

Fig. 6 Annual cool nights (TN10P) of different stations at **a** Adigoshu, **b** Adiremets, **c** Maygaba, and **d** Humera

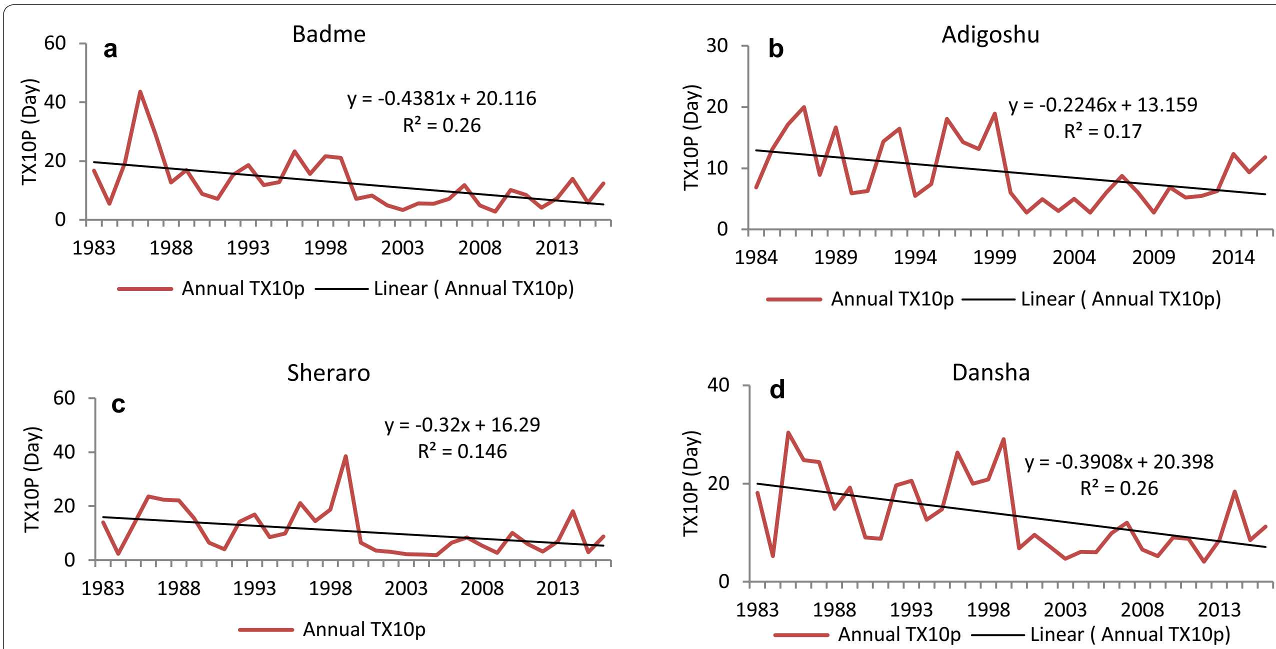

Fig. 7 Annual cool days (TX10P) of different stations at **a** Badme, **b** Adigoshu, **c** Sheraro, **d** Dansha

the highest magnitude was observed at Maygaba with 0.68 days (Table 3). The linear regression analysis showed that the coefficient of determination (R^2) for warm nights vary between 0.225 and 0.25 (Fig. 8).

Besides, to the temporal statistical analysis, we also analyzed spatial analysis on extreme temperature indices (Fig. 9). Warm days and warm nights were highly increased, except at Sheraro and Adigoshu. The average

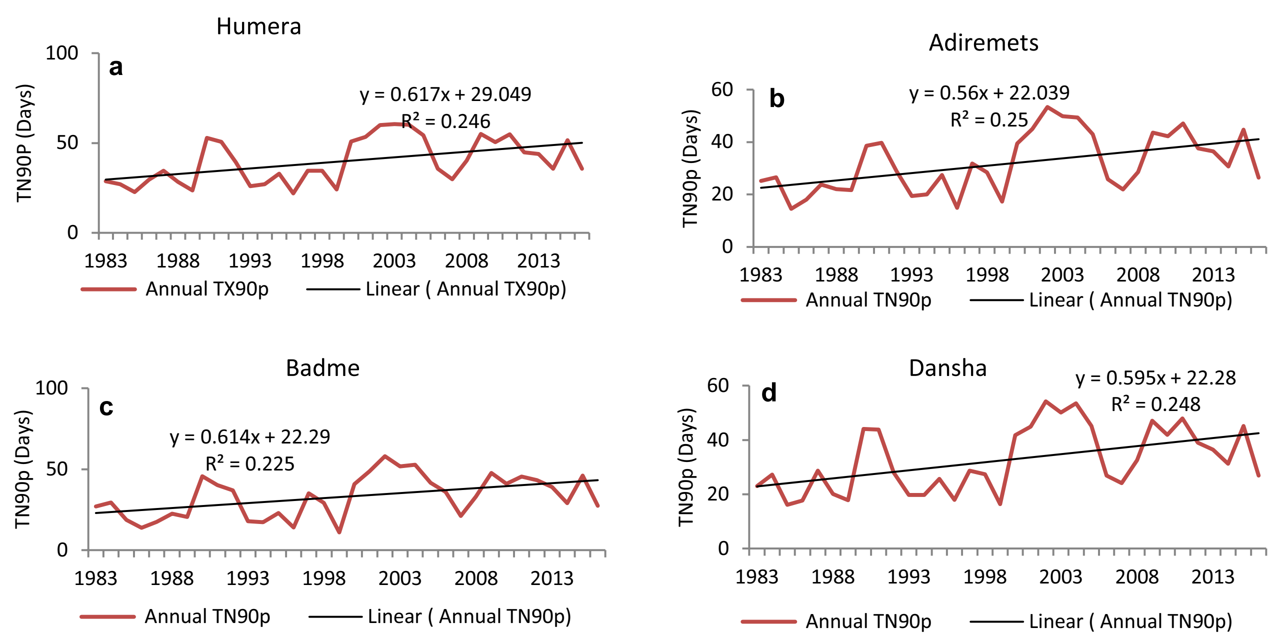

Fig. 8 Average annual warm nights (TN90p) at **a** Humera, **b** Adiremets, **c** Badme and **d** Dansha

