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Monitoring climate extremes using standardized evapotranspiration index and future projection of rainfall and temperature in the wettest parts of southwest Ethiopia

Dessalegn Obsi Gemeda[a,*], Diriba Korecha[b], Weyessa Garedew[c]

[a] *Jimma University College of Agriculture and Veterinary Medicine, Department of Natural Resources Management, Jimma University, Ethiopia*
[b] *Famine Early Warning Systems Network, Addis Ababa Ethiopia, Ethiopia*
[c] *Jimma University College of Agriculture and Veterinary Medicine, Department of Horticulture and Plant Sciences, Jimma University, Ethiopia*

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ABSTRACT

Ethiopia is categorized as one of the most vulnerable countries to climate extremes. A better understanding of climate extremes at short and long timescales is therefore crucial to minimize the potential impacts of these extremes. The present study aimed to characterize the frequency and severity of agricultural and hydrological drought in southwestern parts of Ethiopia over the period 1971 to 2020. Satellite blended/gridded and historical observed monthly rainfall, maximum temperature and minimum temperature data of nine stations (Arjo, Bako Tibe, Bedele, Didessa Dildey, Gedo, Gimbi, Sekoru, Serbo and Nekemte) were obtained from Ethiopia National Meteorological Agency. We used standardized evapotranspiration index (SPEI) to calculate the dry and wet condition at 3-, 6-, and 12-months timescales. Besides, past climate change analysis, future rainfall and temperature were projected under four representative concentration pathways (RCPs) of CMIP5 for the near and mid-term (2041-2060) and end of the twenty-first century (2081-2100). Our results showed that the frequency of drought in the short timescales is much higher than that of the longer timescales. In the present study, a total of 108 and 111 drought months were observed at Bedele and Nekemte, respectively at SPEI 3 and both stations recorded a total of 101 at SPEI 6. An increase in projected mean minimum and maximum temperature by 1.2°C was observed by the end of 21st century comparative to the reference time (1986-2005) under a high emission scenario (RCP8.5). Projected changes in rainfall showed a slight increase over the periods 2041-2060 and 2081-2100 under RCP4.5, RCP6.0 and RCP8.5, while projected trends under RCP2.6 indicated a slight decrease. The results of this study will be useful to design effective climate resilience agriculture in the study area. Moreover, it provides evidences for policy makers towards climate change adaptation and mitigation in the southwestern parts of the country.

1. Introduction

A better understanding of climate extremes and future scenarios will minimize the potential consequences of climate change. Drought and flood are two climate extremes that indicate the climate abnormality. Since the 1950's unusual climatic conditions have been observed in various regions. The global mean temperature for the end of 21stcentury is projected to increase by 1.4°C and 3.1 °C under representative concentration pathway (RCP) 6.0 and between 2.6 °C to 4.8 °C under RCP8.5 (IPCC, 2014a). According to IPCC (2018), the land surface temperature has increased since the pre-industrial period (1850-1900) to 2006-2015, by 1.53 °C (very likely range from 1.38 °C to 1.68 °C) while the global mean surface temperature increased by 0.87 °C, with likely range from 0.75 °C to 0.99 °C. The recent IPCC AR6 projected that the global warming is increased by +1.07 °C (0.8-1.3 °C; likely range) for 2010-2019 period with respect to 1850-1900 (IPCC, 2021). In addition to temperature projections, the IPCC (2014a) also projects an increase in runoff and flood hazard in some region as a result of global warming.

Drought is occurred due to below-normal precipitation over time while flood happened as a result of excess precipitation. Drought has a negative implication on the economy, which can threat development efforts (Fava and Vrieling, 2021) and food security (Xu et al., 2021). At global level, drought resulted in death of almost 12 million people and displacing more than two billion people between the year 1900 and 2013 (Ogunrinde et al., 2020). In 2011, about 12 million people from Eastern African countries were affected by drought that led to famine (Pei et al., 2020). It is projected that drought and flood frequency will intensify in the future and affect millions of people (Kiro et al., 2020; Mishra et al., 2021). Climate extremes have substantially dis-

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* Corresponding authors.
E-mail addresses: dasoobsi@gmail.com, dessalegn.obsi@ju.edu.et (D.O. Gemeda).

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rupted human and natural systems (Potop et al., 2014; Loucks and van Beek, 2017; Abedin et al., 2018; Swain et al.,2020; Shi et al., 2021). Korecha (2014) also documented that extreme event may result in economic failure and humanitarian disasters.

Drought and flood are common global problems, but their effects are not equal across all regions. For instance, tropical region is highly exposed to climate extremes than other regions (Gonzalez-Orozco et al., 2020). More recently, Elagib et al. (2021) clarify that flood in a semi-arid region of Africa becoming more frequent and devastating. East African countries are extremely vulnerable to climate extremes (Omondi et al., 2012; Gebrechorkos et al., 2018; Tegegne et al., 2021; Musei et al., 2021). Rainfed dependent food production systems are highly vulnerable to drought (Temam et al., 2019). Several methods have been developed and used to detect drought severity, which includes; Palmer Drought Severity Index (PDSI) (Palmer, 1965); Reconnaissance Drought Index (Tsakiris and Vangelis, 2005); Drought Severity Index (Mu et al., 2013); Standardized Precipitation Index (SPI) (McKee et al., 1993) and Standardized Precipitation Evapo-transpiration Index (SPEI) (Vicente-Serrano et al., 2010). The PDSI used precipitation, runoff, moisture and evaporation input variables (Tirivarombo et al., 2018) to detect moisture conditions and water balance at regional perspective (Yihdego et al., 2019) at temporal scale of 9 to 12months (Wang et al., 2019) and highly applicable in high evapotranspiration areas (Palmer, 1965). The RDI aims at identifying meteorological drought in Sahel region (Thomas et al., 2016). The DSI calculates drought based on soil water status (Cammaller et al., 2016).

The SPI used precipitation data, while the SPEI, which is the improved version of SPI, used both precipitation and temperature data to quantify drought. This index is calculated by subtracting precipitation from potential evapotranspiration (PET) and adjusted using a 3-parameter log-logistic distribution. Both SPI and SPEI have been widely used around the world (Pei et al., 2020) because of its capacity to detect and monitor droughts at a temporal scale of 1, 3, 6, 12, and 24 months (Liu et al., 2016) and even at longer temporal scale as highlighted in Copernicus European Drought Observatory (EDO, 2020). Despite the existence of various indices, the present study used SPEI to analyze drought based on precipitation and temperature data. It is believed that the SPEI is much better than SPI, since the former uses both precipitation and an estimated value of PET, which considers the effect of warming on water demand (Begueria et al., 2014; Tirivarombo et al., 2018). The SPEI can be analyzed at different timescales, including meteorological (1-month), agricultural (3–6-month timescales) and, hydrological droughts at 12 months timescales (Potop et al., 2014; Tirivarombo et al., 2018; Wang et al., 2021). The timescale for agricultural drought may vary depending on crop variety, agroclimatic setup of the region, and length of the growing period.

Climate extremes are affecting every country and the consequences will get worse for sustainable development of a nation. Climate extremes, particularly drought significantly affects Ethiopian economy and life of the civilian for several decades. The country has been affected by drought in 1984, 1991, 2002, 2009 and 2010 (Randell and Gray, 2016; Gemeda et al., 2020). Besides, the country has experienced drought in 1960s', 1970s', 1980s', 1990s' and 2020s' and affected nearly about 66,941,879 people with about 402, 367 fatalities over the past five decades (Masih et al., 2014). Richman et al. (2016) reported that approximately 400,000-1,000,000 lives were lost due to drought driven famine in Ethiopia between the year 1983-1985.This Fig. clearly indicates that droughts have caused whopping losses every decade in the country and often related to rainfall deficit. According to the global database, Emergency Events Database (EM-DAT, 2020), drought associated with El-Niño affected about 10,200,000 without fatality report from Somali, Afar, Oromia, Amhara and Southern Nations, Nationalities and People's Region (SNNPR) in 2015 (www.emdat.be). EM-DAT also documented that both flash flood and riverine flood affected Ethiopia. Accordingly, about 1,2237,210 people were affected by flood between the year 2013 and 2020.

Substantial studies have been conducted on drought assessment in the central Rift Valley regions of Ethiopia (Biazin and Sterk, 2013; Mechal et al., 2015; Tesfamariam et al., 2019; Mohammed and Yimam et al., 2021; Nasir et al., 2021; Wolteji et al., 2022). Other studies emphasized in the pastoralism and agro-pastoralism areas on climate change adaptation strategies (Berhanu and Beyene, 2015; Egeru, 2016; Ng'ang'a et al., 2016; Mekuyie et al.,2018; Gebeyehu et al., 2021). It is clear that many researches focused in the Rift Valley region, north-eastern, and southeastern parts of Ethiopia while the western and southwestern parts of the country didn't get the attention of scholars and little have been known about this region. In addition, poor understanding on the possibilities of climate extremes in southwest part of Ethiopia is a great deal.

