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ORIGINAL PAPER

Observed changes in extremes of daily rainfall and temperature in Jemma Sub-Basin, Upper Blue Nile Basin, Ethiopia

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Abstract

Climate variability has been a threat to the socio-economic development of Ethiopia. This paper examined the changes in rainfall, minimum, and maximum temperature extremes of Jemma Sub-Basin of the Upper Blue Nile Basin for the period of 1981 to 2014. The nonparametric Mann-Kendall, seasonal Mann-Kendall, and Sen's slope estimator were used to estimate annual trends. Ten rainfall and 12 temperature indices were used to study changes in rainfall and temperature extremes. The results showed an increasing trend of annual and summer rainfall in more than 78% of the stations and a decreasing trend of spring rainfall in most of the stations. An increase in rainfall extreme events was detected in the majority of the stations. Several rainfall extreme indices showed wetting trends in the sub-basin, whereas limited indices indicated dryness in most of the stations. Annual maximum and minimum temperature and extreme temperature indices showed warming trend in the sub-basin. Presence of extreme rainfall and a warming trend of extreme temperature indices may suggest signs of climate change in the Jemma Sub-Basin. This study, therefore, recommended the need for exploring climate induced risks and implementing appropriate climate change adaptation and mitigation strategies.

1 Introduction

Compelling evidence exists 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 for the period 1880–2012 (Intergovernmental Panel on Climate Change (IPCC) 2013). Similarly, the last three successive decades were warmer globally compared to any other decades since 1850 (Folland et al. 2002; IPCC 2013). Temperature has been showing an increasing trend in almost all regions of the world. While the trend and magnitude of change on rainfall is not conclusive, it may vary by regions and seasons (Tank et al. 2006; Alexander et al. 2006; IPCC 2013; Maidment et al. 2015). An increase in rainfall by 0.5–1% per decade over most middle and high latitudes of the Northern Hemisphere and by 0.2–0.3% per decade over the tropical land areas was estimated in the twentieth century (IPCC 2001, 2013). Likewise, an increase in annual rainfall in the Sahel and Southern Africa regions and a decrease in March–May rainfall in East Africa region was observed over the period from 1983 to 2010 (Maidment et al. 2015). While the focus of most long-term climate change studies have been on changes in average climates. Extreme climate events are more sensitive to climate changes (Alexander et al. 2007; World Metrological Organization (WMO) 2009).

Change in the extremes of rainfall and temperature was observed at various regions of the world. For example, a decrease of the number of cold days and nights, an increase in number of warm days and nights, frequency of extreme high temperatures, and frequency of heavy rainfall were discerned on the second half of the twentieth century (IPCC 2001, 2012, 2013). Changes in extreme climate have profound impacts on society by causing property damage, injury, poverty, loss of life, and biodiversity (IPCC 2012). Moreover, extreme events speedup changes in the ecosystem structure and function more than the average climate (Peterson and Manton 2008; Tierney et al. 2013). Such extreme events demand rigorous risk

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management and adaptation measures, which require a detailed understanding of the trend of climate extremes.

Climate extremes are affecting most of the rural poor where their economy is fully dependent on the climate. For example, Ethiopian economy is characterized by high dependency on rain-fed agriculture which has low adaptive capacity to adverse impacts of climate change (World Bank 2006; Conway and Schipper 2011). There are divergent rainfall trends across the country, which makes rainfall-runoff modeling and drought risk assessment difficult. Several studies (Cheung et al. 2008; Mekasha et al. 2013) reported diverse trends and variability of rainfall in different agro-ecological zones in Ethiopia. For instance, a significant decline of *Kiremt* (June to September) rainfall is recorded in the Baro-Akobo, Omo-Ghibe, Rift Valley, and Southern Blue Nile parts of Ethiopia (Cheung et al. 2008). High variability and non-significant trend of rainfall is reported in pastoral, agro-pastoral, and highlands of Rift Valley, southern range-lands and eastern highlands of Ethiopia (Mekasha et al. 2013). On the other hand, Seleshi and Zanke (2004) found a decline of annual and *Kiremt* rainfall in eastern, southern, and southwestern parts of Ethiopia since 1982. Such a difference in the findings related to rainfall variability arises from differences in spatial and temporal scale of used data and topography of the study areas.

Few studies explore the extreme climatic trends in the Upper Blue Nile Basin, which is one of the major food-producing basins in Ethiopia. The basin has also significant international importance since it contributes more than 60% of the flow to Nile River at Aswan, Egypt (Conway and Hulme 1993; Sutcliffe and Parks 1999). Some studies (Baldassarre et al. 2011; Mengistu et al. 2013) showed increasing trends in both annual minimum and maximum temperature. Mengistu et al. (2013), using linear trend analysis, showed a statistically non-significant increasing trend of rainfall by 35 mm per decade. Likewise, applying the Mann-Kendall and Sen's slope test, Tesemma et al. (2010) found a non-significant trend of annual, dry, and rainy season rainfall in the entire Blue Nile Basin from 1963 to 2004. On the other hand, Taye and Willems (2012) observed a significant decrease in 1980s and non-significant increase in the 1960s and 1970s as well as in the 1990s and 2000s on the trend of rainfall extremes for the entire Upper Blue Nile basin. Most of the studies in the Upper Blue Nile basin are done for the entire Upper Blue Nile Basin which has diverse climate. It is, therefore, important to study the spatio-temporal variability of extremes of rainfall and temperature at sub-basins level to implement appropriate local adaptation and mitigation strategies to climate extremes.

This study is focused on one of the sub-basins of the Upper Blue Nile basin called Jemma, which is vulnerable to frequent drought and extreme cold temperature events (Tesso et al. 2012). The Jemma Sub-Basin is characterized by high soil erosion and sedimentation more than any other sub-basins of the Upper Blue Nile basin (Betrie et al. 2011). Frequent climate variability and climate extremes affect agricultural production and also aggravate land degradation unless appropriate watershed management practices are implemented. This paper, therefore, aims to study the recent daily extremes, mean annual and seasonal trends of rainfall, and temperature in selected climatic stations of Jemma Sub-Basin, which aid for planning appropriate adaptation and mitigation strategies. Findings from this study could be applied to areas which have similar agro-ecology to the Jemma Sub-Basin in Ethiopia or other regions in Africa.

2 Materials and methods

2.1 Description of the study area

This study is conducted in Jemma Sub-Basin, which is located in south-eastern part of the Upper Blue Nile Basin in the central highlands of Ethiopia (Fig. 1). It has a catchment area of ~15,000 km^2. It accounts ~8% of the area of the Upper Blue Nile Basin and contributes ~14% of the total annual flow to the Upper Blue Nile basin (Yilma and Awulachew 2009). The Jemma Sub-Basin also discharges significant amount of sediment to the Upper Blue Nile River (Ali et al. 2014). The long-term average annual sediment yield is estimated at 21.2 million t/year (Ali et al. 2014). The elevation of the sub-basin ranges between 1040 and 3814 m above sea level and consists of different agro-ecologies from cold moist sub-afro alpine to warm sub-moist lowlands (Fig. 1) (MoA 2000).

The rainfall of Central Highland of Ethiopia, where Jemma Sub-Basin is located, is driven by the moisture from Indian Ocean, equatorial east Pacific, Gulf of Guinea, Mediterranean region, and Arabian Peninsula (Seleshi and Zanke 2004; Viste and Sorteberg 2011). Jemma Sub-Basin receives annual rainfall between 697 and 1475 mm. The main rainfall season in Ethiopia occur from June to September (summer), which is locally called *Kiremt.* Minor rainfall may also happen from March to May (spring) and this season is locally called *Belg*. Among the stations in the Jemma Sub-Basin, Andit-tid and Lemi stations receive higher annual rainfall while Wereilu and Mehalmeda stations receive lower annual rainfall (Fig. 2). Mean annual temperature in the sub-basin ranges from 9 to 24 °C.

According to the 2007 Ethiopian census, the total population of Jemma Sub-Basin was 1,605,876, and the growth rate of the population was 1.7 and average population density was 106 person/km^2 (CSA 2007). In the year 2017, the projected total inhabitants in the sub-basin is 2 million and the growth rate of the population is 2.41 (CSA 2013). Rainfed agriculture in the form of cultivation of crops and domestication of livestock are the main livelihoods of the inhabitants.