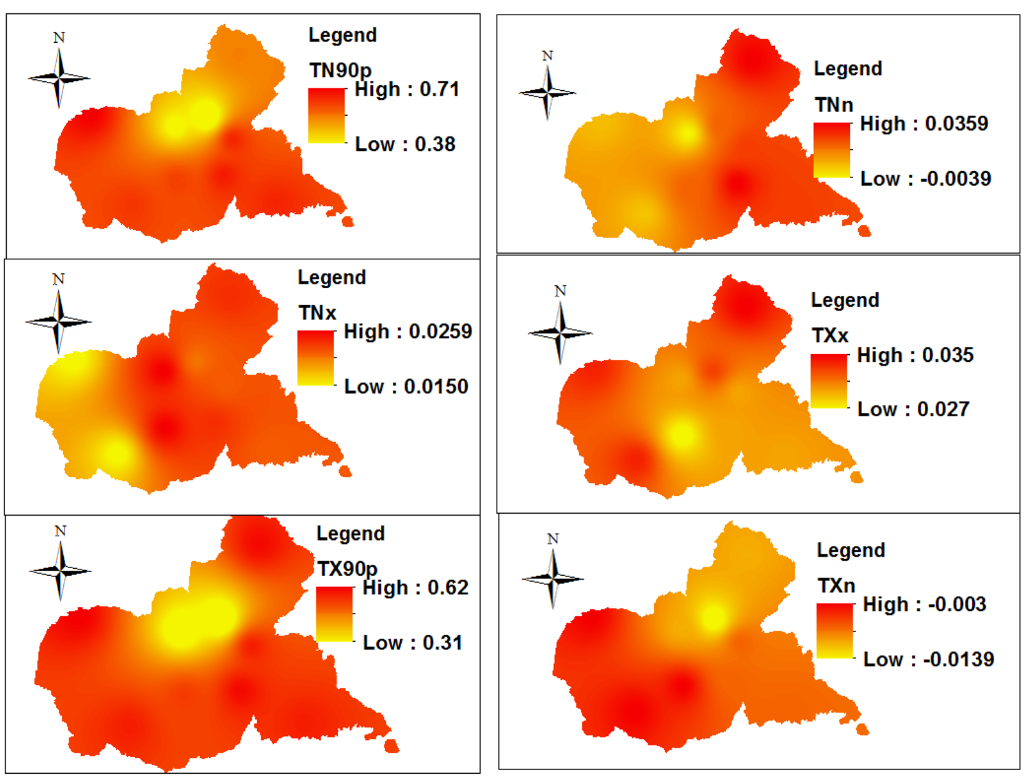

Fig. 9 Extreme temperature indices; TXx (maximum value of monthly maximum temperature), TNn (minimum value of monthly minimum temperature), Tmin (mean of minimum temperature), Tmax (mean of maximum temperature of nine stations from 1983 to 2016 in Western Tigray

annual TXx was relatively high at Humera, Dansha, Sheraro, and Badme, whereas, a relatively moderate increment was observed at Adigoshu, Dedebit, Mygaba and Maytsebri. The smallest variability on TXx was observed at Adiremets. Likewise, a high variability on TNn was observed at Badme and Maygaba, with moderate changes over Dedebit, Sheraro and Maytsebri; whereas, there was relatively steady change over Adigoshu. Maximum value of the daily minimum temperature (TNx) was observed lower around Humera and Dansha areas to the western part of the study area, whereas, the minimum value of the daily maximum temperature (TXn) was observed to be higher in the western part.

Extreme rainfall indices

In this study, total annual rainfall, consecutive dry days, consecutive wet days, number of heavy rain days, number of very heavy rain days, number of wet days, number of extremely wet days, maximum 1 day and fife day rainfall were analyzed (Table 4).

Consecutive dry days (CDD) and consecutive wet days (CWD)

Consecutive dry days (Fig. 10) indicated that there was a significant ($p < 0.05$) increase at Dedebit, Maygaba, Maytsebri and Sheraro (Table 4). However, trend analysis showed that there was no significant ($p < 0.05$) variability on consecutive dry days in Adiremets, Badme, Dansha, and Humera. The smallest number

Table 4 Trends of extreme rainfall indices of nine locations in Western Tigray from 1983 to 2016

Station	PRCPTOT	CDD	CWD	R10mm	R20mm	R95P	R99P	Rx1day	Rx5day
Adigoshu	−8.445	0.62	0.23	−0.38	−0.07	−2.62	−0.01	−0.013	−0.33
Adiremets	−13.853	1.12	−0.36	−0.69	−0.26	−3.87	−074	0.037	−0.65
Badme	−8.866	1.14	−0.35	−0.45	−0.09	−1.4	0.87	0.02	−0.35
Dansha	−13.341	1.01	−0.18	−0.71	−0.22	−4.02	−0.53	0.10	−0.66
Dedebit	−10.901	1.56	−0.55	−0.48	−0.16	−3.38	−0.78	−0.42	−0.78
Humera	−13.341	1.37	−0.18	−0.71	−0.22	−3.85	−1.19	0.10	−0.66
Maygaba	−14.655	1.66	−0.58	−0.72	−0.27	−6.01	−1.76	−0.52	−1.14
Maytsebri	−10.901	1.56	−0.55	−0.48	−0.16	−3.38	−0.78	−0.42	−0.78
Sheraro	−8.826	1.6	−0.53	−0.43	−0.11	−3.35	−0.17	−0.21	−0.35

