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Changes and variability of rainfall amounts and extreme indices in Gedeo Zone, Southern Ethiopia

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Abstract: This study made detailed analysis of variability and trends of rainfall in Gedeo Zone, Southern Ethiopia using climate data tool. Its variability was examined by coefficient of variation, precipitation concentration index, and standardised rainfall anomalies whereas trends were evaluated using Mann-Kendall trend test and Sen's slope estimator. The finding indicated that rainfall variability was high during March-May and September-November which resulted in extended periods of driest years. Insignificant decreasing trends of rainfall amount at annual and seasonal (March-May) timescales were observed. However, most extreme events showed varying trends across studied stations. For example, all rainfall extreme indices showed decreasing trends in Yirgachefe and Kochere and significant increasing trends at Bule. Since climatic variability and trends have been changing in short distances, this type of local level study is thought important to take up to date and appropriate decisions on the management of agriculture, water, and flood risks.

Keywords: extreme indices; Gedeo; Mann-Kendall; trend; variability; Ethiopia.

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1 Introduction

Climate change and variability are known for their holistic effect in deteriorating our globe in recent years. According to IPCC (2013), climate change is unavoidable and has brought about a variety of climate variability including extreme weather events. The cumulative effects of increment of average temperatures and reduction of rainfall shrink crop yields which in turn bring food insecurity in developing countries where their economy is mainly dependent on agriculture (FAO, 2012). Research outputs indicate that Ethiopia is one of the most vulnerable countries due to the adverse effects of climate change.

Ethiopian agriculture is solely depending on rainwater for production which makes it highly sensitive to recent changes of rainfall particularly its variability and extremes. The changes of rainfall in Ethiopia brought a change in distinct patterns of wet and dry seasons (World Bank, 2006; Korecha, 2013). Rainfall extremes resulted in flood and drought conditions with various levels of severity and bring adverse economic crises (World Bank, 2006). Ethiopian smallholder farmers are prone to many climate-induced dangers (like drought, flooding, food insecurity) (Ayanlade et al., 2018; Samy et al., 2019; Simane et al., 2016). Keeping other socioeconomic and political factors constant, Ethiopian agricultural production is likely to drop by 4.4% if the seasonal rainfall amounts decreased by 10% (Bewket and Conway, 2007). The report of World Bank (2006) also indicated that Ethiopia's economic progress shows 8% fluctuation due to rainfall variability.

Ethiopia's rainfall is characterised by its variability in amount and distribution both spatially and temporally. Various research findings (Alemayehu et al., 2020; Alemayehu and Bewket, 2017; Muluneh et al., 2016; Degefu and Bewket, 2013, Bewket and Conway, 2007) revealed that different meso and micro-scale rain-producing factors, geographical location and topographic variations were mentioned as major causes for its high variability.

There are three distinct seasons in Ethiopia; main rainy season (locally named as *kiremt* spanning from June–September), short rainy season (locally named as *belg* spanning from March–May), and dry season (locally named as *bega* spanning from October–February) (NMA, 2018; Alemayehu and Bewket, 2017). Although *belg* season is the second and short rain season in many parts of Ethiopia, it is the major and long rainy period to most parts of south east Ethiopia (Degefu et al., 2021). The high spatio-temporal variability of *belg* rainfall has huge repercussions on the livelihoods of farmers who are more dependent on *belg* rain (Mohammed et al., 2018; Bekele-Biratu et al., 2018; Alemayehu and Bewket, 2016).

In Ethiopia, changes in spatial distribution and duration of rainy time are more noticeable than changes in its total amount. The reports of National and Regional Disaster Risk Management Commission showed that climate change brought changes in rainfall extreme events which led to unprecedented flood incidents in Gedeo Zone (especially in Kochere, Bule, Wonago and Yirga Chefe Woredas). Heavy rainfall in the form of flood has been causing considerable disasters especially in areas having proximity to rivers.

The presence of heavy rainfall and associated flood disaster dictates to make a detailed analysis of extreme events which help prepare evidence-based strategy and take proactive interventions. However, the number of studies regarding variability and trends of rainfall including extreme events at small-scale level in Ethiopia are so limited. Lack of rainfall data covering longer periods (at least 30 years), inaccessibility of areas to record rainfall, and less number of climate experts are considered to be major challenges for the absence of detail scientific rainfall information (Degefu et al., 2021; Alemayehu and Bewket, 2017). The present study is conducted in Gedeo Zone which has peculiar rainfall distribution, getting its maxima during March–May and second rain from September–November, which are known for short rain and dry period respectively in other most parts of Ethiopia.

Thus, this study is conducted to examine the variability and trends of rainfall across stations in different time periods in Gedeo Zone, Southern Ethiopia. We believe that the findings contribute to understand and capture the real picture of rainfall characteristics of the study area which help decision makers take adaptation interventions which correspond to the situation (Degefu et al., 2021; Alemayehu et al., 2020; Asfaw et al., 2018). Moreover, the study area in particular is the largest known agroforestry area in the country where detailed previous studies on rainfall are limited.

2 Materials and methods

2.1 Description of the study area

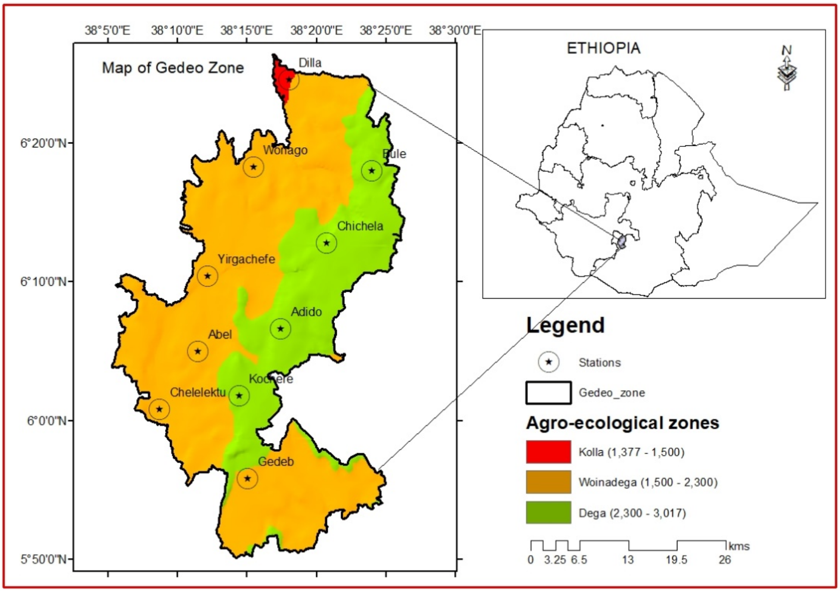
This study area extends from 5°52’ to 6°27’N latitude, and 38°5’ to 38°26’30”E longitude (Figure 1). It is located at the eastern border of the southern Ethiopian Rift Valley. Geographically, most parts of the zone (in the east, west and south) are bordered with Oromia region. It is also bordered with Sidama Regional State in the north. Its total area is estimated to be 1,352 km^2.