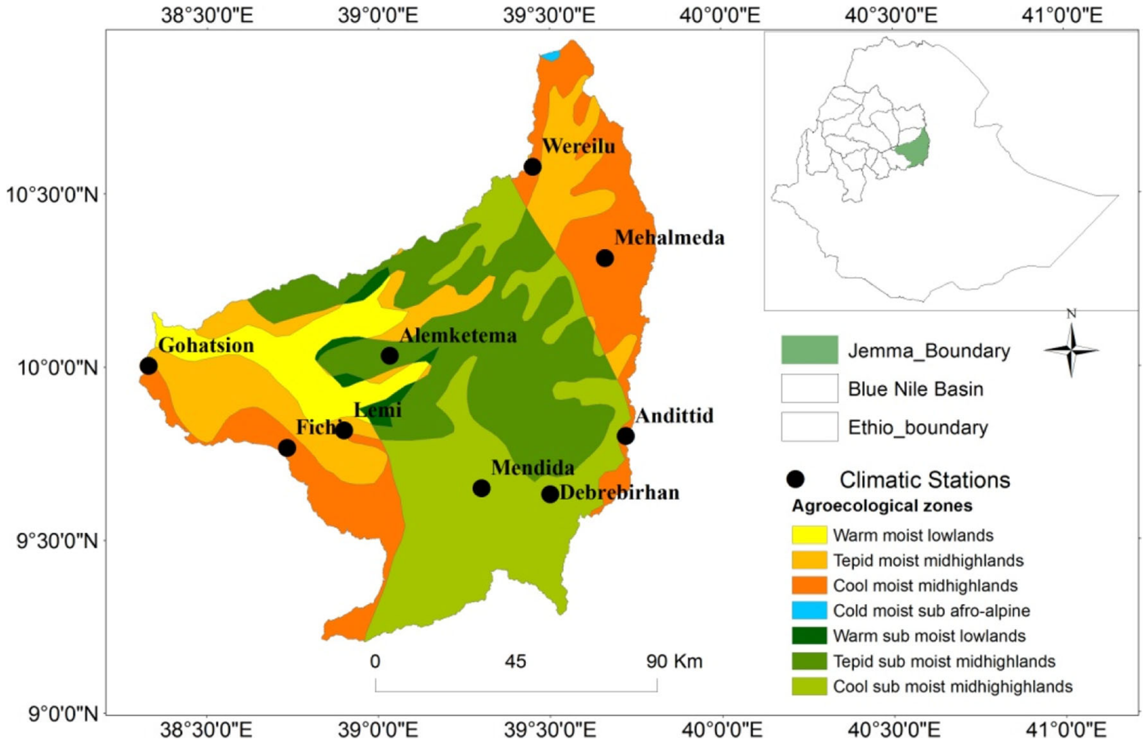
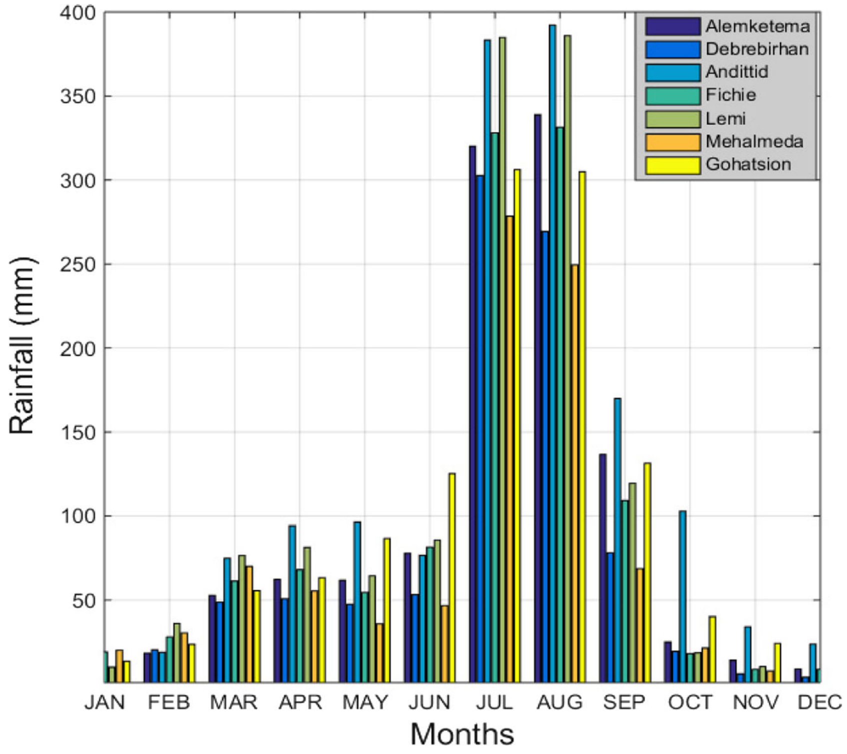


Fig. 1 Agro-ecological zones and climatic stations in Jemma Sub-Basin

The main crops cultivated in the Jemma Sub-Basin are wheat, barley, teff, maize, and sorghum (Fig. 3a). The forest cover in the sub-basin is characterized by sparse woody vegetation, with Eucalyptus trees close to the villages. Cama et al. (2017) reported expansion of cultivated land and grazing lands toward the steep slopes and marginal lands which triggers a change in soil structure and accelerated soil erosion in the form of sheet and gullies. The river channel and the lower part of the sub-basin are characterized by bare-land (Fig. 3a). The majority of the sub-basin (~80%) has *Eutric cambisols*,

Fig. 2 Long-term average monthly rainfall for the climatic stations



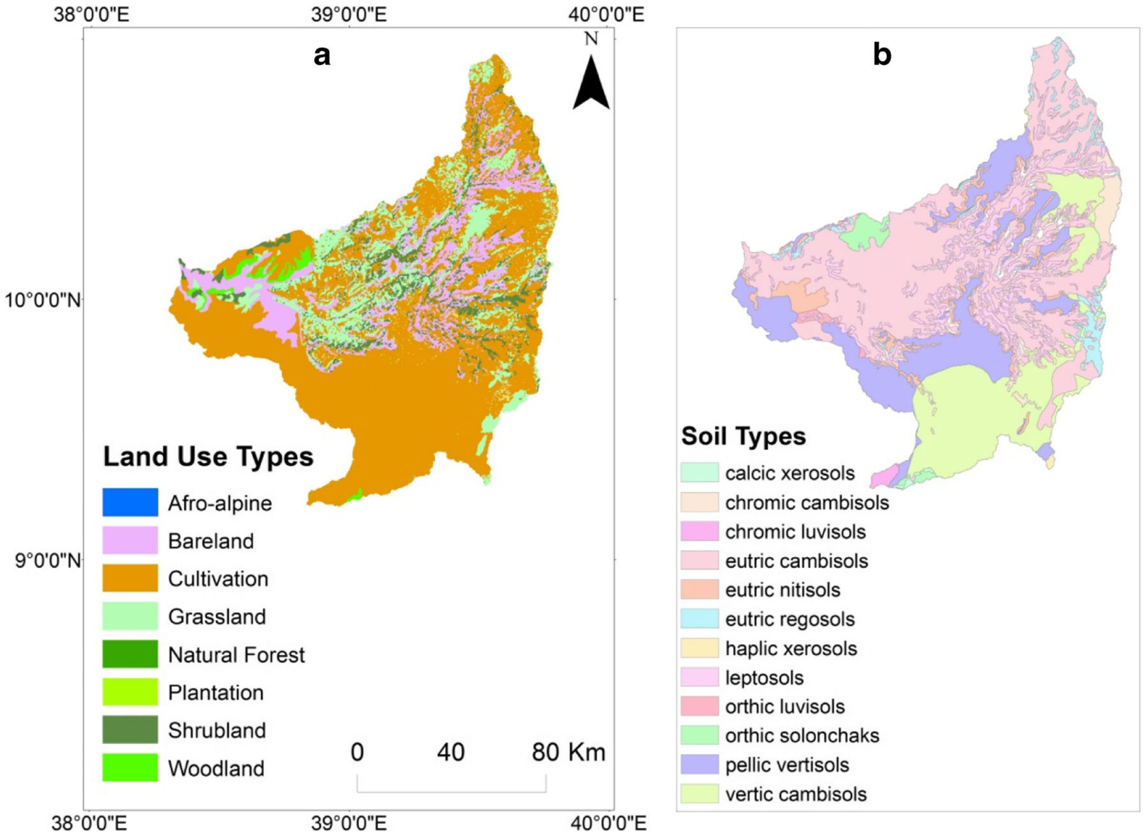


Fig. 3 Soil and land use types in Jemma Sub-Basin

pellic verisols, and *veric cambisols* soil types (Fig. 3b) (MoWR 1998).

2.2 Data pre-processing and quality control

Daily observed climate data (i.e., rainfall, maximum, and minimum temperature) for the period from 1960 to 2015 were collected from the Ethiopian National Meteorological Services Agency (www.ethiomet.gov.et/) for the climatic stations located in the Jemma Sub-Basin. Climatic stations that have better quality data were considered for this study. Climate stations that are characterized by several missing values and having length of less than 30 years of rainfall data were excluded from the analysis. Nine climatic stations were found to have with minimal missing data for the period 1981–2014 (Table 1). The data from these stations was used for trend and extreme value analysis. The studied stations are evenly distributed in the sub-basin and represent the diverse agro-ecological zones in the sub-basin (Fig. 1).

The missing data was completed using Multivariate Imputation by Chained Equations (MICE) algorithm (Buuren et al. 2015), which is available on R statistical software (R Development Core Team 2015). The MICE algorithm calculates missing values at a single station using the complete observed values of all stations under study as predictors. The MICE creates multiple predictions for each missing value and considers uncertainty in the calculations and provides standard errors (Buuren et al. 2015). As such, the MICE algorithm is better than other methods such as inverse distance weighting (IDW) and multiple linear regression (MLR) in completing missing data (Turrado et al. 2014).

The quality of the data of all the stations was examined using RClimDex 1.1 (Zhang and Yang 2004). The quality control involves errors such as minimum temperature greater than maximum temperature, and negative rainfall values, which were corrected using the nearby stations. Outliers which are values plus or minus four times standard deviation were replaced by average values of days before and after the outlier's day. The data after the quality control was used for trend and extremes analysis.