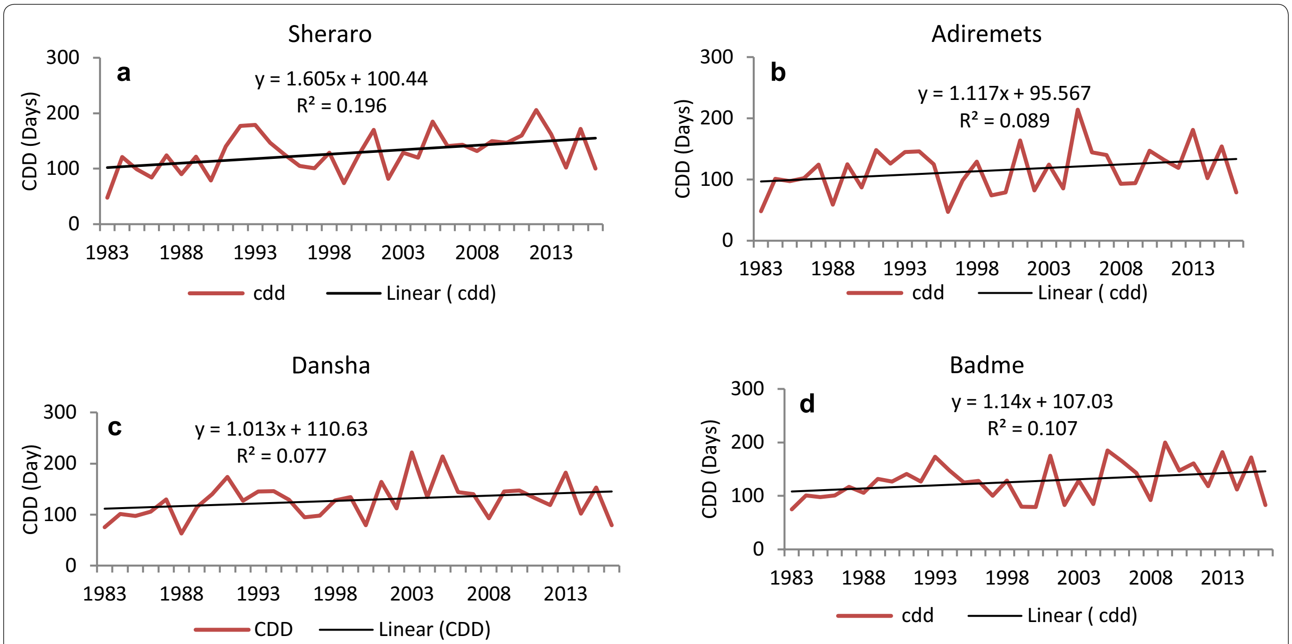

Fig. 10 Consecutive dry days (CDD) of different stations in the study sites; **a** Sheraro, **b** Adiremets, **c** Dansha, **d** Badme, **e** Dedebit and **f** Maygaba

of consecutive dry days was recorded in Adiremets in 1996 with 47 consecutive days. Consecutive dry days at Sheraro was highly significantly ($p < 0.01$) increased by 1.6 days/year. The results from the trend analysis showed that the highest increase in CDD 1.66 days was 1.66 days was observed at Maygaba. However, Adigoshu experienced the smallest variability on consecutive dry days with 0.62 days/year with no significant difference ($p < 0.05$).

On the contrary, trends on number of consecutive wet days (Table 4, Fig. 11) indicated a decreasing trend by 0.55, 0.58, 0.18, 0.55, 0.18, 0.35, 0.53 and 0.37 days/year at Maytsebri, Maygaba, Humera, Dedebit, Dansha, Badme, Sheraro and Adiremets, respectively. However, CWD at Adigoshu revealed an increasing trend by 0.24 days/year. The smallest number of CWD at Dansha, Adigoshu, Adiremets, Badme, Dedebit, Humera, Maygaba, Maytsebri, and Sheraro was 15, 12, 15, 10, 10, 15, 10, 10 and 10 days in 2011, respectively. On the contrary, the largest number of CWD118 and 123 days were observed at Dansha and Humera, and Adiremets in 1987, respectively (Table 4; Fig. 12).

Total rainfall (PRCPTOT)

Trend analysis on total rainfall (Fig. 12) revealed a negative trend across all stations. Total rainfall at Maytsebri, Maygaba, Humera, Dedebit and Dansha was statistically significantly ($p < 0.05$) decreased by 10.9, 14.6, 15.3, 10.9, 15.3 and 16.5 mm/year, respectively. Whereas, total rainfall at Badme, Sheraro and Adigoshu was decreasing by 11.4 mm, 8.83 mm and 8.44 mm/year, respectively, with no significant ($p < 0.05$) variability. The regression analysis for PRCPTOT showed that the coefficient determination (R^2) varied from 0.09 at Sheraro, to 0.16 at Maygaba and Humera, respectively.

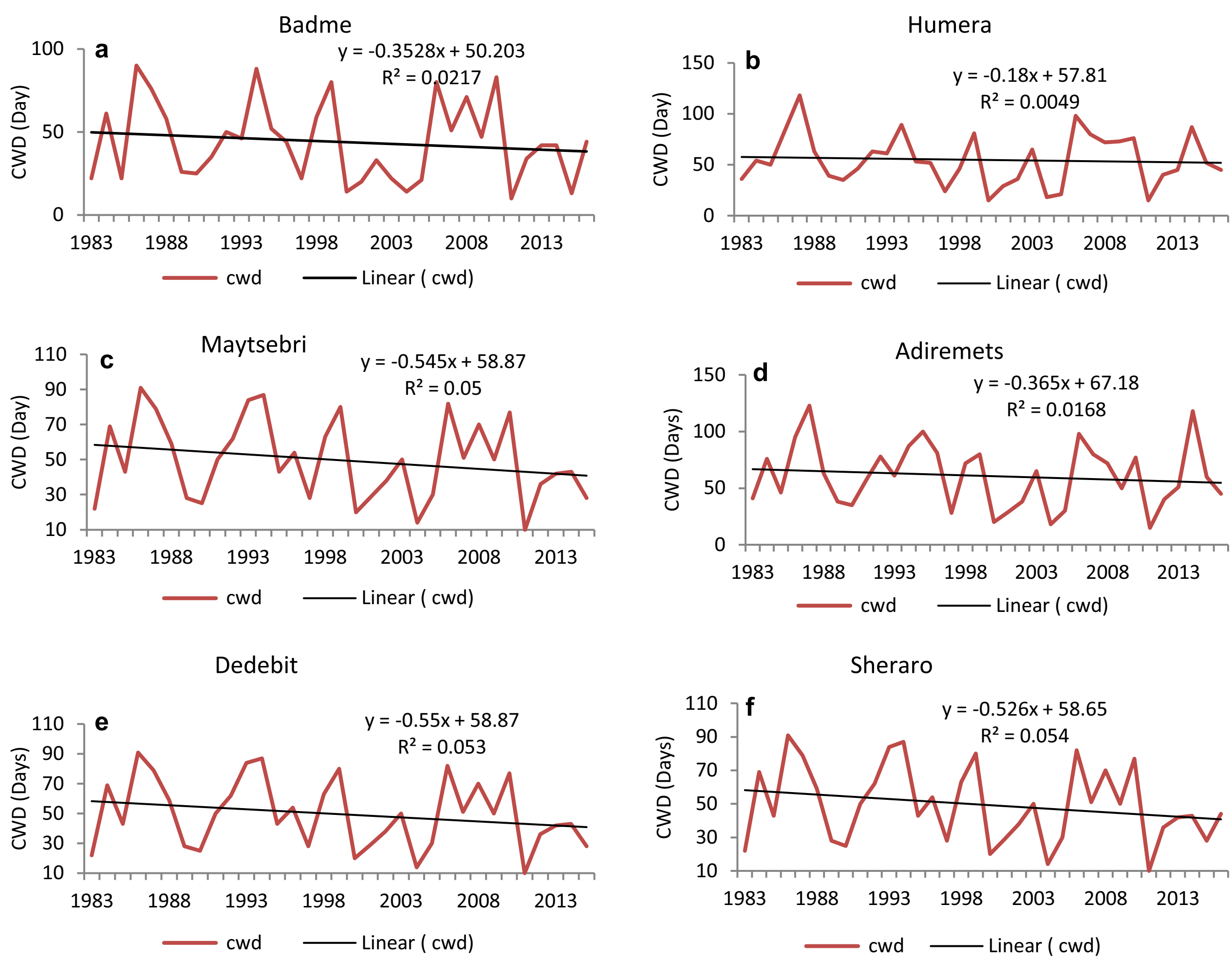

Fig. 11 Consecutive wet days (CWD) at **a** Badme, **b** Humera, **c** Maytsebri, **d** Adiremets, **e** Dedebit and **f** Sheraro