The topography of Gedeo is rugged with slopes range from 5% to 75 % (Legesse, 2013). The altitude of the zone ranges from 1,377–3,017 m a.s.l. There are many intermittent and perennial rivers in the study area. Most of the rivers are flowing to the west and join Lake Abaya.

The traditional climate classification of the area is divided into sub-tropical climate (Woina dega which constitutes 62%), hot tropical climate (Kolla constitutes only 1%) and high altitude climate (Dega constitutes 37%) (Legesse, 2013). The area receives average annual rainfall of 800–1,800 mm. Its main rain period is from March to May and second rain from September to November. The mean annual temperature of the study area ranges from 12.5°C to 25°C (Neash et al., 2012).

Agroforestry is the major and unique livelihood system of the zone. Coffee, Enset, indigenous trees, root crops, shrubs, etc. are major components of the agroforestry system having distinct layers (Legesse, 2013). Coffee is the most known source of earnings for the inhabitants while Enset is their staple food. Cereal crops and livestock production, in non-coffee producing high land areas, are also main income sources of people.

Figure 1 Map of study stations in Gedeo Zone (see online version for colours)



2.2 *Data type and source*

Gridded daily rainfall data for the period 1981–2018, obtained from Ethiopian Meteorological Institute (EMI), were used for this study. Gridded data were selected for this particular study because:

1 the numbers of observation stations found in the study area were very limited and could not be representative

2 missing values are very common in the time series data

3 most stations do not have long time data records to perform trend analysis.

Ten stations that are believed to be representative of Gedeo zone were taken for this study.

EMI in collaboration with International Institute for Climate and Society at Columbia University reconstructed gridded data by blending 550 rainfall and 320 temperature stations with satellite estimates across Ethiopia (Mengistu et al., 2014). The reconstructed data were validated by Reading University, UK. The validation results revealed the existence of strong correlation (r = 0.8) between station and satellite derived data (Mengistu et al., 2014). This indicates that use of gridded data in areas where station data are not available is reasonable (Mengistu et al., 2014; Dinku et al., 2014). Recent studies (Alemayehu et al., 2020; Ademe et al., 2020; Alemayehu and Bewket, 2017; Mengistu et al., 2014; Dinku et al., 2014) used gridded rainfall and temperature data for climate change studies across the country where there is scarcity of climate data.

Table 1 Description of stations used in this study

Station	*Northing (N)*	*Easting (E)*	*Altitude (m)*	*Observation years*	*No. of years with missing values*
Gedeb	5.93°	38.25°	2,255	1981–2018	-
Chelelektu	6.0°	38.14°	1,752	1981–2018	-
Abel	6.08°	38.21°	2,256	1981–2018	-
Adido	6.11°	38.29°	2,758	1981–2018	-
Yirgachefe	6.15°	38.21°	1,844	1981–2018	-
Kochere	6.03°	38.24°	2,436	1981–2018	-
Chichela	6.19°	38.36°	2,865	1981–2018	-
Bule	6.3°	38.4°	2,834	1981–2018	-
Wonago	6.34°	38.25°	1,722	1981–2018	-
Dilla	6.41°	38.30°	1,500	1981–2018	-

2.3 Data quality assurance mechanisms

All the rainfall time series data were checked for missing values and homogeneity using climate data tool (CDT). Homogeneity of the data series was tested by standard normal homogeneity test (SNHT). This test showed absence of inhomogeneity of the data that would require mean adjustments, so the original data was used for further analysis without any prior correction.

2.4 Method of data analysis

The CDT, a free open source R package, was used to analyse the time series daily rainfall data in this study. International Research Institute for Climate and Society (IRI) developed CDT. It is used for data quality control, homogenisation and analysis of climatological time series (mainly air temperature and rainfall). In addition, CDT is a simple and effective statistical software package to create new dataset by merging station data with satellite estimates (Dinku, 2019).

2.4.1 Variability analysis

We calculated the inter-annual variability of annual and seasonal rainfall using the following standard formula (Hare, 2003).

$$CV(\%) = \frac{(\sigma)}{\mu} \times 100 \quad (1)$$

where CV – coefficient of variation, σ – standard deviation and μ – mean. According to Hare (2003), CV < 20 is classified as low, (20 < CV < 30) moderate, and (CV > 30) high.

Precipitation concentration index (PCI) is used to examine seasonal distribution of rainfall.

$$\text{PCI annual} = \left[\sum_{i=1}^{12} Pi^2 \Big/ \left(\sum_{i=1}^{12} pi \right)^2 \right] \times 100 \quad (2)$$

where Pi – the total rainfall of the i^{th} month.

PCI values are categorised as uniform (<10) presents a uniform distribution of rainfall, (11–15) indicates moderate, (16–20) shows irregular, and (> 21) shows a strong irregular monthly rainfall distribution (De Luis et al., 2011; Oliver, 1980).

The year-to-year rainfall fluctuations were also assessed using standardised rainfall anomalies (SRA). It is a commonly used index to detect strange dryness or wetness (Guttman, 1999). SRA were calculated as follows:

$$\text{SRA} = (Pt - Pm)/\sigma \tag{3}$$

where SRA is the standardised rainfall anomaly, Pt is the annual rainfall amount in year t, Pm and σ are the average and standard deviation of annual rainfall for the study period respectively.

The results of SRA were interpreted as per Agnew and Chappel (1999) classification of drought severity level.

2.4.2 Rainfall trend analysis

The Mann-Kendall test (MKT) and Sen's slope were used to identify the trends and calculate rate of changes of rainfall respectively. We applied Mann-Kendall test because distribution, outliers and missing of time series data are unlikely to affect the result (Kundzewicz et al., 2005). However, the data need to be serially independent (Petrow and Merz, 2009). Trend free prewhitening (TFPW) method was applied to test serial correlation between records before running trend test (Petrow and Merz, 2009; Burn et al., 2010). Fortunately, no significant serial autocorrelation at all lags was observed and we ran the Mann-Kendall trend test without any modification of the data.

The MKT statistic S is calculated as

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}\left(x_j - x_k\right) \tag{4}$$

where x_j and x_k are the annual values in years j and k, $j > k$, respectively, and $\operatorname{sgn}(x_j - x_k)$ is defined as:

$$\operatorname{sgn}\left(x_j - x_k\right) = \begin{bmatrix} 1 & \text{if } \left(x_j - x_k\right) > 0 \\ 0 & \text{if } \left(x_j - x_k\right) = 0 \\ -1 & \text{if } \left(x_j - x_k\right) < 0 \end{bmatrix} \tag{5}$$

For samples greater than 10, variance of S (Var S) is computed as

$$= \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p \left(t_p - 1\right)\left(2t_p + 5\right) \right] \tag{6}$$

where q is the number of tied groups and t_p is the number of data values in the p^{th} group.

