

## CHANGES IN THE FREQUENCY AND SEVERITY OF HYDROLOGICAL DROUGHTS OVER ETHIOPIA FROM 1960 TO 2013

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**ABSTRACT.** *Here we present an analysis of drought occurrence and variability in Ethiopia, based on the monthly precipitation data from the Climate Research Unit (CRU-v3.22) over the period from 1960 to 2013. The drought events were characterized by means of the Standardized Precipitation Index (SPI) applied to precipitation data at a temporal scale of 12 months. At the national scale, the results reveal a statistically significant decrease in the severity of droughts over the 54-year period, a pattern that is mostly attributed to a statistically significant decrease in the frequency of high intensity drought episodes (i.e., extreme and very extreme droughts), compared to moderate droughts. To assess the general patterns of drought evolution, a principal component analysis (PCA) was applied to the SPI series. PCA results indicate a high spatial heterogeneity in the SPI variations over the investigated period, with ten different spatially well-defined regions identified. These PCA components accounted for 72.9% of the total variance of drought in the region. These regions also showed considerable differences in the temporal variability of drought, as most of the regions exhibited an increase in wetness conditions in recent decades. In contrast, the regions that receive less than 400 mm of annual precipitation showed a declining trend, with the largest changes occurring over Afar region. Generally, the highly elevated regions over the central Ethiopian Highlands showed the weakest changes, compared to the lowlands. This study confirms the local character of drought evolution over Ethiopia, providing evidence for policy makers to adopt appropriate local policies to cope with the risks of drought. Over Ethiopia, the detailed spatial assessment of drought evolution is required for a better understanding of the possible impacts of recurrent drought on agriculture, food production, soil degradation, human settlements and migrations, as well as energy production and water resources management across Ethiopia.*

## **Cambios en la frecuencia y severidad en las sequías hidrológicas de Etiopía entre 1960 y 2013**

**RESUMEN.** Se presenta un análisis de la ocurrencia y variabilidad de sequías en Etiopía, basado en datos de precipitación mensual de la Climate Research Unit (CRU-v3.22) para el periodo entre 1960 y 2013. Los eventos de sequía se caracterizaron por medio del Índice de Precipitación Estandarizada (SPI) aplicado a los datos de precipitación para una escala temporal de 12 meses. A escala nacional, los resultados revelan un descenso estadísticamente significativo en la severidad de las sequías en un periodo de 54 años, un patrón que se atribuye principalmente al descenso en la frecuencia de episodios de sequía de elevada intensidad. Para comprobar los patrones generales de evolución de sequías se aplicó un análisis de componentes principales (PCA) a las series de SPI. Los resultados del PCA indican una alta heterogeneidad espacial en las variaciones del SPI durante el periodo investigado, habiéndose identificado diez regiones espacialmente diferentes. Los componentes del PCA representaron el 72.9% de la varianza total de sequías en la región. Estas regiones también mostraron un aumento en las condiciones de humedad en décadas recientes. En contraste, las regiones que reciben menos de 400 mm de precipitación anual mostraron una tendencia decreciente, siendo la región de Afar la que presenta los mayores cambios. En general, las regiones más elevadas de las tierras altas del centro de Etiopía son las que mostraron menores cambios en comparación con las tierras bajas. Este estudio confirma el carácter local de la evolución de las sequías en Etiopía, proporcionando evidencias para los políticos y técnicos con el fin de adoptar políticas locales apropiadas para enfrentarse a los riesgos de sequías. En Etiopía, se requiere un estudio especial detallado de la evolución de las sequías para una mayor comprensión de los posibles impactos de sequías recurrentes sobre la agricultura, la producción de alimento, la degradación del suelo, los asentamientos humanos y las migraciones, así como la producción de energía y la gestión de los recursos hídricos en Etiopía.

**Key words:** drought, Standardized Precipitation Index, precipitation, variability, trends, Principal Component Analysis, Ethiopia.

**Palabras clave:** sequía, Índice de Precipitación Estandarizada, precipitación, variabilidad, tendencias, Análisis de Componentes Principales, Etiopía.

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### **1. Introduction**

Drought is a climate phenomenon of importance across a range of disciplines, with implications and impacts in hydrological, agricultural and environmental applications (Brando *et al.*, 2014; Hunt *et al.*, 2014). In the context of global warming, the occurrence, frequency, strength and influence of drought have been the focus of recent climate research

(e.g., Sheffield *et al.*, 2012; Dai, 2013; Hunt *et al.*, 2014; Vicente-Serrano *et al.*, 2015a). A number of these studies have presented an evidence of the upward tendency of the frequency and intensity of drought across many regions (e.g., Glantz, 2001; Santos *et al.*, 2010; Vicente-Serrano *et al.*, 2015a). Although Sheffield *et al.* (2012) have suggested little change in the global drought over the past 60 years, other research has also highlighted the potential implications of future climate changes on drought frequency and severity (Sheffield and Wood, 2008; Dai, 2011), with changes likely to enhance land degradation, particularly in arid and semi-arid regions (Vicente-Serrano *et al.*, 2015b).

The evolution of drought is determined mainly by changes in precipitation: a climate variable that shows a generally low spatial coherence in trends on hemispheric, continental, regional and even local scales (Schonwiese and Rapp, 1997; Williams *et al.*, 2012; Ren *et al.*, 2013; Westra *et al.*, 2013). One pertinent example is Schonwiese and Rapp (1997), who noted regional differences in precipitation trends over Europe, with a general increase occurring in the north and a decrease in the south. Over Africa, numerous studies have reported a significant decrease in rainfall amounts across vast parts of the continent (e.g., Meinke *et al.*, 2005; Hoerling *et al.*, 2006; Ngongondo *et al.*, 2011; Williams *et al.*, 2012). For example, Williams *et al.* (2012) noted a decline in June–September (JJAS) precipitation over the African Horn during the past half century. In contrast, other studies indicate no changes in rainfall totals for some regions (Seleshi and Zanke, 2004). Accordingly, temporal evolution and spatial variations of drought require examination at a more detailed spatial scale (e.g., regional or local scales). Assessing drought characteristics at finer spatial scales is also motivated by the notion that the impact of drought on ecosystems and societies is complex, in the sense that a particular drought severity may have different consequences in different regions, as a consequence of the varying vulnerabilities of these regions (Antwi-Agyei *et al.*, 2012; Vicente-Serrano *et al.*, 2012).

