Spatio-temporal characteristics of meteorological drought under changing climate in semi-arid region of northern Ethiopia

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**Abstract**

**Background:** Below-normal availability of water for a considerable period of time induces occurrence of drought. This paper investigates the characteristics of meteorological drought under changing climate. The meteorological drought was assessed using the Standardized Precipitation Index (SPI) and the Reconnaissance Drought Index (RDI). The climate change was also analyzed using delta based statistical downscaling approach of RCP 4.5 and RCP 8.5 in R software packages.

**Results:** The result of climate change projections showed that the average annual minimum temperature will be increased by about 0.8-2.9°C. The mean annual maximum temperature will also increased by 0.9-3.75 °C. The rainfall projection generally showed an increasing trend, it exhibited an average annual increase of 3.5-13.4 % over the study area. The drought projection showed that there would be extreme drought events in study area for the future (2018-2099). The SPI result indicates that drought will be occurred in the study area after 1-5 and 1-6 years under RCP 4.5 and 8.5 emission scenarios respectively and the RDI value also shows drought will occurred after 1-6 and 2-7 years under RCP 4.5 and RCP 8.5 emission scenarios respectively over the study area. Almost more than 72% of the current and future spatial coverage of drought in the study area will be affected by extreme drought, 22.3% severely and 5.57% also moderate drought.

**Conclusions:** Therefore, the study helps to provide useful information for policy decision makers to implement different adaptation and mitigation measures of drought in the region.

**Keywords:** Climate change, Projection, Meteorological drought, Reconnaissance drought index, Standardized precipitation index
Background

Droughts is regularly happened during the past century across the globe (Rivas-Martínez et al. 1999), these droughts produced huge socio-economic and environmental influences in this semi-arid region resulting in massive-scale migration, famine and desertification, particularly during the last two drought events (Masih et al. 2014). Climate change related meteorological droughts historically have been major causes for loses lives, environmental loses, and forced millions of people to displace and live in poverty (Gebrehiwot et al. 2011). More specific figures from recent drought events in Tigray region exemplify the magnitude of drought-associated impacts. For example, the meteorological drought of 2003 happened in northern highlands of Ethiopia led to the worst famine since the mid-1980s that affected 13.5 million people (Wagaw et al. 2005). In spite of the recurrent and devastating nature of drought in different areas of Tigray, it has received far less attention. Therefore, this study is interested to explore drought event to understand its severity, intensity, frequency, duration, and its spatial extent in different areas using data generated over the specified period.

It is also one of natural hazard explained by a substantial reduction in water availability throughout a prolonged period of time over a given area (Sousa et al. 2011). For instance, drought in Ethiopia is one of the main natural disasters throughout the human history (Gebrehiwot et al. 2011). It has become a main concern in the northern highlands of the country particularly in Tigray region where food security and environmental damages were commonly observed (Nicholson 2000; Ching et al. 2011). Kanello et al. (2008) and Loukas & Vasiliades (2004) argue that Spatio-temporal characteristics of meteorological drought study are important to understand the regional severity of drought to manage it effectively and to reduce the agricultural production losses and to protect the environment.

Drought has increased in most places of Ethiopia, which consistent with expectations for a warming climate. The changing earth temperature could increase evaporation demand and increased Spatio-temporal variability of droughts in the coming period (Ault et al. 2016). Long dry spells are often caused by climate change: duration, intensity and frequency have increased in the past drought events (Stocker 2014). Such incremental trend is projected to continue during the 21st century as a consequence of climate change (Stocker 2014).
Meteorological information, particularly regional rainfall evidences were studied in previous studies using only Standardized Precipitation Index (SPI) (Patel et al. 2007). This approach is being used worldwide due to its low data requirement and its ability to analyze the numerous aspects of drought based on changing time-scales. However, in arid and semi-arid regions, high temperature along with shortage in precipitation is an important factor responsible for the development and progression of droughts (Thomas et al. 2016). In this regard, Reconnaissance Drought Index (RDI) has been used by many researchers for identifying the meteorological drought characteristics as it is more suited to arid and semi-arid areas (Thomas et al. 2016). The RDI uses precipitation as well as potential evapotranspiration (PET) and can also be used to analyze the climate change impacts on the drought scenario of a region (Vangelis et al., 2013; Tsakiris & Vangelis 2005; Tsakiris et al. 2007; Zarch et al. 2011; Elagib & Elhag 2011). Therefore, the temporal explicit drought conditions may offer valuable concerns through this index (Steinemann 2006; Eriyagama et al. 2009), which needs to be applied in case of Tigray region drought assessment.