Assessment of climate extreme and future projections of rainfall and temperature at local scale is a prerequisite for better understanding of the climate change to proposed disaster risk reductions and management. Timely drought assessment is very crucial for securing the yields of agricultural crops in rain-fed dependent economy. Moreover, better understanding of climate extreme itself require scientific evidence to design further research and policy actions. Therefore, this study aimed to quantify climate extremes in southwestern parts of Ethiopia. This research enables policy makers to take appropriate actions or modifying current actions in ways that make them more effective in light of climate extremes and projected changes in the study area and beyond.

2. Materials and methods

2.1. The study area

This study was conducted in southwestern parts of Ethiopia. It covers five Administrative Zones namely Jimma, West Shoa, Buno Bedele, East Wollega and West Wollega (Fig. 1). The study area extends over 7.25°N-10.40°N and 34.35°-38.57°E, and has a total area of 65,553.3 km^2 (6,555,330 ha) of land (Gemeda et al., 2021). The altitude of the study area ranges from 702.5 at Begi in West Wollega to 3372.6 meters above mean sea level in Omo Beyan of Jimma zone. Food crops such as maize, wheat, teff, barley, and millets are the principal crops cultivated in the region. Coffee (*Coffea arabica*), tea, pulses, root and tuber crops, oil seeds mainly sesame and ground nuts are the main important international agricultural commodities cultivated in this region. Arabica coffee grows naturally in the forest in this region (Geeraert et al., 2019).

The climate of the study area is dominated by a tropical monsoon climate, and means annual rainfall varies between 750 and 2400 mm, with an annual average of about 1575 mm (Korecha, 2014). This region experienced the monomodal rainfall pattern that extends from March to November. The study area is categorized under southwest rain forest climate zones (Viste et al., 2013). The area experiences low rainfall and temperature variability, with inconsistent and significantly irregular rainfall and a declining tendency in the main rainy season (Asfaw et al., 2018; Gemeda et al., 2021).

2.2. Data sources and analysis method

2.2.1. Data sources

Long historical observed data for Bedele and Nekemte (1971-2020) and Sekoru (1981-2020) stations were obtained from Ethiopian National Metrological Agency (NMA). Moreover, monthly rainfall, maximum and minimum temperature gridded datasets (1983-2016) of six stations namely Arjo, Bako Tibe, Didessa Dildey, Gedo, Gimbi, and Serbo were obtained from NMA. In the present study, we used the General Circulation Models (GCMS) for future projection. Climate change scenarios from the GCM are generally at large scale and need to be downscaled to get relevant information to our area of interest (Goyal et al., 2012; McSweeney and Jones, 2016; Feyissa et al., 2018; Mekonnen and Dissie, 2018; Shiru et al., 2019). Dataset from GCMS:

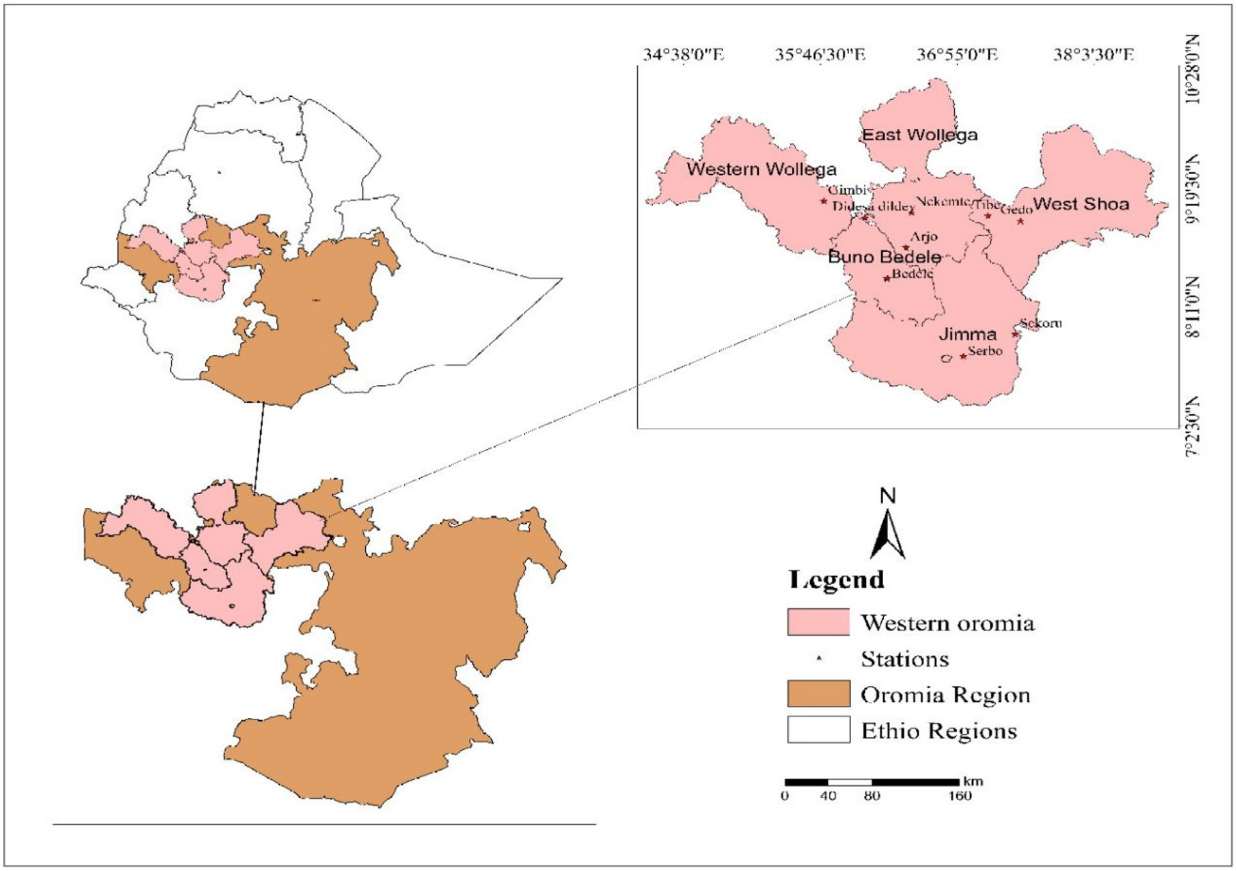


Fig. 1. Map of the study area.

Coupled Inter-comparison Project5 (CMIP5) of the Fifth Assessment Report (AR5) of the IPCC subset under four RCPs 2.6, 4.5, 6.0 and 8.5 (https://climexp.knmi.nl/plot_atlas_form.py) were used for the near to mid-term future (2041-2060) and end of the 21st century (2081-2100) temperature and rainfall projections. Various researchers utilized the CMIPS for future climate projections in different countries (McSweeney and Jones, 2016; Shivam et al., 2017; Feyissa et al., 2018; Muhati et al., 2018). In the present study, we used the reference period 1986-2005 from AR5. According to the IPCC Fifth Assessment Report (IPCC, 2013), the 1986-2005 modern period was chosen as a climate period because the design of the CMIP5 simulations required a recent reference baseline for the projections of future climate (IPCC, 2013; Kharin et al., 2013; Hawkins et al., 2017; Vukovic et al., 2018).

2.2.2. Missed data handling techniques

There are some missing values of historical observed monthly rainfall, maximum temperature and minimum temperature data at three stations (Nekemte, Sekoru and Arjo). To maintain the quality and credibility of the research output for policy maker; we used multi-techniques approach; which includes using data from a station's nearest neighbors to make estimations (Edwards and McKee, 1997). We also used the global data set (https://power.larc.nasa.gov/data-access-viewer/) to replace the missing values of a station.

2.2.3. Data analysis

In the present study, SPEI was employed to estimate the frequency of drought. The SPEI used a series of monthly climatic water balance (CWBAL), which is the difference between precipitation and potential evapotranspiration (PET) and adjusted using a 3-parameter log-logistic distribution (Vicente-Serrano et al.,2012; Stagge et al., 2015) as shown in Eq. 1. The PET is calculated by Thornthwaite method (Thornthwaite, 1948) through normalizing CWBAL into the Log-logistic probability distribution (Tirivarombo et al., 2018).

$$D_i = P_i - PET_i \tag{1}$$

Where D_i the difference, P_i is precipitation, PET_i is the potential evapotranspiration and i is a given month. The estimated D values are combined at various time scales as shown in Eq. 2.

$$D_n^k = \sum_{i-0}^{k-1} P_{n-1} - (PET)_{n-1} \tag{2}$$

$where\ k\ is\ the\ timescale\ (months) of\ the\ aggregation\ and\ n\ is\ the\ calculation\ month$

The probability density function of a Log-logistic distribution is calculated as Eq. 3.

$$f(x) = \frac{\beta}{\alpha}\left(\frac{x-y}{\alpha}\right)\beta\_1\left(\frac{x-y}{\alpha}\right)\beta) - 2 \tag{3}$$

$where\ \alpha, \beta\ and\ y\ are\ scale,\ shape\ and\ origin\ parameters,\ respectively\ for\ y > D < \infty$. Then the probability distribution function for the D series is then given as Eq. 4.

$$f(x) = \left[1 + \left(\frac{\alpha}{x} - y\right)\beta\right] - 1 \tag{4}$$

With f(x), the SPEI can be determined as the standard values of f(x) as previously used by Tirivarombo et al. (2018) as shown in Eq. 5.

$$where\ SPEI = W - \frac{c_0 + c_1W + c_2W^2}{1 + d_1W + d_2W^2 + d_3W^3}\ and\ W = \sqrt{-2\ ln\,(P)}\ \text{for P} \le 0.5 \tag{5}$$

P is the probability of exceeding a determined d_i value and is given as P=1- f (x) while the constants are: c_0=2.515517, c_1=0.802853, c_2=0.010328, d_1=1.432788, d_2=0.189269, d_3=0.001308.