Over Africa, drought is one of the most important of potential natural disasters. Combined with high consumption and low water quality, droughts exacerbate already challenging water scarcity related issues (Mishra and Singh, 2010). Among the African regions, East Africa is frequently portrayed as a drought-stricken region. A catastrophic drought occurred in the region in 1984, which killed an estimated 450,000 people in Ethiopia and Sudan. More recently, a severe drought in Somalia and southern Ethiopia in June 2011 resulted in more than 10 million people seeking humanitarian aid, as well as 380,000 refugees impacting neighboring countries (Vicente-Serrano *et al.*, 2012). Over Ethiopia, a highly populated country whose economy largely depends on rain-fed agriculture, drought is a recurrent climate phenomenon, with a frequency of occurrence approaching one event per decade (Gebrehiwot *et al.*, 2011). Such drought events are often associated with severe economic losses, reduction in GDP growth, crop failure and impact livestock rearing and mortality. According to Meze-Hausken (2004), many farms have shifted to more drought-resistant crops in northern Ethiopia, as a consequence of the decline in rainfall during the last decades. The impact of drought on water resources is also evident, particularly in the most populated areas (e.g., the Rift Valley and the central Ethiopian highlands), where access to water supplies is limited (Funk *et al.*, 2005).

While a number of earlier studies have assessed drought variability over Ethiopia, the spatial and temporal variability of drought is neither well-established nor understood,

especially at the regional and sub-regional scales. This aspect is particularly relevant as many such drought studies tend to focus on either a short-term analysis (e.g., Bewket and Conway, 2007), particular seasons (e.g., Viste *et al.*, 2013), defined drought events (e.g., Viste *et al.*, 2013) or specific regions rather than the whole country (e.g., Meze-Hausken, 2004; Bewket and Conway, 2007; Edossa *et al.*, 2010; Gebrehiwot *et al.*, 2011). For example, Viste *et al.* (2013) found a significant increase in the frequency of spring drought over Ethiopia during the period 1972-2011, albeit with a stronger tendency over lowlands compared to central and northern Highlands. Also, Gebrehiwot *et al.* (2011) employed precipitation and remotely sensed data to assess spatial and temporal variability of drought in semi-arid and arid regions of Northern Ethiopia. They demonstrated that the eastern and southern areas of the Tigray region suffered from a recurrent cycle of drought over the last decade. Similarly, Edossa *et al.* (2010) assessed spatial and temporal variability of meteorological and hydrological droughts in the Awash River Basin, suggesting that the most severe drought events occurred frequently in the Upper and Middle Awash Basin. Complementing these previous works, our study provides the first comprehensive attempt to characterize long-term drought characteristics over Ethiopia at local and regional scales, allowing for the differentiation of drought variability across the entire country. This detailed assessment is demanded due to the high seasonality and the high degree of spatial variability of the Ethiopian precipitation, which are also driven by various geographic variables (e.g., topography) and atmospheric processes (e.g., Indian and tropical configurations). Also, recalling that the impacts of drought depend largely on the severity, duration and spatial extent of the rainfall deficit, assessing the spatial and temporal characteristics of drought is important not only for accurate quantification of its socioeconomic impacts, but for informing and improving forecasting and early warning systems as well (Boken, 2009; Sheffield *et al.*, 2014). This detailed assessment has also implications across a wide range of natural and human environments, including agriculture, water resources, biodiversity, health and food production. Furthermore, given that the Ethiopian Highlands contribute to more than 85% of the Nile discharge, the negative impacts of drought over Ethiopia, potentially accelerated by rapid climate change, may extend beyond the borders of the country to other water-stressed countries in the lower catchment of the Nile Basin (e.g., Egypt and Sudan). These impacts may further limit water supplies to these countries and increasing the risk of national conflicts and political instability (Burke *et al.*, 2009).

The overall objective of our research is to examine the spatial and temporal changes in the severity and frequency of drought over Ethiopia, as described by the Standardized Precipitation Index (SPI), for the period 1960-2013. Ethiopia is a country of high geographic and climatic diversity, which makes it a unique site to assess the possible impacts of recent climate change on drought characteristics (e.g., intensity, severity and spatial extent of occurrence) (Trenberth *et al.*, 2014). These changes could have serious impacts on society, environment, and economy in Ethiopia and neighboring countries (e.g., Sudan and Egypt).

## 2. Study region

Ethiopia is a landlocked country situated in the Horn of Africa; with an area of approximately  $1.12 \times 10^6$  km<sup>2</sup> contained between latitudes 7° 57' and 14° 53' N, and longitudes of 33° and 48°E. Ethiopia is markedly heterogeneous, with altitudes varying

from about 100m below mean sea level (the Dalol Depression, Northeastern Lowlands) to nearly 4550 m (Ras Dejen mount, Northern Highlands) (Figure 1). The East African Rift Valley crosses the country on a northeast-southwest axis. The climate in Ethiopia is very diverse, with almost 10 climate classes following the Köppen-Geiger's scheme. Of these, the dominant climate types are the arid, hot steppe (BSH), the tropical monsoon (Am) and temperate humid warm summer (Cfb). The eastern slopes of the Ethiopian Highlands exhibit a temperate dry summer (Cs) climate, while the western slopes have a temperate dry winter (Cw) climate (Peel *et al.*, 2007). The average annual temperature (1981-2010) is 22.5°C, with the peak in late spring or early summer (March-June). As shown in Figure 1, the coldest temperatures are recorded over mountainous regions in the center, north and northeast, while the warmest temperatures are generally found in the lowlands of the northeast and southeast. As shown in Figure 2, rainfall amounts are characterized by strong seasonality and high spatial variability. According to Diro *et al.* (2008), three different rainy seasons can be distinguished in Ethiopia: (1) February to May (Belg), (2) June to September (Kiremt), and (3) October to January (Bega). Most of the rainfall in the region occurs during the Kiremt season, with the November-February period generally representing the driest months. As illustrated in Figure 1, the annual rainfall totals range from 100-150 mm in arid and semi-arid NE lowlands to more than 1700 mm in the southwest region (Griffiths, 1972; Korecha and Barnston, 2007). Rainfall in the region is largely impacted by the latitudinal migration of the Red Sea Trough (RST), which moves to the north of the equator during summer and to the northern hemisphere during spring (Deng *et al.*, 2015). The study domain is also influenced by the tropical and extratropical atmospheric circulations (e.g., ENSO), as well as the Indian monsoon system that brings substantial moisture from the Indian Ocean into the region (Beltrando and Camberlin, 1993). Rainfall events are also intensified during June-September, due to the northern most shift of the Inter-Tropical Convergence Zone (ITCZ), which brings the African monsoon (Schneider *et al.*, 2014).

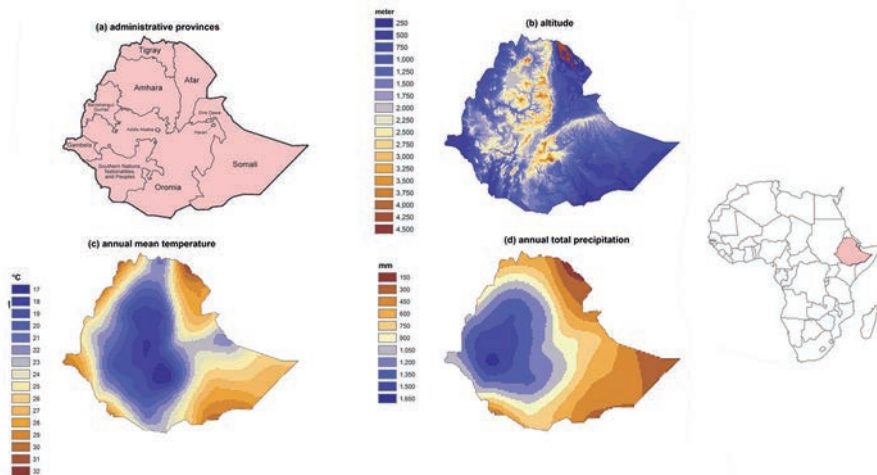


Figure 1. (a) administrative provinces and spatial variations of (b) altitude, (c) annual mean temperature and (d) annual total precipitation over Ethiopia. For each climate variable, climatology was calculated for the long-term (1960-2013) period, using CRU dataset.

