International Journal of Environment and Climate Change

8(4): 283-294, 2018; Article no.IJECC.2018.017
Previously known as British Journal of Environment & Climate Change
ISSN: 2231–4784

Characterizing and Monitoring Drought over Upper Blue Nile of Ethiopia with the Aid of Copula Analysis

Abebe Kebede[1,2*], U. Jaya Prakash Raju[1], Diriba Koricha[3] and Melessew Nigussie[1]

[1]*Department of Physics, Washera Geospace and Radar Science Laboratory, Science College, Bahir Dar University, Bahir Dar, Ethiopia.*
[2]*Department of Meteorology and Hydrology, College of Natural Science, Arba Minch University, Ethiopia.*
[3]*Ethiopia USGS/Famine Early Warning Systems Network, Ethiopia.*

Authors' contributions

This work was carried out in collaboration between all authors. Author AK designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors UJPR and DK managed the analyses of the study. Author MN managed the literature searches. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/IJECC/2018/v8i427181

Original Research Article

Received 20 August 2018
Accepted 03 November 2018
Published 03 December 2018

ABSTRACT

The main aim of this study is to characterize and monitor drought distribution and expansion over Upper Blue Nile of Ethiopia by using univariate standard precipitation index (SPI) and standardized soil moisture index (SMI) whose joint distribution leads to multi standardized drought index (MSDI). The soil moisture and CHIRPS precipitation data from first January 1980 to 2016 are modeled. The indices of SPI, SMI and the joint MSDI value over the Upper Blue Nile are analyzed. The SPI for different time scales is implemented. The correlation between severity, duration and intensity including wetness and drought strengths is computed and analyzed. It is found that the correlation between duration and severity is 0.96 and normal conditions for SPI 3, 6, 12 month time scales are frequently observed rather than moderate, severe and extreme severe drought or wetness. Building on soil moisture and precipitation data of the summer season, the Clayton copula model is selected based on goodness of fit parameters. After setting the best copula family for the Upper Blue Nile then we applied the joint distribution method is applied for characterizing and monitoring drought. It is found that the MSDI more clearly showed that the severity of drought across the time series of each time scales, than SPI and SMI. As the time scale increases there is decline of fluctuation or frequency of drought and the rising of drought duration is shown by SPI, SMI and MSDI. By using

---

*Corresponding author: E-mail: abeasella@gmail.com;

SPI6, SMI6 and MSDI6 the spatial distribution of drought is determined from June to August in the years 1984 and 2015 indicate the drought expansions in the eastern and western parts of Upper Blue Nile during the respective years.

Keywords: Drought; precipitation; soil moisture and copula.

1. INTRODUCTION

Drought occurs due to climate abnormality which damages social and ecological systems in different regions of the world. Drought phenomena can be monitored by using drought indices [1] and droughts can be categorized into four groups: meteorological, hydrological, agricultural and socio-economic drought [2]. Meteorological drought occurs due to less amount of precipitation than from normal while agricultural drought is related to deficit of soil moisture [3].

Ethiopia is frequently influenced by natural hazard of drought catastrophe [4]. According to Tagel et al. [5] in the past few centuries, more than 30 major drought episodes have occurred, of which 13 were severe and covered the entire Ethiopia and several regions were affected. Studies indicate that the frequency of drought occurrence in Ethiopia has been increasing over the past decade [5,6]. Drought caused severe economic losses in the Upper Blue Nile of Ethiopia [7] and the precipitation over Ethiopia, including the Upper Blue Nile, is influenced by intertropical convergence zone of climate condition [8]. The frequency of drought threshold is characterized by its duration, severity and spatial coverage [9]. Droughts are multivariate natural phenomenon by nature may be univariate frequency analysis method is inadequate to describe their probabilistic nature [10].

A copula is a joint multivariate distribution in which the marginal distributions are uniform [11]. Copulas are functions used to derive the joint distribution of two or more variables, depending on their marginal distributions. Over the last decade, copulas have emerged as a method for addressing multivariate problems in several disciplines. Probabilistic analysis using a copula method has various positive features; the main one is it does not assume that the variables have the same types of probability distribution functions [12]. Copulas can deal with combination of margins because of the margin-free characteristics due to use of ranks for estimating parameters [13]. In bivariate context, [14] used five bivariate copulas to construct a joint distribution between drought duration and severity. As [15] investigated the cross-dependence between meteorological and hydrological drought based on bivariate copulas.

Drought risk assessment based on univariate frequency analyses may lead to erroneous or incomplete conclusions about the occurrence of drought events [16,17]. At the spatial and temporal level, different drought indices, like the standardized precipitation index (SPI), are used for drought monitoring [18] over the Upper Blue Nile however, the complexity of drought phenomena cause and influence for drought monitoring reliably based on a single variable may be insufficient for detecting drought conditions [19]. SPI is broadly acceptable index based on probability concept used as a measure of drought threshold due to precipitation deficit at regional and global levels [17]. For higher dimensions [20] constructed a four-dimensional joint distribution of drought duration, interval time, severity, and minimum SPI (Standardized Precipitation Index) values based on elliptical and Archimedean copulas. The SPI is the most widely used index, because it is simple, spatially invariant and only needs monthly precipitation data to calculate it. It is used to describe droughts in different parts of the world. Therefore, drought properties are investigated by using SPI in numerous studies. Since drought is a complex phenomenon, one variable cannot provide a comprehensive evaluation of droughts [21]. Therefore, drought duration and severity are derived from SPI to describe the droughts. Thus for agricultural activities it is of great importance in the planning and management of water resources to minimize the risk of drought.