2.3 Rainfall and temperature trend analysis

Trend of annual rainfall, annual maximum temperature ($T_{\max}$), and annual minimum temperature ($T_{\min}$) were estimated using non-parametric Mann-Kendal test (Kendall 1975; Mann 1945). The test is considered statistically significant when the level of significance is less than or equal to 5%. The Mann-Kendall test statistic is calculated as

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{sgn}\left(X_j - X_i\right) \quad (1)$$

Table 1 Description of studied climatic station

Stations	Geographical coordinates		Elevation (m)	Annual rainfall (mm)	Period of observation
	Longitude (°)	Latitude (°)			
Alemketema	39.03	10.03	2280	1123	1981–2014
Debrebirhan	39.50	9.63	2750	908	1981–2014
Fichie	38.73	9.77	2784	1106	1981–2014
Lemi	38.90	9.82	2500	1278	1981–2014
Mehalmeda	39.66	10.32	3084	884	1981–2014
Gohatsion	38.24	10.00	2507	1187	1981–2014
Wereilu	39.44	10.58	2708	697	1981–2014
Andit Tid	39.72	9.80	3248	1475	1986–2014
Mendida	39.30	9.65	2800	956	1988–2014

$$sgn(x) = \begin{cases} 1 \ if \ x > 0 \\ 0 \ if \ x = 0 \\ -1 \ if \ x < 0 \end{cases} \quad (2)$$

where X_j and X_j are the annual values in years j and i, $j > i$, respectively. A positive and negative value of S indicates an increasing and decreasing trend, respectively.

The seasonal Mann-Kendall trend test (Hirsch et al. 1982) was computed for each season separately to estimate the trend of rainfall on two main rainy seasons of the study area, i.e., *Kiremt* and *Belg*. The seasonal Kendall tests monotonic trend in a time series with seasonal variations such as hydro-meteorological data (Hirsch et al. 1982). Seasonal rainfall was computed using the monthly rainfall for the period 1981–2014.

Unlike ordinary least square (OLS) methods, Mann-Kendall and seasonal Mann-Kendall tests were used for trend detection since they are non-parametric (distribution-free) and not sensitive to single outliers and skewed distributions. Therefore, for rainfall and temperature data which are not normally distributed, it is commendable to use Mann-Kendall and seasonal Mann-Kendal tests for trend detection.

The slope of trends was calculated using the non-parametric Theil-Sen's slope estimator (Sen 1968; Theil 1950). The Theil-Sen's slope estimator is a robust non-parametric estimator which uses the median slope to assess the trend over time (Sen 1968; Theil 1950). The Theil-Sen's approach is not sensitive to outliers and extreme values which are common in climatological data. It also provides consistent performance in statistical metrics of standard deviation, root-mean-square error (RMSE), and bias of the slope estimator than parametric slope estimators (Shah et al. 2016). Theil-Sen test estimates the median of the slopes (β) using the following equation:

$$\mathrm{b_{Sen}} = \mathrm{median}\left(\frac{y_j - y_i}{x_j - x_i}\right) \quad (3)$$

where $i < j$ and $i = 1, 2, \ldots, n - 1$ and $j = 2, 3, \ldots, n$.

All tests in this study were estimated using the "trend" package (Pohlert 2016), which is built in on R statistical software (R Development Core Team 2015).

2.4 Rainfall and temperature extreme indices analysis

Expert Team on Climate Change Detection and Indices (ETCCDI) (WMO 2009) has defined 27 extreme indices for temperature and rainfall. The indices describe the frequency, amplitude, and persistence of extremes. Based on ETCCDI, 10 rainfall and 12 temperature extreme indices were selected for this study area. Table 2 presents the selected indices with their description and units. The indices were calculated at each climatic station using RClimDex 1.1 (Zhang and Yang 2004). Daily observed rainfall, $T_{\max}$, and $T_{\min}$ were used to calculate these indices. Average of index of all metrological stations was used to estimate sub-basin-wide trend of indices. The standardized anomaly of each index at sub-basin level was calculated as

$$SA_{x,t} \ \frac{(X_t - X_{mean})}{\sigma} \quad (4)$$

where $\mathrm{SA}_{x,t}$ is the standardized anomaly of index x at year t, x_t is the annual index value in year t, x_{mean} is the long-term mean annual index over a period of observation, and σ is the standard deviation of annual index over the period of observation. The 5-year moving average was used to show the annual variation of extremes within the analysis period.

3 Result and discussion

3.1 Trends in annual rainfall and temperature

The annual and seasonal rainfall trend analysis exhibited different trends in the studied climatic stations for the period

Table 2 Selected ETCCDI rainfall and temperature extreme indices for the study area

Index	Index name	Definition of the Index	Units
PRECPTOT	Annual total wet-day rainfall	Annual total PRCP in wet days (RR > =1 mm)	mm
R95p	Very wet days	Annual total PRCP when RR > 95th percentile	mm
R99p	Extremely wet days	Annual total PRCP when RR > 99th percentile	mm
CDD	Consecutive dry days	Maximum number of consecutive days with RR < 1 mm	Days
CWD	Consecutive wet days	Maximum number of consecutive days with RR > =1 mm	Days
R10mm	Number of heavy rainfall days	Annual count of days when PRCP> = 10 mm	Days
R20mm	Number of very heavy rainfall days	Annual count of days when PRCP> = 20 mm	Days
Rx1day	Max 1-day rainfall amount	Monthly maximum 1-day rainfall	mm
Rx5day	Max 5-day rainfall amount	Monthly maximum consecutive 5-day rainfall	mm
SDII	Simple daily intensity index	The ratio of annual total rainfall to the number of wet days (≥ 1 mm)	mm/day
TXx	Max T_{max}	Monthly maximum value of daily maximum temp	°C
TNx	Max T_{min}	Monthly maximum value of daily minimum temp	°C
TXn	Min T_{max}	Monthly minimum value of daily maximum temp	°C
TNn	Min T_{min}	Monthly minimum value of daily minimum temp	°C
TN10p	Cool nights	Percentage of days when TN < 10th percentile	%
TX10p	Cool days	Percentage of days when TX < 10th percentile	%
TN90p	Warm nights	Percentage of days when TN > 90th percentile	%
TX90p	Warm days	Percentage of days when TX > 90th percentile	%
WSDI	Warm spell duration indicator	Annual count of days with at least 6 consecutive days TX > 90th percentile	Days
CSDI	Cold spell duration indicator	Annual count of days with at least 6 consecutive days when TN < 10th percentile	Days
SU25	Summer days	Annual count when TX(daily maximum) > 25 °C	Days
FD0	Frost days	Annual number of days when T_{min}<0 °C	Days

Detailed discussion of the indices is available at WMO (2009)

1981–2014. A decreasing trend of annual rainfall was found in Alemketema and Mehalmeda stations. In the remaining stations, positive trend of rainfall was observed. The annual rainfall trend showed a statistically significant increase in Debrebirhan and Fichie stations (Table 3). For the *Kiremit* rainfall, decreasing trend was observed only in Alemketema station (Table 3). Similar to the annual rainfall trend, a significant increase in *Kiremt* rainfall was found in Debrebirhan and Fichie stations. A decreasing trend in *Belg* rainfall was observed in Fichie, Debrebirhan, Mehalmeda, and Mendida stations and significant at Alemketema station (Table 3 and Fig. 4). This indicates a shift of bimodal pattern of the rainfall to unimodal in the Jemma Sub-Basin.

Similar to this study, Mengistu et al. (2013) found an increase of annual rainfall in moist and sub-moist agro-ecologies of Jemma Sub-Basin for the period 1981–2010. Bewket and Conway (2007) have also reported positive but non-significant trend of rainfall in Debrebirhan station for the period 1975–2003. On the other hand, Cheung et al. (2008) estimated a decrease of *Kiremt* rainfall by 2.6 mm/year and an increase of *Belg* rainfall by 0.6 mm/year for the period 1960–2002 in Fichie station. The difference with these findings may be related to difference in the study period.