Several researches have been carried out on droughts and related issues in semi-arid highlands of northern Ethiopia. Most of those researches used Standardized Precipitation Index (SPI). For instance, Gidey et al. (2018) Standardized Precipitation Index (SPI) was used to predict meteorological drought hazard under medium emission scenarios in Northern Raya Valley. Bayissa et al. (2015) also used SPI to study the effect of the length of records and to characterize drought in the Upper Blue Nile Basin. However, the effect of RDI under both high and medium emission scenarios and incorporating the finding on the Spatio-temporal characteristics of meteorological drought under changing climate using SPI in semi-arid highlands of northern Ethiopia have not yet been considered.

Thus, the overall objectives of this study are to analyze and assess the spatial-temporal variation of meteorological drought in semi-arid highlands of northern Ethiopia, using the SPI and RDI under both high and medium climate change emission scenarios. Moreover, we tried to characterize the meteorological droughts, duration, severity, intensity, relative frequency and to map out the spatial extent of drought using GIS applications for better understanding drought severity in the near-term, mid-term, and end-term. The results can provide support policy decision-making, effective drought monitoring, and early warning system in the region.
Material and Methods

The study area

The study was conducted in four districts (Raya Azebo, Endamohoni, Ofla, and Raya Alamata) of Southern zone of Tigray regional state. Geographically, they are located between 12° 15’ 27” up to 12° 56’ 38” N latitude and 39° 10’ 34” up to 39° 58’ 56” E longitude and have a total land area of 6651 Km². The districts receive up to an average of 766 mm of rainfall annually for the period of (1980-2009). Rainfall is erratic and bimodal in this area (Ayene et al., 2013). During the last 30 years, the maximum (Tmax) and minimum temperature (Tmin) were 28 up to 33 and 14 up to 16 °C respectively (Gidey et al. 2018).

Data and data Sources

Fig.1: Location of study area
Thirty years daily meteorological data such as rainfall, maximum temperature, and minimum temperature for the period 1980–2009 obtained from the National Meteorological Agency (NMA) were collected from four meteorological stations. Fortunately, all districts have meteorological stations and located in Mekoni, Maichew, Korem and Alamata respectively (Table 1). Some data were missed and inconsistency was also observed. To fill out the missing meteorological data AgMIP data were used.

**Table 1: Location of meteorological stations in the study area**

| SN | Station | Longitude (E) | Latitude (N) | Z(m) | Period       |
|----|---------|---------------|--------------|------|-------------|
| 1  | Alamata | 39.71         | 12.42        | 1589 | 1980-2009   |
| 2  | Korem   | 39.50         | 12.51        | 2450 | 1980-2009   |
| 3  | Maichew | 39.53         | 12.78        | 2432 | 1980-2009   |
| 4  | Mekoni  | 39.65         | 12.80        | 1590 | 1980-2009   |

**Climate Modelling**

Climate projection was done using R-programing language through delta approach described in the Agricultural Model Intercomparison and Improvement Project (AgMIP) Protocols (Hudson & Ruane 2013) using two Representative Concentration Pathway (RCPs) such as RCP 4.5 and RCP 8.5. The time period was classified into three terms near-term (2010-2039), mid-term (2040-2069), and end-term (2070-2099). Form the total 26 General Circulation Models (GCMs) five GCMs were selected such as Community Climate System Model (CCSM4), GGFDL-ESM2M, HadGEM2-ES (Met Office Hadley Centre) of UK, MIROC5 (Model for Interdisciplinary Research on Climate) and MPI-ESM-MR. Those were selected based on their consistency, and resolution performance for East and sub Saharan Africa (Rosenzweig et al. 2013; Sillmann & Roeckner 2008).