According to Bayissa et al. [7] there was less exploration of drought over the Upper Blue Nile by comparing six drought indices and evaluating their performance with respect to identifying historic drought events in the Upper Blue Nile basin. Mostly El Niño events that begin from April to June result in droughts over upper catchment areas of the Blue Nile [22]. The best fit distribution is selected for drought characterization and monitoring based on the like Akaike information criterion (AIC), Bayesian information criterion (BIC) and loglikelihood. After the selection of the goodness of fit, the best copula model is selected by using summer season precipitation and soil moisture.

The shortage of precipitation has capacity to evaluate drought characteristics and onset, while the deficit of soil moisture has the capacity to detect drought persistence. This indicates that one variable cannot detect the physical characteristics of drought. For this reason, a single index cannot evaluate different types of drought and the multi-index approach is applicable for operational drought monitoring and prediction [17]. Therefore, the aim of the study is characterizing drought, investigating the copula family for drought modeling and evaluating multivariate standardized drought index (MSDI) for drought monitoring by combining precipitation and soil moisture variables over the Upper Blue Nile of Ethiopia. The science question to be answered in this study is: “Can copula be applicable for standardized precipitation index (SPI) and standardized soil moisture index (SMI) and used for drought assessment?”

2. DESCRIPTION OF STUDY AREA

The Upper Blue Nile basin is located in the north-western part of Ethiopia (Fig. 1). It is frequently affected by climate extremes [23]. The topography of the basin is comprised of highlands and hills in the north-eastern part, and is dominated by valleys in the southern and western parts [24]. The elevation varies from 480 m near the Ethio-Sudan border to over 4200 m near the central part of the basin [24].

The climate of the basin is tropical highland monsoonal, with the majority of the rain falling from June to October. Traditional classifications of climate in the upper basin use elevation as a controlling factor to categorize climate zones; the Kolla zone below 1800 m with mean annual temperatures in the range 20-28°C, the Woina Dega zone between 1800-2400 m with mean annual temperatures in the range 16-20°C, and the Dega zone above 2400 m with mean annual temperatures in the range 6-16°C [8]. The average annual rainfall varies between 1400 and 1800 mm/year, ranging from an average of about 1000 mm/year near the Ethio–Sudan border to 1400 mm/year in the upper part of the basin, and in excess of 2000 mm/year in the Didessa and Beles sub basins [25]. In the Sudan, potential evaporation increases, this produces a significant loss in the Blue Nile water [8].

The geology of the basin is mainly volcanic rocks and Precambrian basement rocks with small areas of sedimentary rock [8]. The dominant land covers of the basin are savannah, dry land crop and pastures, grassland, crop and wood- land, water body and sparsely vegetated plants [24].

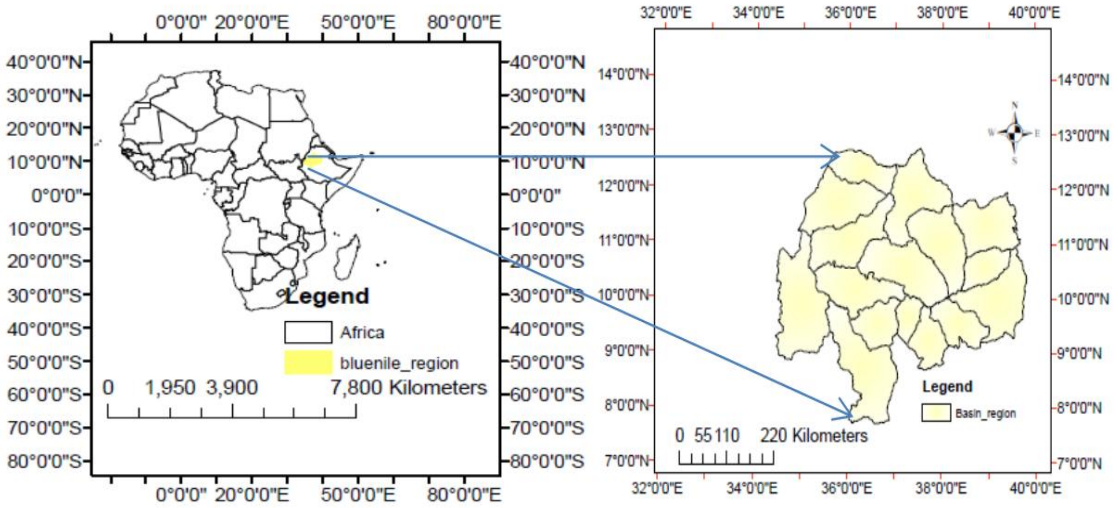

Fig. 1. Map of Upper Blue Nile (UBN) basin and its location in Africa

3. DATA AND METHODOLOGY

To evaluate drought characteristics and monitoring in the Upper Blue Nile of Ethiopia in this study used monthly precipitation data and soil moisture data from 1980 to 2016. The Upper Blue Nile basin which has largest amount of water supply for the Nile river.

It is hard to identify the onset and the end of a drought event, but using drought indices especially the joint distribution of precipitation and soil moisture one can monitor and analyze the drought characteristics. For drought characteristics SPI time scales that refer to duration, severity and intensity. We implemented the standard precipitation index to evaluate the thresholds of wetness and drought according to the time scales. Duration is the length of period in which the index values are less than truncation level; severity is the cumulative index value based on the duration time; and the intensity, sometimes known as magnitude, is defined as severity divided by duration [14].

$$s = \sum_{i=1}^{d} SPI_i \tag{3.1}$$

where s is drought severity and i starts with the first month of a drought and continues until the end of the drought duration d.