An increasing trend but different in magnitude was observed for T_{max} and T_{min} in all the climatic stations of the Jemma Sub-Basin (Table 4). Statistically significant increase of T_{max} was observed in 88% of the stations. This may suggest that climate change is behind the increase in temperature in the Jemma Sub-Basin. An increasing trend

Table 3 Trend of annual summer and autumn rainfall

Stations	Annual		Summer		Spring	
	S	b_{sen}	S	b_{sen}	S	b_{sen}
Alemketema	−1.50	−6.54	−0.20	−0.48	−2.00*	−2.43
Debrebirhan	2.00*	3.45	2.40*	5.02	−0.60	−0.79
Fichie	2.80*	5.88	3.70*	8.70	−1.60	−1.72
Lemi	1.30	6.70	1.30	5.40	1.00	1.80
Mehalmeda	−0.30	−0.76	0.80	2.06	−0.60	−1.00
Gohatsion	1.40	4.70	1.20	2.58	0.20	0.53
Wereilu	0.40	1.00	1.20	2.12	0.00	−0.07
Andittid	1.30	9.67	1.30	6.10	0.10	0.41
Mendida	1.10	6.02	1.60	5.64	−0.60	−0.39

S and b_{sen} are Mann-Kendal test and Sen slope values, respectively

*Trends significant at the 5% level

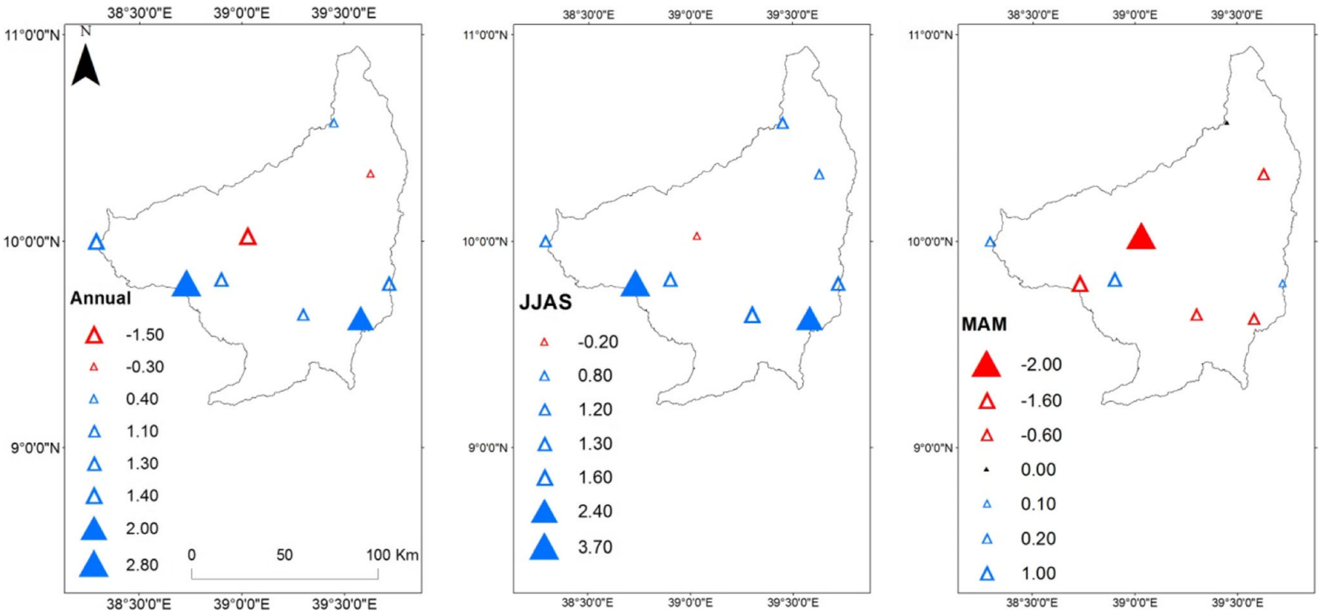


Fig. 4 Spatial variations of rainfall trends at the annual and seasonal scales in Jemma Sub-Basin for the period 1981–2014. Blue and red triangles indicate increasing and decreasing trends, respectively. Filled triangles indicate significant trends at the 5% significance level based on the Mann-Kendall test. While the open triangles show non-significant trends. The size of triangles is proportional to the magnitude of the trend

was divulged in T_{min} in all of the stations except Andit-tid and Gohatsion. The increase in T_{min} is insignificant in Debrebirhan and Mehalmeda stations. While, increasing trend of T_{min} in stations located in higher altitude and cool sub-moist, cool moist, and sub-afro-alpine agro-ecologies is low in magnitude and statistically insignificant. The trend of T_{min} in Andit-tid station which is located in cold sub-afro-alpine agro-ecology is significantly negative. Perhaps, the presence of forests may stabilize the local climate and contribute to the reduction in T_{min}. However, such an assertion requires detailed investigation.

The increase in trend for the maximum temperature was higher than the minimum temperature. Mengistu et al. (2013) corroborated the findings to this study reporting an increasing trend in mean T_{max} and T_{min} in moist and sub-moist agro-ecologies of Jemma Sub-Basin. Likewise, Tesso et al. (2012) also reported increasing trend in T_{max} for Fichie station by 1.5 °C from 1982 to 2014.

3.2 Trends in rainfall extremes

The trend in annual total wet-day rainfall (PRECPTOT), very wet days (R95p), and extremely wet days (R99p) showed an increase in most of the stations (Fig. 5). The trend in PRECPTOT was similar to the annual rainfall trend and it was only in Alemketema and Mehalmeda

Table 4 Trends for annual T_{max} and T_{min} in the climatic stations of Jemma Sub-Basin

Stations	Longitude (°)	Latitude (°)	T_{max}		T_{min}	
			S	b_{sen}	S	b_{sen}
Alemketema	39.03	10.03	0.05*	4.20	0.05*	3.90
Lemi	38.90	9.82	0.03	1.50	0.09*	3.80
Fichie	38.73	9.77	0.03*	2.30	0.02*	2.30
Gohatsion	38.24	10.00	0.05*	3.90	0.00	0.1
Debrebirhan	39.50	9.63	0.03*	3.40	0.02	1.70
Mehalmeda	39.66	10.31	0.03*	4.10	0.01	1.10
Wereilu	39.44	10.58	0.02*	4.90	0.01*	4.2
Andittid	39.72	9.80	0.09*	3.20	−0.06*	−4.4
Mendida	39.30	9.65	0.03*	2.50	0.03*	2.9

S and b_{sen} are Mann-Kendal test and Sen slope values, respectively

*Trends significant at the 5% level

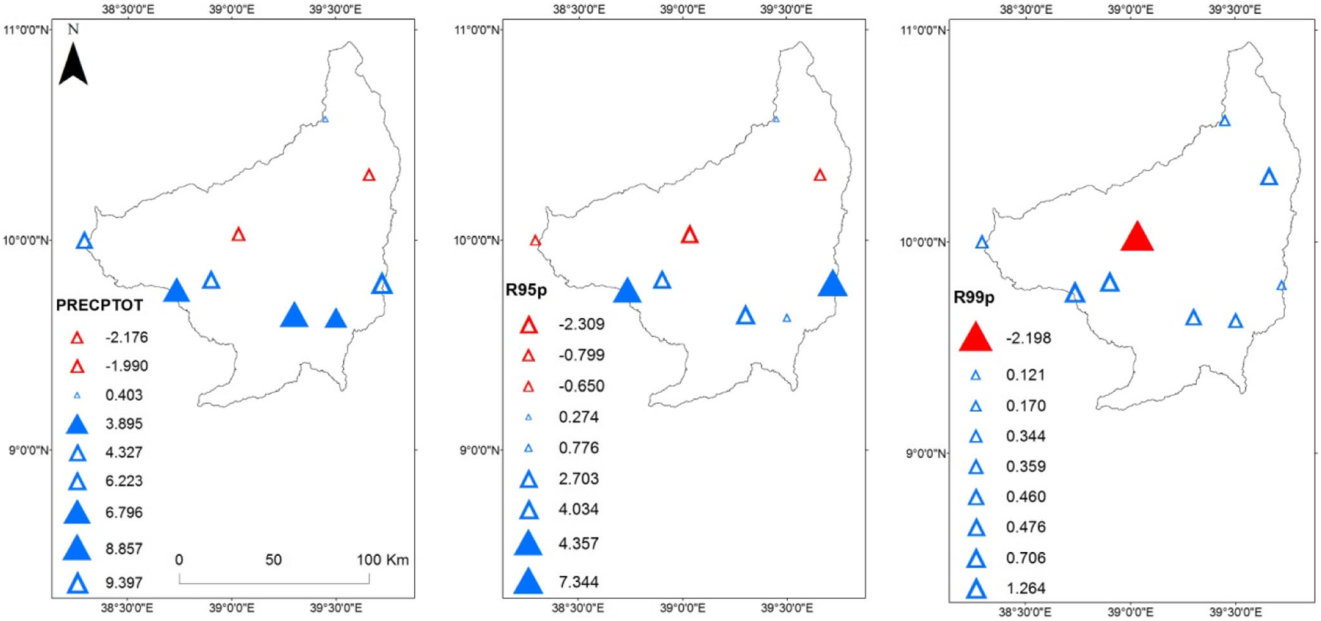


Fig. 5 Trends (mm/year) in PRECPTOT (annual total wet-day rainfall), R95p (very wet days), and R99p (extreme wet days). Blue and red triangles indicate increasing and decreasing trends, respectively. Solid triangles indicate significant trends at the 5% significance level. While the open triangles show non-significant trends. The size of triangles is proportional to the magnitude of the trend

where the trend was decreasing. The increase of R95p in Fichie and Andit-Tid stations and R99p in Fichie and Lemi stations were higher than other stations. Alemketema is the only climatic station where all rainfall extreme indices (e.g., Rx1DAY, Rx5DAY, R99p, and R95p) showed a downward trend. An increasing trend of intensity of extreme rainfall (e.g., R95p and R99p) in most of the climatic stations suggests growing climatic risk on human's livelihoods and other ecosystems. The decreasing trend of rainfall indices in Alemketema may be related to the presence of sub-moist agro-ecological zone.

Higher spatial coherence was found on trend of max 5-day rainfall amount (Rx5DAY). Of all the climatic stations, 88% of the climatic stations had positive trends while only 12% had negative trend. Significant increasing trend of Rx5DAY in Fichie and Mendida stations and significant decreasing trend of Rx1DAY in Alemketema station were observed. In Alemketema, Andit-Tid, Mendida, and Lemi stations, consistency was found between the trend in annual rainfall and Rx1DAY and Rx5DAY indices (Fig. 6). Unlike other extreme rainfall indices, the trend in Simple Daily Intensity Index (SDII) is negative in most of the stations. This suggested that the daily rainfall has been declining.