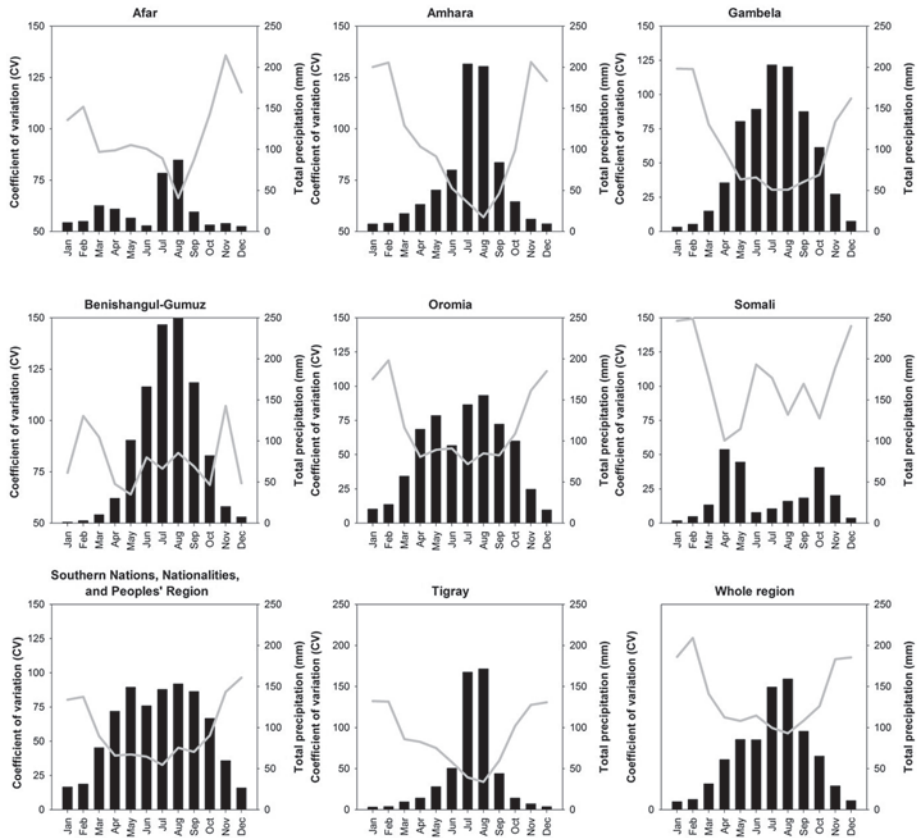


Figure 2. Seasonal cycle of total precipitation (mm) and coefficient of variation (CV) calculated for the different regions over Ethiopia. All calculations are made based on the CRU data for the period 1960-2013.

### 3. Data and methods

#### 3.1. Data

In order to determine the spatial variations and evolution of drought at a fine spatial scale over Ethiopia, high quality, long-term and spatially dense precipitation data are required. The current network of rain gauges over the region suffers from an uneven spatial distribution and fragmentation, which makes the assessment of drought characteristics a challenging task (Viste *et al.*, 2013). The strong seasonality of rainfall, combined with complex orography and an overall low density of observatories, adds additional complexity to drought calculation via observational data. With the development of modern observation and massive computing technologies, the estimation of climatic variables (e.g., precipitation) based on a combination of multi-source data products helps to obtain more reliable data, particularly in areas where long-term reliable

observation data is not available or gauge are sparse. In this regard, gauge-based gridded precipitation products are often used by the scientific community due to their spatial and temporal continuity and availability for extended periods. In this work, we employed the updated Climate Research Unit (CRU) version 3.22 rainfall data to characterize drought in Ethiopia. CRU (v.3.22) is a monthly gridded data set provided by the East Anglia University (UK) that is produced on a  $0.5^{\circ} \times 0.5^{\circ}$  global grid for the period 1901-2013 (Harris *et al.*, 2014). This dataset was compiled from monthly rainfall observations at meteorological stations across the global land areas, providing anomalies from a 1961 to 1990 mean and allowing absolute monthly values to be obtained when combined with the climatology (Harris *et al.*, 2014). CRU data (v.3.22) have been validated against in situ observations in many regions worldwide, confirming their reliability (e.g., El Kenawy and McCabe, 2015; Livneh *et al.*, 2015; Stagge *et al.*, 2015). Accordingly, this dataset can provide valuable information on relatively reasonable spatial and temporal resolutions for assessment of current droughts and their impacts in the region. Here, we constrained our analysis to the period 1960-2013 to minimize the possible influence of year to year variations in the number of observatories used for interpolating CRU (v.3.22) data. Changes in station networks over space and time can introduce anomalous data and spurious variability into precipitation data, particularly in earlier decades.

### 3.2. Drought calculation

A large number of indices have been developed to quantify drought, including the Palmer Drought Severity Index [PDSI], Crop Moisture Index [CMI], Agro-hydro Potential [AP], Surface Water Supply Index [SWSI], Soil Moisture Deficit Index (SMDI), Evapotranspiration Deficit Index (ETDI), Normalized Difference Vegetations Index [NDVI], Standardized Precipitation Index [SPI] and the Standardized Precipitation Evapotranspiration Index [SPEI] (Mishra and Singh, 2010; Sheffield and Wood, 2011). In all the indices, precipitation is the common climate variables for drought monitoring and assessment. In this work, we selected the SPI for drought calculation using the monthly precipitation data at each grid cell for the 54-year study period. The SPI was proposed by McKee *et al.* (1993), and has been used frequently during the two last decades (e.g., Lloyd-Hughes and Saunders, 2002; Vicente-Serrano, 2006; Hirschi *et al.*, 2011; Vicente-Serrano *et al.*, 2015a). In addition to its simplicity and ease of calculation, SPI is suitable for spatial representation of drought variability in regions of complex topography and climate, as it is a normalized index that accounts for comparison between different areas (Lloyd-Hughes and Saunders, 2002). The SPI is based on the conversion of precipitation data to probabilities based on long-term precipitation records computed on different time scales. Probabilities are transformed into standardized series with an average of 0 and a standard deviation of 1. Among the different cumulative probability distributions used to fit the precipitation series, the Pearson III distribution shows enhanced adaptability to precipitation series at different time scales (Vicente-Serrano, 2006; Quiring, 2009). Here, we used the algorithm described by Vicente-Serrano (2006) to calculate the SPI values based on the Pearson III distribution and L-moments approach to obtain the distribution parameters. In this regard, the Pearson III distribution is preferred to other models (e.g., Gamma), because it is described using three different parameters (scale, shape

