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ASSESSMENT OF DROUGHT IN ETHIOPIA BY USING SELF CALIBRATED PALMER DROUGHT SEVERITY INDEX (ScPDSI)

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ABSTRACT

A drought index is a variable, which characterizes drought with respect to its intensity, duration, frequency and severity at a given location and time. The aim of this study is to review drought indices in Ethiopia. During the study period (1901-2014) the Northern and North West parts of Ethiopia; the trend reveals precipitation deficit and positive signal of the temperature anomaly relative to the other parts of the country. This condition apparently has been caused by global surface warming as a complementary cause to the precipitation deficit particularly after 1940 of the study period. Very dry drought spells (ScPDSI=-2 to -2.99) per decade observed three times during in the 1941-1950, four times in 1951-1960, five times in 1980-1990, two times in 1991-2000 and three times in 2001-2010 period. Drought occurrences in Ethiopia were irregular frequency.

KEYWORDS: Drought, ScPDSI, Precipitation, Temperature, Ethiopia.

INTRODUCTION

Droughts are a type of environmental disaster that occurs in every climatic zone, no matter if high or low rainfall area. A heat wave can increase evapotranspiration and dry out lakes. Reduced precipitation can let a groundwater reservoir run dry if it is continuously exploited for agricultural needs (Mishra & Singh, 2010).

Droughts are usually divided into four different stages. The first stage is a meteorological drought is defined as the cumulative lack of precipitation in a region over a prolonged period of time. Second a lack of water in the soil causes an agricultural drought, which usually is accompanied by reduced crop yields or shortage of soil moisture. Third a hydrological drought is characterized by a shortage of water in surface or underground water resources (Azorin-Molina, 2012), it can be visible through dried up rivers and lakes. Finally, a socio-economic drought is apparent when the supply of good water does not meet the demand (Sirak Tekleab Gebrekristos, February 2015).

Analysis of observations and reconstructions shows that the El Nino southern oscillation ENSO, the Northern Atlantic Oscillation NAO, and the Atlantic Multidecadal Oscillation AMO are the main drivers of the global hydro climate (Seager et al., 2007).

The Ethiopian National Meteorological Services Agency NMSA defines three seasons in Ethiopia: rainy season (June to September), dry season (October to January) and short rainy season (February to May) (NMSA, 1996).

The short rains, originating from the Indian Ocean, are brought by south-east winds, while the heavy rains in the wet season originate mainly from the Atlantic Ocean and are related to south-west winds (Seleshi and Zanke, 2004). The study by (Camberlin, 1997) reported that the monsoon activity in India is a major cause for summer rainfall variability in the East African highlands. Some studies show that the climate in the basin is governed by the migration of the Inter tropical Convergent Zone (ITCZ), which moves seasonally from the South to the North and back (Mohamed et al., 2005). The aim of this study to review drought indices in Ethiopia.

In current time due to El Nino the world is affected by drought. So our country Ethiopia is also affected by this drought in major parts of the country such as; Amhara region, east Gojjam, north Gonder and north wollo; some parts of Tigray region, Afar, somaly and Oromia are the first parts of the country affected by drought in 2015, due to these we are interested to study drought impacts in Ethiopia. Drought indices are one of the most important elements of an effective drought monitoring and early warning system. They help to characterize drought and guide appropriate responses to reduce drought impacts. The main advantages of these study is that indices to make drought declarations and to identify cases that leads drought.

DATA AND METHODS

The data were obtained from Climatic Research Unit CRU, dataset. The data contains monthly average temperature and precipitation for adoration of 114 year from 1901 to 1914. We are interested to precipitation and temperature data rather than evapotranspiration because evapotranspiration is a very complicated function of climate elements such as net radiation, vapor pressure, wind speed, humidity, crop characteristics and land use (American Meteorological Society, 2010). The data are obtained monthly average precipitation and temperature for the CRU dataset due to easily understand or analysis.