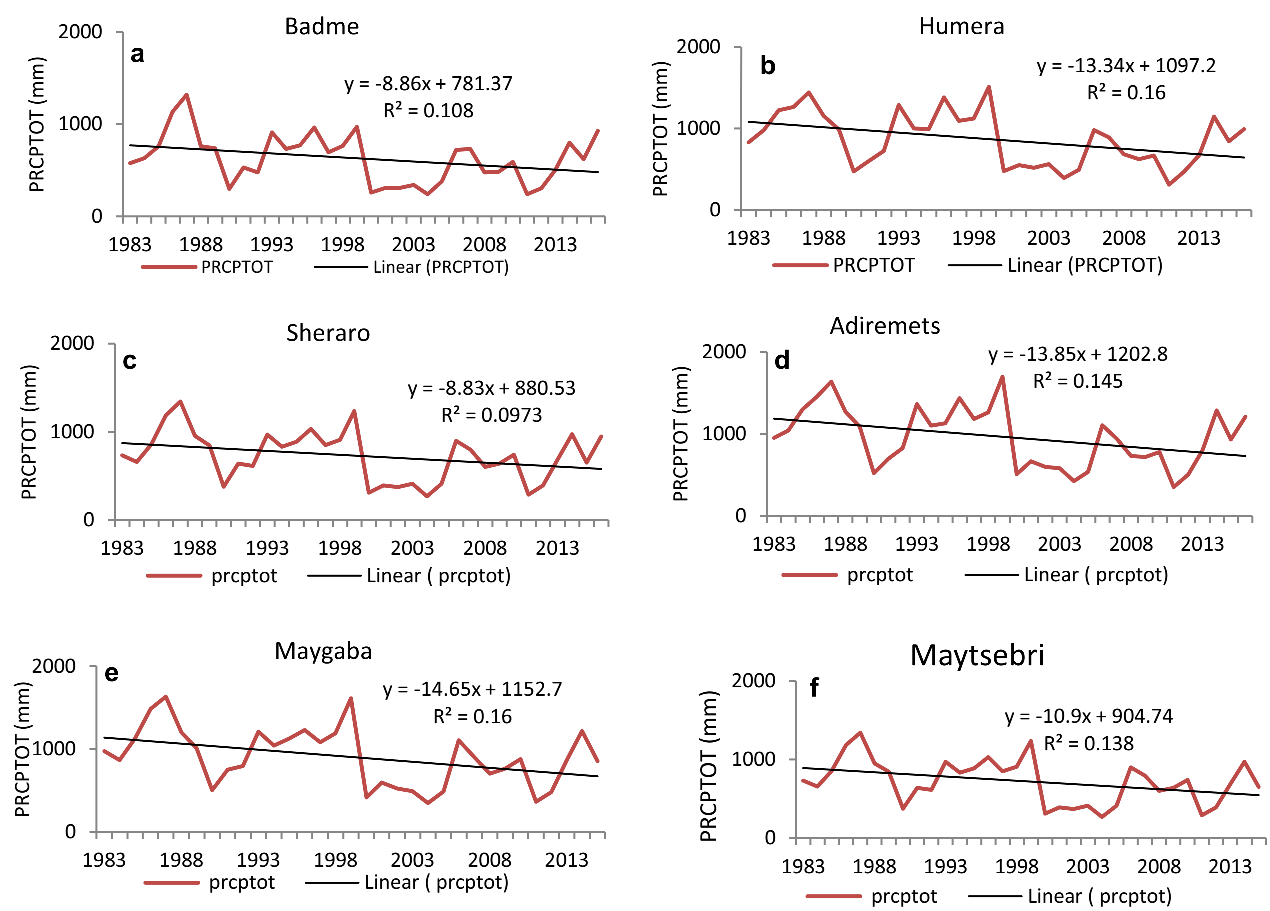

Fig. 12 Total annual precipitation (PRCPTOT) of **a** Badme, **b** Humera, **c** Sheraro, **d** Adiremets, **e** Maygaba, **f** Maytsebri

Number of heavy rain days (R10 mm)

Trend analysis on number of heavy rain days (Fig. 13) revealed that there was a significant ($p < 0.05$) reduction throughout the study area (Table 4). The number of heavy rain days was very small in 2004, 2005 and 2011 at all sites, where the number of heavy rain days was below 10 days. However, heavy rain days were not observed at Badme in 2011 and 2012. The number of heavy rain days varying between 50 and 68 and were observed at Adiremets station in 1986, 1987, 1996, 1998 and 1999. Similarly, number of heavy rain days ranging from 50 to 63 days, were recorded at Humera and Maygaba in 1986, 1987 and 1999. However, 59 heavy rain days was observed in Dansha in 1999. The annual count of heavy rain days at Sheraro indicated the number of heavy rainfall days decreased by 0.436 days every year in the time span.

Number of very heavy rain days (Rx20mm)

Trend analysis for very heavy rain days (Fig. 14) revealed that there was a negative trend throughout the study area. Very heavy rain days for 20 mm at Humera, Adiremets, Dedebit, Maytsebri, and Dansha was statistically significantly ($p < 0.05$) decreased from 1983 to 2016; whereas, there was no statistical significant ($p < 0.05$) decrease at Sheraro, Adigoshu, Maygaba, and Badme (Table 4). The highest number of count with Rx20mm was 20 and 19 days at Adiremets in 1999 and 1986, respectively, followed by 18 days at Humera in 1986. The smallest number of heavy rain days count/year in 2011 and 2012 was zero at all stations. The highest number of very heavy rain days at Sheraro from 1983 to 2016 varied from zero to 15 days with no statistical significant ($p < 0.05$) reduction.