The standardised test statistic Z was calculated using S and var(s) values as follows:

$$Z = \begin{bmatrix} s - 1\big/\sqrt{\text{var}(s)} & \text{if} > 0 \\ s + 1\big/\sqrt{\text{var}(s)} & \text{if} < 0 \\ 0 & \text{if} = 0 \end{bmatrix} \tag{7}$$

The value of Z in the MKT statistics follows standard normal distribution with average of 0 and variance of 1. Z values evaluates whether statistically significant trends were existed. Negative figures represent decreasing trend and positives increasing trend. The rate of changes in the time series is estimated by non-parametric Sen's slope estimator which uses the median of slopes (β) using the following equation:

$$(B) = median \frac{x_j - y_i}{x_j - x_i} \tag{8}$$

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

Table 2 Definitions of extreme rainfall indices used in this study

S/N	*Index*	*Index name*	*Definition*	*Unit*
1	RX1 day	Maximum precipitation in a day	Highest precipitation amount in one day period	mm
2	RX5day	Maximum five day precipitation	Highest precipitation amount in five days period	mm
3	R10 mm	Heavy precipitation days	Count of days where daily precipitation amount ≥ 10 mm	Days
4	R20 mm	Very heavy precipitation days	Count of days where daily precipitation amount ≥ 20 mm	Days
5	CDD	Consecutive dry days	Maximum length of dry spell (precipitation < 1 mm)	Days
6	CWD	Consecutive wet days	Maximum length of wet spell (precipitation ≥ 1 mm)	Days
7	PRCPTOT	Total wet-day precipitation	Total precipitation in wet days (rainfall ≥1 mm)	mm
8	SDII	Simple daily intensity index	Mean precipitation amount in wet days	mm day^{-1}
9	R95p	Precipitation due to very wet days	Annual total precipitation when RR > 95th percentile	mm
10	R99p	Precipitation due to extremely wet days	Annual total precipitation when RR > 95th percentile	mm

Source: World Meteorological Organization (WMO) (2009)

2.4.3 Extreme rainfall trend analysis

The calculation of extreme rainfall indices was made from the daily rainfall data as per WMO (2009) Guidelines. All indices (Table 2) are defined as per the definition given by the expert team on climate change detection indices (ETCCDI). The trends of extreme indices were calculated using CDT (Dinku, 2019). Averages of indices of all study stations were used to estimate areal average trends of extreme indices. The standardised anomaly of each extreme index at the study area level was calculated as

$$SA_{p,y} = \frac{(py - Pm)}{\sigma} \quad (9)$$

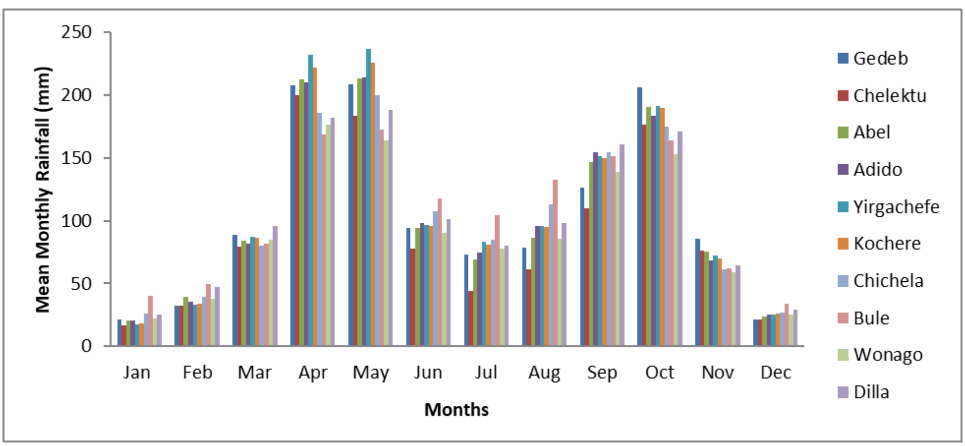
where $SA_{p,y}$ is the standardised anomaly of index p at year y, py is the annual index value in year y, Pm is the mean annual index over the study period, and σ is the standard deviation of annual index. The 3-year moving average curve is used to show variation of extremes at annual time step.

3 Results

3.1 *Variations of rainfall at different time steps*

The study area receives rainfall throughout the year (Figure 2) although the amount and distribution significantly varies seasonally. From seasonal rainfall cycle perspective, three wet seasons were identified; March–May (major rain season), September–November (second rain season) and June–August (small rain season). However, March–May rainfall season is the second rainy season for most parts of the country. Unlike other parts of Ethiopia which receive the highest amount of rain during *kiremt* (June–August), Gedeo zone receives less rainfall amount in this season. At station level, the highest rainfall was observed in Yirgachefe (1981–2018) during March and April. However, Bule received the highest rainfall during *kiremt* season (highest elevation in the study area).

Figure 2 Mean monthly rainfall of the study stations (see online version for colours)



With regard to average annual rainfall, the zone is estimated to obtain 1,231.77 mm during the observation period (1981–2018). With respect to each station, a comparable long-term annual rainfall ranging from 1,078 mm at Chelelektu to 1,322.79 mm at Yirgachefe was observed. The average rainfall for the main and second rain seasons were 483.74 and 393.31 mm respectively. They contribute around 40% and 32% to the total annual rainfall amount respectively.

In terms of spatial distribution, except the northwest and a few pocket areas at south west, all areas had similar rainfall distribution at annual timescale. At seasonal timescales, the rainfall distribution showed clear patterns. During the main rainy season (March–May), the rainfall was decreasing towards the north. However, during the second rainy season (September–November), south and central parts of the zone had highest rainfall and it was decreasing in north central and south west parts. At this season, the northern tips of the zone had similar rainfall distribution with southern parts of the study area (Figure 3).