An increasing trend of R10mm was observed in most of the stations while divergent trends in R20mm were observed among the stations. Fichie station was characterized by significant increase in R10mm and R20mm (Fig. 7). An increase in these indices suggests potential risks related to flooding and soil erosion around the Fitchie area. Likewise, Mekasha et al. (2013) reported a mix of significant decreasing (Negele-Borena and Asela stations) and increasing (Koka station) trends in R10mm and R25mm.

The presence and absence of rainfall greater than 1 mm was measured using consecutive wet days (CWD) and consecutive dry days (CDD), respectively. Unlike other climatic stations, Alemketema station showed a decreasing trend in CWD and an increasing trend in CDD. This suggests an increase in aridity in this station. An increasing trend of CWD is significant in Debrebirhan and Mendida stations, which are found in cool sub-moist agro-ecological zone (Fig. 8). CDD is significantly decreasing in Lemi station.

The extreme rainfall indices analysis showed an increase in most extreme rainfall indices in the entire sub-basin except SDII (Fig. 9). This divergent trend in rainfall extremes substantiates that rainfall trend has not been stable in the Jemma Sub-Basin. This suggests that extreme rainfall events may pose damages on socio-economic activities and ecosystems.

Similar to this study, other research (Seleshi and Zanke 2004; Seleshi and Camberlin 2006) reported non-significant increase in Rx5DAY, very wet day, and extreme wet day rainfall in the central highlands of Ethiopia for the 1965–2002. Mekasha et al. (2013) have also investigated an increasing trend of precipitation extreme indices such as Rx1DAY, Rx5DAY, and R99p in stations located in the highlands of Ethiopia (e.g., Asela, Kulumsa, and Kofele stations) for the period 1967 to 2008. However, they reported a mix of significant decreasing (Negele-Borena and Asela climatic stations) and increasing (Koka climatic stations) trends in R10mm and R25mm. In contrast, significant decrease of Rx5DAY, very wet day, and extreme wet day rainfall was detected in eastern

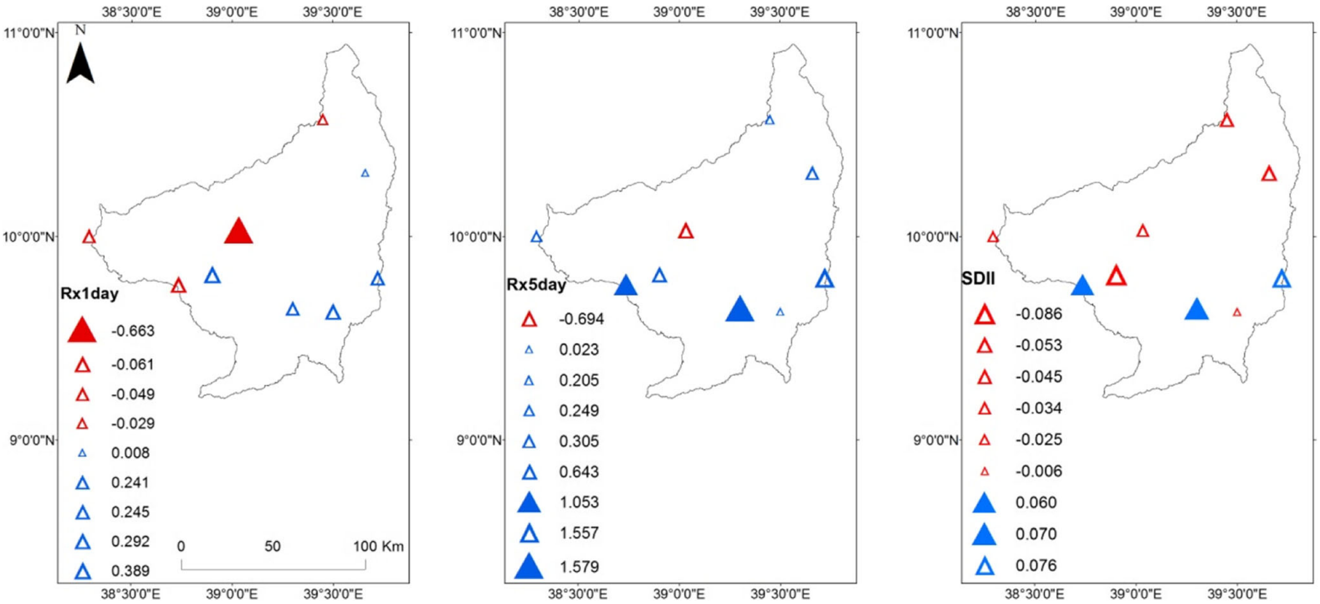


Fig. 6 Trends (mm/year) in Rx1DAY (max 1-day rainfall amount), Rx5DAY (max 5-day rainfall amount), and trends (mm/day) in SDII (Simple Daily Intensity Index). Blue and red triangles indicate increasing and decreasing trends, respectively. Solid triangles indicate significant trends at the 5% level. While the open triangles show non-significant trends. The size of triangles is proportional to the magnitude of the trend

(e.g., Jigjiga and Negele stations) and south-western (e.g., Gore station) part of Ethiopia from 1965 to 2002 (Seleshi and Zanke 2004; Seleshi and Camberlin 2006). Shang et al. (2011) reported no significant increasing trend in extreme

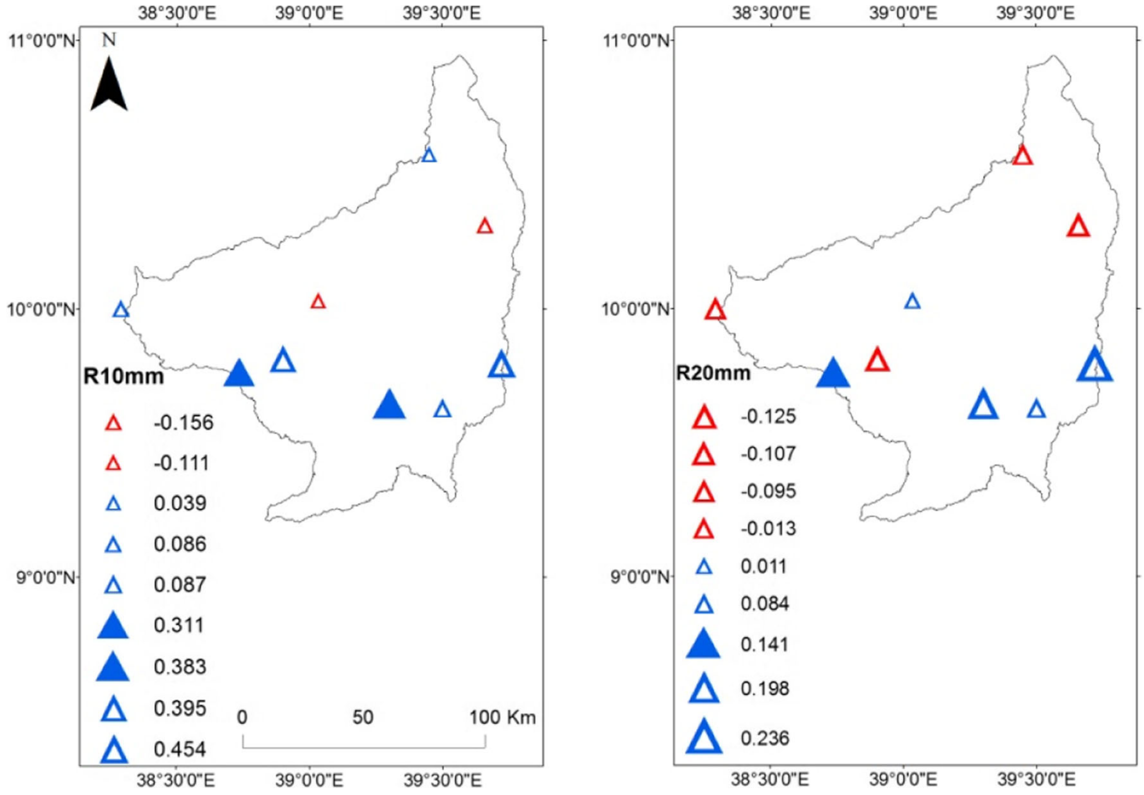


Fig. 7 Trends (days/year) in R10mm (number of heavy rainfall days) and R20mm (number of very heavy rainfall days). Blue and red triangles indicate increasing and decreasing trends, respectively. Solid triangles indicate significant trends at the 5% significance level. While the open triangles show non-significant trends. The size of triangles is proportional to the magnitude of the trend