Very wet days (R95p) and extremely wet days (R99p)

Trend analysis on R95p (Table 4) indicated that there was a negative trend throughout the study area. Very wet days exceeding the 95th percentile statistically significantly ($p < 0.05$) decreased at Adiremets, Dansha, Humera, and Maytsebri while R95p was highly significantly ($p < 0.01$) decreased at Maygaba. Conversely, there was no significant ($p < 0.05$) variability in R95P exceeding the 95th

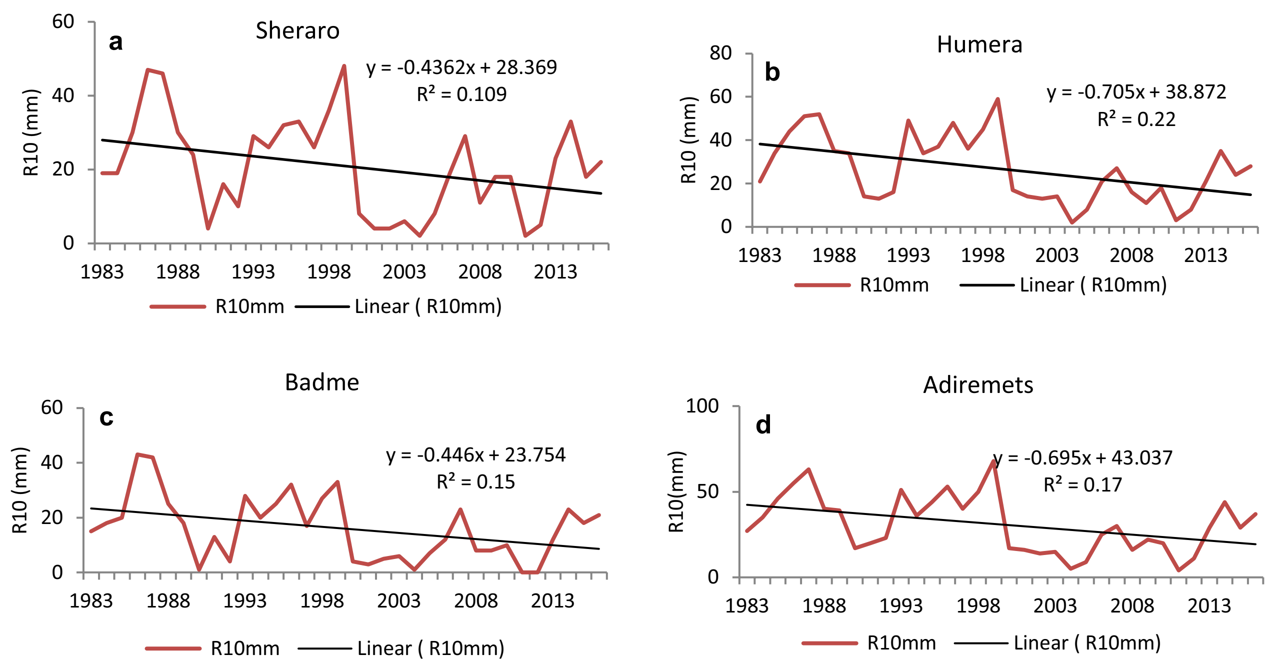

Fig. 13 Number of heavy rain days (R10mm) at **a** Sheraro, **b** Humera, **c** Badme, **d** Adiremets

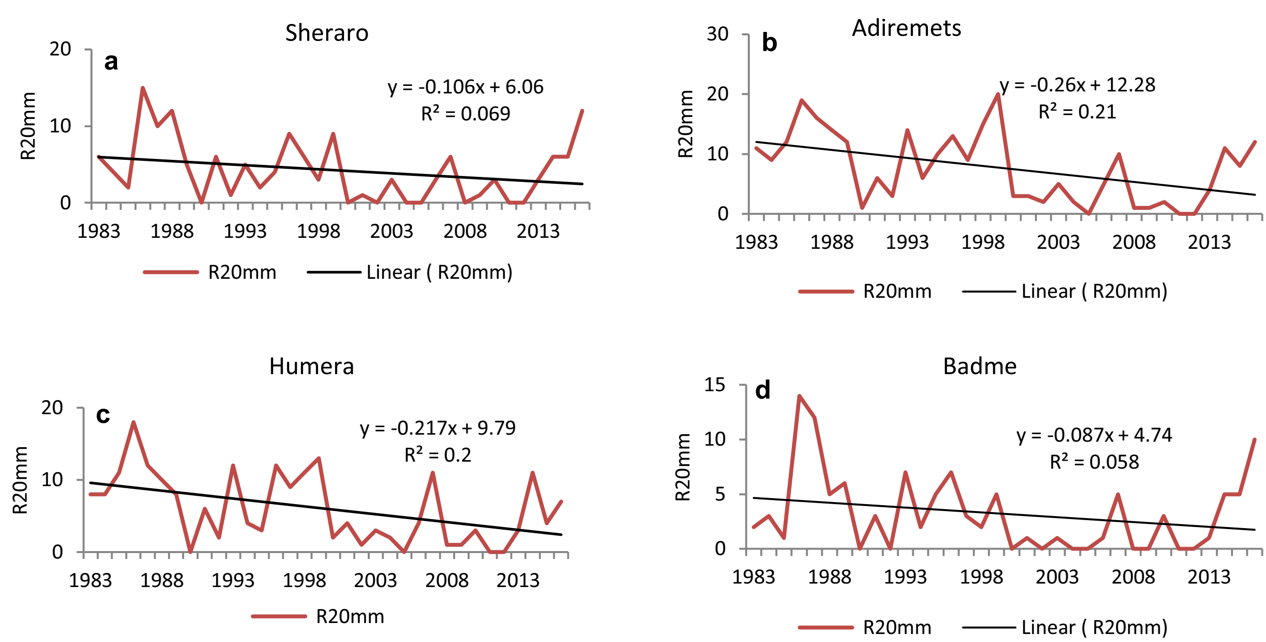

Fig. 14 Number of very heavy rain days (R20mm) at **a** Sheraro, **b** Adiremets, **c** Humera, **d** Badme

percentile at Badme, Sheraro, and Adiremets. The highest reduction on very wet days exceeding the 95th percentile was observed at Maygaba with 6 days/year. The magnitude for very wet days at 95th percentile at Sheraro, Humera, Adigoshu, Adiremets, Badme, Dedebit, Dansha, and Maytsebri was 3.35, 3.85, 2.6, 3.88, 1.4, 3.38, 4.02 and 3.38 days/year, respectively.