**Drought Indices Analysis**

**Standardized Precipitation Index (SPI)**

The SPI was analyzed based on the long-term precipitation record for a desired period. This long-term record is fitted to a probability distribution, which is then transformed into a normal distribution. The gamma distribution is defined by its frequency or probability density function:

\[
g(x) = \frac{1}{\beta^\alpha P(a)} x^{\alpha - 1} e^{-\frac{x}{\beta}}, \text{for } x > 0
\]
Where, \(\alpha\) and \(\beta\) are the shape and scale parameters respectively, \(x\) is the precipitation amount and \(\Gamma(\alpha)\) is the gamma function. Parameters \(\alpha\) and \(\beta\) of the gamma pdf has been estimated for each station and for each time scale of 12- months. Maximum likelihood estimations of \(\alpha\) and \(\beta\) are:

\[
\alpha = \frac{1}{4A} \left( 1 + \sqrt{1 + \frac{4A}{x}} \right), \quad \beta = \frac{x}{\alpha}
\]

Where, \(A = \ell n(x) = \frac{\sum \ell n(x)}{n}\) and \(n\) is number of observations.

The resulting parameters are then used to find the cumulative probability of an observed precipitation event for the given month and time scale for the location in question. The gamma function is undefined for \(x = 0\) and a precipitation distribution may contain zeros, while the cumulative probability has been determined by:

\[
H(x) = q + (1 - q)G(x)
\]

In which \(q\) is the probability of zero precipitation and \(G(x)\) is the cumulative probability of the incomplete gamma function. If \(m\) is the number of zeros in a precipitation time series, then \(q\) estimated by \(m/n\). The cumulative probability \(H(x)\), is then transformed to the standard normal random variable \(z\) with mean zero and variance of one, which is the value of the SPI. The SPI has been calculated for the baseline (1980-2009) and near-term (2010-2039), mid-term (2040-2069), and end-term (2070-2099) for both RCP 4.5 and RCP 8.5 emission scenarios. They are computed with one running time interval that is 12-months.

This index helps to distinguish dry years from wet years or deficit years from surplus years (McKee et al. 1993). A drought occurs when the SPI is consecutively negative and its value reaches an intensity of minus one or less and ends when the SPI becomes positive. A classification of the drought is carried out according to the values of the SPI (Table 2).

### Table 2: Classification of SPI values

| SN | Description      | Criterion         |
|----|------------------|-------------------|
| 1  | 2 or more        | Extremely wet     |
| 2  | 1.5 to 1.99      | Severely wet      |
| 3  | 1.0 to 1.49      | Moderately wet    |
| 4  | -0.99 to 0.99    | Near normal       |
| 5  | -1.0 to -1.49    | Moderately dry    |
| 6  | -1.5 to -1.99    | Severely dry      |
| 7  | -2 or less       | Extremely dry     |

Source : adopted from (McKee et al. 1993)

Estimation of Evapotranspiration (ETo)
Drought index calculator (DrinC) provides a module for the calculation of PET with the following temperature based methods: - Hargreaves & Samani 1982; Hargreaves & Samani 1985; Rivas-Martínez et al 1999 and Blaney – Criddle Doorenbos 1975. In this study the Hargreaves & Samani method has been used to estimate reference evapotranspiration (ETo) as described in equation 2.4:

\[ \text{ETo}_{\text{Har}} = 0.0023Ra(T_{\text{max}} - T_{\text{min}})^{0.5} \left( \frac{T_{\text{max}} - T_{\text{min}}}{2} + 17.8 \right) \]  

Where, \( \text{ETo}_{\text{Har}} = \text{ETo} \) estimated by the Hargreaves equation (mm day^{-1}); Ra = extraterrestrial radiation (MJ m^{-2} day^{-1}); Tmax = maximum air temperature (°C); Tmin = minimum air temperature (°C).

**Reconnaissance Drought Index (RDI)**

Drought severity was assessed through the computation of RDI. The RDI was developed to approach the water deficit in a more accurate way, as a sort of balance between input and output in a water system (Tsakiris & Vangelis 2005; Tsakiris et al. 2007). The RDI calculated based both on cumulative Precipitation (P) and Potential Evapotranspiration (PET), which are measured (P) and calculated (PET). The calculation method of PET, however, does not seem to affect the results of RDI in any way (Vangelis et al. 2013). The initial value (\( \alpha_k \)) of RDI calculated for the \( i^{th} \) year in a time basis of \( k \) (months) as describe in equation 2.4:

\[ \alpha_k^i = \frac{\sum_{j=1}^{k} P_{ij}}{\sum_{j=1}^{k} PET_{ij}}, i = 1(1)N \text{ and } j = 1(1)K \]  

Where, \( P_{ij} \) and \( PET_{ij} \) are the cumulative precipitation and potential evapotranspiration of the \( j^{th} \) month of the \( i^{th} \) year respectively and \( N \) is the total number of years of the available data.

\[ \text{RDI}^i = \frac{Y^i - \bar{Y}}{\hat{\delta}} \]  

Where, \( Y_i \) is the \( \ln (\alpha_k^i) \), \( \bar{Y} \) is its arithmetic mean and \( \hat{\delta} \) is its standard deviation.