The design of a drought index can be separated into four steps: First, the variables to be used in the index are selected (e.g., precipitation and temperature). Ideally, they are available yearly or monthly in our case monthly for as long time spans as possible. Secondly, a water balance model is applied to the weather variables to deduce a new variable, d, that accounts for the surplus or deficit of water in a specific time step (Vicente-Serrano et al, 2010).

$$d(x, t)=M[a_1(x, t), a_2(x, t)\ldots,a_n(x, t)] \qquad [1]$$

where, x is the location on the grid, t is the time step, n the number of variables considered in the first step, M is the model function and a is a variable. Thirdly, a recursive memory can be implemented that accounts for the fact that the drought situation in a given month may depend on the previous months.

$$Z(x, t) = R[d(x, t), d(x,t-1,\ldots, d(x,t-m+1)] \qquad [2]$$

where R is the model function that defines the memory of the system and m the number of time steps of d that have an influence on current Z. Fourthly, a normalization procedure is applied to the index to guarantee spatial comparability, given that the same Z value may have different meaning in different places.

$$I(x, t) = N_{month}[x, Z(x, t)] \qquad [3]$$

where N is the chosen normalization procedure depending on the probability distribution function of Z at a certain location for a given month and I is the final drought index. In the following, some of the most prominent examples of drought indices are discussed using the framework described above. Finally, a new generalized drought index is proposed.

Standardized Precipitation Index (*SPI*)

SPI is calculated using the normalization method, Precipitation is a random variable with a lower limit and often positive asymmetry, and does not conform to the normal distribution (Labędzki; 2007). The standardized precipitation index is one of the simplest indices because it only relies on monthly precipitation as input variable (Edwards & McKee, 1997; McKee et al., 1993). As only one variable, whose influence on drought is simply that a low value implies dry conditions, is considered there is no need for a complex model and hence equation 2.1 becomes

$$d(x, t)=M[P(x, t)]=P(x, t) \qquad [4]$$

where P is the monthly precipitation, x the location and t the time. The next step is to introduce a memory into the system, which is done for this index as a running sum over the previous m months where m usually is set between 3 and 48. Hence, all the previous m -1 months influence the drought condition in a specific time step t. Equation 2.2 becomes

$$Z(x,t) = \sum_{i=0}^{m-1} d(x,t-i) = \sum_{i=0}^{m-1} P(x,t-i) \qquad [5]$$

where Z is the drought variable after introducing a memory, but before normalization, so a Z value can only be interpreted in relation to the time series at its location. Therefore, the Z values are normalized at each location and for each month of the year separately, which removes the annual cycle. The idea of the SPI is to map the Probability Distribution Function PDF of all Z values for each location x and for each month onto a standardized normal distribution with a standard deviation of one (Tigkas D., Vangelis H., Tsakiris G., 2015). .

The SPI is also criticized for its physical model since it only incorporates precipitation and thus, relies on the assumption that all other contributions to the water balance like evaporation, temperature, runoff, or soil water content are neglected. Hence, the SPI might ignore indirect effects of climate change on drought probabilities (Vicente-Serrano et al., 2010).

Standardized Precipitation Evapotranspiration Index

The Standardized Precipitation Evapotranspiration Index (SPEI) was developed by (Dai, 2011, 2013), as an attempt to include temperature effects into the SPI. The major influence of temperature on drought conditions is through evapotranspiration (ET). The advantage of this variable over ET is that it can be estimated by the Thornthwaite method using only temperature data and the geographical location (Thornthwaite, 1948). The variables used in SPEI are the precipitation P and the potential evapotranspiration PET. They are merged using a simple water balance by subtracting PET from P, so equation 2.4 becomes

$$d(x, t) = P(x, t)-PET(x, t) \qquad [6]$$

$$Z(x,t) = \sum_{i=0}^{m-1} d(x,t-i) \qquad [7]$$

where m the number of months having an influence on the SPEI at a specific time t.