Similarly, trends on extremely wet days exceeding the 99th percentile (Fig. 15) showed a negative trend with no statistically significant ($p < 0.05$) change in most of the

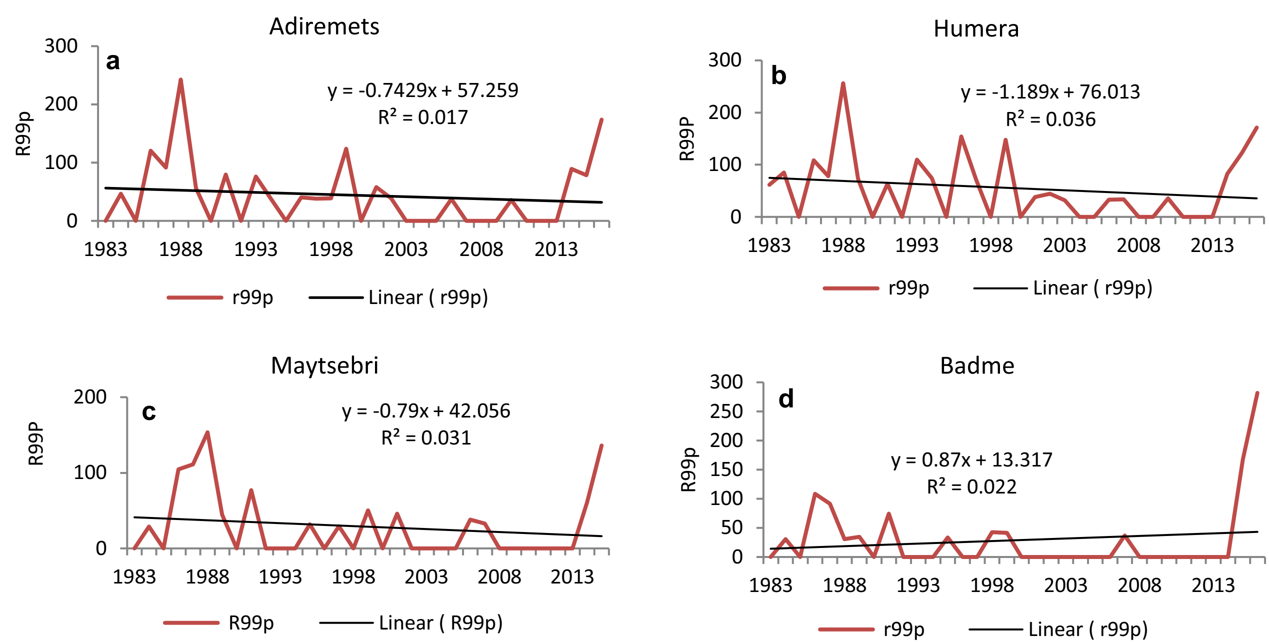

Fig. 15 Extremely wet days (R99p) at **a** Adiremets, **b** Humera, **c** Maytsebri and **d** Badme

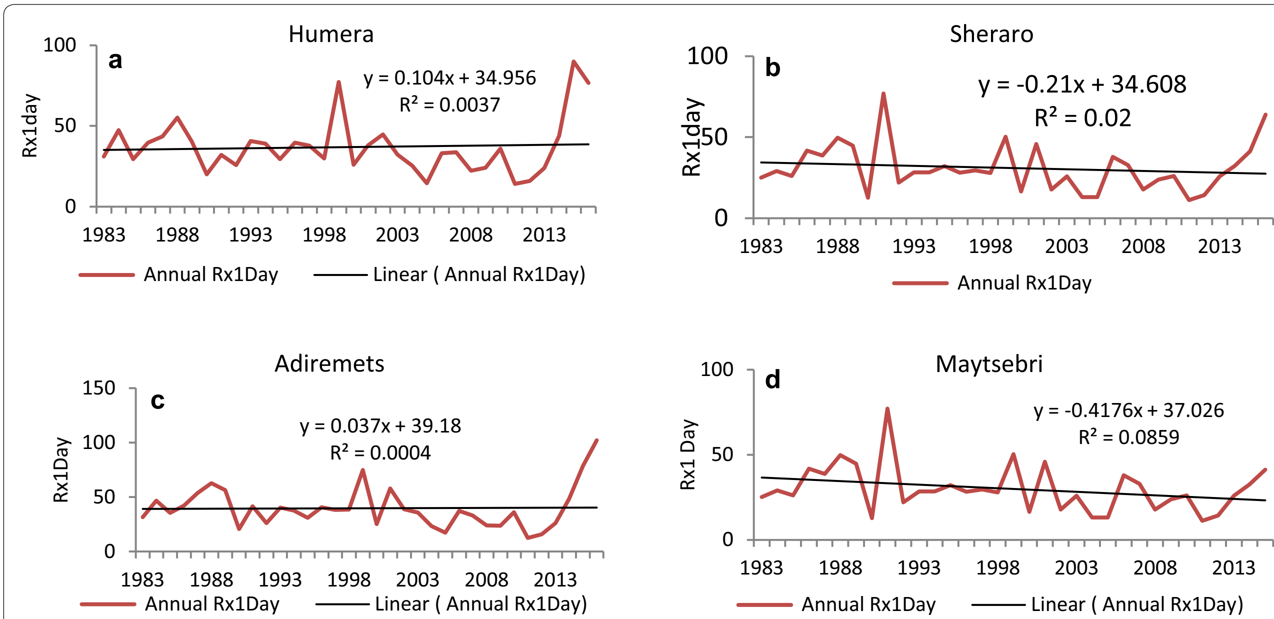

Fig. 16 Annual maximum one-day rainfall (Rx1Day) at **a** Humera, **b** Sheraro, **c** Adiremets, **d** Maytsebri

study areas except at Badime, where there was a positive trend. The steepest values for extremely wet days were −1.76 and −1.18 days/year at Maygaba, and Humera, respectively while, the smallest negative value on R99p 0.012 days/year was recorded at Adigoshu.