Figure 3 Spatial distribution of rainfall at different time steps in the study area (see online version for colours)

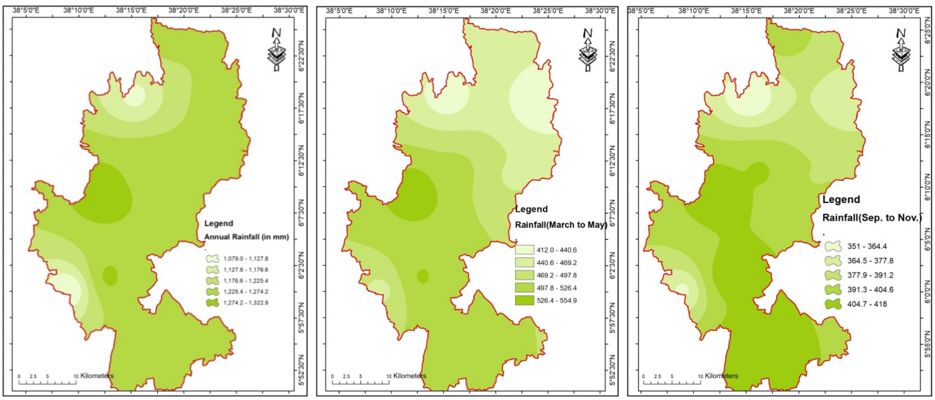
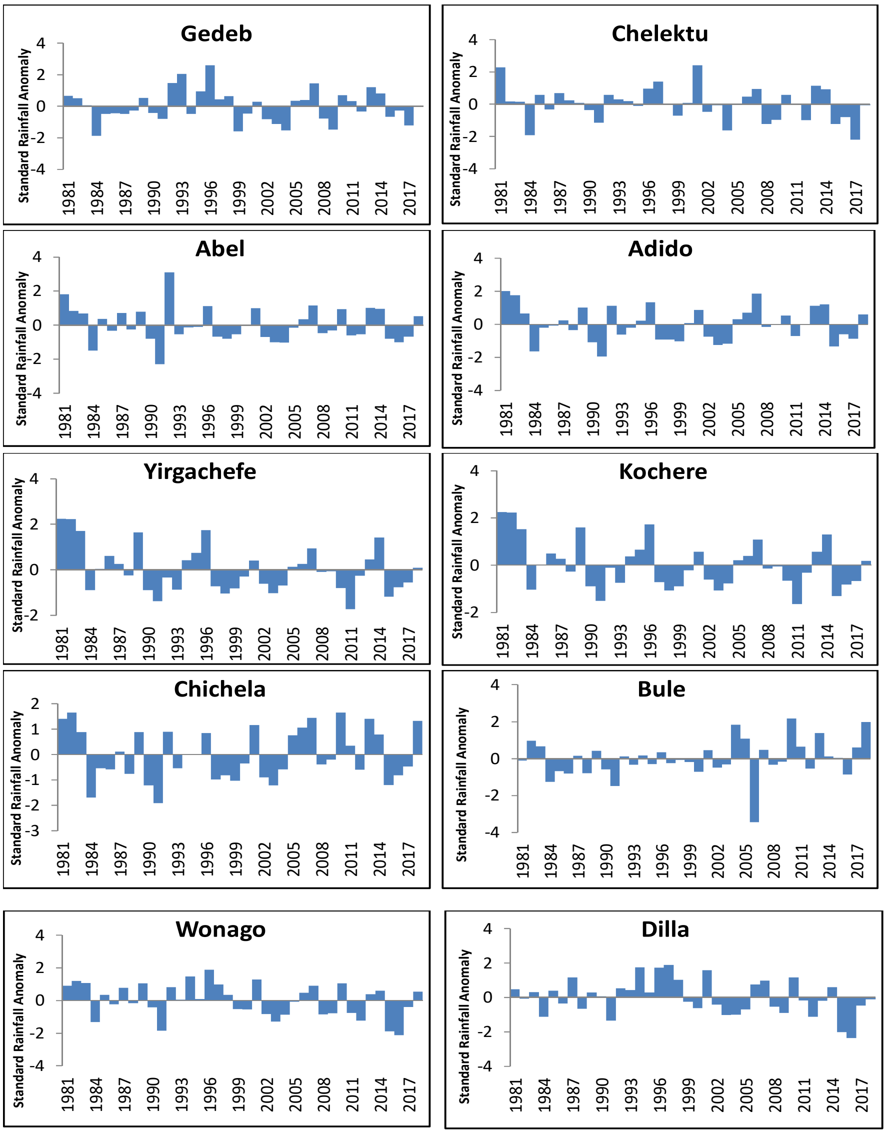


Table 3 Average annual and seasonal rainfall (mm), CV and PCI during the study period (1981-2018)

Stations	*Annual*		*Main rain season (March–May)*			*Second rain season (September–November)*			*PCI*
	Total	*CV*	*Total*	*Contribution to annual RF (%)*	*CV*	*Total*	*Contribution to annual RF (%)*	*CV*	
Gedeb	1,243.93	20.93	504.37	40.55	27.14	418.3	33.63	33.55	13.1
Chelelektu	1,078.58	18.59	461.87	42.82	31.2	362.42	33.60	32.8	14.8
Abel	1,255.9	16.87	509.93	40.6	24.73	412.8	32.87	29.79	13.67
Adido	1,259.98	16.28	504.99	40.08	24.23	406.39	32.25	26.05	13.15
Y/chefe	1,322.79	20.57	555.4	41.99	26.1	415.5	31.41	31	13.65
Kochere	1,292.14	19.24	533.13	41.26	25.68	409.63	31.70	29.22	13.42
Chichela	1,254.68	14.07	465.96	37.14	22.73	391.07	31.17	22.75	12.25
Bule	1,251	19.4	411.86	32.92	25.99	369.23	29.51	30.3	11.64
Wonago	1,114.88	13.86	424.69	38.09	24.24	350.86	31.47	21.52	12.14
Dilla	1,243.82	14.98	465.21	37.4	27.33	396.85	31.91	22.74	12.36

Table 3 presents the inter-annual rainfall variability. They varied from 13.86% at Wonago station (at the escarpment of the rift valley) to 20.93% at Bule station (highland area). The CV of annual rainfall at all stations was less (below 20%) and it was moderate (20–30%) in the two rainy seasons (March–May and September–November) (Table 3). PCI was calculated to measure the distribution of rainfall in the study area. Accordingly, all stations experienced moderate rainfall distribution ranging from 11.64% to 14.8% (Table 3).

Figure 4 Standardised annual rainfall anomalies in Gedeo Zone in the study period (see online version for colours)



The inter-annual rainfall fluctuation was also evaluated by standardised rainfall anomalies (SRA) (Figure 4) and it showed more negative anomalies in the inter-annual rainfall, ranging from 44.74% (at Chelelektu) to 57.9% (at Abel) during the study period. More than 70% of the studied stations had more number of negative rainfall anomalies than positive anomalies.

Based on SRA analysis, 1984, 1991, 1999, 2003/2004, 2009, 2012, 2015/2016 were the driest years while 1981–1983, 1996 were identified as the wettest years across the study stations (Figure 4). In our analysis we found that there is a good match between driest years of the study area and the drought years occurred in Ethiopia. The worst drought year (1984) in Ethiopian history was clearly detected at all study stations. 1991 was also extremely dry (–2.3) at Abel compared to other stations. 2015 and 2016 were the driest years across all study stations except Bule. During these years, extreme droughts were recorded in Wonago (–2.13) and Dilla (–2.35)

On the other hand, although all stations received high annual rainfall amount, Chelelektu, Adido, Yirgachefe and Kochere stations were extremely wet (2.24) in 1981. The average annual rainfall at these stations was above long-term average (1981–2018). Similarly, all stations received excess amount of rainfall above long-term average in 1996. Gedeb was also extremely wet (2.61) during this period.