and location) (Santos *et al.*, 2010). Based on a comparison of different drought indices, Ntale and Gan (2003) found that the SPI was the best index to characterize droughts in East Africa, but after fitting precipitation data to the Pearson type III distribution rather than gamma distribution. As SPI can be generated for different time scales based on the requirement of monthly, seasonal, or long-term drought assessment, we calculated the SPI at a temporal resolution of 12 consecutive months, as this temporal scale is more closely associated with hydrological droughts. In addition, this scale indicates long-term trends in precipitation. Over Ethiopia, the rainfed agriculture is the primary source of national income as well as the main consumer of water. Accordingly, it is likely that the economy can be impacted by the hydrological droughts, as summarized by the SPI-12 timescale. Furthermore, hydrological droughts over Ethiopia could have detrimental effects on many hydrological aspects (e.g., water availability) over the lower tributaries of the Nile Basin. In this study, we also estimated the surface area represented by each drought class, following the drought intensity scheme described in Agnew (2000) (Table 1). Due to its simplicity, this classification scheme has been widely applied in a number of drought studies (e.g., Vicente-Serrano and Cuadrat-Prats, 2007).

Table 1. Drought categories according to Agnew's (2000) scheme.

SPI values	Drought category
Less than 0	No drought
Less than -0.50	Mild drought
Less than -0.84	Moderate drought
Less than -1.28	Severe drought
Less than -1.65	Extreme drought
More than -1.65	Very extreme drought

### 3.3. PCA analysis

To obtain more detailed knowledge of the spatial variability of drought at the sub-regional scale, principal component analysis (PCA) was used to identify homogenous spatial patterns. PCA is a multivariate variable-reduction procedure, which is commonly used in climate research for defining the leading spatial and temporal patterns of climate variability (Richman, 1986). Following this approach, the original "raw" intercorrelated variables are reduced to a few number of linear, non-correlated variables that explain most of the total variance (Santos *et al.*, 2010). In hydrometeorology research, PCA has been used for the regionalization of climate variables and phenomenon at different spatial and temporal scales, including precipitation (e.g. Llasat *et al.*, 2007), temperature (e.g., El Kenawy *et al.*, 2013), evapotranspiration (e.g., Guanghui *et al.*, 2011), snow depth (e.g., Dedieu *et al.*, 2014) and drought (e.g., Santos *et al.*, 2010; Vicente-Serrano *et al.*, 2015a), in addition to classification of synoptic weather types (e.g., Peters and Schumacher, 2014) and air masses (e.g., Bejaran and Camilloni, 2003). In this research, an S-mode of the PCA was applied for temporal association among SPI time series calculated for 405 grid points over Ethiopia. According to this procedure, the time series of SPI at various grid



points were used as variables in PCA. The aim was to maintain the empirical orthogonal functions (EOFs) that explain the dominant long-term (1960-2013) components and their spatial patterns across the region. Here, we followed the Kaiser stopping rule (i.e., eigenvalues greater or equal to 1.0) (Kaiser, 1960), only keeping the components with valuable and independent information. To verify the outputs of the Kaiser rule, we also applied Veelicer's Minimum Average Partial (MAP) test, which is based on the average partial correlations between the variables after iteratively removing the effect of the factors. The number of factors from the data that minimizes the (squared) average partial correlation was just retained (Wilks, 2011). The defined components were rotated by means of the varimax orthogonal technique to reduce data dimensionality and capture the maximum variability in the input data. The rotation procedure is common to simplify the structure of the patterns by producing physically distinct patterns, with a clearer division between the retained components (Richman, 1986). Grid points were assigned to factors based on their maximum factor loadings (correlations). Here, a 0.6 threshold was used as a cutoff loading. The isopleths of the computed PCA loadings were also mapped to give insights into the spatial variability of the obtained drought components. Finally, a least squares method was used to assess long-term trends and periodic behavior in the SPI frequency series corresponding to the significant components. In particular, the analysis was performed for the SPI time series averaged for each particular region, as suggested by the PC patterns. The non-parametric Spearman *Rho* was used to assess the significance of the trend at a confidence interval of 95% ( $p$  value < 0.05). *Rho* has been widely employed in the climatological and hydrological applications, as it is robust to outliers and does not assume prior probability distribution of the residuals (Arismendi *et al.*, 2012).

## 4. Results

### 4.1. Changes in drought intensity

Figure 3 illustrates the temporal evolution of the SPI, averaged over 405 grid cells, across Ethiopia between 1960 and 2013. Overall, z-unit values suggest that the relative frequency of dry ( $SPI < 0$ ) and wet ( $SPI > 0$ ) months is almost equal, with 48.8 and 51.2% of all months, respectively. A linear trend analysis applied to a 60-month moving average of the SPI regional series suggests a significant decline in the frequency of drought over the study period (-0.16 Z-unit per decade,  $p < 0.01$ ). Nonetheless, there is a pronounced intra-decadal variation in the frequency of dry and wet episodes. Results reveal that the dry periods were less intense in the 1960s and 1970s, followed by a general dry period that extended from the beginning of the 1980s until the mid 2000s. The most intense drought episodes were recorded in 1984, 1985 and 1988 and between 2002 and 2004. Some exceptional drought events occurred, especially in May-June 1988 ( $SPI < -2.8$ ) and October-December 1984 ( $SPI < -2.5$ ). In contrast, typical wet periods were recorded between January and June of 1968 ( $SPI > 3.1$ ) and between November 1961 and March 1962 ( $SPI > 2.5$ ). Overall, results indicate that intense droughts characterized more the cold period (October-March) of the year, compared to the warm period (April-September). The mean duration of a consecutive period of dry months was 7.6 months. The maximum

length of dry months was 42, extending between September 2001 and February 2005, although droughts during this horizon were generally mild or moderate ( $SPI < -0.9$ ). Another notable extended dry period was found between May 1990 and April 1993. On the other hand, the mean duration of the wet episodes was 7.8 months, with the longest extended wet period occurring between May 1967 and August 1969 (28 months), and between April 1963 and June 1965 (27 months).