In case the gamma distribution is applied, the RDI can be calculated by fitting the gamma probability density function (pdf) to the given frequency distribution of \( \alpha_k \) (Tigkas 2008; Tsakiris et al. 2008). For short reference periods (e.g. monthly or 3-months) which may include zero values for the cumulative precipitation of the period, the RDI can be calculated based on a composite cumulative distribution function including: the probability of zero precipitation, and the gamma cumulative probability.
Positive values of RDI indicate wet periods, while negative values indicate dry periods compared with the normal conditions of the area. The severity of drought events increases when RDI values are getting highly negative. According to Tigkas et al. 2013 RDI drought severity can be categorized in mild, moderate, severe and extreme classes, with corresponding boundary values of RDIst (-0.5 to -1.0), (-1.0 to -1.5), (-1.5 to -2.0) and (< -2.0), respectively.

The gamma distribution was applied; the RDI calculated by fitting the pdf to the given frequency distribution of $\alpha_k$. RDI has been determined for the current and future periods for a hydrological year in 12-month time scale.

**Drought characteristics**

In this study, SPI and RDI meteorological drought indicators were used and calculated for 12 months. The negative and positive values of SPI are considered as the drought and non-drought events, respectively. As drought is defined when the values of SPI fall below zero, a drought event is considered a period with negative SPI values. In order to measure length of drought duration and magnitude of drought severity, a threshold value must be defined.

*Drought duration (D)*: the period length in which the SPI is continuous negative, started from the SPI values is equal to minus one and ends when the SPI values turn out to be positive.

*Drought severity (S)*: the cumulated SPI values within the drought duration, which is defined by equation 2.7 and intensity of drought is the ratio of severity of drought to its duration.

$$S = -\sum_{i=1}^{D} SPI_i$$  \hspace{1cm} 2.7

*The relative frequency (RF)*: the ratio of number of years with drought events ($n$) (Negative SPI) to number of total years ($N$), as defined by Saravi et al. (2009).

$$RF = \frac{n}{N} \times 100$$  \hspace{1cm} 2.8

**Spatial variation maps of drought severity**

The inverse distance weighted (IDW) method was used to map the spatial extent of drought from point data. It is intuitive and efficient for spatial analysis (Shepard 1968). The analysis was done using Geostatistical analysis tool of ArcMap 10.2.

**Results**

**Climate change modelling**
The temperatures were increased with the time period in both RCP’s overall districts. The highest minimum and maximum temperature were simulated during the end term period under RCP 8.5 (Tables 3 and 4). The highest temperature was recorded in Raya Azebo and Enda-Mekoni district (4.2°C & 3.4 °C) in RCP 8.5 for both minimum and maximum temperatures respectively. The lowest temperatures recorded were 0.6 °C, 1.0 °C, 0.9 °C, and 1.0 °C for Raya Alamata, Ofia, Enda Mekoni and Raya Azebo districts in RCP 4.5 near-term periods respectively. Similarly, in the Raya Azebo mean annual rainfall was increased by 28.7% during the end term period under RCP 8.5, while in Ofia increased by 1.6% (Table 5).

**Table 3:** Changes in Temperature minimum (°C) compared to the baseline over the four districts in RCP 4.5 and RCP 8.5

| Districts        | RCP 4.5 Near Term | Mid Term | End Term | RCP 8.5 Near Term | Mid Term | End Term |
|------------------|-------------------|----------|----------|-------------------|----------|----------|
| Raya Alamata     | 0.9               | 1.5      | 1.7      | 1.0               | 2.1      | 3.7      |
| Ofia             | 1.0               | 1.8      | 2.3      | 1.0               | 2.5      | 4.1      |
| Enda-Mekoni      | 1.0               | 1.7      | 2.2      | 1.0               | 2.3      | 3.0      |
| Raya Azebo       | 1.0               | 2.0      | 2.3      | 1.0               | 2.5      | 4.2      |