Pearson correlation coefficient and Kendall's tau (τ) are used to identify the relationships between the drought characteristics like severity, duration and intensity.

3.1 Standard Precipitation Index (SPI)

To calculate SPI, first a frequency distribution of rainfall data for the selected time scale is constructed. Second, a theoretical probability density function is fitted to the empirical rainfall frequency distribution. Rainfall data of most climatic zones may be fitted by a gamma distribution, although the best distribution type may vary with temporal and spatial scale. Third, equiprobability transformation from the fitted distribution to the standard normal distribution is applied to have a zero mean and unit variance, which represents SPI [26]. The transformed distribution allows to determine the extent of rainfall deficit which facilitates comparison of spatial drought conditions for monitoring droughts at various temporal scales since SPI is the normalization of rainfall data.

This study also used the gamma distribution which is defined by its probability density function [26].

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} \text{for } x>0 \tag{3.2}$$

The maximum likelihood method was used to estimate the optimal values of the α (shape) and β (scale) parameters as:

$$\alpha = \frac{1}{4A}\left(1+\sqrt{1+\frac{4A}{3}}\right) \text{and } \beta = \frac{\overline{x}}{\alpha} \tag{3.3}$$

where $\overline{x}$ represents the sample statistic, the rainfall average,

$$A = \ln(\overline{x}) - \frac{\sum ln\,(x)}{n} \tag{3.4}$$

and n is the number of observations. The obtained parameters were then used to derive the cumulative probability function as

$$G(x) = \int_0^x g(x)dx = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} \int_0^x x^{\alpha-1} \frac{e^{-x}}{\beta} \tag{3.5}$$

The rainfall dataset may contain zero values, since the gamma distribution is undefined for zero rainfall, then the cumulative probability of zero and nonzero rainfalls, H(x), was calculated as

$$H(x)=q+(1-q)G(x) \tag{3.6}$$

where q is the probability of zero rainfall.

If m is the number of zeros present in the dataset, then q is estimated by m/n. The cumulative probability is then transformed into a standardized normal distribution so that the SPI mean and variance are 0 and 1, respectively.

3.2 Modeling the Joint Probability Distribution

Rather than using univarate index of drought multivariate index is more preferable because it determine characteristics or monitoring drought in detail [17].

To characterize drought, Multi Standardized Drought Index (MSDI) is used by considering precipitation and soil moisture deficit [18] which is an extended approach of SPI [26]. MSDI indicates valuable information about drought like SPI by using different time scales.

Arranging precipitation and soil moisture at particular time scales as random variables (X and Y); the joint distribution of these two variables is expressed as follows.

$$P(Xx,Yy) = p \qquad (3.7)$$

where p →joint probability of the precipitation and soil moisture. The MSDI can then be defined based on the joint probability p as [18]

$$\text{MSDI} = \emptyset^{-1}(p) \qquad (3.8)$$

where $\emptyset$ → standard normal distribution function.

For standardized precipitation index (SPI) and standardized soil moisture index (SMI), the gamma distribution is used to compute the cumulative probability distribution of the precipitation and soil moisture, which will then be transformed using the inverse of the standard normal distribution [26]. An empirical cumulative probability distribution such as the Weibull plotting position formula has also been used to estimate the SPI or soil moisture percentiles [19].

An empirical approach to get the marginal probability using the univariate form of the Gringorten plotting position formula expressed as [27]

$$P(xi) = \frac{i-0.44}{n-0.12} \qquad (3.9)$$

where i →rank of the observed values from the smallest and n is the number of the observations.

This indicates that standard precipitation index (SPI) and standard soil moisture index (SMI) are derived by standardizing the marginal probabilities as described by the Gringorten plotting position formula Eq. (3.9).

The multivariate Standard Drought Index (MSDI) is implemented by using the joint distribution of precipitation and soil moisture in the region of Upper Blue Nile. This index serves, to evaluate deficit of precipitation and soil moisture which are very important for water regulation in cycles. It also evaluates the onset, persistence and offset of drought. Using the summer season (JJAS), we tested over eight copula models for the Upper Blue Nile region to understand which copula model performs better over this region by using precipitation and soil moisture data. The performance copula model is evaluated by using goodness of fit in the study region before applying to the multivariate (MSDI). Some of the copula's name and mathematical descriptions are listed below which are implemented in JJAS season.

Name	**Mathematical description**	**Parameter range**
Clayton	$\max\frac{((u^{-\theta}+v^{-\theta}-1,0)^{-1}}{\theta}$	$\theta\epsilon[1,\infty)$
AMH	$\frac{uv}{1-\theta(1-u)(1-v)}$	$\theta\epsilon[-1,1]$
Frank	$\frac{1}{\theta}\ln\left[1+\frac{(exp^{(-\theta u)}-1)(exp^{(-\theta v)}-1)}{exp^{(-\theta)}-1}\right]$	$\theta\epsilon R\backslash 0$
Gaussian	$\int_{-\infty}^{\phi^{-1}(u)}\int_{-\infty}^{\phi^{-1}(u)}\frac{1}{2\pi\sqrt{1-\theta^2}}exp^{(\frac{2\theta xy-x^2-y^2}{2(1-\theta)})dxdy}$	$\theta\epsilon[-1,1]$

4. RESULTS AND DISCUSSION

From the year 1980 to 2016, we observed maximum precipitation in July, soil moisture in September, and runoff in August respectively. These months indicate that summer seasons for Upper Blue Nile and Ethiopia.