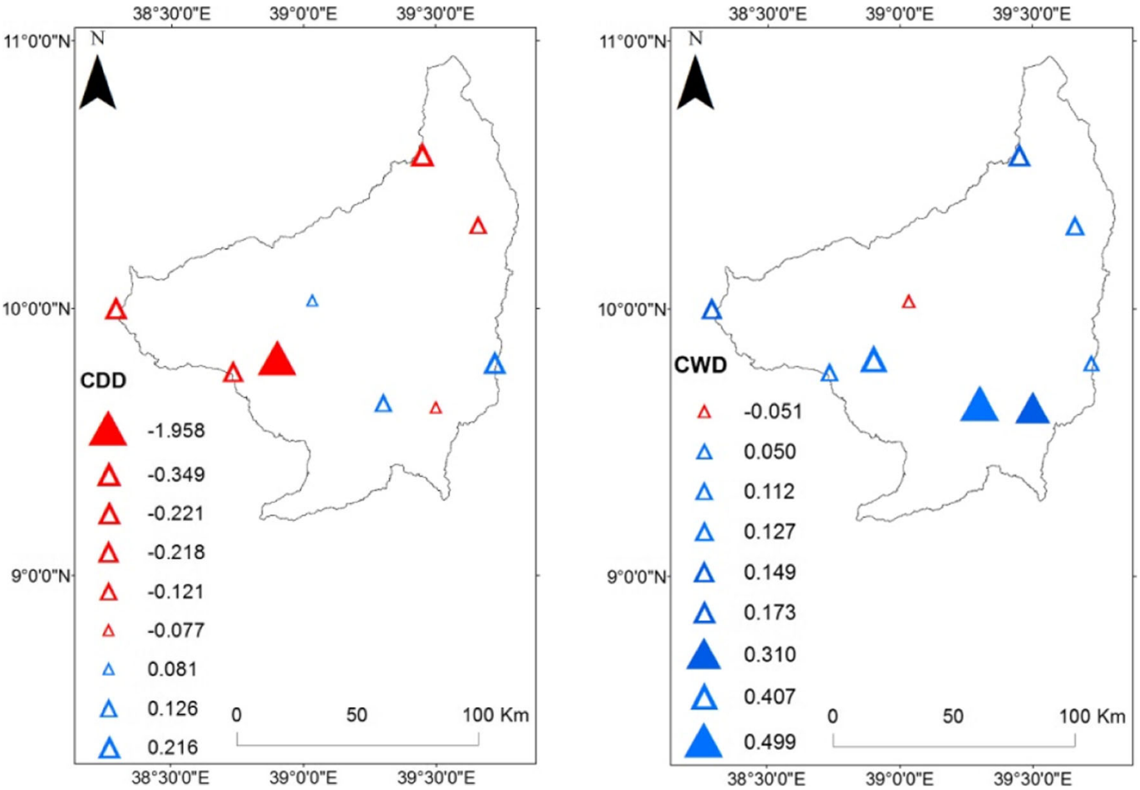


Fig. 8 Trends (days/year) in CDD (consecutive dry days) and CWD (consecutive wet days). Blue and red triangles indicate increasing and decreasing trends, respectively. Solid triangles indicate significant trends at the 5% significance level. While the open triangles show non-significant trends. The size of triangles is proportional to the magnitude of the trend

precipitation (R95p) in north-western highlands of Ethiopia (e.g., Debremarkos station) during the period 1953–2006.

The change in most of rainfall extremes indices in Jemma Sub-Basin is in agreement with the global trend, where an increase in frequency, intensity, and spatial extent of rainfall extremes was reported (IPCC 2012, 2013). This can be attributed to global climate change and other large-scale as well as local-scale drivers. For example, on 70% of global land area, an increase in the number of heavy rainfall days and its contribution to annual total rainfall amount is reported (Alexander et al. 2006). Large-scale processes such as Intertropical Convergence Zone (ITCZ), pressure systems of Indian Ocean, equatorial east Pacific, Gulf of Guinea, Mediterranean region, and Arabian Peninsula also influence the rainfall in the central highlands of Ethiopia (Seleshi and Zanke 2004; Viste and Sorteberg 2011). Apparently, extreme weather events in Ethiopia are associated with global climate drivers such as tropical Pacific Ocean currents (EPCC 2015). Therefore, the changes in rainfall extremes in Jemma Sub-Basin can also be contributed by changes in these large-scale climate drivers. Similarly, local-scale climatic controls (e.g., diverse physiographic features) can be important drivers to the changes in rainfall extremes in the region (NMSA 1996; Shanko and Camberlin 1998; Bewket and Conway 2007; EPCC 2015).

3.3 Trend in temperature extremes

A warming trend as reflected by an increase on most of the warm extreme indices and a decrease on most of cold extreme indices in the entire stations of the study was observed. The trend of indices of intensity of temperature extremes (TXx, TXn, TNx, and TNn) emphasizes warming in the Jemma Sub-Basin (Fig. 10 and Table 2). For instance, upward trend of TXx and TNx is observed in 89 and 78% of the stations, respectively. The trend in TXx and TNx is significant increase in several of the stations even though a large inconsistency was observed. In magnitude, change on indices related to minimum daily temperature (TNx and TNn) is higher than indices related to daily maximum temperature (TXx and TXn). This is in contrast with trend of annual maximum and minimum temperature trend where higher increase is on annual maximum temperature than annual minimum temperature (Sect. 3.1).

Similar to intensity of temperature extreme indices (TXx, TXn, TNx, and TNn), frequency of temperature extremes indices (TN10p, TX10p, TN90p, and TX90p) demonstrate coherent significant warming in most stations (Fig. 11 and Table 2). Increasing trend of warm extreme indices (TX90p and TN90p) and decreasing trend of cold extreme indices (TN10p and TX10p) were observed. This shows that

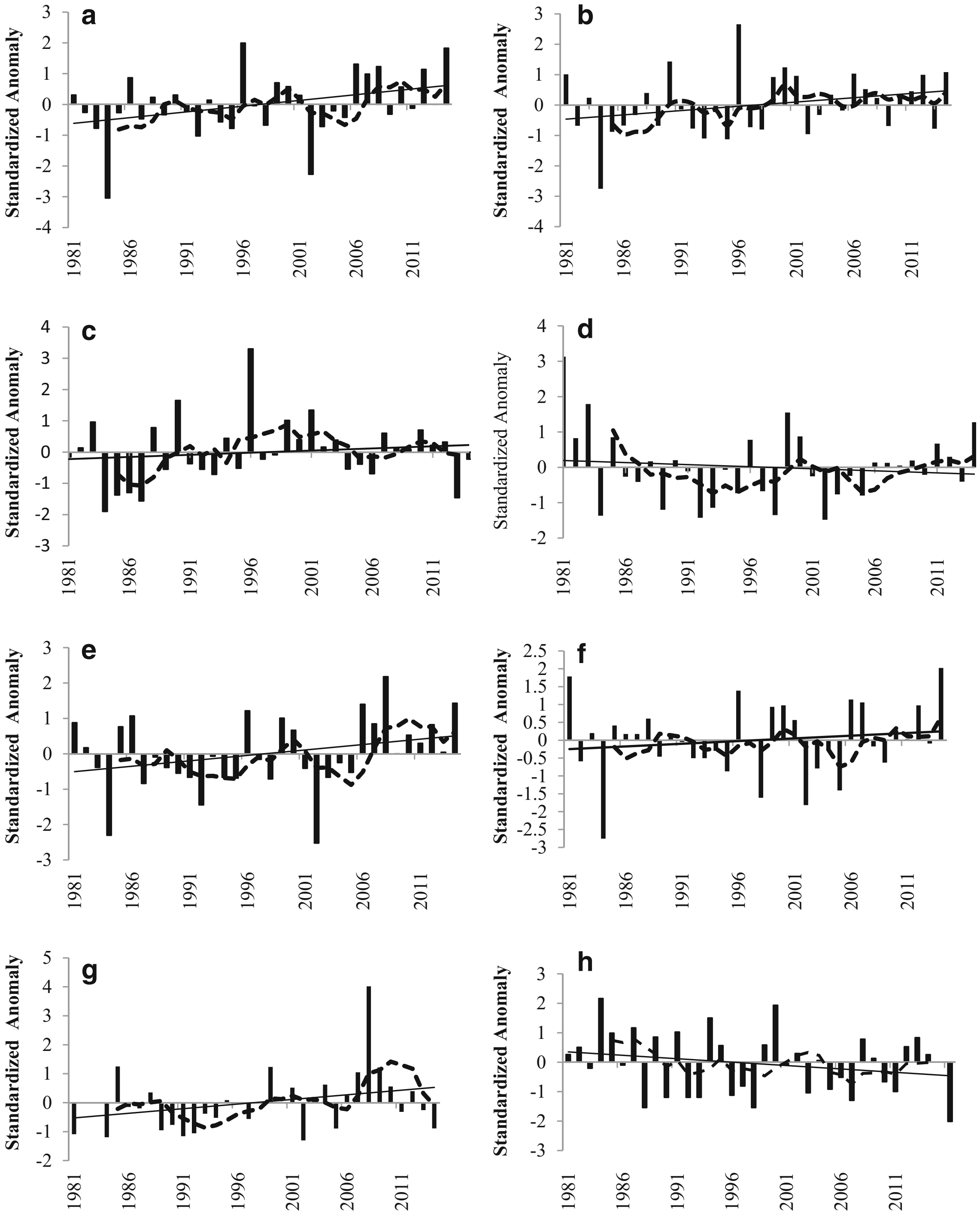


Fig. 9 Average sub-basin wide trends of rainfall extreme indices. **a** Annual total wet-day rainfall (PRCPTOT). **b** Very wet days (R95p). **c** Extremely wet days (R99p). **d** Simple Daily Intensity Index (SDII). **e** Number of heavy rainfall days (R10 mm). **f** Number of very heavy rainfall days (R20 mm). **g** Consecutive wet days (CWD). **h** Consecutive dry days (CDD). The straight line is the linear trend for each variable, whereas dashed line is the trend for the corresponding 5-year moving average

proportion of cool days (TX10p) and cool nights (TN10p) is decreasing and the proportion of warm days (TX90p) and warm nights (TN10p) is increasing. Significant warming trend of TX10p and TN10P at 78% of the stations was observed. Temperature of cool days and cool night was increasing in most of the stations, but the magnitude was higher on TN10p than TX10p. Inconsistent trend of TX10p (cool nights) and TN90p (warm nights) was observed in Andit-tid station. This suggests that night temperature in Andit-tid was getting cold over time and this is perhaps because of afro alpine agro-ecology in Andit-tid area. Such phenomenon of decreasing in the number of cold days and nights and increasing in the