Despite the improvements the SPEI suffers from the same conceptual drawbacks as the SPI. It still requires a long data record to appropriately determine and fit a matching model to the PDF. As for the water balance models it is questionable whether the PET is the correct variable to incorporate the influence of ET on drought conditions because it is calculated only the given temperature (Ma et al. 2014) due to this rejected the method.

Palmer Drought Severity Index (PDSI)

The Palmer Drought Severity Index PDSI, developed by (Palmer, 1965), was one of the first successful quantitative attempts to build a drought index that represents the drought severity and is comparable between different locations. Hence, the index is based on the difference of water supply and demand, given by the equation

$$d(x,t) = P(x,t) - \hat{P}(x,t) \qquad [8]$$

Where, $\hat{P}(x,t) = (\alpha_j PE + \beta_j PR + \gamma_j PRO - \delta_j PL)$

$$\alpha_j = \overline{ET_j}/\overline{PE_j}, \quad \beta_j = \overline{R_j}/\overline{PR_j},$$

$$\phi_j = \overline{L_j}/\overline{PL_j}, \quad \gamma_j = \overline{RO_j}/\overline{PRO_j}$$

P is the precipitation and $\hat{P}$ ‘‘climatologically appropriate for existing conditions” (CAFEC) water demand. $\hat{P}$ is calculated using the water balance of a simple soil model from the above equation. Four variables are calculated that represent the average water demand for evapotranspiration, runoff, recharge of water to the soil, and loss of water from the soil (Nathaniel B. Guttman, April, 1999). The PDSI is based on four input indices that characterize observed soil moisture conditions in relation to their potential values for each month of every year. These values are evapotranspiration (ET), recharge (*R*), runoff (RO), loss (*L*), potential evapotranspiration (PE), potential recharge (PR), potential runoff (PRO), and potential loss (PL). Thus, it is an estimate for ET based on the assumption that the time dependence of ET is determined by the time dependence of PET (Istva´n Janko´ Sze´p, 2005). d(x, t), called soil moisture departure by Palmer, is now multiplied by a climate characteristic coefficient that accounts for latitude and month, K_i and Z is siol moisture anomaly, which was originally calculated in the equation given below.

$$Z(x\ t) = d(x,t)K_i \qquad [9]$$

$$K = \frac{2}{\pi}\arccos\left(-tan(\varphi)\,tan\left(0.4093sin\left(\frac{\pi}{12}(2i-1)\right)\right)\right) \qquad [10]$$

where φ is the latitude in radian and i is the month (Vicente-Serrano et al.2010).

The Z index has a somewhat similar meaning for the same value in different locations. Note that unlike the SPI or the SPEI, the normalization procedure in the PDSI is applied before the memory is introduced. The PDSI is finally calculated using the recursive formula.

$$\mathbf{I}(x\ t) = 0.897\mathbf{I}(x,t-1) + \frac{1}{3}Z(x,t) \qquad [11]$$

where I is the PDSI and I(0) = 0. The duration factors 0.897 and 1/3 were derived by Palmer for two locations to obtain a "nice" distribution with few extreme values and the maximum and mean value close to zero. The one limitation of PDSI is the use of duration factors the same amount for different locations. These problem is resolved by self calibration of Palmer Drought severity index (ScPDSI) the model by itself adjusts the duration factor for each location in a suitable value. Values below -3 are called an "extreme drought" and values above 3 represent an "extremely wet" situation (World Meteorological Organization, 2011).

RESULT AND DISCUSSION

The first goal of this study is to analyze drought indices to improve characterization and detection of droughts.

Seasonal Variability of drought

To understand the seasonal contribution to the observed characteristics of dryness and wetness we analyze the trend of drought, rainfall and temperature of the PDSI for summer, springs and annually. Many of the PDSI deficiencies were resolved by development of the self-calibrated PDSI (scPDSI) (Wells et al., 2004).