3.2 Trends of rainfall amount at different time steps

Although the changes were insignificant, there were decreasing signals in annual and Mar-May rainfall in the studied stations for the period 1981–2018. However, Chichela and Bule stations showed increasing signal (Table 4). During the main rainy season (March–May), insignificant negative rainfall trends were observed in all studied stations except Wonago which showed significant increasing trends (Table 4). The rates of these decreasing changes of annual rainfall varied between –69.2 mm decade^{-1} and 53.8 mm decade^{-1} at Yirgachefe and Bule respectively. Rainfall in the main rainy season (March–May) varied from –40.3 mm decade^{-1} to –4.7 mm decade^{-1} at Yirgachefe and Bule respectively (Table 4). Conversely, an increasing signal of rainfall was detected in almost all study stations except Yirgachefe, Kochere and Wonago during the small rainy season (September–November). The increasing trend was significant only at Bule.

Table 4 Trends of rainfall (mm decade^{-1}) at annual and seasonal timescales

Station name	*Annual trend*	*Main rainy season (March–May)*	*Second rainy season (September–November)*
Gedeb	–11.1	–27.1	30.18
Chelelektu	–38.7	–33.8	10.74
Abel	–27.0	–15.2	12.47
Adido	–16.4	–13.6	07.66
Yirgachefe	–69.2	–40.3	–19.06
Kochere	–60.6	–32.5	–15.08
Chichela	10.9	–12.2	19.01
Bule	53.8	–4.7	36.01 *
Wonago	–47.2	–31.9 *	–6.30
Dilla	–43.8	–34.8	0.29

Note: *Significant at 0.05 level.

3.3 Trends in extreme rainfall indices

The finding revealed the absence of clear trends of extreme rainfall indices across the study stations except R10mm, CDD and PRCPTOT. There were significant decreasing trends of maximum one day (Rx1) annual rainfall at Chelelektu, Yirgachefe and Kochere and significant increasing trend at Bule and Dilla. The maximum consecutive five days (Rx5) annual rainfall showed significant increasing trend only at Bule. Heavy rainfall days (R10mm) showed insignificant decreasing trend in most (8 out of 10) of the stations (Table 5). The finding indicates consistent increasing changes of CDD in all study stations which shows the persistence of dry condition in the study area. The decreasing signals in PRCPTOT were very much similar to the negative trends of annual rainfall and heavy rainfall days (R10mm) except Chichela and Bule where they had positive changes. The decreasing trend of PRCPTOT showed variations across study stations ranging from –89.7 mm decade^{-1} at Yirgachefe to 75.07 mm decade^{-1} at Bule. PRCPTOT was significantly ($P < 0.05$) decreased at Yirgachefe, Kochere and Wonago and significantly ($P < 0.01$) increased in Bule. Similarly, SDII exhibited decreasing trend in seven stations (but significant at Chelelektu and Kochere at $P < 0.05$) and increasing in three stations (significant $P < 0.01$ only at Bule). The decreasing trend of SDII spans from –.48 mm to 0.9 mm decade^{-1} at Chelelektu and Bule, respectively.

Decreasing trends of Rx1 day, R10mm, R20mm, PRCPTOT, SDII, R99p, and R95p) were detected at Chelektu. Conversely, Bule is the only station detected for increasing trends of almost all extreme events (e.g., Rx1 day, Rx5 day, R10mm, R20mm, CDD, PRCPTOT, SDII, R99p, and R95p). The significant increasing trends of extreme events in Bule suggest existence of increasing climatic risks on the agricultural production and ecosystems. These positive trends in Bule may be related to its unique topography and cool sub-moist agro-ecology. There was similarity between the trends of R10mm, CDD and PRCPTOT across the study stations. 70% of the stations had downward trends in R10mm and PRCPTOT whereas 100% of the stations showed upward trends in CDD.

From station perspectives, Gedeb and Cheleketu stations showed decreasing trends in seven out of ten extreme indices. All extreme indices showed decreasing trends at Yirgahefe and Kochere except CDD. Exceptionally, eight extreme indices showed significant increasing trend at Bule. R95p also showed noticeable variation across the stations ranging from –53.64 at Chelelektu to 106.36 at Bule. Both R95p and R99p showed significant opposing trends in Chelelektu (decreasing) and Bule (increasing). Most extreme rainfall indices (Rx1 day, Rx5 day, R20mm, CWD, R95p and R99p) showed divergent trends. This indicates that rainfall changes over the entire study area have not been stable.

Generally, out of 100 extreme event indices at ten stations, about 23 of them showed significant and 77 non-significant trends. Out of the 23 statistically significant trends, only 11 showed increasing trends and 12 decreasing trends. Even though most of the indices did not show significant trends, 39 showed decreasing signals and the remaining 38 indices increasing signals (Table 5). Trends of CDD, PRCPTOT and SDII at some selected stations were shown in Figure 5–7.

Table 5 Trends of extreme rainfall indices

Station name	*Rx1 day mm/decade*	*Rx5 day mm/decade*	*R10 mm days/decade*	*R20 mm days/decade*	*CWD days/decade*	*CDD days/decade*	*PRCPTOT mm/decade*	*SDII mm/decade*	*R95p mm/decade*	*R99p mm/decade*
Gedeb	–0.59	–0.07	–0.72	–1.83	4.93**	2.76	–11.01	–0.37	–23.05	0.72
Chelelektu	–4.04**	0.72	–2.14	–1.82***	0.19	6.88**	–4.5	–0.48***	–45.76***	–16.11**
Abel	1.12	–1.06	–2	0.6	–2.48	4.44	–26.29	–0.02	15.5	6.7
Adido	–0.79	0.88	–0.51	0.12	0.24	3.02	–14.86	0.06	–2.94	–5.89
Yirgachefe	–2.76**	–2.92	–4.24	–1.28	–1.19	2.42	–89.7*	–0.45	–34.42	–19.1
Kochere	–2.68*	–1.78	–3.85	–0.97	–1.64	2.22	–76.12*	–0.45*	–28.25	–19.06*
Chichela	0.45	1.38	0.5	0.42	2.44	1.25	13.63	0.14	30.55	9.47
Bule	4.26***	6.98**	0.5***	3.36***	–4.09	2.64	75.07**	0.9***	127.06***	63.12***
Wonago	1	–0.75	–1.58	0.12	–2.3	1.36	–46.17*	–0.13	3.26	2.73
Dilla	4.56**	1.63	–1.46	0.11	–2.6	4.24	–51.12	–0.02	0.84	3.68

Note: ***, **, * indicate significant at 0.001, 0.01 and 0.05 level, respectively.