For this study, SPEI R-Software packages that developed by Begueria et al. (2014) was used to monitor the dry and wet condition at 3-, 6-, and 12-months' timescales. The SPEI have been applied in other similar works (Jiang et al., 2014; Fung et al., 2017; Tirivarombo et al.,2018; Spinoni et al., 2019; Tefera et al., 2019; Pei et al., 2020). Positive (above mean) and negative (below mean) values of SPEI show wetter and drier conditions, respectively (Li et al., 2015). Drought can be expressed based on the values of SPEI as 'Extremely wet' for SPEI>2, 'Very Wet' for SPEI=1.50 to 1.99, and 'Moderately wet' for SPEI=1.00 to 1.49, 'Near Normal' for SPEI=0.99 to -0.99, 'Moderately dry' for SPEI=-1.00 to -1.49, 'Severely dry' for SPEI=-1.5 to -1.99, and 'Extremely dry' with -2 or less (Li et al., 2017).

The CMIP5 of the AR5 of the IPCC subset under four RCPs 2.6, 4.5, 6.0 and 8.5 was used to project the changes in mean minimum temperature, mean maximum temperature and annual rainfall for southwestern parts of Ethiopia for the years 2041-2060 and 2081-2100 relative to bassline (1986-2005). The significant trend for the bassline and future projections were performed using the trend package of Open R software (Pohlert, 2016). The mean minimum temperature, maximum temperature and annual rainfall for the bassline and future projections were computed. Statistical analyses and timeseries graph for the bassline and future temperature and rainfall projection were produced using the OriginPro 2019 program (OriginPro, 2019b).

3. Results and discussions

3.1. Long-term drought event and drought categories

In this section, long-term drought event and drought categories at three timescales (3-, 6-, and 12-months) were detected using SPEI [Supplementary material (SM), Table, SM 1). In the present study, 3 and, 6-month timescale, which is about 90, and 180 days were considered as agricultural drought as used by previous studies (Potop et al., 2014; Tirivarombo et al., 2018; Wang et al., 2021). The temporal occurrence of extreme, severe and moderate drought at Bedele and Nekemte (Fig. 2A; Fig., 2B) and Sekoru (Fig., 3) stations at different time scales were presented. Results showed that the occurrence of extreme and severe drought at shorter and longer timescales indicating the presence of agricultural and ecological, and hydrological drought in the study areas. Drought significantly affects the food security particularly in Sub-Saharan African countries (Ahmed, 2020). Shortage or deficit of precipitation significantly affects agricultural yield (Waseem et al., 2022). According to the recent IPCC Sixth Assessment Report (IPCC, 2021), agricultural and ecological drought is a period with abnormal soil moisture deficit, which results from combined shortage of precipitation and excess evapotranspiration during the growing season. In contrast, observed changes in meteorological droughts (precipitation deficits) and hydrological droughts (streamflow deficits) are distinct from those in agricultural and ecological droughts.

The frequency of drought occurrence in the short timescales is much higher than that of the longer timescales. For instance, the 3 months scale detected a total of 108 at Bedele and 111 at Nekemte while the 6-moths scale detected 101 for both Bedele and Neketme stations. Ayantobo et al. (2017) also found that there is a declining frequency of drought with increasing timescales. The total number of droughts detected at SPEI-12 was 92 for both Bedele and Nekemte stations. The total number of drought months at SPEI 3 and SPEI 6 are almost comparable, i.e., 108 to 111 while at SPEI 6 and 12 the total numbers of drought are identical for both Bedele and Nekemte stations, this might be due to the homogeneity of the landscape.

The drought frequency for Sekoru station at short (3 months) and intermediate (6 months) timescales detected comparable results, i.e., 86 and 85. At Sekoru station a total of 86, 85 and 76 droughts detected for the SPEI 3, SPEI-6 and SPEI-12, respectively. The results show that there is a presence of one extreme drought per decade and almost eight severe drought per decade at SPEI-3 timescale for Bedele, Nekemte

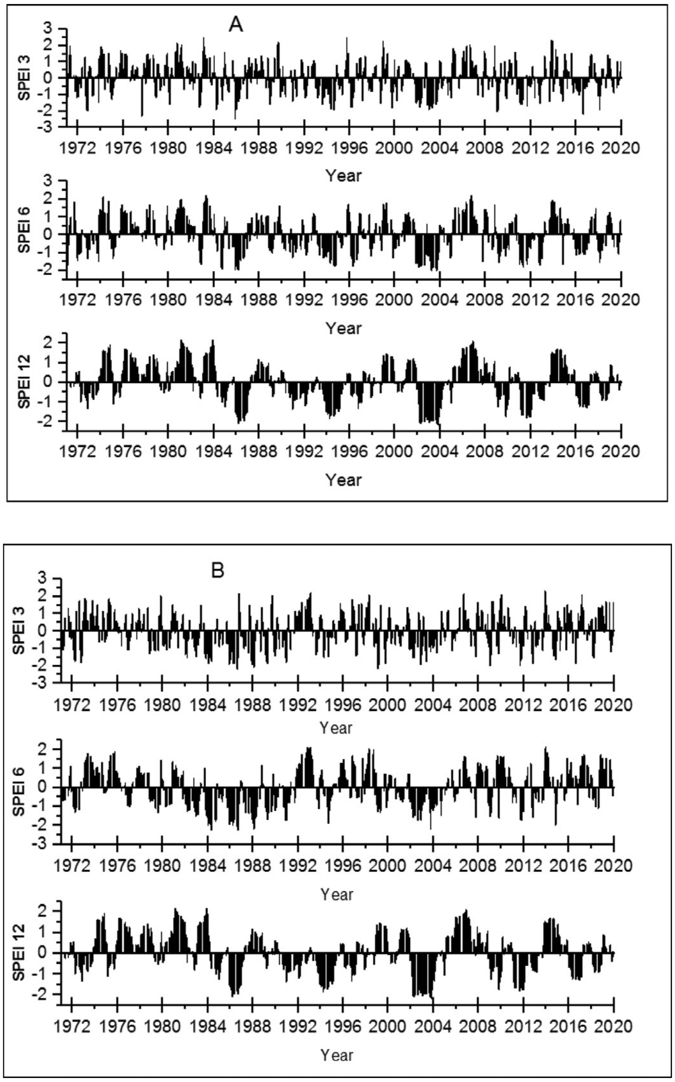


Fig. 2. SPEI at different timescales for Bedele (2A) and Nekemte (2B) stations during 1971-2020.

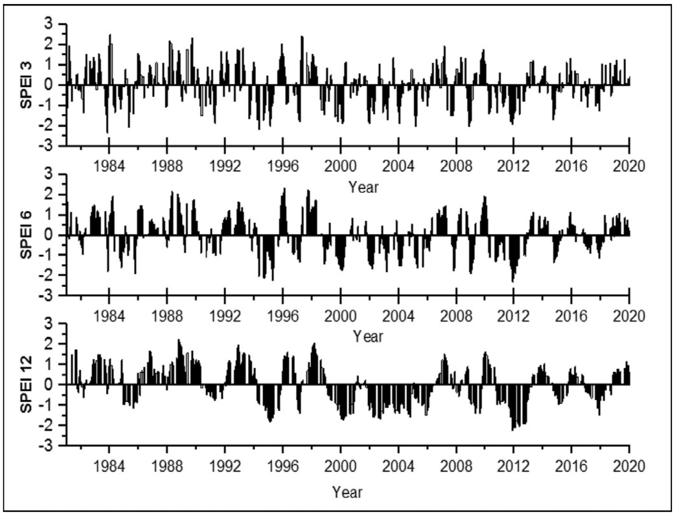


Fig. 3. SPEI at different timescales for Sekoru station during 1981-2020

and Sekoru stations. Agricultural drought quantification can be used to improve farmers decision to cultivate the right crops at the right time that can minimize the risk of yield loss due to precipitation deficit. Spatiotemporal understanding of drought occurrence is crucial to minimize the adverse effects of drought on food security (Zeng et al., 2019). It has been proved that drought events substantially affect the agricultural yields and human life in the past several decades in Ethiopia and expected to increase as global warming is expected to increase in the future.

On yearly basis, at Bedele station, extreme drought was observed in 1978, 1986, 2009 and 2017 at SPEI-3 while only severe and moderate drought were observed at SPEI 6 while extreme drought was observed in 1986, 2002-2004 at SPEI 12. Thus, the year 1986 experienced both agricultural and hydrological drought. The year between 1994 and 1995 also experienced severe drought at SPEI 3, SPEI 6 and SPEI 12 (Table, SM 2). Comparable results have been reported by Viste et al. (2013) by using SPI. At Nekemte, extreme drought was recorded during the years 1987-1988, 1999, and 2002 at 3-month timescales. At 6 months timescales extreme drought were observed in 1984, 1987-1988 while on the 12-moth timescale extreme drought were observed during 1986, 2002-2004 (Table, SM 3).