**Table 4:** Changes in Temperature maximum (°C) compared to the baseline over the four districts in RCP 4.5 & RCP 8.5

| Districts        | RCP 4.5 Near Term | Mid Term | End Term | RCP 8.5 Near Term | Mid Term | End Term |
|------------------|-------------------|----------|----------|-------------------|----------|----------|
| Raya Alamata     | 0.6               | 1.4      | 1.6      | 1.0               | 1.7      | 1.9      |
| Ofia             | 1.0               | 1.8      | 2.3      | 1.2               | 2.6      | 3.3      |
| Enda-Mekoni      | 0.9               | 1.6      | 2.1      | 1.2               | 2.4      | 3.4      |
| Raya Azebo       | 1.0               | 1.6      | 2.1      | 1.2               | 2.6      | 3.0      |

**Table 5:** Changes in annual rainfall (%) compared to the baseline over four districts in RCP 4.5 & RCP 8.5

| Rainfall Districts | RCP 4.5 Near Term | Mid Term | End Term | RCP 8.5 Near Term | Mid Term | End Term |
|--------------------|-------------------|----------|----------|-------------------|----------|----------|
| Raya Alamata       | 2.8               | 1.3      | 3.0      | 5.2               | 4.0      | 8.2      |
| Ofia               | 1.6               | 2.7      | 4.4      | 6.6               | 5.4      | 9.6      |
| Enda-Mekoni        | 2.7               | 3.3      | 5.3      | 6.3               | 5.1      | 7.1      |
| Raya Azebo         | 7.1               | 10.3     | 16.6     | 8.5               | 16.1     | 28.7     |

**Projection of meteorological droughts**

The temporal variation of projected SPI in Ofia district is shown in (Fig.2). RCP 4.5 emission scenario predicted for near-term in the year 2013/14, mid-term in the year 2043/44, and end-term in the year of 2073/74 had the maximum severity indicated extreme drought with the magnitude -
2.61, -2.72, -2.62, and -2.68 respectively. RCP 8.5 emission scenario was projected extreme drought the with the magnitude of -2.71, -2.47, and -2.46 with the above respective year.

Similarly, the RDI was observed extreme drought event in the near-term in the year 2013/14, mid-term in the year 2043/44 and end-term in the year 2073/74 with the magnitude of -2.72, -2.62, and -2.67 respectively. The RCP 8.5 emission scenario was projected extreme drought for all future terms with different magnitude -2.69, -2.51, and -2.48 in the years.

![Temporal variation of predicted SPI and RDI in Ofla district](image)

**Fig. 2:** Temporal variation of predicted SPI-12 and RDI-12 in Ofla district

The temporal variation of projected SPI in Raya Azebo district is given in Fig. 3. It can be observed that in the baseline period in the year 1983/84 and 2007/09 had the medium severity (-1 and -1.2) respectively indicating moderate drought. In the future RCP 4.5 emission scenario prediction for near-term in the year 2013/14 and 2037/39, mid-term in the year 2067/69, and end-term in the year 2097/98 had the medium severity indicated that moderate drought with the magnitude of -1.04 and -1.1, -1.1, and -1.13 respectively. RCP 8.5 emission scenario prediction showed moderate drought in the near-term in the year 2013/14 and 2037/39, mid-term in the year 2043/44 and 2067/68, and end term in the year 2097/98.

The RDI was observed moderate drought near term in the year 2013/14 and 2037/39, mid-term 2043/44 and 2067/69 and end term 2097/98 for RCP 4.5 emission scenario, whereas RCP 8.5 emission scenario predicted moderate drought except for end-term in the year of 2073/74.
Fig. 3: Temporal variation of predicted SPI-12 and RDI-12 in Raya Azebo district

The temporal variation of projected SPI in Enda-Mekoni district is given in (Fig. 4). It can be observed that in the baseline period in the year of 1983/84 and in the future under RCP 4.5 emission scenarios showed for near-term in the year 2013/14, mid-term in the year 2043/44, and end-term in the year 2073/74 had the maximum severity indicated extreme drought with the magnitude of -2.13, -2.32, -2.09, and -2.16 respectively. Both RCP 4.5 and RCP 8.5 predicted extreme drought with the magnitude of -2.41 and -2.09 respectively.