This study considered soil moisture and CHIRPS precipitation data since first January 1980 to 2016. The indices of SPI, SSI and joint value SPI and SMI is MSDI are analyzed over Upper Blue Nile. The MSDI determines drought onset as standard precipitation index. It also determines the duration and offset of drought like the SMI for each drought indices. The univariate distribution and joint distribution values are not the same so that the drought severity capturing ability mays not be the same. This implies that the MSDI may not follow the same pattern of drought index.

Meteorological drought occurred frequently than agricultural and hydrological drought over Upper Blue Nile of Ethiopia, which is one of the richest water basins areas. The duration, severity, intensity and loses of economy relies on each type of drought. In this study we used standardized precipitation index (SPI) to find the correlation between severity, duration and intensity. We applied SPI for the wetness and dryness strength levels. However, a single type of drought may not be enough to quantify drought. Therefore, using joint distribution method is more recommendable.

The following table estimates the standard precipitation index values by their percentage occurrence of drought and wet as well as normal condition under consideration over the Upper Blue Nile region. In this study the percentage value evaluates the time scale of three, six and twelve months.

Table 1. Monthly anomaly of precipitation in percent

	SPI value	SPI12	SPI6	SPI3
Extremely wet	2	6.93	5.19	6.62
Very wet	1.5 to1.9	7.84	14.26	7.87
Moderate wet	1.0 to1.49	14.48	11.83	14.38
Normal	0.99 to −0.99	38.11	37.06	40.01
Moderate drought	−1.0 to −1.4	10.95	17.12	14.05
Very drought	−1.5 to −1.99	18.52	9.97	11.72
Extremely drought	<−2.	3.15	4.55	4.88

Table 1 indicates different ranges of drought and wet values according to their threshold levels from wet to drought. We identified that the estimated percentage of each time scale indicates the normal condition SPI3, SPI12, SPI6 from higher to lower values. However, SPI12 and SPI6 month time scales indicate very drought and moderate drought respectively. From this analysis, we visualized that there is less percentage of extreme events of wet and dry, even their challenges are very difficult based on their severity and longer duration.

Fig. 2 indicates the occurrences of dryness and wetness throughout the given years of study. Throughout these years as we visualized that the normal years for standard precipitation index (SPI) 3, 6 and 12 are considered. There is the maximum value precipitation occurrence while standardized falls into the normal condition. The three month time scale indicates from the normal condition the threshold levels of probability severity occurrence decreases as the severity level of wetness and dryness increases. In addition to this, during normal condition the values for each time scale are closer to each other.

The standard precipitation index determines that the wetness and drought severity, but the SPI of negative values determine the drought cases. Due to this, handling drought severity is one mechanism among the three drought characteristics. This is the cumulative value of standard precipitation index (SPI) with a given drought duration. The drought severity is then the cumulative of SPI values within the drought duration. The following figures (Fig. 3) explains drought severity with its duration.

The three month time scale indicates the frequently occurrence of drought over the Upper Blue Nile region. Its duration is compared with the others. For longer duration the 12 month time scale indicates with its higher magnitude severity.

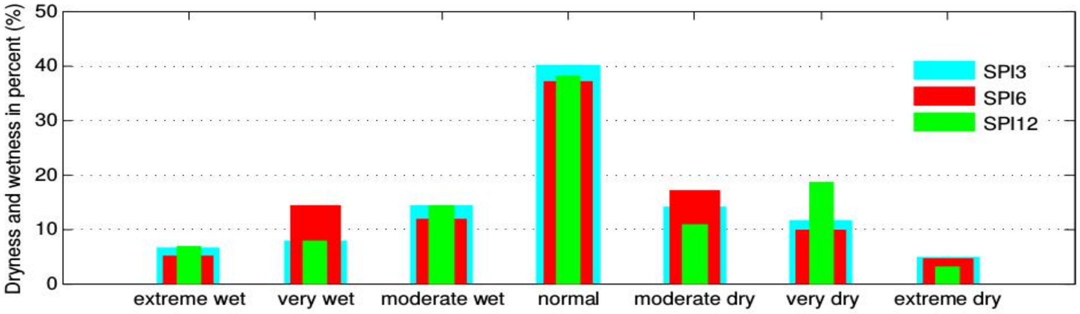

Fig. 2. Dryness and Wetness of SPI3, SPI6 and SPI12 from (Top to bottom Panels) of upper Blue Nile

Table 2. Six months Pearson and Kendall correlation

Correlation	Pearson			Kendall		
	Severity	Duration	Intensity	Severity	Duration	Intensity
Severity	1	0.96	0.79	1	0.81	0.76
duration	0.96	1	0.76	0.81	1	0.59
intensity	0.79	0.76	1	0.76	0.59	1