Sekoru station experienced extremely drought during the years 1984-1985, 1994, 2005 and 2009 at 3 months scale (Table, SM 4). Viste et al. (2013) conclude that the year 1984 and 2009 were the first and second driest year recorded particularly around the Rift Valley region, northeastern and central highlands of Ethiopia. At 6 months scale, extreme droughts were observed in the years 1994-1995, and 2012. Extreme drought was observed in 2012 both at 6- and 12-months timescales. Severe drought is also detected in 2015 at Sekoru at 3- and 6-months timescales.

3.2. Long-term wet event and its categories

The number of extreme, severe and moderate wet months at SPEI 3, 6, and 12 at Bedele, Nekemte and Sekoru stations is presented (Table, SM 5). The most extreme wet occurred between 1981 and 1990 at Bedele and Sekoru stations. The number of extreme wet months recorded at Bedele and Nekemte stations are almost identical at SPEI 3, SPEI 6 and SPEI 12. The results indicate that the number of extreme wet months at short timescales (e.g., 3 months timescales) is twice greater than the number extreme drought in the same stations. Study conducted by Jiang et al. (2014) found that the total number of extreme wet months exceeds the number of extreme drought months. In contrast, the total number of extreme drought month is higher than the number of extreme wet months at SPEI 12. The results showed that there is a tendency of declining number of extreme wet months in the recent decade particularly, at Sekoru station. At this station, no extreme wet months recorded over the last two decades (since 1998) across the three SPEI time scales.

The study area under investigation experienced extremely and severe wet, which may affect the agricultural production in the study area particularly during the main growing and harvesting times. For instance, Bedele station experienced extreme wet during the years 1981, 1983, 1990, 1996, 1999, 2005, 2007, and 2014 on 3-month scales. At 6-month scale, extremely wet was observed in 1974, 1983 and 2007. The years 1981, 1984 and 2007 were experienced extremely wet on 12-month time scale.

At Nekemte, extremely wet years at 3-month time scales were occurred in the years 1980, 1987, 1990, 1993, 1998, 2007, 2010, 2014 and recently in 2017. At 6-month scale the years 1993, 1998, and 2014 were experienced extremely wet while at 12-month scale the years 1981, 1984, and 2007 observed extremely wet. Both Bedele and Nekemte stations recorded surplus amount of precipitation (Extremely wet) in the year 1984, which is completely different from other parts of the country. Several studies reported that Ethiopia was affected by drought in 1984 (Kumar, 1990; Araya and Stroosnijder, 2011; Kenawy et al., 2016; Richman et al., 2016; Suryabhagavan, 2017; Mera, 2018; Liou and Mulualem, 2019).

At Sekoru station, extremely wet were recorded in the years 1981, 1984, 1988, 1990, 1996 and 1997 at 3-month scale while 1988-89,1996, and 1998 were extremely wet at 6-month scale. At 12-month scale only the years 1989 and 1998 recorded extremely wet. When we compare the three long historical climate data of three stations (Bedele, Nekemte and Sekoru), the number of extremely wet months recorded at Sekoru is relatively small in numbers. This is probably due to less forest cover relative to other districts.

3.2. Drought and wet months based on satellite blended data (1983-2016)

3.2.1. Drought detection

Results showed that extreme agricultural drought (3- and 6-month timescale) and extreme hydrological drought (12-month timescale) experienced in southwestern parts of Ethiopia over the study period of 1983-2016 (Table, 1; Fig. 4; Fig. 5). Accordingly, extreme drought at SPEI-3 were detected during the years 1986, 1995-1996, 1999, 2002-2003, 2013 and 2015-2016. Extreme agricultural drought also detected during the years 1986, 1995, 2002, 2012 and 2015 at SPEI-6. Hydrological drought was observed during the years 1986, 1995-1996, 2003-2004, 2012, 2015-2016. At Gedo and Bako stations, the occurrence of extreme drought has been increased recently. Three of six stations experienced extreme drought in the year 1986 across the three drought timescales. Gedo and Bako Tibe experienced the highest number of extreme droughts followed by Arjo station between the year 1983 and 2016.

1983-1990

The number of drought and wet months at 3-, 6-, and 12-month time scales is presented in (Table 2 and; Table 3). The results showed that the occurrence and magnitude of drought varies across time and space in the study areas. At Arjo station, the year 1986 was the driest year across the three timescales; SPEI 3, SPEI-6 and SPEI-12 (Table, SM 6). During 1983-1990 extreme drought months has been detected at Arjo and Gimbi at SPEI 3, SPEI 6 and SPEI 12 while Didessa Dildey experienced extreme drought at 6- and 12-months timescales. Severe drought was occurred at Serbo, Bako Tibe, Gedo, Arjo, Gimbi and Didessa Dildey at SPEI 3, which can significantly affect the farming communities. Drought occurrence have been reported in different parts of the country in the 1980s' (Viste et al., 2013; Randell and Gray, 2016; Tefera et al., 2019; Nasir et al., 2021). Extreme climate events can have significant effects on crop yields, particularly during the main growing seasons (Tirivarombo et al., 2018).

1991-2000

The number of drought months in 1990s'was greater than that of 1980s' at five stations namely, Serbo, Bako Tibe, Gedo, Gimbi, and Didessa Dildey. These results clearly indicate the disparities in the occurrence of extreme and severe drought across the study area. During 1991-2000, extreme drought has been recorded at small scales (SPEI-3) at Gedo, Arjo and Didessa Dildey. Didessa Dildey experienced extreme drought both at short (SPEI-3) and longer timescale (SPEI-12) in the year 1995 (Table, SM 7). Extreme drought was also detected at Serbo and Gimbi at SPEI 6 and Didessa Dildey at SPEI-12. In 1990s' substantial number of moderate droughts has been detected at all stations. Study by Tefera et al. (2019) in the northern parts of Ethiopia reported that drought severity has been detected in 1990-1992 at 3-months and 6-months timescales.

2001-2010

During 2001-2010 Bako Tibe and Gedo stations experienced extreme drought at SPEI 3, SPEI 6, and SPEI 12. Also, Serbo station experienced extreme droughts at SPEI 3 and SPEI 6 while Arjo experienced extreme drought at SPEI 3 and SPEI 12. Only two stations namely; Gimbi and Didessa Dildey did not experience extreme drought at any timescales between 2001 and 2010. This might be due to the presence of ev-