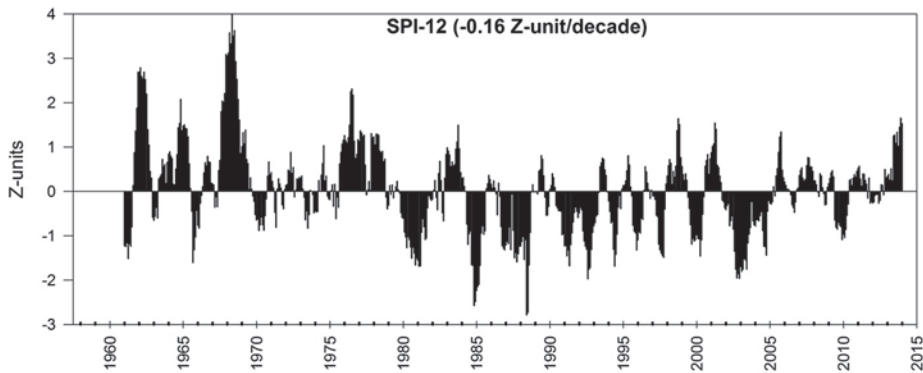


Figure 3. Evolution of the regional SPI-12months over Ethiopia during the period 1960-2013. The cumulative probability gamma function of precipitation was transformed into a standard normal random variable, expressed in Z-units, with mean of zero and standard deviation of one. Changes in the SPI over the period 1960-2013 are also provided for the regional SPI series (Z-unit per decade), using a moving average of 10 years.

Figure 4 presents the temporal evolution of the area corresponding to each specified drought category following the Agnew (2000) scheme. Results indicate that, during some periods, more than 90% of the study domain were not affected by any category of drought classification (i.e.,  $SPI > 0$ ). This pattern was mainly observed during the 1960s (e.g., 1964, 1967 and 1968). In contrast, the drought episode in October-December 1984 was the most drastic and distinct-wide dry episode over the last five decades, as it swept more than 95% of the entire domain. Among them, 39.6% of the country were affected by very extreme droughts, compared to 20.7% for extreme droughts, 15.4% for severe droughts, 8.5% for moderate droughts and 8.3% for mild droughts. An inspection of all drought categories indicates that mild drought ( $SPI < -0.5$ ) was the dominant drought category, affecting –on average– 20.5% of the country over the 54-year period. In contrast, the moderate, severe, extreme and very extreme droughts were less distributed over space, affecting just 10.8, 9.9, 4.9 and 4.2% of the total surface, respectively. The most widespread mild drought occurred in January-May 2004, covering almost 50% of the entire area, followed by the episode of October-December 2003 (40%). Figure 4 also shows that the number of mild drought events affecting more than 40% of the area was restricted to the last decade (e.g., 2003, 2004, 2006, 2009 and 2011). In contrast, the areas affected by moderate drought were less spread during recent decades, relative to

earlier decades. The moderate droughts of November-December 1991, January-February 1996 and between December 2009 and February 2010 were the most widespread moderate episodes, covering almost 25% of the entire area. With few exceptions, more than 30% of the country was under very extreme drought threat ( $SPI > -1.65$ ). Among them, the August-December dry episode of 1984 and that of May-June 1988 pointed to exceptionally widespread and intense droughts. The analysis implies that drought intensity can vary considerably over space and that these exceptionally extreme droughts show a local character, where small areas were affected, while others had a less severe drought intensity or even no drought.

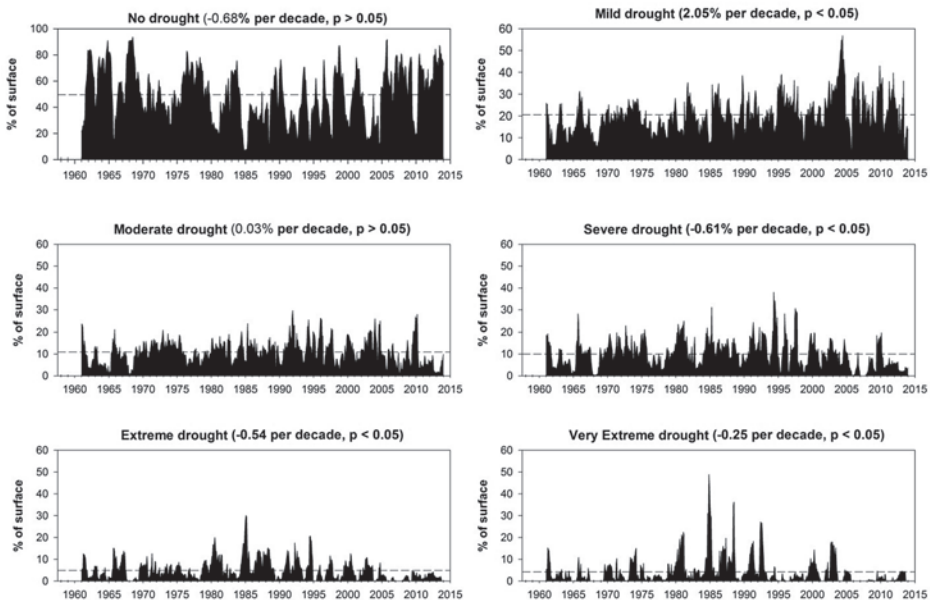


Figure 4. Temporal evolution of the surface impacted by droughts of different intensity over Ethiopia, following Agnew scheme (2000). The confidence interval for the observed changes is provided for each drought category. Only significant changes are given in bold. The central dotted line indicates the mean of the affected surface over the entire period of investigation.

Results on the temporal evolution of each drought category from 1960 to 2013 suggest that statistically significant changes ( $p < 0.05$ ) were found for all drought categories, except for moderate droughts. Nonetheless, these significant changes showed a different sign of change (Figure 4). In particular, while areas dominated by mild droughts exhibited a statistically significant increase (2.05% per decade) in its surface over the 54-year period, the total area impacted by severe, extreme and very extreme droughts showed a significant decline on the order of -0.61, -0.54 and -0.25% per decade, respectively. The increase in areas affected by moderate droughts was not significant at the 95% confidence interval. A comparison of Figures 2 and 3 suggests that the decrease

in the frequency of drought in recent decades, as revealed by the regional series of SPI, can be linked to the statistically negative changes in the frequency of droughts of higher intensity (i.e., severe, extreme and very extreme) rather than changes in the frequency of mild and moderate droughts. Under climate change conditions, this result may raise a question whether changes in the upper tail of precipitation distribution over the region follow the same rates of changes of the mean values of precipitation. In this respect, our findings suggest that the shift in the precipitation distribution may be inconsistent over the region, with rapid changes in the mean conditions rather than changes in the upper percentiles of the distribution. This could explain why changes in the mild drought events, which are more associated with changes in the moderate percentiles, are more pronounced compared to severe droughts that are linked particularly to changes in the upper percentiles.