Maximum 1-day (Rx1day) and maximum 5-day (Rx5day) rainfall

The maximum average annual Rx1day rainfall (Fig. 16) revealed a negative trend in most of the stations, except at Humera, Dansha, and Adiremets. The maximum Rx1day

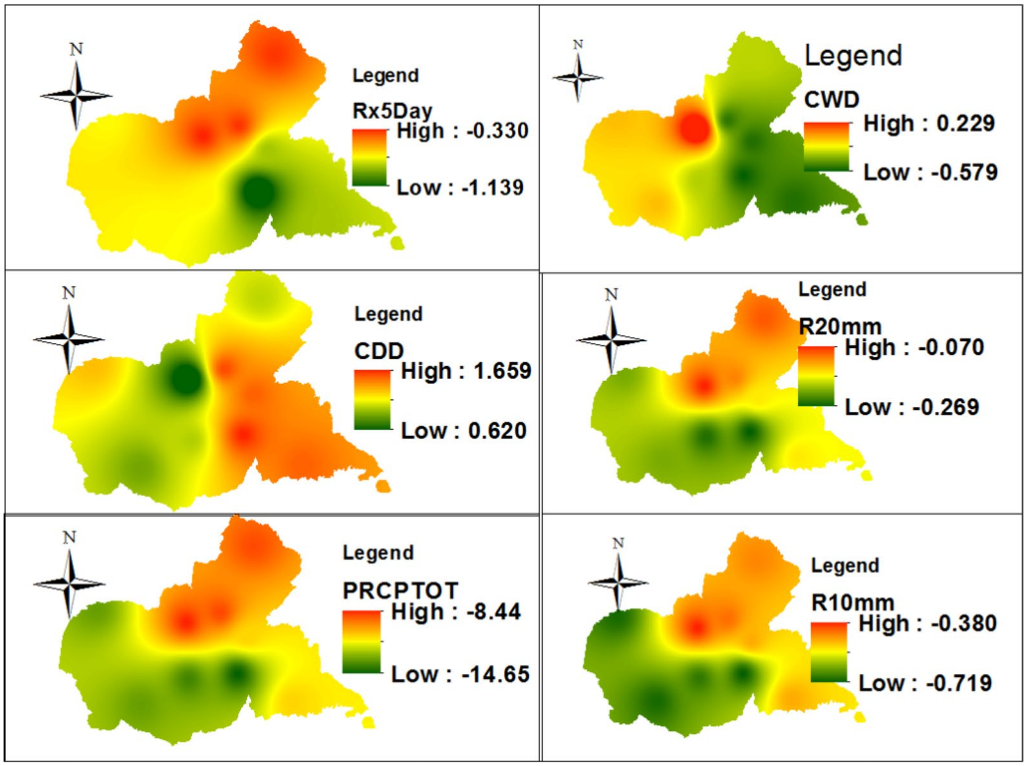

Fig. 17 Total rainfall (PRCPTOT), CDD (consecutive dry days), R10mm (heavy rain days), R20mm (very heavy rain days), Rx1Day (maximum 1 day rainfall), Rx5Day (maximum 5xDay rainfall) of nine stations from 1983 to 2016

rainfall at Humera, Dansha, and Adiremets showed an increasing trend between 0.1 and 0.037 mm/year; with maximum Rx1day annual rainfall of 89.9 mm at Humera, and Dansha in 2015, and 102.3 mm at Adiremets in 2016.

Trend analysis on maximum Rx5day rainfall (Table 4) showed a negative trend throughout the study site. The maximum Rx5day rainfall at Adigoshu, Adiremets, Badme, Dansha, Dedebit, Humera, Maygaba, Maytsebri, and Sheraro, decreased by 0.33, 0.65, 0.35, 0.66, 0.78, 0.66, 1.14, 0.78, 0.35 mm/year, respectively. The results indicated that there was no significant ($p < 0.05$) variability on Rx1day and Rx5day throughout the study sites.

In addition to temporal analysis on extreme rainfall indices, we also analyzed spatial analysis for the different rainfall indices. The results on PRCPTOT revealed, the highest variability was observed at Humera, Dansha, Adiremets and Maygaba in the Western part of the study area; whereas, there was a relatively smaller variability around Badme, Sheraro, and Adighoshu, when compared to areas around Dedebit and Maytsebri where, relatively moderate reduction was observed (Fig. 17).

The highest and smallest spatial variability on CDD was observed at Maytsebri and Humera in the time series, respectively; whereas, at Adigoshu and Adiremets, CDD was relatively moderately increasing. On the contrary, the highest reduction on CWD was observed at Sheraro, Dedebit, Maygaba and Maytsebri areas. The spatial analysis on CWD revealed that there was a relatively lowest (steady) reduction at Adigoshu. Similarly, the highest reduction on Rx1day was observed at Dedebit, Maygaba, and Maytsebri, and Humera, Dansha and Badme revealed a relatively smaller change on Rx1day in the time series. The spatial analysis results also showed that there was high variability on R10mm around Humera, Dansha, Adiremets and Maygaba in the western part, whereas, there was a relatively smaller variability around Adigoshu areas. The results also showed that Maytsebri and Dedebit experienced moderate change on R10mm when compared with the highest and smallest changes in the western part and in areas around Badme and Sheraro. Similarly, there was a relatively high variability on R20mm in the western parts of the study area with a relatively smaller change at Adigoshu areas. The western parts of Tigray experienced a relatively similar change on R10mm and R20mm throughout the study area with the highest changes around Humera, Dansha, Adiremets, and Maygaba areas, with smaller changes around Adigoshu (Fig. 17).

Discussion

In this study, eight and nine extreme temperature and nine rainfall indices, respectively were analyzed using RClimDex software. We analyzed temporal and spatial variability of extreme temperature (Tables 2, 3, and Fig. 9) and rainfall indices (Tables 2, 4, and Fig. 17) using ArcMap software, and simple statistical analysis using excel, after analyzing using RClimDex software. Cooling indicator values like monthly minimum value of daily maximum temperature, cool nights and cool days indicator values revealed a negative trend throughout the study area. Whereas, warming indicator values like minimum and maximum temperature, warm days and warm nights showed a significant increase over the study area. The coefficient of determination (R^2) for TXx and TNn in the time coarse range between 0.1 to 0.22, and 0.04 to 0.09, respectively; with an increase in the time span ranging from 10% to 22% for TXx, and 4% to 9% for minimum temperature.

Conversely, extreme rainfall indices like total rainfall (PRCPTOT), R10mm, R20mm, Rx1day, Rx5day, and heavy and very heavy rains were decreasing significantly ($p < 0.05$) throughout the study area. The highest annual rainfall (PRCPTOT) variability was observed at Adiremets, and Maygaba areas with 13.85 mm and 14.65 mm, respectively; and the smallest change in RPCTOT 8.44 mm was observed at Adigoshu.

Increasing in the number of CDD and decreasing in the number of CWD in the study area, especially during the main rainy season, could affect crop growth and yield, availability of water for irrigation, animals and municipal uses. Total rainfall (PRCPTOT), R10mm, R20 mm, R95p, R99p, and Rx5Day, showed a negative trend from 1983 to 2016 throughout the study areas. Results from linear regression on PRCPTOT showed, 9% to 16% of the variability was expressed by the temporal changes in the time span. The reduction in amount of rainfall in the time span, can affect crop water requirement of rain-fed crops, increase water demand for supplementary irrigation, and affecting groundwater potential in the semi-arid areas of the western Tigray. Subsequently, rural livelihood could be prone to prolonged drought and water stress (Addisu et al. (2015), with inevitable impact on surface and groundwater losses through evapo-transpiration.