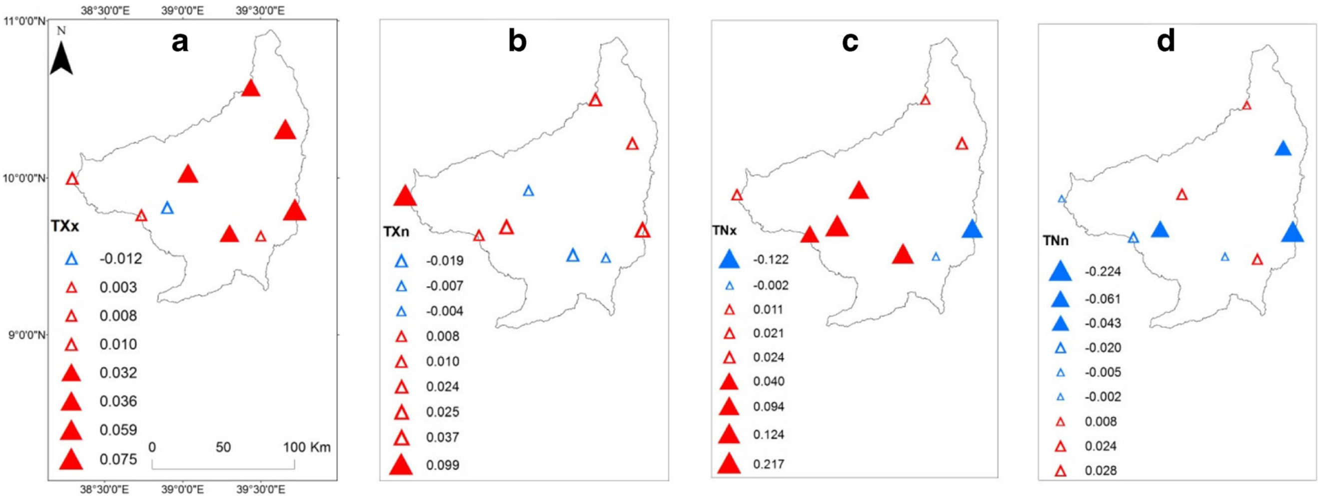


Fig. 10 Trends (°C/year) in **a** TXx (monthly maximum value of daily maximum temp), **b** TXn (monthly minimum value of daily maximum temp), **c** TNx (monthly maximum value of daily minimum temp), and **d** TNn (monthly minimum value of daily minimum temp). Red and blue triangles indicate increasing and decreasing trends, respectively. Solid triangles indicate significant trends at the 5% significance level. While the open triangles show non-significant trends. The size of triangles is proportional to the magnitude of the trend

number of warm nights and warm days was reported as a consistent trend globally (IPCC 2012, 2013).

Higher inconsistency and lower spatial coherence was detected on trend of Warm Spell Duration Indicator (WSDI) among the climatic stations of the study area (Fig. 12). A decline on WSDI in ~44% of the stations and an increase on 56% of the stations were discerned. In regards to Cold Spell Duration Indicator (CSDI), a decrease in 78% of the stations was observed. A warming trend was substantiated by an increasing trend of summer days (SU25) in most of the stations. Trend in SU25 index exemplified that there was an increase on 78% of the stations (significant at 44% of the stations). Trend of frost days is observed only in stations located at cold moist highlands and sub-afro alpine agro-ecologies. On Debrebirhan station, frost days were significantly decreasing, while frost events were persistent in Andit-tid and Mehalmeda stations.

In the entire sub-basin, average anomaly series of all temperature extreme indices except TNn prove warming trend. However, pronounced fluctuation on the trend and 5-year moving average of TNx, TX10p, TX90p, TN10p, TN90p, and CSDI was detected (Fig. 13). Furthermore, the magnitude of change was higher and persistent on cold extreme indices (TN10p, TX10p, and CSDI) than warm extreme indices (TX90p, TN90p, and WSDI). Concurrent with this, significant decreasing trend was obtained on TX10p, TN10p, and CSDI indices in Rift Valley, southern rangelands, and the eastern highlands of Ethiopia (Mekasha et al. 2013). Globally, higher rate of increase was simulated by current climate models in minimum temperature extremes than maximum

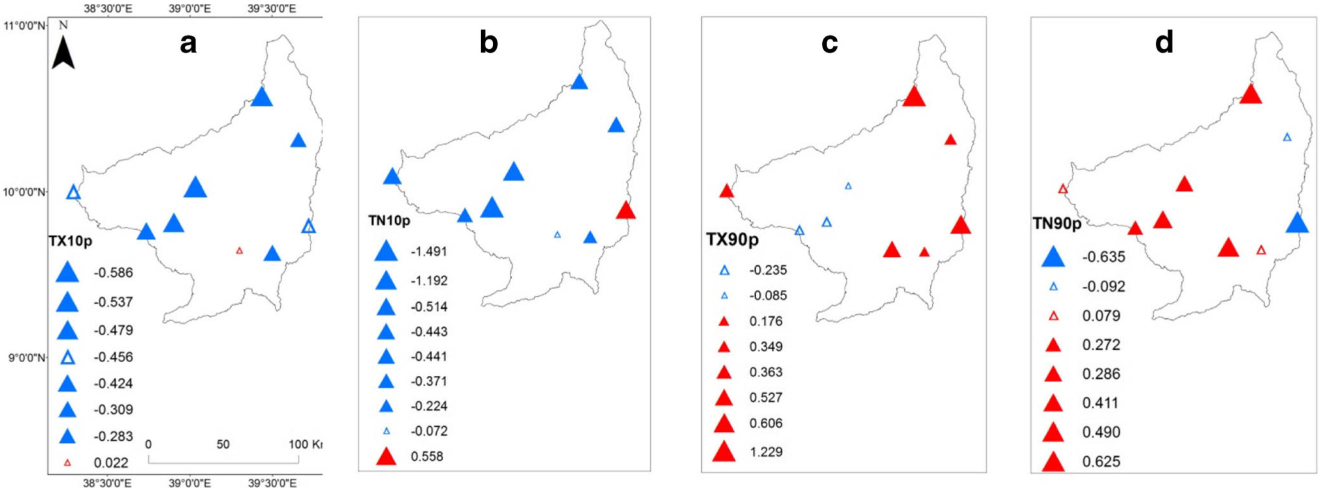


Fig. 11 Trends (%/year) in **a** TX10p (cool days), **b** TN10p (cool nights), **c** TX90p (warm days), and **d** TN90p (warm nights). Red and blue triangles indicate increasing and decreasing trends, respectively. Solid triangles indicate significant trends at the 5% significance level. While the open triangles show non-significant trends. The size of triangles is proportional to the magnitude of the trend

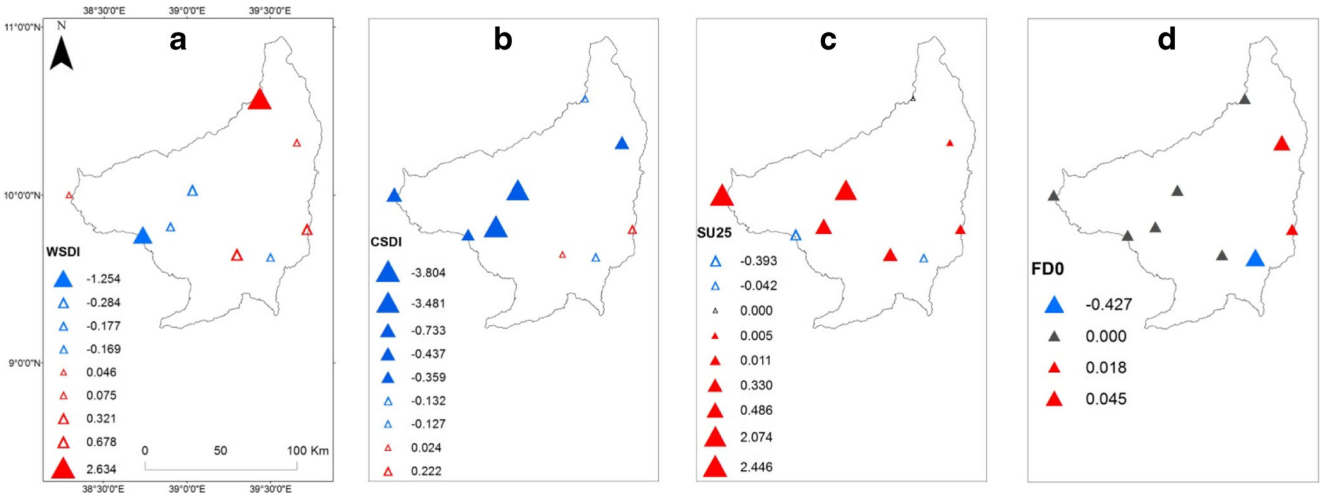


Fig. 12 Trends (days/year) in **a** WSDI (Warm Spell Duration Indicator), **b** CSDI (Cold Spell Duration Indicator), **c** SU25 (summer days), and **d** FD0 (frost days). Red and blue triangles indicate increasing and decreasing trends, respectively. Black triangles indicate no trend. Solid triangles indicate significant trends at the 5% significance level. While the open triangles show non-significant trends. The size of triangles is proportional to the magnitude of the trend