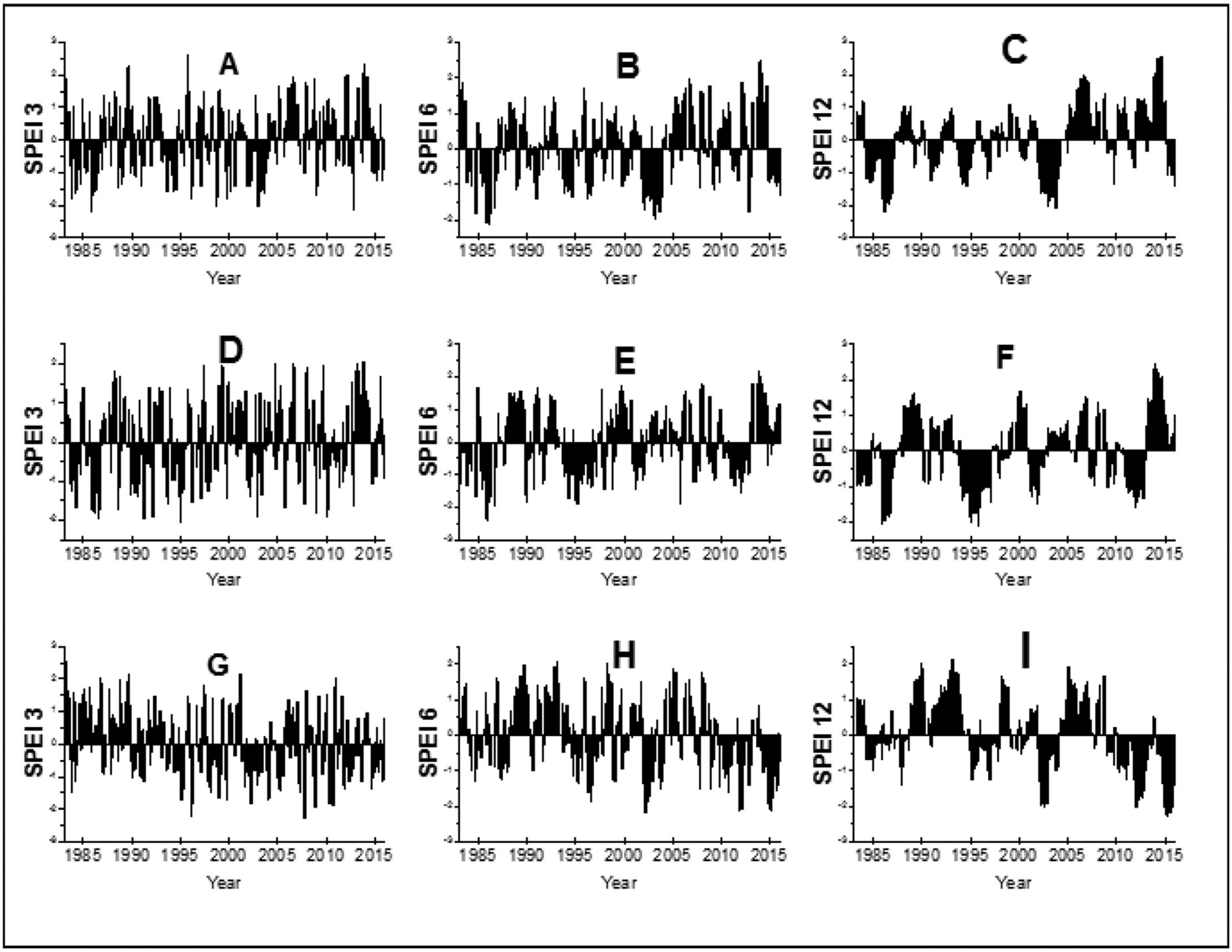


Fig. 4. Temporal variations of SPEI AT 3-, 6- and 12-month timescales (A) Arjo 3-month, (B) Arjo 6-month, (C) Arjo 12-month, (D) Didessa Dildey 3-month, (E) Didessa Dildey 6-month, (F) Didessa Dildey 12-month (G) Gedo 3-month, (H) Gedo 6-month and (I) Gedo 12-month timescales during 1983-2016.

Table 1
Extreme drought years detected at SPEI-3, SPEI-6 and SPEI-12 of six stations (1983-2016).

Station	Study period	SPEI-3	SPEI-6	SPEI-12
Arjo	1983-2016	1986,1999,2003 and 2013	1986	1986,2003 and 2004
DidessaDildey	1983-2016	1995	1986	1986, 1995 and 1996
Gedo	1983-2016	1996	2002, 2012, 2015	2003,2012, 2015 and 2016
Gimbi	1983-2016	1986	1986	1986,1995 and 1996
Serbo	1983-2016	2002,2015, 2016	1995, 2002	-
Bako Tibe	1983-2016	2002	2002, 2012,2015	2003,2012,2015 and 2016

ergreen and forest coffee plantation. However, majority of the study area experienced severe and moderate droughts. For instance, Gedo station recorded significant number of severe and moderate drought across three timescales in 2002 (Table, SM 8).

2011-2016

Arjo and Serbo experienced extreme drought at SPEI 3 while Bako Tibe and Gedo experienced extreme drought both at SPEI 6 and SPEI 12. The total number of drought months tend to increase from the period of 2001 to 2010 to 2011 to 2016 substantially at Serbo, Bako Tibe and Gedo stations.

3.2.2. Wet and wet categories

1983-1990

Four stations namely; Serbo, Bako Tibe, Gedo and Arjo experienced extreme drought at SPEI 3 while no extreme wet was detected at SPEI 6 and SPEI 12. Between the year 1983 and 1990, all stations experienced severe and moderate wet except Arjo station, where there was no severe wet detected with SPEI 12.

1991-2000

Between 1991 and 2000, Serbo and Bako Tibe stations experienced an extreme wet months at SPEI 3, SPEI 6, and SPEI 12 while

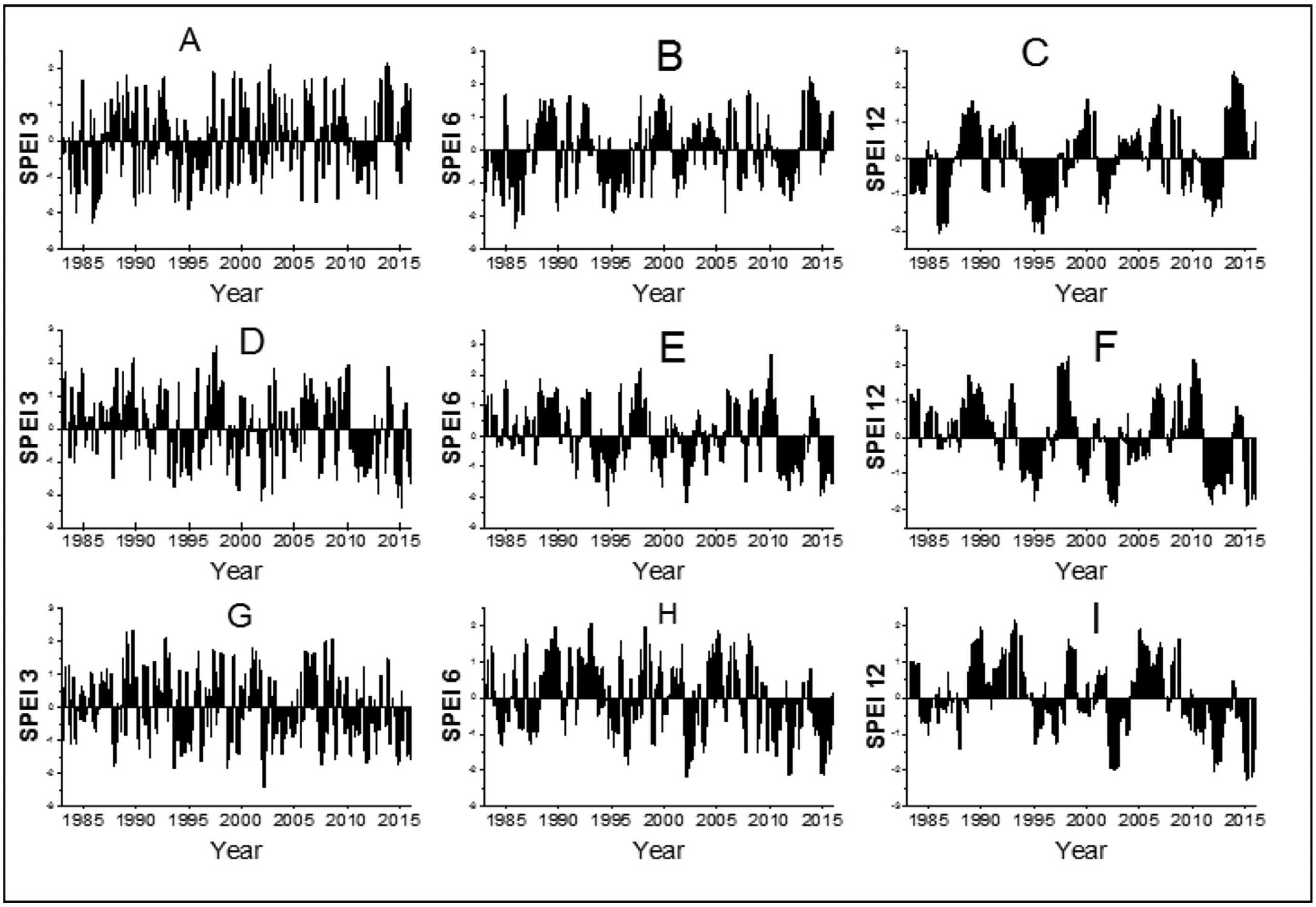


Fig. 5. Temoral variations of SPEI at different timescales (A)Gimbi 3-month, (B) Gimbi 6-month (C) Gimbi 12-month, (D) Serbo 3-month, (E) Serbo 6-month, (F) Serbo 12-month (G) Bako Tibe 3-month, (H) Bako Tibe 6-month and (I) Bako Tibe 12-month timescales during 1983-2016.

Gedo stations experienced extreme wet at SPEI 6 and SPEI 12. More specifically, extreme wet was observed at Arjo, Gedo, Serbo, and Bako Tibe. Two years, in 1993 extreme wet was observed both at Gedo and Bako Tibe. Gimbi station didn't experience extreme wet at SPEI-3, SPEI-6 and SPEI-12 between 1991 and 2000 (Table, SM 9). Similarly, Arjo,and Didessa Dildey didn't experienced extreme wet at short, medium and long timescales.

2001-2010

Between the year 2001 and 2010, extreme wet events were detected at Bako Tibe, Gedo, Gimbi, and Didesa Dildey stations at short timescales, while Serbo station experienced extreme wet at SPEI 6 and SPEI 12 (Table, SM 10). However, all stations experienced a severe and moderate wet.

2011-2016

During the study period between 2011 and 2016, Arjo, Gimbi and Didessa Dildey stations experienced an extreme wet month at 3-, 6- and 12-months timescales. Results showed that the southwestern parts of Ethiopia experienced significant number of extreme wet at SPEI-3. The year 2014 was the wettest year as three stations namely Arjo, Didessa Dildey and Gimbi across the three timescales. It is clear that extreme wet months resulted in flash flood and riverine flood. The EM-DAT reported that more than one million people in Ethiopia have been affected by flood between 2013 and 2020. However, no extreme wet were observed at Serbo, Bako Tibe and Gedo. Moreover, no severe and moderate wet months detected at Bako Tibe and Gedo stations at SPEI 6 and SPEI 12.