#### *4.2. Spatial Variability of Droughts*

In order to define the leading temporal components of drought variability and their associated spatial patterns over the study region, the SPI series calculated for the period 1960-2013, for 405 grid points, were used as inputs for the spatial domain of PCA (S-mode). As the SPI series represent normalized values following the index underlying concept, all series had an equal weight. For this reason, a data matrix based on the inter-series correlation was obtained to characterize the dependency among the data. Following the results of the scree plot as well as Velicer's minimum average partial test (Figure 5), ten main patterns (EOFs) were retained, which together account for 72.9% of the total explained variance in the original SPI series. The spatial structure of the identified components was plotted using the values of the rotated factorial matrix (Figure 6). A correlation threshold of 0.6 between each component and the SPI series at the 405 grid points was applied. As illustrated in Figure 6, the defined regions are spatially distinct. Overall, the number of retained components as well as the small variance explained by each of them suggests a high spatial variability of drought over Ethiopia. Specifically, apart from component 1, the remaining components explained a small percentage of variance (less than 9% for each), suggesting that these components represent more localized spatial patterns of SPI. In other words, it is common over the study domain to have extremely wet areas during specific periods, while other areas are in drought conditions. Overall, component 1 explained the largest proportion of the total variance (19.03%), with higher loadings (correlations) over the lowlands located in the southeast (Somalia province). The higher amount of variance explained by this component, relative to other components, may imply that this region is more vulnerable to frequent cycles of hydrological droughts (SPI at 12 months scale). The second component explained 8.81% of the total variance, reflecting the wet/dry conditions in Afar region northeast. The correlations among the values of component 3 and SPI series were much higher in Tigray province northward. On the other hand, component 4 represents southern areas of Oromia province. Hydrologically, the first four components, which explained together 42.29% of the total variance, are spatially associated with the most arid zones (150-450mm/year) over Ethiopia. In contrast, the behaviour of drought in the highly elevated

humid zones are best described by components 6 and 10, which are distributed across the central regions of the Ethiopian Highlands.

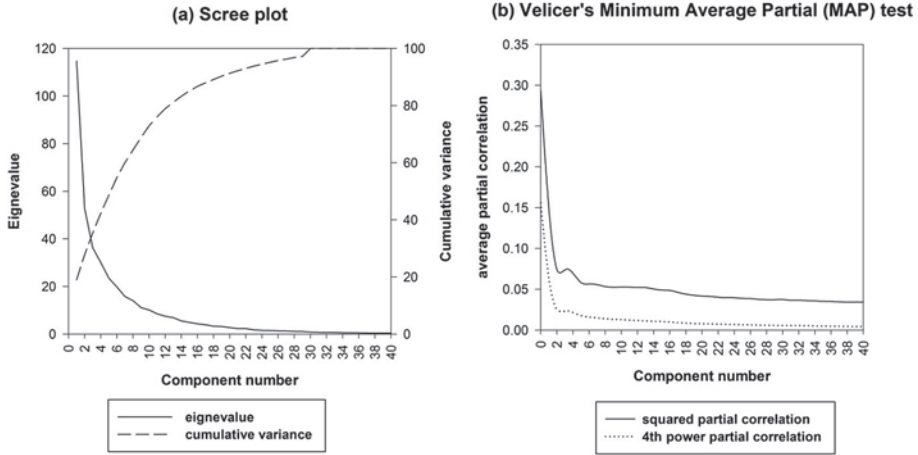


Figure 5. (a) Scree plot and (b) Velicer's minimum average partial test showing the number of selected components.

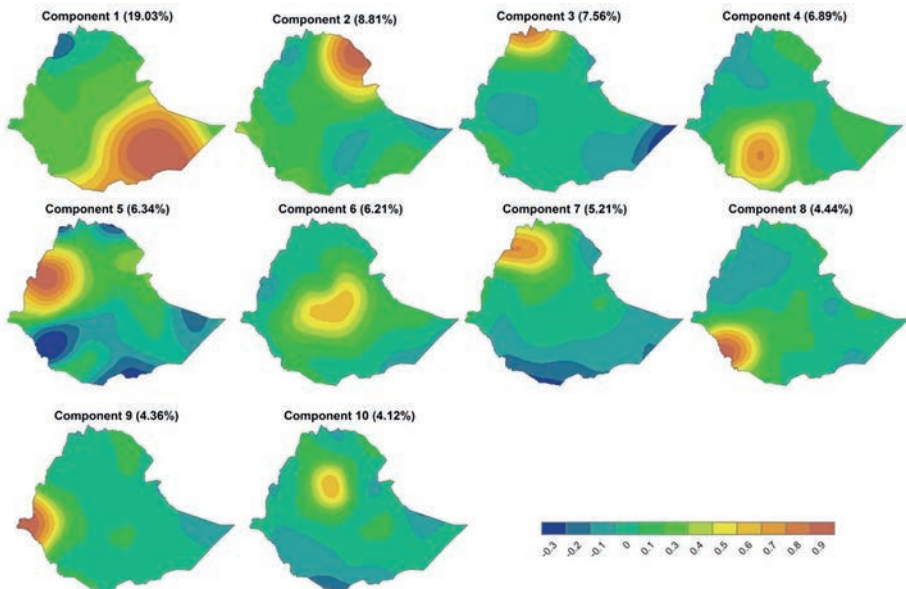


Figure 6. Spatial distribution of the rotated empirical orthogonal functions (EOFs) from PCA of the SPI series. Numbers between parentheses indicate the amount of variance explained by each component.

Figure 7 depicts the temporal evolution of the SPI series and their corresponding trends (Z-unit per decade) for the identified EOFs. Overall, the majority of the historical droughts that occurred in the study region were of mild and moderate severity. As illustrated, there are large differences in the wet and dry pattern among the different components, suggesting high spatial and temporal variability of drought across the region. The southeastern regions that express the first component were generally characterized by mild and moderate droughts ( $SPI < -0.84$ ). In few exceptions, this region suffered particularly from very extreme droughts ( $SPI > -1.65$ ), such as the prolonged drought episodes in April-August 1992. For component 1, the 1980s and 1990s were the driest decades, while the 1960s and 1970s were the wettest decades on record. The peaks of the wet conditions were found from February to July 1968, with SPI values exceeding 2.5. In the Afar region (component 2), stronger multi-decadal variations of SPI values were observed, where earlier decades (1960s and 1970s) were more humid, while large magnitude droughts were usually centered in the 1980s and 1990s. The most drastic drought episode in Afar region corresponds to the period from July 1984 to March 1985, in which the SPI values exceeded -2.1. Another distinct extreme drought episode was found between May and June 1988. Conversely, the last decade exhibited mild, wet periods, with almost no distinct dry episodes. For Tigray region in northern Ethiopia (component 3), the temporal evolution of SPI shows significant differences, compared to the first two components. In particular, prolonged wet conditions predominated over the Tigray region ( $SPI > 1.5$ ) from 1975 to 1985, which does not coincide with the drastic dry episode spanning the first two components over the same period. In contrast, Tigray region exhibited severe drought episode during the last decade, with SPI values ranging from -1.5 to -2: a pattern that is typically reversed for the first two components. Component 4 mainly affects the drought change in the southwestern Oromia region. Over the 54 years, the annual drought has more variations, with early 1960s and the last decade representing the wettest periods. Three periods dominated by dry conditions (1969-1974, 1984-1986 and 1999-2004) and wet conditions over 1960-1962 and 2005-2015. Notably, the northwestern Gumaz region (component 5) has become less drier in recent years. The climate is relatively dry in 1980s, 1990s and early 2000s. After 2006, it tends to be wet. Similar to other components, the temporal evolution of SPI corresponding to components 6, 7, 8, 9 and 10 was characterized by rainfall shortages during the period 1984-1987, while wet conditions prevailed in the last decade. The temporal analyses of 12-month SPI values show that component 8 (Oromia region) was predominantly characterized by more frequent mild droughts, relative to other components. Exceptionally, component 9 (Gambela region) exhibited drier episodes in the recent years, where the maximum 12-month SPI was observed in June 2009 ( $SPI = -1.85$ ). In earlier decades, the behaviour of drought showed large differences, as 1960s was generally wet in regions corresponding to components 6 and 9, while it was drier in regions associated with components 7, 8 and 10.