Except for Rx1Day and Rx20mm, nine of the selected extreme rainfall indices illustrated a negative trend at all stations. Rx1Day and 20mm indices did not reveal similar distribution across the selected stations in the study area. Negative trends on consecutive dry days (Fig. 10), consecutive wet days (Fig. 11) and Rx10mm (Fig. 13) are similar to the results reported by Mekasha et al. (2014). This study is in agreement with the results found by Yirga et al. (2017), Addisu et al. (2015) and Asfaw et al. (2018), and Conway et al. (2011) in different parts of Ethiopia. Gummadi et al. (2017) stated that there is a temporal and spatial variability of rainfall in Ethiopia, might be due to seasonal changes and topography. Similarly, Gebrechorkos et al. (2018) also found that there was a tendency in increasing extreme temperature indices, and irregular rainfall pattern in Ethiopia, Kenya and Tanzania.

The temporal and spatial analysis of extreme rainfall indices indicated that total annual rainfall at all stations was decreasing; which is similar to the rainfall decrement in Eastern and Southern zones of Tigray (Hadgu et al. 2013). The spatial analysis of extreme rainfall indices (Fig. 17) indicated there was a high spatial variability across the different stations. Total rainfall (PRCPTOT), consecutive wet days, consecutive dry days, heavy rainfall, very heavy rainfall, maximum 1xday, and 5xday rainfall revealed that there was high variability from station to station. The pattern of variability for Rx1Day at the different stations indicated a positively varying pattern at Adiremets, Humera, Badime, and Dansha, whereas, there was a negatively varying trend at Adigoshu, Dedebit, Maytsebri, Maygaba, and Sheraro. In this case, the increase in Rx1Day at the different stations may cause flash floods. Such variability on extreme rainfall indices in the study area might due to the migration of the Inter-tropical Convergence Zone (ITCZ) in the northern parts (Diro et al., 2011; Seleshi and Demaree 1995).

Results on TXx, TX90P, TN90P, WSDI; and negative trends on TX10P, TN10P and CSDI values were in agreement with the findings by Gebrechorkos et al. (2018) and, Mekasha et al. (2014). Alexander et al. (2006) found there was a significant decrease in the annual occurrence of cold nights and a significant increase in the annual occurrence of warm nights over 70% of the global land area sampled. The frequency of extreme weather events such as cold days and cold nights have become less frequent, while hot days and hot nights become more frequent (IPCC 2007); which can exacerbate distribution and infection of malaria. Moreover, leishmaniasis, a vector-borne disease commonly infects human being, in particular to laborers coming from highland areas (Tedla et al. 2018), during peak times of sesame production and harvesting. Such infection can be inevitably caused due to seasonal variability on extreme climatic conditions; which the distribution and infection of the vector depend on extreme weather conditions (Cardenas et al. 2006), like extreme temperature and rainfall indices.

The results showed that the western part of Tigray experienced extreme warming, and substantial reduction in extreme rainfall indices during the past three decades. The increase in warming indicator values across the stations would have negative consequences on increasing crop evapo-transpiration, soil moisture and ground water

(Setegn et al. 2011). Consequently, there could also be a negative impact on irrigation schemes, dry-spell and drought and livestock production in semi-arid areas. In almost all stations, extreme temperature indices indicated similar positive trend, unlike; extreme rainfall indices; which are similar to the results reported by Asfaw et al. (2018) and Ayalew et al. (2012). Increasing in extreme temperature can cause severe yield reduction, and subsequent negative impact in the reproduction stage of many crops (Hatfield and Prueger 2015; Thornton et al. 2014). The rate of photosynthesis and transpiration processes can be hampered by changes in the weather extremes, for example, diurnal temperature variations (Tamiru et al. 2015), and subsequent effects on crop water requirement and soil water balance. Besides, the western part of Tigray is an unexploited high agricultural production area; wshere, livestock production, crop production like sorghum, sesame and cotton crops; and boswellia (*Boswellia papyrifera* (Del)) Hochyst; as industrial tree for export purpose are commonly practiced. However, the area is prone to extreme temperature and rainfall impacts; and to resolve such climatic circumstance, research on suitable climate adaptation strategies are very important.

Conclusions

In this study, we analyzed the foremost extreme temperature and rainfall indices across nine stations in the semi-arid areas of western Tigray as climate variability-indicator variables. The results indicated that there was an increase in warming indicator indices such as warm nights (TN90p), and warm days (TX90p) while there was a significant decrease in cooling indicator values like cold days (TX10p) and cold nights (TN10p), which showed negative trends at all stations.

Results on annual total rainfall (PRCPTOT) showed substantial, decrease from 1983 to 2016 throughout the study area. Similarly, number of heavy rains at all stations showed a considerable reduction. Consecutive dry days in most of the study sites significantly increased, and this increase in the frequency of CDD could have a considerable negative impact on the length of crop growth period (LGP), which affects crop growth and yield.

On the other hand, warming over the study area could have also an increase in water loss through evaporation rate from water bodies, transpiration rate from plant stomata, leading to subsequent decrease in water for agriculture, domestic and municipal uses. On the other hand, the reduction in annual rainfall in the study area could have a negative effect on crop production, livestock feed and food insecurity. Warming of day and night temperatures, and reduction in total annual rainfall, might affect crop growth and productivity, requiring heat resistant and drought tolerant crop genotypes as adaptation strategies. This study provided evidence on the warming of the western part of Tigray, and which the area experienced extreme warming over the last 33 and 34 years. Finally, we conclude, this study develops profound evidence on extreme temperature and rainfall variability, which can be used as a reference for decision-making, planning, and policy implications on agriculture, climate change adaptation and mitigation in the study area, and in Ethiopia at large.

Abbreviations

IPCC: Intergovernmental Panel for Climate Change; MoA: the Ethiopian Ministry of Agriculture; NMA: National Meteorological Agency of Ethiopia.

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Authors' contributions

AB conceptualized this study, collect necessary data, analyzed, interpreted the data, and wrote the manuscript. GH revised and edited the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The authors declare that data is available on the hands of the corresponding author, and can be available on request for the corresponding author.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that there is no competing interest in publishing this manuscript.

Author details

[1] Department of Plant Sciences, Aksum University, Aksum, Ethiopia. [2] Tigray Agricultural Research Institute, Mekelle, Ethiopia. [3] School of Plant and Horticultural Sciences, Hawassa University, Awasa, Ethiopia. [4] Department of Dryland Crop and Horticulture Science, Mekelle University, Mekelle, Ethiopia.

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