Extreme wet was recorded in 1990, 1996, 2012, and 2014 at Arjo station. At Didessa Dildey, the extreme wet was recorded during the years 2005, 2007, 2013-2015. At Gedo, the years 1983, 1987, 1990 and 2001 were identified as the extreme wet years. Gimbi experienced extreme wet in the years 2003, 2014-2015. Serbo station recorded extreme wet in 1990, 1997-1998 and 2010. At Bako Tibe, extreme wet was observed in the years 1990, 1997-1998 and 2010 (Table, SM 11).

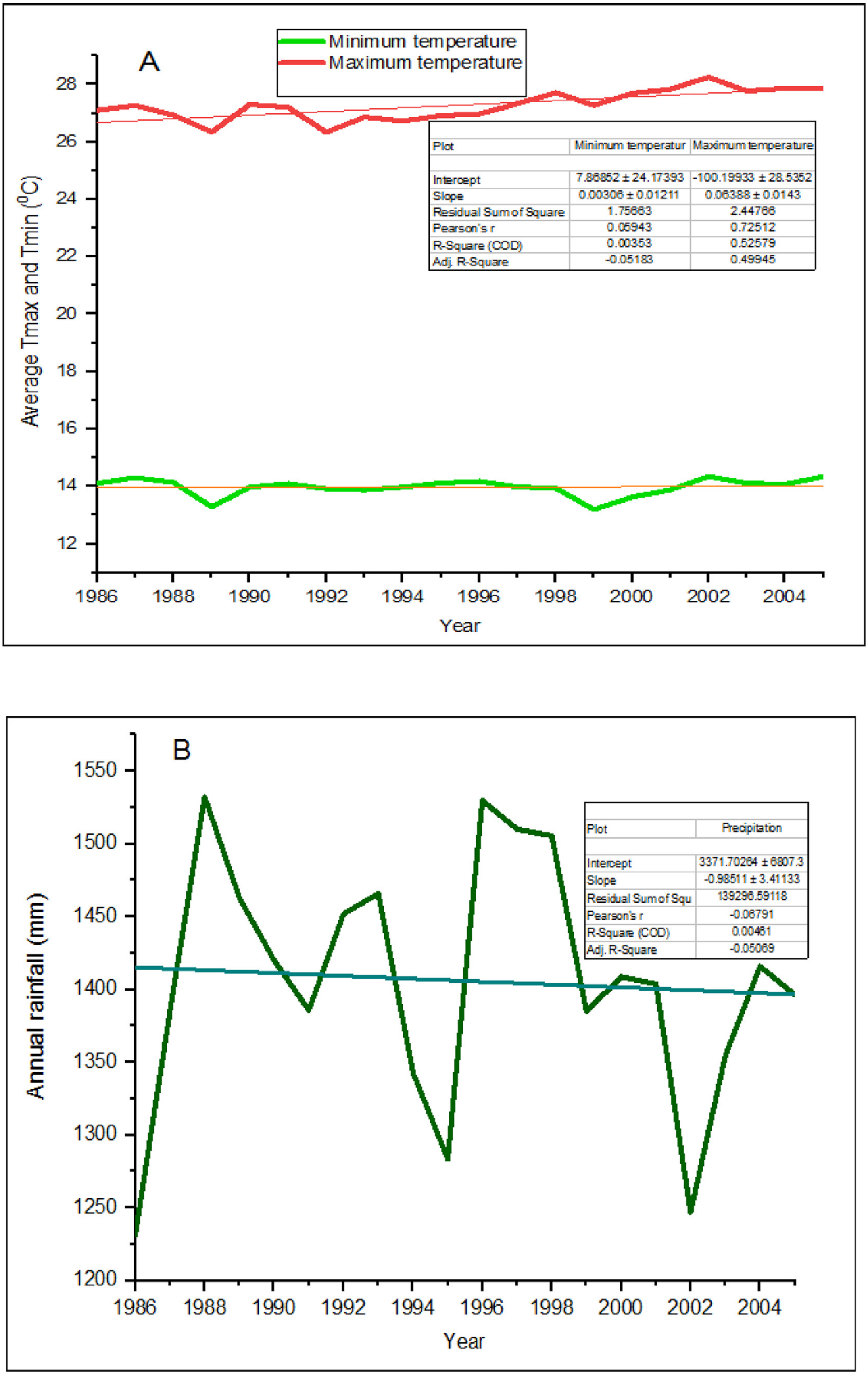
3.3. Temperature and rainfall baseline and projection under four RCPs scenarios

3.3.1. Temperature and rainfall baseline periods under AR5 (1986-2005)

There is tangible evidence of increasing trend of maximum and minimum temperature as global temperature will continue to rise over the 21st century. The mean maximum temperature was increased by 0.063 per year with $R^2=0.52$ (Fig., 6A) during the reference period while the increment in annual rainfall was small, i.e., not valid with $R^2=0.004$ (Fig., 6B). The mean minimum temperature increment during the reference periods was also not valid with $R^2=0.003$.

3.3.2. Projected changes in annual mean minimum temperature relative to 1986-2005

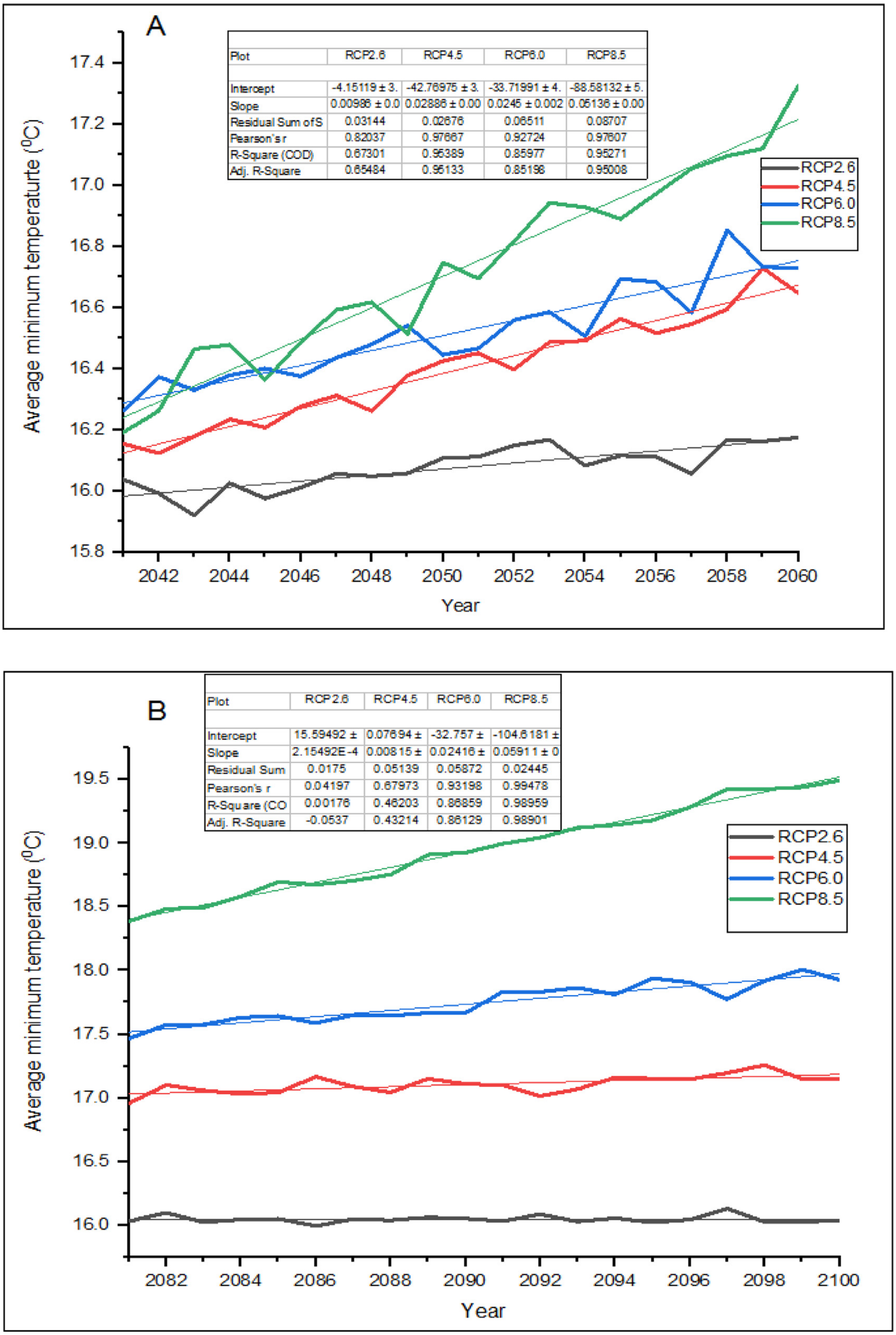
The IPCC has adopted the four RCPs for climate projections based on GHGs concentration, land use, air pollution (IPCC, 2014b). Table 4 presented the projected changes in mean minimum temperature, maximum temperature and precipitation in southwestern parts of Ethiopia



Plot	Minimum temperatur	Maximum temperature
Intercept	7.86852 ± 24.17393	-100.19933 ± 28.5352
Slope	0.00306 ± 0.01211	0.06388 ± 0.0143
Residual Sum of Square	1.75663	2.44766
Pearson's r	0.05943	0.72512
R-Square (COD)	0.00353	0.52579
Adj. R-Square	-0.05183	0.49945