Similarly, RDI was observed under RCP 4.5 emission scenario for near-term in the year 2013/14, mid-term in the year 2043/44, and end-term in the year 2073/74 had the maximum severity indicated extreme drought with the magnitude of -2.10, -2.29, -2.06, and -2.12 respectively. RCP 8.5 for near-term and end-term predicted extreme drought with the magnitude of -2.37, and -2.07 respectively with the above respective year except end-term were predicted to be severe drought.
The temporal variation of projected SPI in Raya Alamata district is given in (Fig.5) it can be observed that in the baseline period in the year 1983/84 and future under RCP 4.5 emission scenario for near-term in the year 2013/14, mid-term in the year 2043/44, and end-term in the year 2073/74 had the maximum severity indicated extreme drought with the magnitude of -2.61, -2.88, -2.62, and -2.68 respectively. Both RCP 4.5 and RCP 8.5 emission scenario predicted extreme drought in the near-term, mid-term, and end term with different the magnitude (-2.71, -2.49, and -2.46) respectively.

Similarly, RDI was observed under RCP 4.5 emission scenario for near-term in the year 2013/14, mid-term in the year 2043/44, and end-term in the year 2073/74 had the maximum severity indicated extreme drought with the magnitude of -2.58, -2.86, -2.62, and -2.67 respectively. RCP 8.5 emission scenario predicted extreme drought in the near-term, mid-term, and end term with different magnitude (-2.69, -2.51, and -2.48) respectively with the above respective years.

The total mean drought magnitude of 30 years during the future will increase when compared to the past. The results in the case of almost all timescales were increased during the end future under both RCP 4.5 and RCP 8.5 emission scenario.
Drought characteristics

As shown in the Table 6 & 7, SPI and RDI summary results of duration, severity, intensity, and relative frequency calculation for each district with the 12-month times-scales. Recapitulation has shown the apparent difference in duration, severity, intensity, and relative frequency of each station, it describes the characteristics of drought in one district had little difference with other district except Enda-Mekoni.

The SPI highest length of drought duration (6-years) had in Ofla and Enda-Mekoni district. In Ofla district, the highest length of drought (duration) was estimated in the current year, whereas in Enda-Mekoni under RCP 8.5 emission scenario during end of the century.

Table 6: Recapitulation of Projected drought events for SPI-12

| No. | Districts | Period    | RCP 4.5 | RCP 8.5 |
|-----|-----------|-----------|---------|---------|
|     |           |           | D | S | I | RF% | D | S | I | RF% |
| 1   | Ofla      | Current   | 6 | 7.9 | 1.3 | 20 | 6 | 7.9 | 1.3 | 20 |
|     |           | Near-term | 4 | 6.0 | 1.5 | 10 | 5 | 7.1 | 1.4 | 20 |
|     |           | Mid-term  | 4 | 6.0 | 1.5 | 10 | 4 | 5.9 | 1.5 | 10 |
|     |           | End-term  | 4 | 6.3 | 1.6 | 10 | 4 | 6.0 | 1.5 | 10 |
|     |           | Current   | 3 | 3.4 | 1.1 | 10 | 3 | 3.4 | 1.1 | 10 |
|     |           | Near-term | 3 | 3.2 | 1.1 | 10 | 3 | 3.3 | 1.1 | 10 |
| 2   | Raya Azebo| Mid-term  | 2 | 2.2 | 1.1 | 10 | 1 | 1.1 | 1.1 | 3.3 |
|     |           | End-term  | 1 | 1.1 | 1.1 | 3.3 | 1 | 1.1 | 1.1 | 3.3 |
|     |           | Current   | 4 | 5.6 | 1.4 | 10 | 4 | 5.6 | 1.4 | 10 |
The highest duration of RDI of 6-years was predicted under RCP 4.5 emission scenario in Ofla, Enda-Mekoni, and Raya Alamata districts. In Ofla district the highest length of drought (duration was recorded) in the current year and in the mid-term, whereas in Enda-Mekoni only in the mid-term. In Raya Alamata district, observation was for the current, near, and mid-term. RCP 8.5 emission scenario were predicted the highest of drought duration of 7-years and it was in Ofla and Raya Alamata districts in the mid-term.