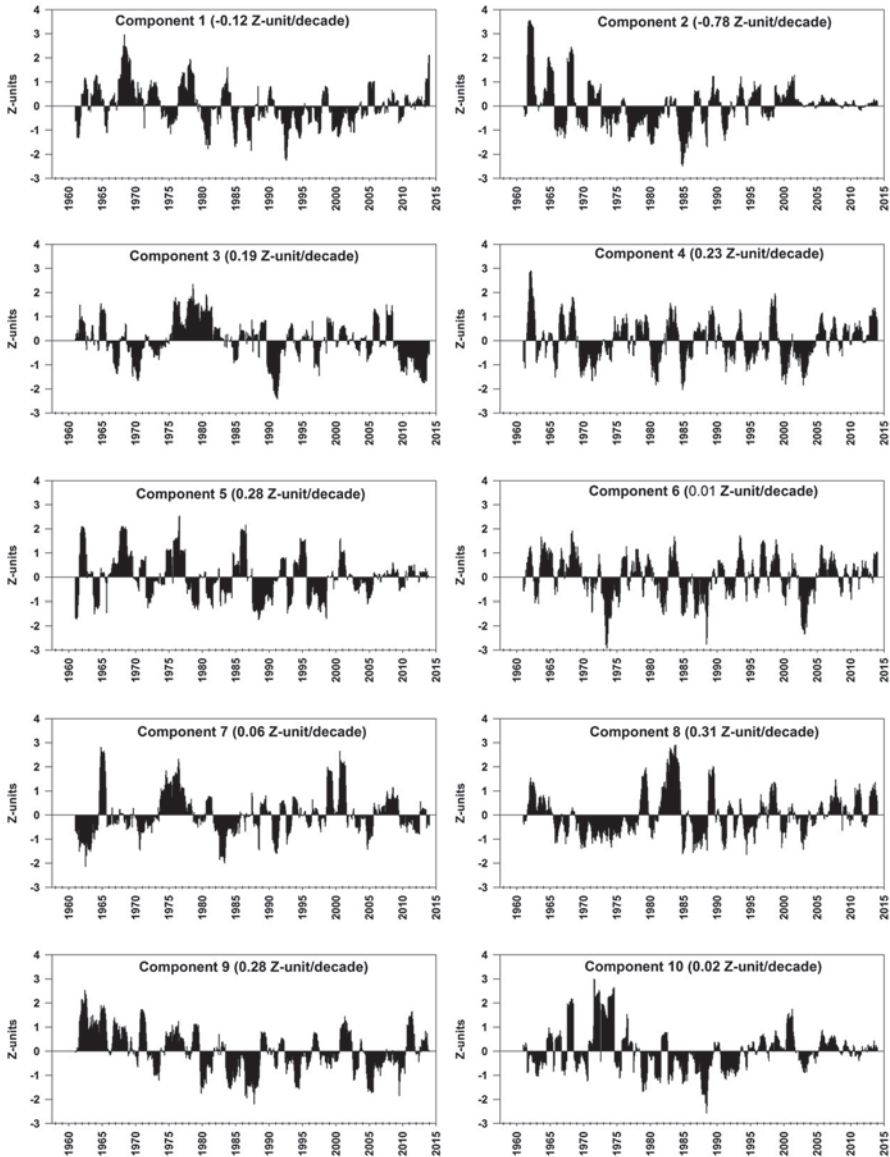


Figure 7. Temporal evolution of the ten components, extracted following the application of PCA to SPI series. Changes in the SPI time series over the period 1960-2013 are provided for each component and expressed in Z-unit per decade.

A comparison of the different components in terms of the duration of the drought episode shows some considerable results. The mean length of the drought episodes does

not vary greatly among components, as it ranges between 7.9 months (component 3) and 13.1 consecutive months (component 10). In contrast, the highest duration of a dry episode varied considerably from one component to another, with the most prolonged drought (115 consecutive months) found in component 8 (Oromio province) between September 1968 and March 1978. Another exceptionally extended dry episode, with 83 consecutive months, was observed for component 10 (central highlands), which extended in the period from August 1982 to June 1989.

Figure 7 also illustrates the linear trends in the 12-month SPI over the period 1960-2013. Overall, the SPI values increased significantly in most regions of Ethiopia, suggesting a decrease in the severity of drought over the 54-year period. This finding indicates that most of the regions showed the same pattern of positive trend in SPI, which was consistent with the results for the whole country. However, the amounts of change exhibited a wide range of values, ranging between 0.01 Z-unit per decade (component 6: central highlands) and 0.31 Z-unit per decade (component 8: Southern Nations province). The first two components, which accounted for the largest proportion of the explained variance (19.03%), showed a dry trend, implying that these regions exhibited a large increase in dryness over the investigated period. However, the largest decrease in SPI was seen in Afar region (-0.78 Z-unit per decade), compared to the lowlands in the southeast (-0.12 Z-unit per decade). Interestingly, the lowest increase in SPI values was found over the most humid and topographically complex regions across the central areas of the Ethiopian Highlands (components 6 and 10), relative to other drier and low elevated areas. Importantly, an inspection of Figure 7 suggests that the strong dryness in the 1980s and 1990s significantly accounted for the observed negative trend in SPI values over the entire period, suggesting a strong inter-decadal variations in drought evolution over these two regions. This is particularly because these two components exhibited a decrease in dryness conditions after 2005.