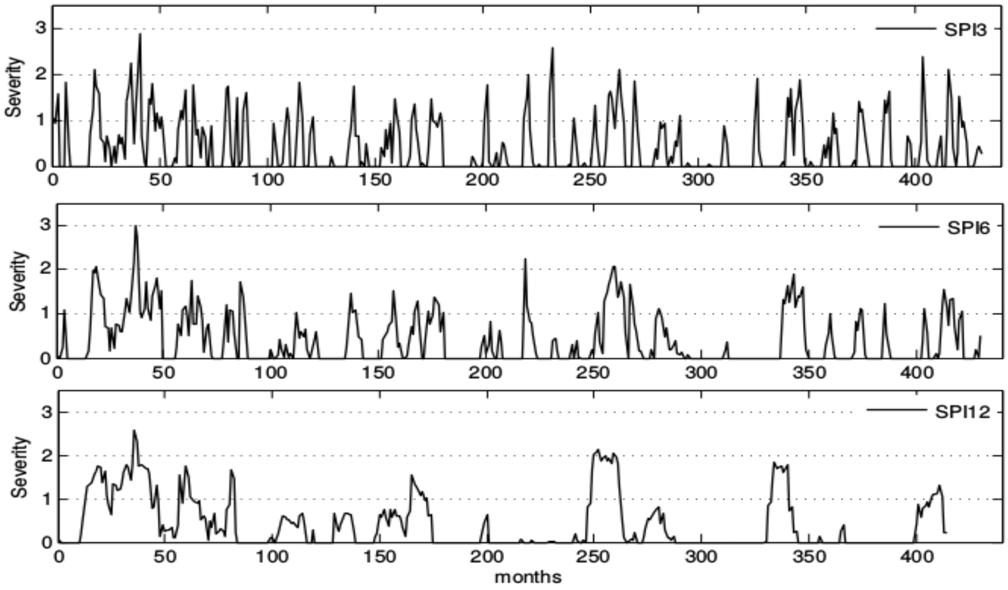

Fig. 3. The severity of drought by using SPI3, 6 and 12 from (top to bottom panel) of Upper Blue Nile

Before applying copula model, the capability of copula to function is examined by using goodness of fit maximum likelihood, AIC, BIC, RMSE and NSE. For the Upper Blue Nile we tested around eight copula models but we set five of them which in the following tables to evaluate drought severity, duration and intensity by implementing the joint variables.

As Table 3 depicted, Clayton, AMH and Frank copula are the best among other copulas'. They have low AIC and BIC values. Besides, their RMSE approaches to zero and NSE approximately close to one. For the joint distribution of precipitation and soil moisture, the Clayton copula and the rest five are implemented.

As the three to twelve month duration increases, the gradual, and repetitive decreasing of drought is depicted in Fig. 3. The standardized precipitation index (SPI) and soil moisture index (SMI) according to their duration of time scales are used to evaluate the long term and short term of drought with severity and intensity. In this study, meteorological drought is recorded frequently than agricultural drought. However, the agricultural drought occurred for a longer duration this reduced crop production since 1999 to 2005 throughout 3, 6 and 12 month time scales over the Upper Blue Nile.

We observed that for each time scale the frequency or variation of precipitation (SPI) is more clearly than soil moisture (SMI) in the year 2015. However, the duration of drought's clearly seen by soil moisture index. For this reason applying the univariate distribution value (SPI or SMI) might lead to an error, so applying the joint variables is the best mechanism to clearly understand the beginning, continuity and ending time of drought along with drought severity. We observed that MSDI is more applicable than SPI and SMI in controlling the drought characteristics.

Table 3. Sort copulas based on different criteria over upper Blue Nile using summer season soil moisture and precipitation

Rank	Max-Likelihood	AIC	BIC	RMSE	NSE
1	Clayton	Clayton	Clayton	0.1218	0.9981
2	AMH	AMH	AMH	0.1323	0.9978
3	Frank	Frank	Frank	0.1380	0.9976
4	T	T	T	0.1389	0.9976
5	Gaussian	Gaussian	Gaussian	0.1485	0.9972

We have seen that for three months the frequency of SPI is much higher than the soil moisture index (SMI). In the years 1981, 1983, 1984, 2003, 2009 and 2015, drought occurred due to precipitation. This case also happened for each of the individual time scale. These occurrences differ which are different depending up on their frequency and length of duration.

For the beginning eight years the soil moisture is higher. For this we did not yet seen severe drought. But, there is a gradual varying frequency of soil moisture. The MSDI clearly shows that the severity of drought across the time series of each time scale. For four time steps the precipitation leads the soil moisture by some months across the time series.

It seems obvious that as the time step increases there is a decline of fluctuation or frequency of drought and the increasing duration of drought is clearly seen for SPI, SMI and MSDI.

The 1984 Drought

Frequent occurrence of drought was observed in the years including1984 and 2015 in Upper Blue Nile, Ethiopia. There was a drought occurrence in the year 1984 and 2015. In these years the spatial distribution of drought was determined from June to July over the Upper Blue Nile by using SPI6, SMI6 and MSDI6 respectively.

In the following figures, the first column displays standard precipitation index (SPI) for June to August of the 1984. The second and third columns show 6- month standard soil moisture index (SMI), and multi standard drought index (MSDI), respectively. Based on the SPI, extreme severe drought is observed in June 1984 in eastern parts and moderate drought in the south eastern parts of the Upper Blue Nile.