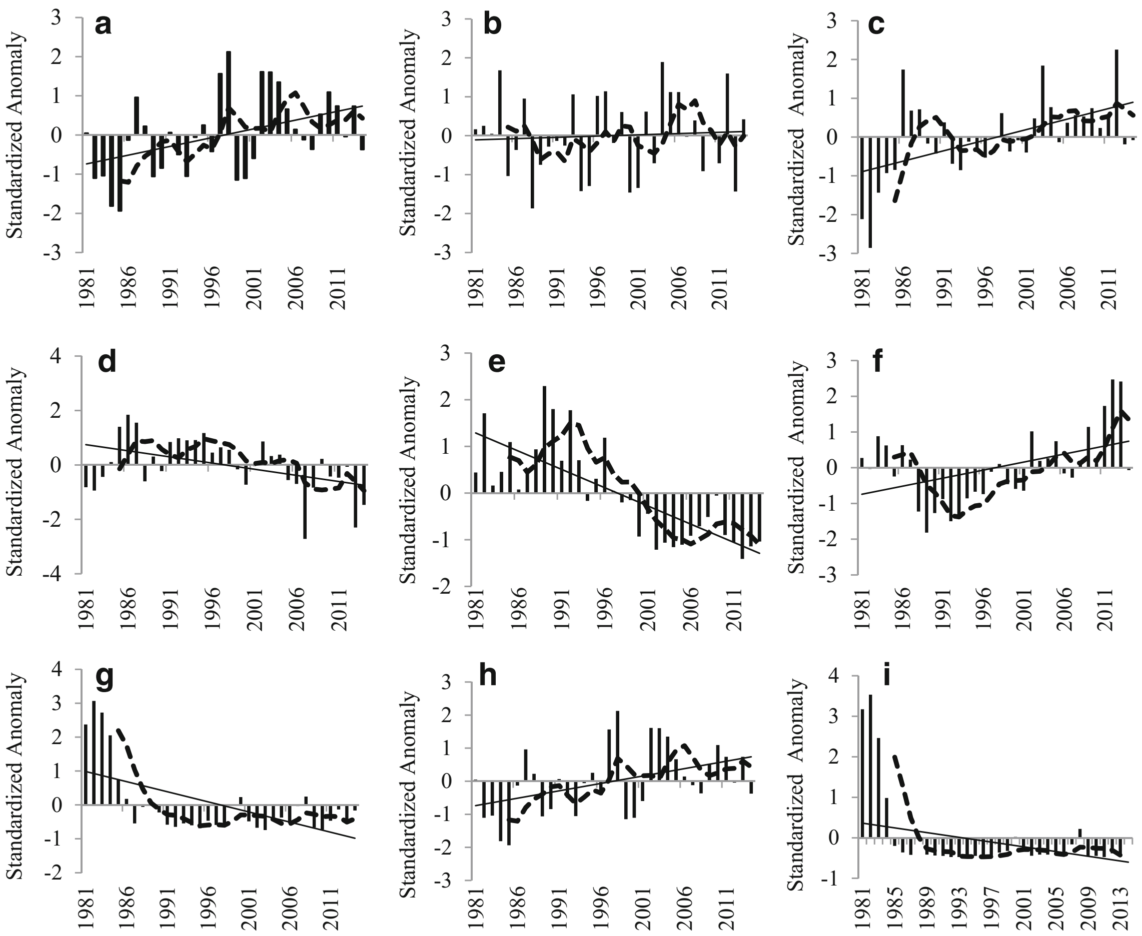


Fig. 13 Average sub-basin wide trends of temperature extreme indices. **a** Monthly maximum value of daily maximum temp (TXx). **b** Monthly minimum value of daily maximum temp (TXn). **c** Monthly maximum value of daily minimum temp (TNx). **d** Monthly minimum value of daily minimum temp (TNn). **e** Cool days (TX10p). **f** Warm days (TX90p). **g** Cool nights (TN10p). **h** Warm nights (TN90p). **i** Cold Spell Duration Indicator (CSDI). The straight line is the linear trend for the variables, whereas dashed line is the 5-year moving average

temperature extremes (IPCC 2013). Moreover, significant decrease of cold nights and significant increase of warm nights is reported (Alexander et al. 2006; Zhang et al. 2011). However, in Georgia, higher change was observed on warm extremes than cold extremes (Keggenhoff et al. 2014).

Trend on mean annual maximum and minimum temperature and most extreme temperature indices confirm higher warming trend in Jemma Sub-Basin than warming trend of Ethiopia and the world. For example, in Ethiopia, annual minimum temperature increased by 0.37 °C/decade for the period 1953–1999 (NMA (2007) and there was an increase of annual mean temperature by 1.3 °C from 1960 to 2006 (McSweeney et al. 2006). This could be related to an increase in global temperature, multiple large-scale and local-scale drivers. Particularly, an increase in temperature extremes can be attributed to the change in global temperature extremes (Alexander et al. 2006). The higher elevation and the diverse physiography in the sub-basin could be other reasons which trigger a change in temperature extremes (Beniston 2003; Bewket and Conway 2007). In the higher-altitude areas, there is an elevation-dependent warming (EDW) where higher-elevation areas experience more rapid changes in temperature than environments at lower elevations (Revadekar et al. 2013; MRI 2015) and temperature extremes of higher-elevation areas are more influenced by local factors (Revadekar et al. 2013).

3.4 Potential impacts of climate extremes

The changes in rainfall and temperature extreme events like frosts, droughts, floods, and landslides associated with high rainfall can trigger multifarious effects on agriculture. In Jemma Sub-Basin, climate extremes particularly heavy storms, landslides, floods, spells of high temperature, frequent drought, and extreme cold temperature events seriously disrupt crop production system of smallholder farmers. An increase in frequency of extreme weather events from 1981 to 2011 resulted in an estimated damage of > 50% of crop production (Tesso et al. 2012). In BasoWerana and Menz Gera Meder areas of the sub-basin, climate variability and changes in extremes have significant influence on crop production and food security (Alemayehu and Bewket 2016). A decreasing trend of *Belg* rainfall and a shift of bimodal pattern of the rainfall toward a unimodal pattern of rainfall in the Jemma Sub-Basin could cause *Belg* crop failure and livestock losses due to lack of pasture and water.

In Ethiopia, an increase and a decrease of temperature extremes events bring about serious crop damage. Temperature extremes trigger crop diseases and pests; for instance, rust is a major threat to wheat production in the highlands of Ethiopia (EPCC 2015). Temperature extremes also affect pasture and forage production and caused livestock diseases. On the other hand, extreme rainfall events reduce the rain and reduce water availability for crop production (Funk et al. 2012).

4 Conclusion

This study analyzed annual trend of rainfall, minimum temperature, maximum temperature, and the change on rainfall and temperature extreme indices in Jemma Sub-Basin of the Upper Blue Nile Basin. Annual and *Kiremit* rainfall showed increasing trends in the majority of the climatic stations. However, a decreasing trend was observed on the *Belg* season rainfall in most of the stations. This implied a shift in the rainfall pattern from bimodal to monomodal. This may strongly affect agricultural practices that take place during the *Belg* season. Unlike the mean annual and seasonal changes of rainfall, a statistically significant change on extremes of rainfall was observed. Most of rainfall extreme indices demonstrated rising of extreme rainfall events and contribution of extreme rainfall to total rainfall in the sub-basin. On the other hand, at sub-basin level average value of SDII revealed trend of dryness than wetness. Among the stations and agro-ecologies of the study, lower spatial coherence was observed on trend of most rainfall extreme indices than temperature extreme indices.

Almost all temperature extreme indices in almost all stations of the Jemma Sub-Basin showed a warming trend. Sub-basin wide analysis illustrated abrupt change on nighttime temperature extreme indices than daytime temperature extreme indices. Warm extremes at nighttime were increasing while cold extremes at nighttime were decreasing more strongly than other indices. Unlike trends of rainfall extremes, trends of temperature extremes revealed consistency and spatial coherence. In stations located in higher altitude and cool sub-moist, cool moist, and sub-afro-alpine agro-ecologies, the trend of annual minimum temperature and most temperature extreme indices derived from minimum temperature was different from other stations where cold extremes are persistent.

In conclusion, this study proved that the intensity and frequency of climate extremes has been increasing in the last three decades. Plausible climate change may aggravate the situations of climate extremes. Therefore, appropriate adaptation and mitigation strategies should be planned to lessen the impacts of such climatic risks in the Jemma Sub-Basin.

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