Plot	Precipitation
Intercept	3371.70264 ± 6807.3
Slope	-0.98511 ± 3.41133
Residual Sum of Squ	139296.59118
Pearson's r	-0.06791
R-Square (COD)	0.00461
Adj. R-Square	-0.05069

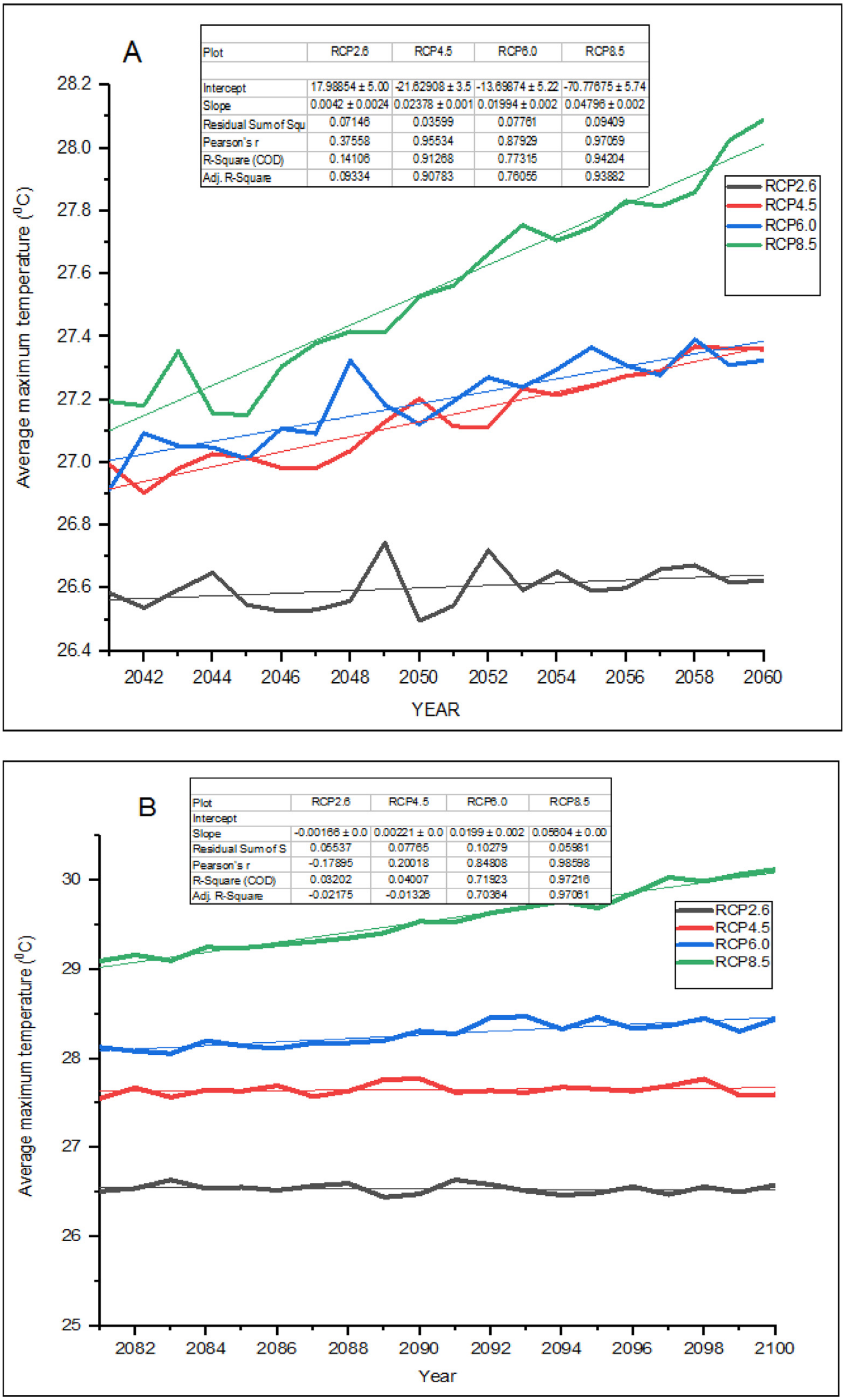
Fig. 6. Average maximum and minimum temperature (6A) and annual rainfall during the reference periods 1986-2005 over southwestern parts of Ethiopia (7.22-10.36 N and 34.12-38.56 E).



Plot	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Intercept	-4.15119 ± 3.	-42.76975 ± 3.	-33.71991 ± 4.	-88.58132 ± 5.
Slope	0.00986 ± 0.0	0.02886 ± 0.00	0.0245 ± 0.002	0.05136 ± 0.00
Residual Sum of S	0.03144	0.02676	0.06511	0.08707
Pearson's r	0.82037	0.97667	0.92724	0.97607
R-Square (COD)	0.67301	0.95389	0.85977	0.95271
Adj. R-Square	0.65484	0.95133	0.85198	0.95008

Plot	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Intercept	15.59492 ±	0.07694 ±	-32.757 ±	-104.6181 ±
Slope	2.15492E-4	0.00815 ±	0.02416 ±	0.05911 ± 0
Residual Sum	0.0175	0.05139	0.05872	0.02445
Pearson's r	0.04197	0.67973	0.93198	0.99478
R-Square (CO	0.00176	0.46203	0.86859	0.98959
Adj. R-Square	-0.0537	0.43214	0.86129	0.98901

Fig. 7. Projected average annual minimum temperature for 2041-2060 (A) projected average annual minimum temperature for 2081-2100 (B) for southwestern parts Ethiopia (7.22-10.36N and 34.12-38.56E) Jan-Dec wrt 1986-2005 AR5 CMIP5 subset.



Plot	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Intercept	17.98854 ± 5.00	-21.62908 ± 3.5	-13.69874 ± 5.22	-70.77675 ± 5.74
Slope	0.0042 ± 0.0024	0.02378 ± 0.001	0.01994 ± 0.002	0.04796 ± 0.002
Residual Sum of Squ	0.07146	0.03599	0.07761	0.09409
Pearson's r	0.37558	0.95534	0.87929	0.97069
R-Square (COD)	0.14106	0.91268	0.77315	0.94204
Adj. R-Square	0.09334	0.90783	0.76055	0.93882

Plot	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Intercept				
Slope	-0.00166 ± 0.0	0.00221 ± 0.0	0.0199 ± 0.002	0.05604 ± 0.00
Residual Sum of S	0.05537	0.07765	0.10279	0.05981
Pearson's r	-0.17895	0.20018	0.84808	0.98598
R-Square (COD)	0.03202	0.04007	0.71923	0.97216
Adj. R-Square	-0.02175	-0.01326	0.70364	0.97061

Fig. 8. Projected average annual maximum temperature for the year 2041-2060 (A) and Projected average annual maximum temperature for southwestern parts of Ethiopia (7.22-10.36N and 34.12-38.56E) Jan-Dec wrt 1986-2005 AR5 CMIP5 subset.

Table 2

Drought and wet years in six stations in southwestern parts of Ethiopia at 3, 6, and 12-months' time scales.

Stations	Years	Drought and its SPEI categories												Wet and its SPEI categories											
		SPEI 3				SPEI 6				SPEI 12				SPEI 3				SPEI 6				SPEI 12			
		Extreme	Severe	Moderate	Σ	Extreme	Severe	Moderate	Σ	Extreme	Severe	Moderate	Σ	Extreme	Severe	Moderate	Σ	Extreme	Severe	Moderate	Σ	Extreme	Severe	Moderate	Σ
Serbo	1983-1990	-	1	2	3	-	-	-	-	-	-	-	-	1	8	11	20	-	8	13	21	-	3	21	24
	1991-2000	-	6	18	24	1	6	15	22	-	2	16	18	3	5	16	24	4	4	12	20	6	6	8	20
	2001-2010	1	7	6	14	1	6	6	13	-	10	3	13	-	7	18	25	2	7	18	27	2	4	17	23
	2011-2016	3	13	12	28	-	13	25	38	-	15	29	44	-	2	1	3	-	-	3	3	-	1	3	4
	Sum	4	27	38	69	2	25	46	73	-	27	48	75	4	22	44	72	6	19	46	71	8	14	49	71
Bako Tibe	1983-1990	-	4	8	12	-	-	5	5	-	-	3	3	2	5	14	21	-	6	15	21	-	8	7	15
	1991-2000	-	6	14	20	-	2	11	13	-	-	7	7	2	7	21	30	2	9	17	28	2	12	17	31
	2001-2010	2	5	15	22	2	6	13	21	1	8	6	15	2	9	11	22	-	9	16	25	-	7	19	26
	2011-2016	-	5	17	22	7	8	9	24	9	12	10	31	-	-	4	4	-	-	-	-	-	-	-	-
	Sum	2	20	54	76	9	16	38	63	10	20	26	56	6	21	50	77	2	24	48	74	2	27	43	72
Gedo	1983-1990	-	1	2	3	-	-	5	5	-	-	3	3	3	14	19	38	-	6	15	21	-	8	7	15
	1991-2000	1	6	16	23	-	2	11	13	-	-	7	7	-	1	13	14	2	9	17	28	2	12	17	31
	2001-2010	1	10	18	29	2	7	12	21	1	8	6	15	1	2	14	17	-	9	16	25	-	7	19	26
	2011-2016	-	2	10	12	7	8	10	25	9	12	10	31	-	2	2	4	-	-	-	-	-	-	-	-
	Sum	2	19	46	67	9	17	38	64	10	20	26	56	4	19	48	71	2	24	48	74	2	27	43	72

Σ=the total value over the study period.