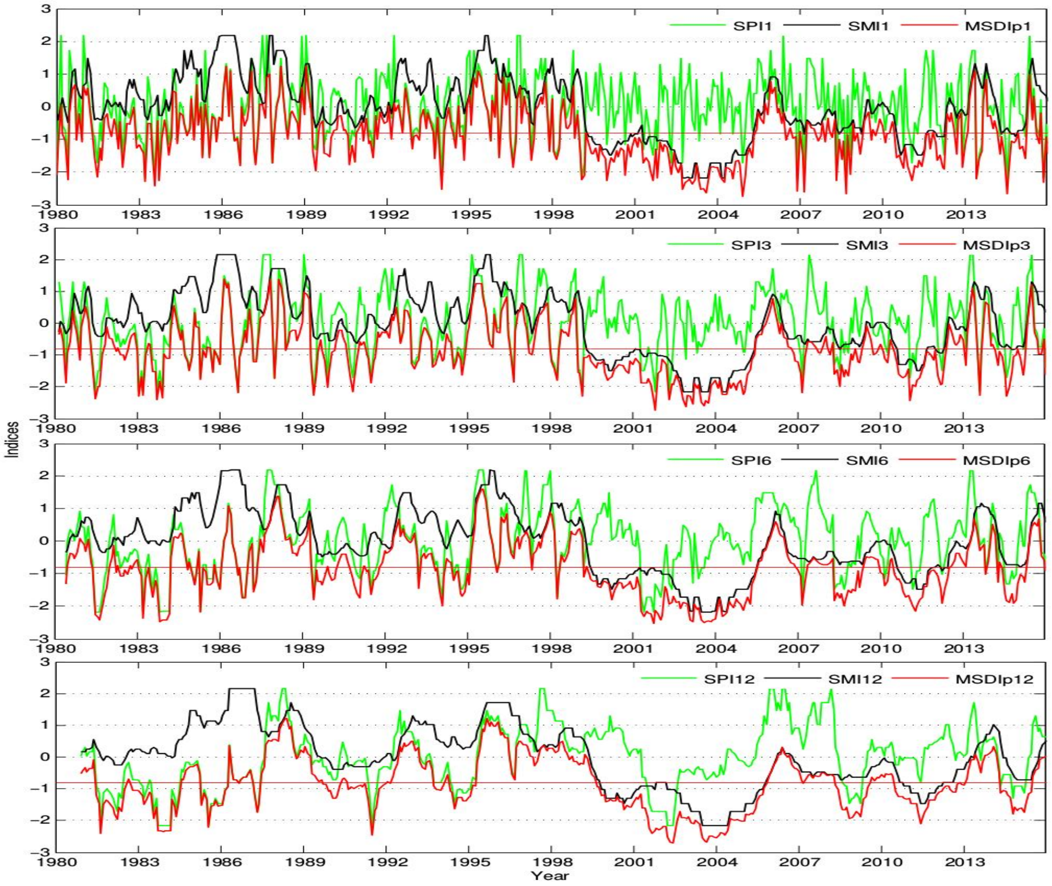

Fig. 4. Comparison of SPI, SMI and MSDI for the 1, 3, 6 and 12 time steps from (top to bottom) respectively

The extreme severe drought condition expanded to the western parts in August 1984 of SPI. A six month multi standard drought index (MSDI) for June 1984 in eastern parts was moderate and in a western parts there was moderate and severe drought. Beginning from July 1984 drought shifted to western parts. The 6-month July1984 indicates drought conditions in western parts with large coverage areas than June and August SMI. The 6-month multistandard drought index (MSDI) shows larger area coverage of drought conditions than the SMI, June and July 1984 MSDI good agreement with the drought condition SPI. In August, large coverage area in the western and eastern parts shown by SPI. However, in south western parts, low coverage of drought is visualized SMI and MSDI. Severity is portrayed by SMI and MSDI.

The 2015 Drought

In the following figures column one indicates 6-month SPI (SPI6), column two MSI6 and column three MSDI6 from June to August, 2015.

In the SPI6 in June 2015, moderate and severe drought conditions are observed. This situation is extended in July with increasing of severity in the eastern areas. In the months SPI6 are observed the moderate drought condition in eastern areas and the moderate and severe drought extension in the western regions of Upper Blue Nile. In the months June and July the SMI indicates moderate and severe drought in the eastern areas with small coverage areas compared to SPI6 and MSDI6, but more extension of moderate and severe drought conditions are observed in August, 2015.

During In August, south western parts also experienced different threshold of drought. Throughout June to August there is gradually a more gradual expansion of drought conditions to the western parts than Eastern parts of Upper Blue Nile. SPI6 and MSDI indicate better consistency of drought condition from June to July, 2015 than MSI.