## 5. Discussion and conclusions

Here we assessed the drought patterns over Ethiopia from 1960 to 2013. Based on the CRU 3.22 monthly gridded precipitation data set for 405 grid points across the country, the Standardized Precipitation Index (SPI) was computed on a 12-months timescale for each grid point. Results indicate that the study domain experienced a decline drying trend on the order of -0.16 Z-unit per decade. In particular, less severe droughts were observed in the last decades, particularly from 2005 onwards, compared to earlier decades (1980s and 1990s). This finding agrees well with previous works over Ethiopia (e.g., Beltrando and Camberlin, 1993; Bewket and Conway, 2007; Edossa *et al.*, 2010; Viste *et al.*, 2013). For example, apart from spring droughts, Viste *et al.* (2003) observed a decrease in the frequency of droughts over Ethiopia from 1971 to 2010 on annual, seasonal and biannual timescales. The significant decline in the severity of droughts over the 54-year period can partially be linked to the decline in the amount of precipitation, though being statistically insignificant over the majority of the Ethiopian territory (Seleshi and Zanke, 2004; Viste *et al.*, 2013). According to Seleshi and Zanke (2004), there is no trend in either the seasonal or annual rainfall totals over central, northern and



northwestern Ethiopia for the period 1965-2002. Similarly, Conway (2000) found no recent trends in rainfall amounts over the northeastern Ethiopian Highlands. Significant decline was observed only for the annual and the June-September total rainfalls across the eastern, southern and southwestern regions. According to this study, the declining trend was more pronounced from 1982 onwards, suggesting a particular influence of the enhanced warm El Niño–southern oscillation episodes. In the same regard, Shanko and Camberlin (1998) attributed the humid conditions in Ethiopia during recent decades to the years of exceptionally low frequency of tropical cyclones. Similarly, Viste *et al.* (2013) noted that the southern region in Ethiopia is the only region, which exhibited a significant decrease in precipitation over the last four decades (at the 95% confidence level). Given the likelihood of increased air temperatures ( $0.28^{\circ}$  per decade) in the region in recent decades (McSweeney *et al.*, 2007; Conway and Schipper, 2011), our results could highlight a possible impact of temperature variability on drought evolution in the region, particularly for meteorological droughts. This dependency is still lacking and needs further investigation at a detailed spatial scale over Ethiopia. In this regard, some drought indices that account for the joint influence of temperature and precipitation on drought characteristics (e.g., the Standardized Precipitation Evapotranspiration Index [SPEI], Vicente Serrano *et al.*, 2010) can be exploited to assess the role of temperature variations on drought development across the region.

Our findings also suggest that all zones experienced some degree of drought at the annual scale. The most severe or extreme droughts occurred in the period from 1984 to 1988. The proportional area affected by mild and severe droughts showed a statistically negative trend over the 54-year period. The areas subjected to the droughts of high intensity (i.e., extreme and very extreme) also exhibited a statistically significant decrease ( $p < 0.05$ ), with the peak of the decline occurring mostly in the 1990s and 2000s. In contrast, changes were only statistically insignificant for moderate droughts ( $SPI < -0.84$ ;  $p > 0.05$ ). These findings imply that the decrease in the frequency of drought in the recent decades is associated more with the decrease in the frequency of intense drought episodes, relative to moderate droughts. Our analysis also indicates that a non-synchronous occurrence of drought episodes over the country, where some severe drought episodes were witnessed in specific periods, while there were no droughts corresponding to these episodes across other regions of the study domain.

The general evolution of drought was obtained by means of the rotated empirical orthogonal function (REOF). Results of the PCA analysis revealed a high spatial heterogeneity in the SPI variations over the investigated period, with ten components explaining 72.9% of drought variability across the region. These patterns are related to distinct geographical areas and are associated with distinct temporal variations. It is observed that there is a strong relationship between the rainfall distribution and drought potential zones in the region, where the most significant patterns of drought were specifically found over the most arid zones, while less significant patterns were observed over the most humid regions. Overall, there are two spatially-broad components, which are distributed over the low elevated areas in the southeast (Somalia province) and the north (Afar province). These two components accounted for 27.9% of the variance. The first broad zone extends over arid, low elevated and agro pastoral lands in the

southeast (Gebrehiwot *et al.*, 2011), while the second zone is located in Afar region, in a semi-arid zone stretching from the northern slopes of the Ethiopian Highlands. These regions are the most vulnerable to recurrent droughts over Ethiopia. The remaining components explained a reduced level of variance (generally less than 9% of variability for each component), suggesting a more localized pattern of drought evolution. This finding is supported by Gebrehiwot *et al.* (2011) in their evaluation of the spatial and temporal characteristics of meteorological and vegetative drought in Tigray (Northern Ethiopia). They concluded that eastern and southern zones of the Tigray province suffered a recurrent cycle of drought over the last decade, compared to northern and western areas. Such spatial inhomogeneity can be viewed in the context of climate diversity, strong seasonality of precipitation, complex topography and soil types over Ethiopia. For example, winter precipitation is more important in southwestern lowlands, while summer precipitation is important over central and western areas (Seleshi and Zanke, 2004). Based on a comprehensive Austrian data set consisting of 44 catchments, Van Loon and Laaha (2015) concluded that drought duration and severity are largely governed by a combination of climate and catchment control (e.g., meteorological forcing, soils, topographic slope, elevation, etc.). In this regard, an investigation of the influence of geographic factors (e.g., elevation, distance to closing water bodies, slope and vegetation cover) on regional variability of drought could provide an avenue for future research. Given the local character of drought over the majority of the region, a detailed assessment of this dependency at a regional scale can properly characterize the drought phenomenon, providing evidence for policy makers to adopt appropriate policies to the risks of drought at local scale. Further assessments may also extend to evaluate the dependency between the spatial components of drought and large-scale atmospheric teleconnections. The atmospheric processes accounting for spatial and temporal changes in drought over Ethiopia can include the tropical configurations over the Atlantic as well as the Indian Ocean. These teleconnections can explain variations in the advection and transport of moisture to the study domain.

This study also assessed changes in the severity of droughts for the identified EOFs. Our findings suggest a statistically significant decrease ( $p < 0.05$ ) in the severity of droughts for most regions, implying that many areas witnessed an increase in wetness during the 54-year study period. Nonetheless, results also indicate that the evolution of drought in Ethiopia is mainly linked to the distinct progression of this phenomenon between two specific regions: the southeast lowlands and Afar region. These regions accounted for 27.9% of the explained variance in SPI over the study period. Hydrologically, these two regions correspond with the most arid climate zones in Ethiopia, with annual precipitation generally below 400mm. Our results indicate that these arid regions exhibited the largest decrease in SPI over Ethiopia, on the order of -0.12 and -0.78 Z-unit per decade for the southeast and Afar regions, respectively. This finding is important given the low precipitation over these regions on one hand, and their heavy dependence on irrigation for agriculture on the other hand. Accordingly, these regions are highly sensitive to rainfall fluctuations and even a slight change could induce significant influences on the socio-economic activities in the region. Meze-

Hausken (2004) found that many farms have shifted to more drought-resistant crops in northern Ethiopia, as a consequence of the decline in rainfall during the last decades.

Assessing the spatial and temporal extent of droughts in Ethiopia, a country that is prone to recurrent drought episodes, is crucial to understand the possible impacts of this natural hazard on agriculture, food production, soil degradation, human settlements and migrations, energy production and water resources management. The negative impacts of prolonged and intense droughts over Ethiopia may create political instability and regional conflicts, given that the Ethiopian tributaries contribute to the vast majority of the Nile discharge. Access to water resources is generally limited in the countries lying at the lower catchment of the Nile (e.g., Sudan and Egypt), which further challenges water resources monitoring, planning and policy in the entire basin. These problems are likely to grow in the future under current population projections, higher water demands and enhanced climate change.

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