Table 7: Recapitulation of Projected drought events for RDI-12

| No. | Districts       | Period      | RCP 4.5 |       | RCP 8.5 |       |
|-----|-----------------|-------------|---------|-------|---------|-------|
|     |                 |             | D      | S    | I      | RF%  | D    | S    | I    | RF%  |
| 1   | Ofla            | Current     | 6      | 7.9  | 1.3    | 20   | 6    | 7.9  | 1.3  | 20   |
|     |                 | Near-term   | 5      | 7.0  | 1.4    | 20   | 5    | 7.0  | 1.4  | 20   |
|     |                 | Mid-term    | 6      | 7.9  | 1.3    | 20   | 7    | 8.8  | 1.3  | 20   |
|     |                 | End-term    | 5      | 7.1  | 1.4    | 20   | 5    | 6.8  | 1.4  | 20   |
|     |                 | Current     | 3      | 3.5  | 1.2    | 10   | 3    | 3.5  | 1.2  | 10   |
| 2   | Raya Azebo      | Near-term   | 3      | 3.4  | 1.1    | 10   | 3    | 3.5  | 1.2  | 10   |
|     |                 | Mid-term    | 3      | 3.3  | 1.1    | 10   | 2    | 2.2  | 1.1  | 10   |
|     |                 | End-term    | 1      | 1.2  | 1.2    | 10   | 2    | 2.2  | 1.1  | 10   |
|     |                 | Current     | 5      | 6.7  | 1.3    | 20   | 5    | 6.7  | 1.3  | 20   |
|     |                 | Near-term   | 3      | 4.8  | 1.6    | 10   | 4    | 5.9  | 1.5  | 10   |
|     |                 | Mid-term    | 4      | 5.7  | 1.4    | 10   | 5    | 6.6  | 1.3  | 20   |
|     |                 | End-term    | 6      | 7.9  | 1.3    | 20   | 5    | 6.6  | 1.3  | 20   |
|     |                 | Current     | 6      | 8.1  | 1.4    | 20   | 6    | 8.1  | 1.4  | 20   |
|     |                 | Near-term   | 6      | 8.2  | 1.4    | 20   | 5    | 7.0  | 1.4  | 17   |
|     |                 | Mid-term    | 6      | 7.9  | 1.3    | 20   | 7    | 6.3  | 0.9  | 23   |
|     |                 | End-term    | 5      | 7.1  | 1.4    | 17   | 6    | 7.9  | 1.3  | 20   |

Spatial variation maps of drought severity

The variation of drought characteristics spatial coverage has been carried out using SPI and RDI by interpolation of the SPI and RDI values of the driest year at various districts for the 12 months’ meteorological drought. The analysis has been carried out in ArcGIS using the inverse distance
weighted (IDW) method. The duration and deficit volume severity of a spatial drought event, at a particular time, is relevant information for drought management.

In the current time-series, the SPI drought shows 73% which covers extreme drought in Ofla, Enda-Mekoni, and Raya Alamata districts of the southern part of Tigray region.

The RCP 4.5 emission scenarios projection shows that the spatial coverage of SPI drought expected to be 82%, 72%, and 75% for near-term, mid-term, and end-term period respectively, which can cause extreme drought observed in Ofla, Enda-Mekoni, and Raya Alamata and nearly in Raya Azebo district.

The RCP 8.5 emission scenarios projection shows that in the spatial coverage of SPI drought expected to be 82%, 65%, and 58% in the near-term, mid-term, and end-term period respectively, which can cause extreme drought observed in Ofla, and Raya Alamata and widely covered in Raya Azebo. In the End-term period severe drought up to 35% can happen in Enda-Mekoni and some part of Raya Azebo districts as shown in Fig.5.

Fig. 6: SPI classes of the driest year of the four districts

In current time-series, the RDI drought shows 71% covers extreme drought in southern districts in all part of Ofla and Raya Alamata and nearly in Enda-Mekoni and Raya Azebo districts.
The RCP 4.5 emission scenarios projection shows that the spatial coverage of RDI drought expected to be 81%, 70%, and 74% in the near-term, mid-term, and end-term period respectively and this extreme drought can happen some part of southern Tigray, as in ofla, Raya Azebo, and Raya Alamata and in almost half parts of Enda-Mekoni district.

The RCP 8.5 emission scenarios projection shows in all districts the spatial coverage of RDI drought expected to be 65%, and 58% in the mid-term and end-term periods respectively, extreme drought can happen in ofla, and Raya Alamata and nearly Raya Azebo districts. While, 33% severe drought will be expected Enda-Mekoni given in the Fig. 7.