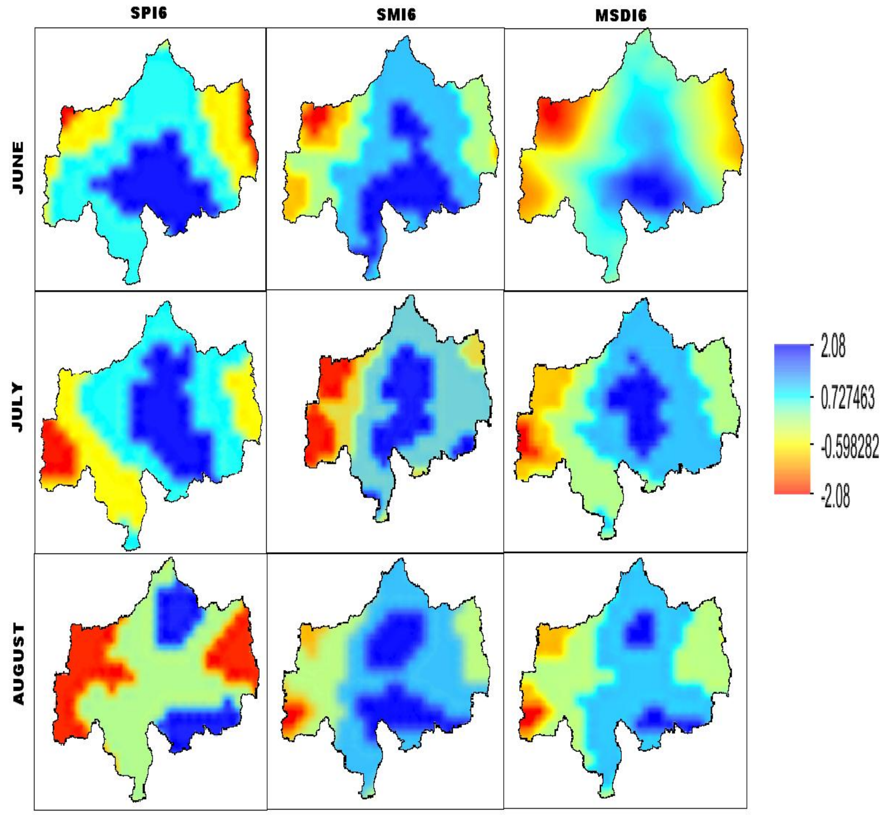

Fig. 5. Left to right six-month time scales: SPI, SMI, and MSDI. (Top to bottom) June to August 1984

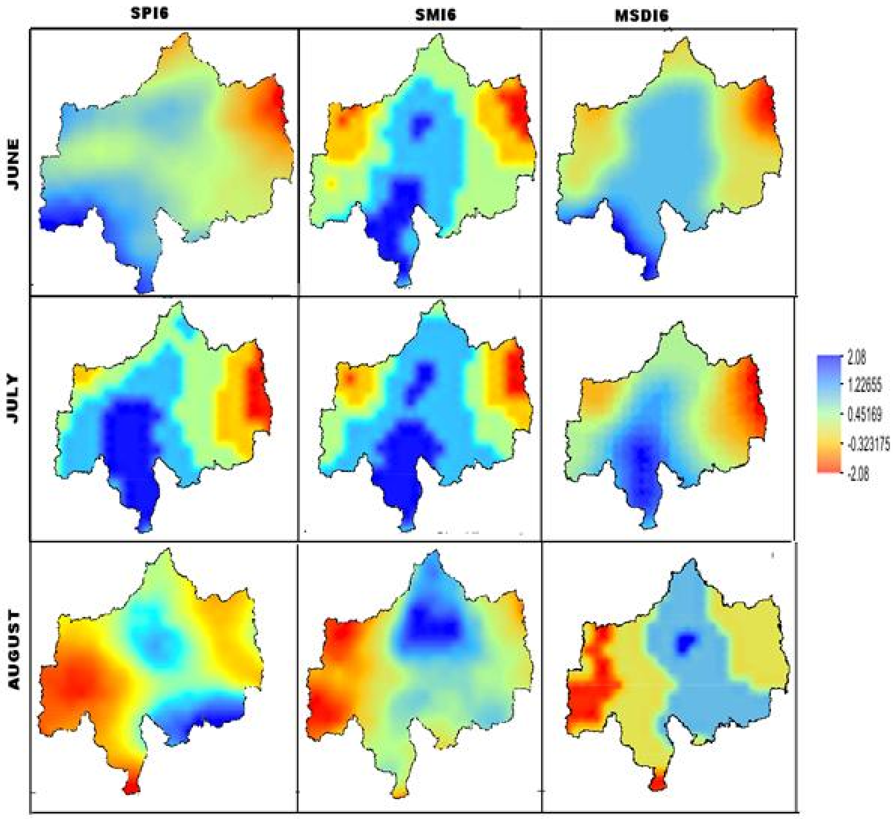

Fig. 6. (Left to right) six-month time scales: SPI, SMI, and MSDI. (Top to bottom) June to August 2015

5. CONCLUSION

In the summer season of the years 1980 to 2016 we found that maximum precipitation in July, soil moisture in September and runoff in August months.

Applying SPI across different time scales we analyzed duration, severity and intensity of drought. Moreover, this normal, moderate, severe and extreme severe drought and wet conditions are evaluated. However, most results indicate normal conditions for different time scales. Pearson and Kendall correlation tests are made for six month time scales. From the comparisons of eight copula models the Clayton copula is selected based on goodness of fit parameters for the Upper Blue Nile in light of summer season precipitation and soil moisture data. This copula model is functional for applying the joint distribution method to characterize drought. We determined that over Upper Blue Nile, the multivariate (MSDI) drought index indicates that severity of drought when compared with SPI or SMI. We observed that MSDI is more applicable than SPI and SMI in controlling the drought characteristics.

We have seen that for the three month time scale, the frequency of SPI is much higher than the soil moisture index (SMI). In the years 1981, 1983, 1984, 2003, 2009 and 2015 drought occurred due to deficit of precipitation. This case also happened in each individual time scales which are different depending up on their frequency and length of duration.

The standardized precipitation index (SPI) and soil moisture index (SMI) according to their duration of time scales served to evaluate the long term and short terms of drought with their severity including intensity as per their time scales. Meteorological drought is recorded frequently, according to this study than agricultural drought. However, the dryness of soil moisture occurred with longer duration which affected the crop production since 1999 to 2005 continuously throughout 3, 6, 12 month time scales over Upper Blue Nile. The spatial and temporal drought distribution of the summer season (June-July) is analyzed in the years 1984 and 2015. During these two years SPI6, SMI6 and MSDI6 showed drought expansions in the eastern and western parts of Upper Blue Nile respectively.