Figure 5 Trends of consecutive dry days (CDD), (a) Abel (b) Adido (c) Bule (d) Chelelktu

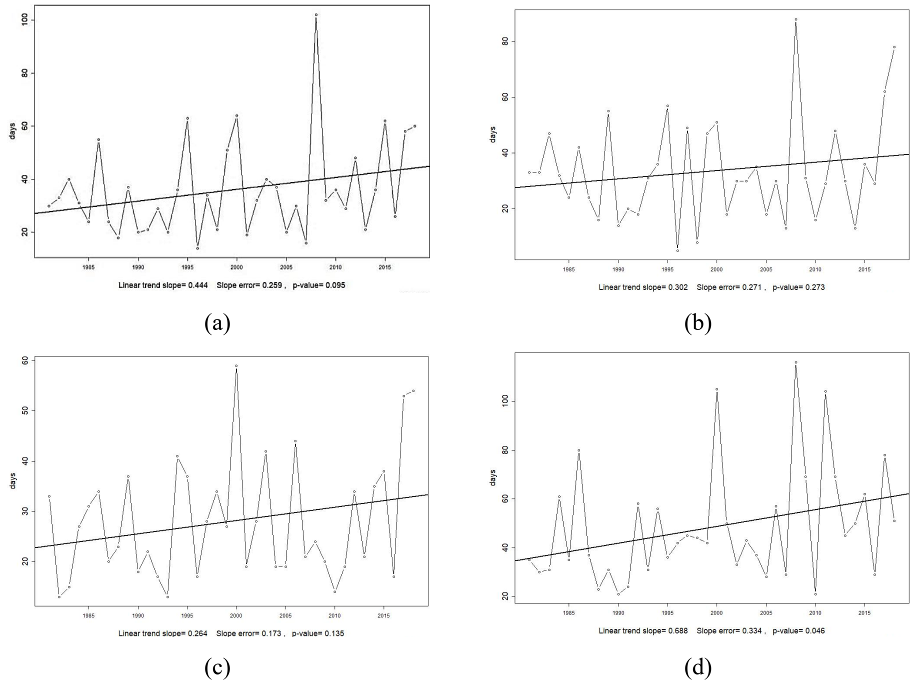


Figure 6 Trends of precipitation total (PRCPTOT), (a) Bule (b) Kochere (c) Wonago (d) Yirgachefe

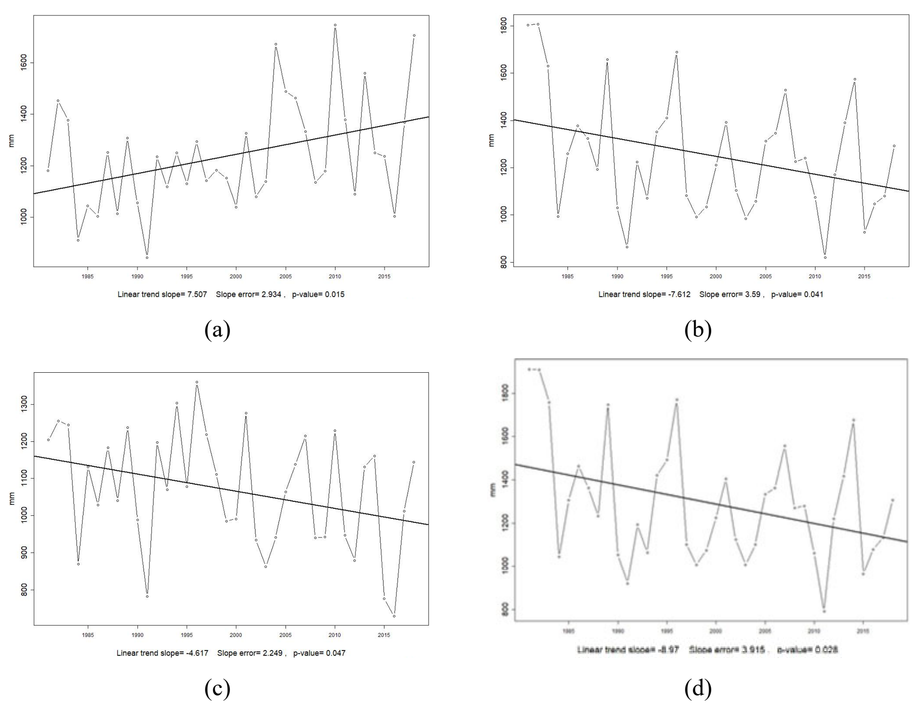
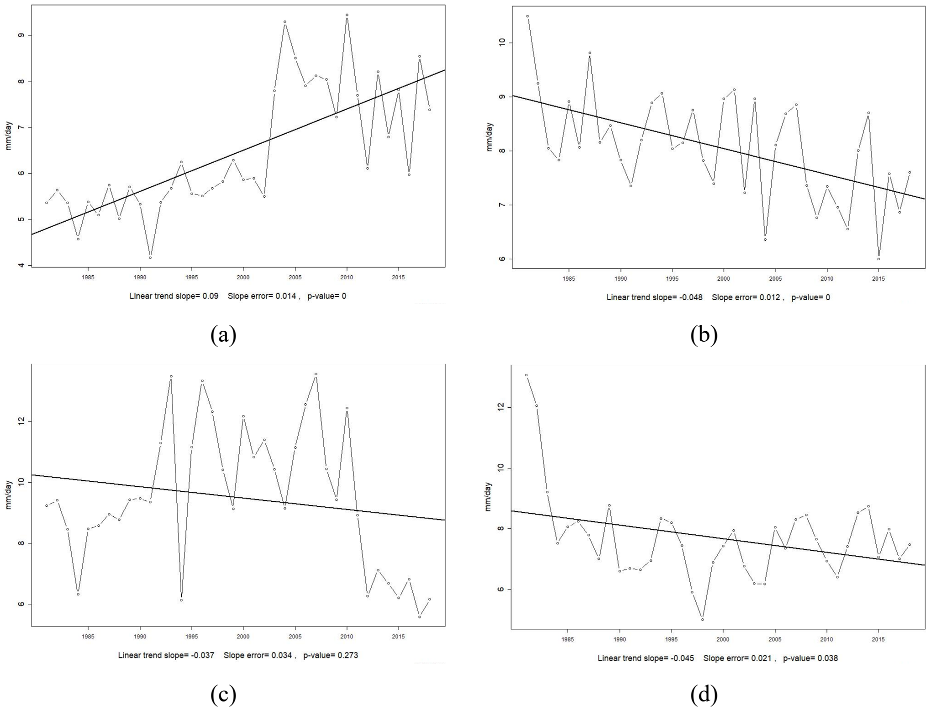


Figure 7 Trends of Simple daily intensity index (SDII), (a) Bule (b) Chelektu (c) Gedeb (d) Kochere



The changes of extreme rainfall events in the entire study area were diverse. R10mm, R20mm, CWD, PRCPTOT and R95p indices demonstrated decreasing trends (Figure 8). On the other hand, CDD showed an increasing trend in the study area. The above detected decreasing and increasing changes of extreme events might have drastic effect on agricultural productivity. There was also decreasing trend of SDII in the entire study area. This indicates that the insufficient amount of rain which falls in rainy days has implications on the availability and accessibility of water for agriculture and other activities.