**Fig. 7**: RDI classes of the driest year of the four districts

**Discussion**

This study analyzed the Spatio-temporal characteristics of meteorological drought under changing climate in semi-arid highlands of northern Ethiopia using meteorological drought indices SPI and RDI and incorporated with RCP 4.5 and RCP 8.5 emission scenarios for near-term, mid-term, and end-term as mentioned above in introduction section. In preparation for drought mitigation, it is important to understand the drought characteristics through drought analysis. It consists of reliable information as the primary factor in the decision-making process (Wilhite & Svoboda 2000).

The climate projection result shows in the end term the average annual maximum and minimum temperature are expected to raise 3.4 and 4.2°C respectively. Numerous investigation also clearly
shown that average annual minimum and maximum temperature are predictable to increase in the future (Araya et al. 2015; Ashenafi 2014). For instant, Elshamy et al. (2009) shows average annual temperature increase over the northern Ethiopia between 2°C and 5°C at the end of the 21st Century compared to the baseline period. Our result shows that the change in minimum temperature rise is higher in magnitude than the maximum temperature (Table 4-5). The climate projection result shows the precipitation projection exhibited an increase in annual mean rainfall (Table 6). Future projections of rainfall are more complex to disentangle unlike temperature. Elshamy et al. (2009) indicate a future projection positive shift of change in rainfall magnitude for most models with increases in average annual rainfall for most of east Africa, including Ethiopia.

The SPI result of the study shows that drought increases under both RCP 4.5 and RCP 8.5 emission scenario for the future time segments (2018-2099) as shown in Fig. 2-5. Similarly, the RDI result also shows an increment for the future as shown in Fig. 2-5. The result of this research have also similarities with research findings of Gidey et al. (2018) which were carried out in Raya valley. At the same time studies by Gebrehiwot et al. (2011) also confirm that the drought will increase at an alarming rate due to climate change for the future in Tigray region.

Experts have long predicted that the frequency and intensity of droughts would increase as a result of climate change, especially in semi-arid areas (Zhao & Dai 2015). In our study also RDI showed an increasing drought duration, intensity, and relative frequency under high climate change emission scenarios (Table 7). The spatial analysis of moderate drought occurrences indicates that a tendency to happen in the eastern and south zones of Tigray at a 3-month time scale (Gebrehiwot et al. 2011). In this study, due to impacts of climate change on the spatial extent of meteorological drought, the drought changed to extreme drought. It extended for 12-month timescale steps. According to RDI based the spatial extent of meteorological drought showed no noticeable decrease coverage of extreme drought.

In our study shows RDI had greater number of drought year compared with the SPI. In its standardized form, in most of the cases, the RDI responds in a similar way as the SPI and the various thresholds representing the borders of severity classes are the same (Tsakiris & Vangelis 2005). We also seen in this study RDI shows the same drought severity indicated by the SPI indices in each drought duration.
Conclusion

Projected mean annual temperature and rainfall show that an increasing trend in the future climate. The projected precipitation reveals an annual increase for all the three-time scales (i.e. near-term, mid-term, and end-term) in both RCP 4.5 and RCP 8.5 emission scenario over the southern part of Tigray.

The temporal variation of SPI and RDI values shows that in Ofila, Enda-Mekoni, and Raya Alamata districts for the next 100 years and in the selected time series slices, such as in the years of 2013/14, 2043/44, and 2073/74 was projected to have extreme drought events. In Raya Azebo district both indices show moderate drought in the years of 2037/39, 2043/44, 2067/68, and 2097/98. The drought projection shows that the drought occurred in the base period, will reoccurred with in the first five years of all the future terms by a different magnitude.

The drought conditions in Ofila and Raya Azebo districts will continue without changing the current drought frequency. In the other two districts show an increasing and a decreasing in drought frequency under changing climate, prominent to higher risk in terms of strengthened destruction of drought. This in turn delivers indication for proper policy enforcement to safeguard and control drought and flooding associated risks in the study area. Spatial extent of meteorological drought, they are almost the same to the study area, but unlikely for meteorological drought characteristics of duration, intensity, and relative frequency, because of the result had different in magnitude.

The current and future spatial coverage of drought in the study area affected by extreme drought and the remain percent affected by severely and moderate drought. The entire study area of those four districts can be considered as drought prone areas. Thus, different land and water management activities should be implemented in place to minimize the drought impacts in the region.

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Authors' contributions
BY developed the design of the model, analyze and evaluated the results, and BY, HS and HA drafted the manuscript. AG, HH, and KA read and approved the final manuscript.

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