ACKNOWLEDGEMENTS

We are grateful to Dr. Tadesse Tsegaye for his technical assistance, and Dr. Yared Ashenafi who moderated this paper and improved it significantly. We are also immensely grateful to Dr.Samuel Takele for his valuable comments on our earlier versions of the manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Wan Z, Wang P, Li X. Using MODIS land surface temperature and normalized difference vegetation index products for monitoring drought in the southern Great Plains, USA. International Journal of Remote Sensing. 2004;25(1):61-72.
2. Wilhite DA, Glantz MH. Understanding: The drought phenomenon: The role of definitions. Water International. 1985; 10(3):111-120.
3. Hayes M, Svoboda M, Wall N, Widhalm M. The Lincoln declaration on drought indices: Universal meteorological drought index recommended. Bulletin of the American Meteorological Society. 2011;92(4):485-488.
4. McCann JC. A great Agrarian cycle? Productivity in Highland Ethiopia, 1900 to 1987. The Journal of Interdisciplinary History. 1990;20(3):389–416.
5. Tagel G, Van Der Veen A, Maathuis B. Spatial and temporal assessment of drought in the Northern highlands of Ethiopia. International Journal of Applied Earth Observation and Geoinformation. 2011;13:309–321. DOI: 10.1016/j.jag.2010.12.002
6. Edossa DC, Babel MS, Gupta AD. Drought analysis in the Awash river basin, Ethiopia. Water Resources Management. 2010; 24(7):1441-1460.
7. Bayissa Y, Maskey S, Tadesse T, van Andel SJ, Moges S, van Griensven A, Solo Matine D. Comparison of the performance of six drought indices in characterizing historyical drought for the Upper Blue Nile Basin, Ethiopia. Geosciences. 2018;8(3): 81.
8. Conway D. The climate and hydrology of the Upper Blue Nile River. Geographical Journal. 2000;166(1):49-62.
9. Xu K, Yang D, Xu X, Lei H. Copula based drought frequency analysis considering the spatio-temporal variability in Southwest China. Journal of Hydrology. 2015;527: 630-640.
10. Shiau JT, Modarres R. Copula-based drought severity-duration-frequency analysis in Iran. Meteorological Applications. 2009;16(4):481-489.
11. Genest C, Rivest LP. Statistical inference procedures for bivariate Archimedean copulas. Journal of the American Statistical Association. 1993;88(423):1034-1043.
12. Salvadori G. Bivariate return periods via 2-copulas. Statistical Methodology. 2004; 1(1-2):129-144.
13. Kojadinovic I, Yan J. Modeling multivariate distributions with continuous margins using the copula R package. Journal of Statistical Software. 2010;34(9):1-20.
14. Shiau JT. Fitting drought duration and severity with two-dimensional copulas. Water Resources Management. 2006; 20(5):795-815.
15. Wong G, Van Lanen HAJ, Torfs PJJF. Probabilistic analysis of hydrological drought characteristics using meteorological drought. Hydrological Sciences Journal. 2013;58(2):253-270.
16. Vergni L, Todisco F, Mannocchi F. Analysis of agricultural drought characteristics through a two-dimensional copula. Water Resources Management. 2015;29(8):2819-2835.
17. Hao Z, AghaKouchak A. Multivariate standardized drought index: A parametric multi-index model. Advances in Water Resources. 2013;57:12-18.
18. Svoboda M, LeComte D, Hayes M, Heim R, Gleason K, Angel J, Rippey B, Tinker R, Palecki M, Stooksbury D, Miskus D. The drought monitor. Bulletin of the American Meteorological Society. 2002;83(8):1181-1190.
19. Hao Z, AghaKouchak A. A nonparametric multivariate multi-index drought monitoring framework. Journal of Hydrometeorology. 2014;15(1):89-101.

20. Chen L, Singh VP, Guo S, Mishra AK, Guo J. Drought analysis using copulas. Journal of Hydrologic Engineering. 2012;18(7):797-808.
21. Shiau JT, Feng S, Nadarajah S. Assessment of hydrological droughts for the Yellow River, China, using copulas. Hydrological Processes: An International Journal. 2007;21(16):2157-2163.
22. Zaroug MA, Eltahir EA, Giorgi F. Droughts and floods over the upper catchment of the Blue Nile and their connections to the timing of El Niño and La Niña events. Hydrology and Earth System Sciences. 2014;18(3):1239-1249.
23. Teferi Ermias, Uhlenbrook S, Woldeamlak Bewket, Wenninger J, Belay Simane. The use of remote sensing to quantify wetland loss in the Choke Mountain range, Upper Blue Nile basin, Ethiopia. Hydrology and Earth System Sciences. 2010;14(12):2415-2428.
24. Gebremicael TG, Mohamed YA, Betrie GD, van der Zaag P, Teferi E. Trend analysis of runoff and sediment fluxes in the Upper Blue Nile basin: A combined analysis of statistical tests, physically-based models and landuse maps. Journal of Hydrology. 2013;482:57-68.
25. Jain Figueroa A. Using a water balance model to analyze the implications of potential irrigation development in the Upper Blue Nile Basin (Doctoral Dissertation, Massachusetts Institute of Technology); 2012.
26. McKee TB, Doesken NJ, Kleist J. January. The relationship of drought frequency and duration to time scales. In Proceedings of the 8th Conference on Applied Climatology. Boston, MA: American Meteorological Society. 1993;17(22):179-183.
27. Gringorten II. A plotting rule for extreme probability paper. Journal of Geophysical Research. 1963;68(3):813-814.