Table 3

Drought and wet years in six stations in southwestern parts of Ethiopia at 3, 6, and 12-months timescales.

Stations	Years	Drought and its SPEI categories												Wet and its SPEI categories											
		SPEI 3				SPEI 6				SPEI 12				SPEI 3				SPEI 6				SPEI 12			
		Extreme	Severe	Moderate	Σ	Extreme	Severe	Moderate	Σ	Extreme	Severe	Moderate	Σ	Extreme	Severe	Moderate	Σ	Extreme	Severe	Moderate	Σ	Extreme	Severe	Moderate	Σ
Arjo	1983-1990	1	9	13	23	4	10	6	20	1	13	6	20	2	2	8	12	-	2	7	9	-	-	3	3
	1991-2000	1	7	10	18	-	-	18	18	-	-	10	10	1	2	14	17	-	1	10	11	-	-	1	1
	2001-2010	1	7	14	22	-	13	12	25	2	15	9	26	-	9	15	24	-	11	12	23	-	13	9	22
	2011-2016	1	2	7	10	-	3	5	8	-	-	8	8	4	6	4	14	5	7	10	22	9	3	12	24
	Sum	4	25	44	73	4	26	41	71	3	28	33	64	7	19	41	67	5	21	39	65	9	16	25	50
Gimbi	1983-1990	2	7	12	21	2	9	9	20	1	10	1	12	-	4	12	16	-	5	11	16	-	10	8	18
	1991-2000	-	6	22	28	-	8	20	28	2	12	18	32	-	9	9	18	-	7	15	22	-	4	5	9
	2001-2010	-	4	10	14	-	1	11	12	-	-	10	10	1	10	15	26	-	7	11	18	-	5	13	18
	2011-2016	-	1	6	7	-	1	8	9	-	1	19	20	3	5	11	19	4	10	9	23	11	2	10	23
	Sum	2	18	50	70	2	19	48	69	3	23	48	74	4	28	47	79	4	29	46	79	11	21	36	68
DidessaDildey	1983-1990	-	10	9	19	1	10	9	20	1	10	1	12	-	5	12	17	-	5	11	16	-	2	16	18
	1991-2000	1	4	24	29	-	8	20	28	2	12	18	32	-	5	18	23	-	7	15	22	-	4	6	10
	2001-2010	-	9	9	18	-	1	9	10	-	-	10	10	2	5	14	22	-	7	12	19	-	1	18	19
	2011-2016	-	2	4	6	-	1	8	9	-	1	19	20	2	9	6	17	4	10	9	23	11	2	10	23
	Sum	1	25	46	72	1	20	46	67	3	23	48	74	4	24	50	78	4	29	47	80	11	9	50	70

Σ=the total value over the study period.

Table 4

Annual rainfall, mean minimum and mean maximum temperature change over the periods 2041-2060 and 2081-2100 over southwestern parts of Ethiopia (7.22-10.36N and 34.12-38.56E) under four RCP scenarios relative to 1986-2005smal.

Variables	Projected periods	Test	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Precipitation	2041-2060	Z_S	-0.61	0	0.68	*2.82
		P	0.53	1	0.49	0.00
		Sen's	-0.64	-0.2	0.86	2.88
Precipitation	2081-2100	Z_S	0.29	0.94	0	*2.37
		P	0.77	0.35	1	0.02
		Sen's	0.28	1.08	-0.1	3.20
Minimum temperature	2041-2060	Z_S	*4.12	*5.54	*2.62	*5.61
		P	0.00	0.00	0.01	0.00
		Sen's	0.01	0.03	0.01	0.05
Minimum temperature	2081-2100	Z_S	-0.92	*2.63	*4.96	*6.00
		P	0.77	0.01	0.00	0.00
		Sen's	0.00	0.01	0.02	0.06
Maximum temperature	2041-2060	Z_S	1.91	*4.89	*4.38	*5.29
		P	0.05	0.00	0.00	0.00
		Sen's	0.00	0.02	0.02	0.05
Maximum temperature	2081-2100	Z_S	-0.35	*3.92	*3.93	*5.74
		P	0.72	0.00	0.00	0.00
		Sen's	0.00	0.02	0.02	0.06

* Statistically significant at Zs.1.96 ($\alpha = 0.05$) at 5% level of significance.

for the periods 2041-2060 and 2081-2100, relative to 1986-2005. The mean minimum temperature is projected to increase by 0.01 °C per year (0.1°C/decade) under RCP2.6 (high mitigation scenario) and by 0.03 °C per year (0.3°Cper decade) and 0.05 °C per year (0.5 °C per decade) under RCP4.5 and RCP8.5 (high emission scenario), respectively (Fig. 7A). The magnitude of change in mean minimum temperature of the bassline years (1986-2005) was 0.0035 °C per year, which is statistically not significant while the projected mean minimum temperature under RCPs 4.5, 6.0 and 8.5 is likely to increase by 0.01 °C, 0.02 °C and 0.06 °C per year, respectively between 2081 and 2100 (Fig., 7B). The four RCPs indicate how the future climate will respond to the ongoing increase of GHG concentration in the atmosphere and shouldn't exceeded the year 2100 (Muhati et al., 2018). By the end of twenty-first century, the mean minimum temperature of the study area is projected to increase by 1.2°C under RCP8.5.

3.3.3. Projected changes in annual mean maximum temperature relative to 1986-2005

Results showed that the mean annual warming trend was projected to increase by +0.02 °C under both RCP2.6 and RCP4.5 for the periods 2041-2060 while the mean annual maximum temperature was projected to increase by 0.05 °C per year between the year 2041 and 2060 ((Fig., 8A). Under RCP4.5 and 6.0, the maximum temperature of the study area is projected to increase by 0.02 °C per year between the year 2081 and 2100 (Fig., 8B). With an increase of 0.06 °C per year in the RCP8.5 scenario, temperature in the study area will increase by 1.2 °C between the year 2081 and 2100. By the end of twenty-first century, the mean maximum temperature of the study area is projected to increase by 0.4 °C under RCP6.0. The increasing trend of minimum and maximum temperature could result in excess evapotranspiration, which may affect food and water availability in the region under business as usual. The increasing trend of mean minimum and maximum temperature over southwestern Ethiopia is associated with increasing global mean temperature due to land use land cover change and other anthropogenic activities.

3.3.4. Projected changes in rainfall relative to 1986-2005

Unlike temperature, the rainfall projection during the periods 2041-2060 and end of the 21st century (2081-2100) shows both increasing and decreasing trend under different scenarios. For instance, rainfall is projected to decrease slightly under RCP2.6 and RCP4.5 and a small increase under RCP6.0 and RCP8.5, which is in line with the report of IPCC (2007). However, the amount of rainfall is projected to increase slightly under four scenarios at the end of the 21st the century. Our findings contradict the findings of Tegegne et al. (2021) in Afar and Tigray regions of Ethiopia, which reported the declining trend of rainfall under RCP 2.6 by end of the 21st century (Fig., SM 1).

4. Conclusions

In this study, agricultural (3-month and 6-month) and hydrological drought (12-month) were identified in the study area over the study period 1971-2020. Results showed that the wettest parts of southwestern Ethiopia experienced extreme drought, extreme wet, severe drought and severe wet during the study period. Extreme agricultural drought was identified in 1978, 1984-1988, 1994-1996, 1999,2002-2003, 2005, 2009,2012-2013, 2015-2017 while hydrological drought was recorded in 1986-1987,1994-1996, 2000,2002-2005, 2012-2013, and 2015-2016. The occurrence of extreme drought has been increased recently at Gedo and Bako Tibe stations. In the present study, significant number of extreme, severe and moderate drought as well as wet months were recorded at all stations. It is evident that every country is experiencing climate extremes mainly drought due to the increasing of evapotranspiration driven by excess heat and global warming. The projected changes in minimum and maximum temperature for the periods 2041-2060 and 2081-2100 indicates a significant increasing trend particularly under RCP6.0 and RCP8.5. The future projections of minimum and maximum temperature will likely increase the number of hot days and night in the future, which will lead to extreme and severe drought in the study area. In contrast, the projected change for precipitation was not significant under low, middle and higher emission scenarios. Although the projected rainfall changes in the near and middle (2041-2060) as well as the end of the twenty-first century (2081-2100) is not statistically significant, there is high inter-annual variability is expected to continue up to the end of the century. The amount of rainfall will likely to decrease under RCP2.6, which may affect the farming communities in the study area.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author Contribution Statement

DOG: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Resources; Software; Visualization; Writing original draft; Wrote the paper; Writing-review and editing. DK and WG involved in Conceptualization; Data curation; Formal analysis; Methodology; Resources; Supervision; Review and editing.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.envc.2022.100517.

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