Figure 8 Areal average and three years moving average trends of rainfall extreme indices in the study area, (a) maximum one day rainfall (Rx1) (b) maximum five days rainfall (Rx5) (c) Heavy rainfall days (R10mm) (d) very heavy rainfall days (R20mm) (e) consecutive wet days (CWD) (f) consecutive dry days (CDD) (g) annual total wet-day rainfall (PRCPTOT) (h) simple daily intensity index (SDII) (i) very wet days (R95p) (j) extremely wet days (R99p) (see online version for colours)

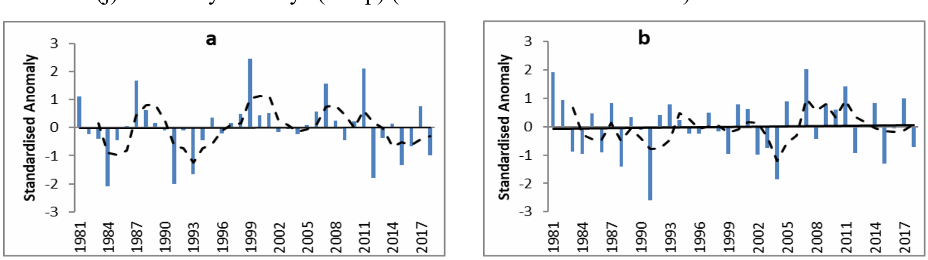
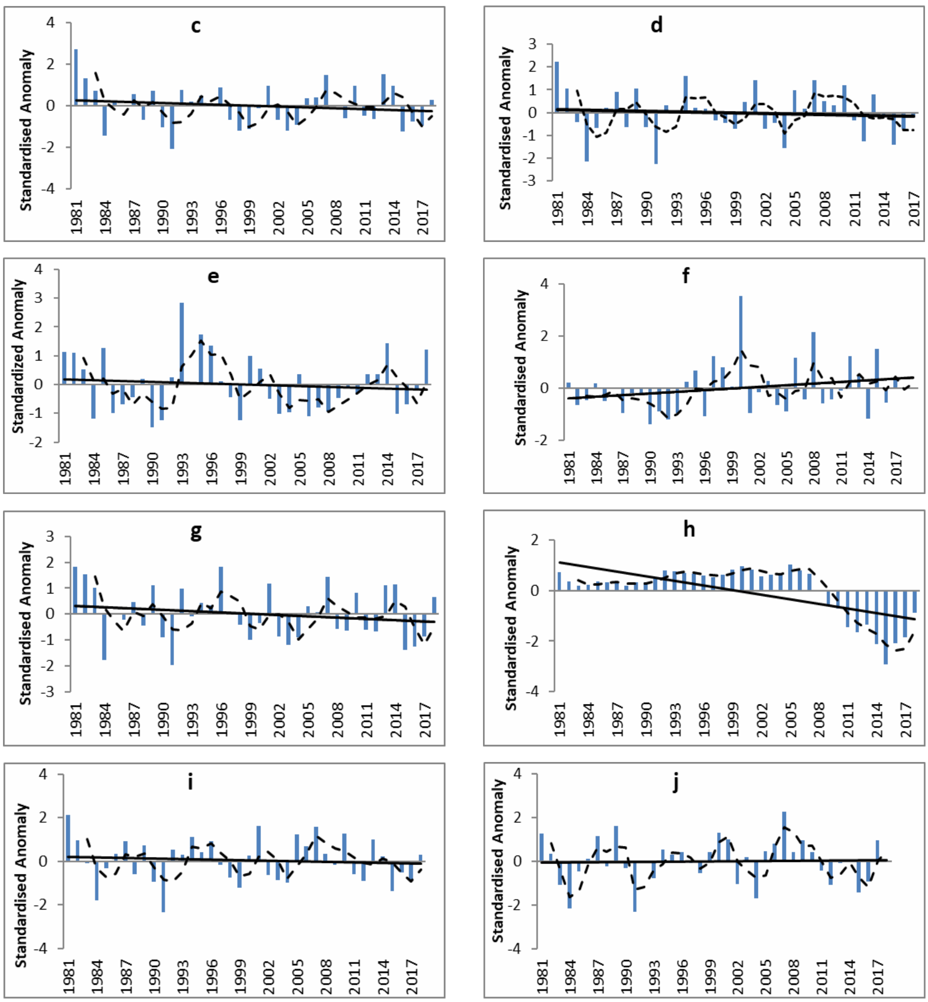


Figure 8 Areal average and three years moving average trends of rainfall extreme indices in the study area, (a) maximum one day rainfall (Rx1) (b) maximum five days rainfall (Rx5) (c) Heavy rainfall days (R10mm) (d) very heavy rainfall days (R20mm) (e) consecutive wet days (CWD) (f) consecutive dry days (CDD) (g) annual total wet-day rainfall (PRCPTOT) (h) simple daily intensity index (SDII) (i) very wet days (R95p) (j) extremely wet days (R99p) (continued) (see online version for colours)



4 Discussion and conclusions

This section tried to discuss the findings of rainfall variability and trends at different time steps in the period 1981–2018. The variability of rainfall at annual and seasonal time steps has shown moderate variability. This finding was similar with the findings of Degefu et al. (2021), Matewos and Tefera (2020), Dessalegn et al. (2019), Misrak et al. (2019) and Belihu et al. (2017) discussed below.

The study area can be considered as wettest region in which it receives rainfall throughout the year with its maxima during March–May and September–November

(Figure 2). The evergreen landscape in the area is a manifestation of the availability of moisture throughout the year. Our finding revealed that the study area receives its highest rainfall in the main rainy season (March–May) and get the second considerable amount of rain during September–November and small rainfall in *kiremt* (June–August) season. Similar findings were reported by Degefu et al. (2021) and Belihu et al. (2017) in their study conducted in south and south east parts of Ethiopia and Gidabo catchment of rift valley lakes basin respectively. The contributions of March–May and September–November rainfall to the total annual rainfall were nearly 40% and 32% respectively. This finding is similar with the finding of Degefu et al. (2021) who reported the contribution of March–May and September–November rainfall to the total annual rainfall to be 47.1 and 32.8% respectively in their study areas.

The variability of annual rainfall was low (CV < 20%) at all stations which implies the presence of steady annual rainfall. On the other hand, CVs of main and second rainy seasons were moderate (20–30) indicating the presence of irregular rainfall distribution. The main rainy season (March–May) showed less inter-annual variability compared to second rainy season (September–November). The analysis of PCI indicates the presence of moderate rainfall distribution over most of the study area (Table 3). Our findings are in agreement with the study reports of Degefu et al. (2021), Misrak et al. (2019) and Dessalegn et al. (2019) who reported slight annual rainfall and medium March–May rainfall variation in most of the stations in south east Ethiopia, Bilate catchment and upper Omo-Ghibe river basin respectively.

The study found that 1984, 1991, 1999, 2003/2004, 2009, 2012, 2015 were driest years of the study area which are coinciding with known Ethiopian driest years as a result of El Niño events. The recent documented droughts of Ethiopia (1984, 1987–1988, 1991–1992, 1993–1994, 1999, 2002–2003, 2008–2009, 2011) were all strong El Nino years (FAO, 2014). Among those years, 2015 was the worst drought year in Ethiopia and affected nearly 10 million people. The annual household consumption was reduced by 8% and exposed rural communities of Ethiopia to starvation in the same year (Gidey et al., 2018).

This study found that the highest and lowest rainfall trends at annual timescale were observed at Bule (53.8 mm decade^{-1}) and Yirgachefe (–69.2 mm decade^{-1}). Similarly, Bule and Yirgachefe had also the highest (–4.7 mm decade^{-1}) and lowest (–40.3 mm decade^{-1}) rainfall record during the main rainy season (March–May). This shows that there was considerable variation in rainfall trends at different time steps. The rainfall at annual and main rainy season (March–May) showed decreasing trends. This finding was similar with the works of Degefu et al. (2021), Matewos and Tefera (2020), Tesfamariam et al. (2019), Misrak et al. (2019), Mekonnen et al. (2018) and Belihu et al. (2017) who reported significant decreasing trends of annual and March–May rainfall in south east Ethiopia, Sidama district, central rift valley sub-basin, middle of Bilate catchment, Arsi Negele district and Gidabo catchment respectively. These considerable changes in variability and trends of annual and seasonal rainfall might affect the livelihoods.

Studies indicate that the downward changes of rainfall during March–May were highly associated with sea surface temperature (SST) fluctuations of Equatorial Pacific Ocean (Tesfamariam et al., 2019; Misrak et al., 2019; Diro et al., 2011). The increment of equatorial Pacific Ocean SST increases the local rainfall distribution over the same ocean and shrinkage of the normal rainfall amount over Ethiopia and other Horn of African countries (Funk et al., 2014). When El Nino occurs in the equatorial Pacific Ocean, the *kiremt* rainfall in Ethiopia generally decreases to below average and spring rainfall increases. In contrast, during La Nina, the spring (March–May) rainfall recipient areas in the country experience shortage of rainfall (Tesfamariam et al., 2019; Misrak et al., 2019; Fekadu, 2015). On the other hand, the decreasing of March–May rainfall amount is linked with the increment of temperature over Indian Ocean (Funk et al., 2008; Verdin et al., 2005; Haile, 1986). These studies reported that the increment of SST over the Indian Ocean lessens the transportation of moisture towards the Horn of Africa including Ethiopia by increasing air instability over the ocean.

The trends of rainfall extremes did not show any pattern among the studied stations (Table 5). PRCPTOT showed significant ($P < 0.05$) negative trends at Yirgachefe, Kochere and Wonago and significant ($P < 0.05$) positive trend at Bule. SDII showed downward trends in most of the stations. Except significant positive trend at Bule and significant negative trend at Chelelektu and Kochere, SDII showed insignificant trends at all studied stations. Both Rx5 day and R10mm showed insignificant trends in all studied stations except significant increasing trend at Bule. The trend of CDD indicates insignificant positive changes in all studied stations whereas CWD showed insignificant negative trends in 90% of the studied stations. Except the significant decreasing trend in R90p and R95p at Chelelektu and significant increasing trends in R90p and R95p at Bule, all studied stations showed insignificant divergent trends.

Our findings are similar with the findings of Degefu et al. (2021) and Mekasha et al. (2014) who reported insignificant negative trends of RX5 day, R10mm, CDD, CWD, PRCPTOT and SDII in most of their studied stations in south eastern Ethiopia and over three eco-environments of south eastern Ethiopia respectively. However, there were differences between our findings and the results of Degefu et al. (2021) and Mekasha et al. (2014) with regard to CDD and CWD. The present study revealed that CDD and CWD showed insignificant increasing trend and no clear pattern in the study stations respectively. On the other hand, our findings are similar with the results of Esayas et al. (2018) who reported the absence of significant trends of CDD, CWD and SDII in Wolaita zone of Southern Ethiopia.

Although most of the rainfall indices showed insignificant trends, they might have an effect on the performance of agriculture in the study area. The changes of these rainfall extreme events together with other temperature extreme events (which will appear in the proceeding paper) will affect the productivity of coffee and other agroforestry products. The analysis of areal average indices showed that SDII was below long-term average in recent decades (starting from 2000) (Figure 6). This will have implications on the availability of water and moisture in the soil which in turn affects coffee productivity as well as other ecosystem.

Generally, our study produced important and up-to-date information on the trends and variability of rainfall amount and extreme events using the daily rainfall data gathered from various stations which represent different agroecologies of the study area. The study emphasised on the analysis of two wet seasons March–May and September–November which are the distinct rain seasons for the study area. The trend results of these seasons help gain in-depth information to realise the likelihood impacts resulted from rainfall changes and to design appropriate adaptation strategies for specific season and local contexts. The trends of rainfall in the main rain season (March–May) showed a declining tendency in all stations which have significant impact on the livelihood of smallholder farmers who directly depend on this season for their livelihood systems as shortage of water affects the production of coffee and other subsistent crops. On the contrary, the trends of rainfall at the second rainy season (September–November) showed increasing tendencies in most of the station which suggest the need to take adaptation strategies to earn more production from this season.

There were inconsistent trends of rainfall extreme indices and clear decreasing signals of annual and seasonal rainfall. Most extreme rainfall indices showed divergent trends in the study area. Significant increasing trends at eight out of ten rainfall extreme indices observed at Bule and significant decreasing trends at six out of ten rainfall extreme indices observed at Chelelektu were unique from other extreme results of the study area which need further investigation. Since climatic variability and trends have been changing in short distances, this type of local level study is thought important to take appropriate decisions on the management of agriculture, water and flood risks in local contexts. Although smallholder farmers have the opportunity to use the increasing amount of rainfall received during small rain period (September–November), they might encounter shortage of water as the months next to this season are dry. This study recommends further researches to identify most promising adaptation strategies to strengthen the availability of water in the dry months.

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