Figure 3.1 shows the original PDSI, Self calibrated palmer drought severity index (ScPDSI), CRU temperature value per decade and CRU rainfall spatial distribution throughout Ethiopia.

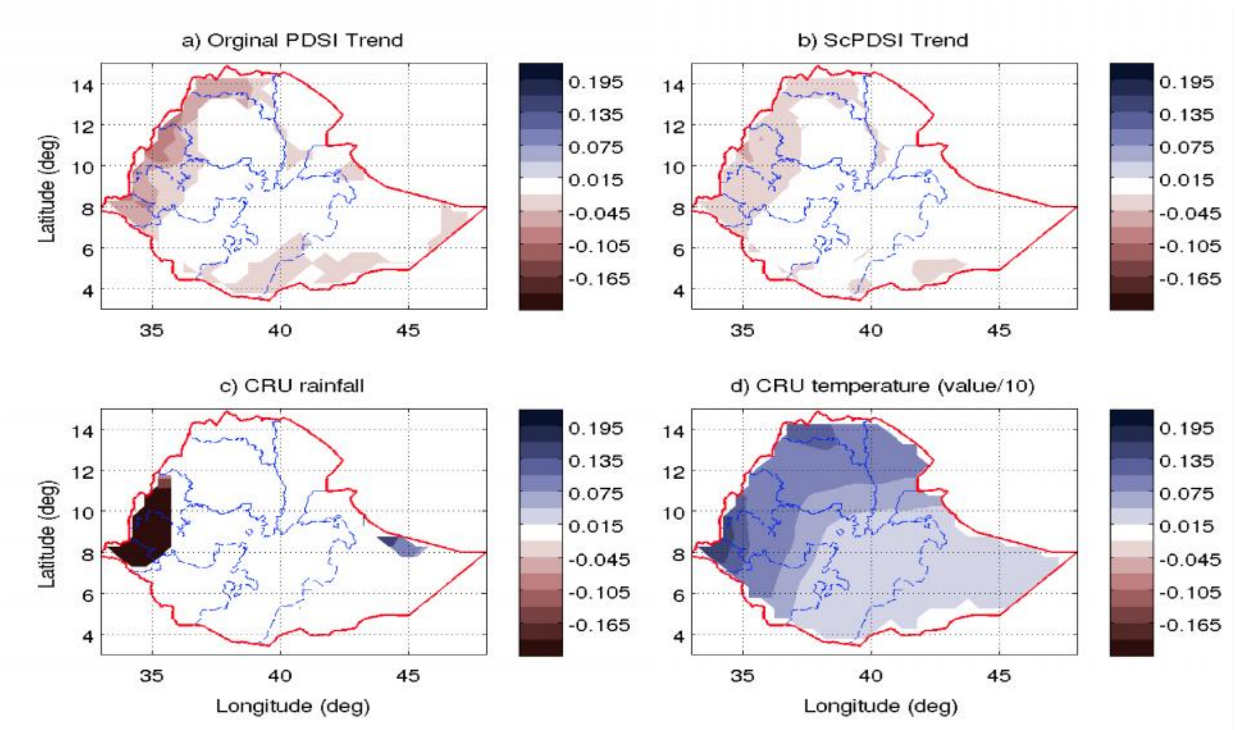

Figure 3.1. Spring session drought, temperature, and rainfall spatial distributions by using original PDSI and ScPDSI from 1901-2014.

Dry/wet events (negative/positive) number of severely dry/wet places using the PDSI for different periods in the CRU dataset. During the study period in figure 3.1a; indicated that the drought distribution of the study area using original PDSI, the northern and north west of the country indicated dry spell; the same that of ScPDSI shown figure 3.1b except its magnitude. South and south eastern portions of the country were dry but not as much as the northern and North West portion of country while the ScPDSI shown fig 3.1b is the similar distribution but eastern part is normal unlike PDSI.

In summer season the distribution of drought, temperature, and rainfall as shown in figure 3.2

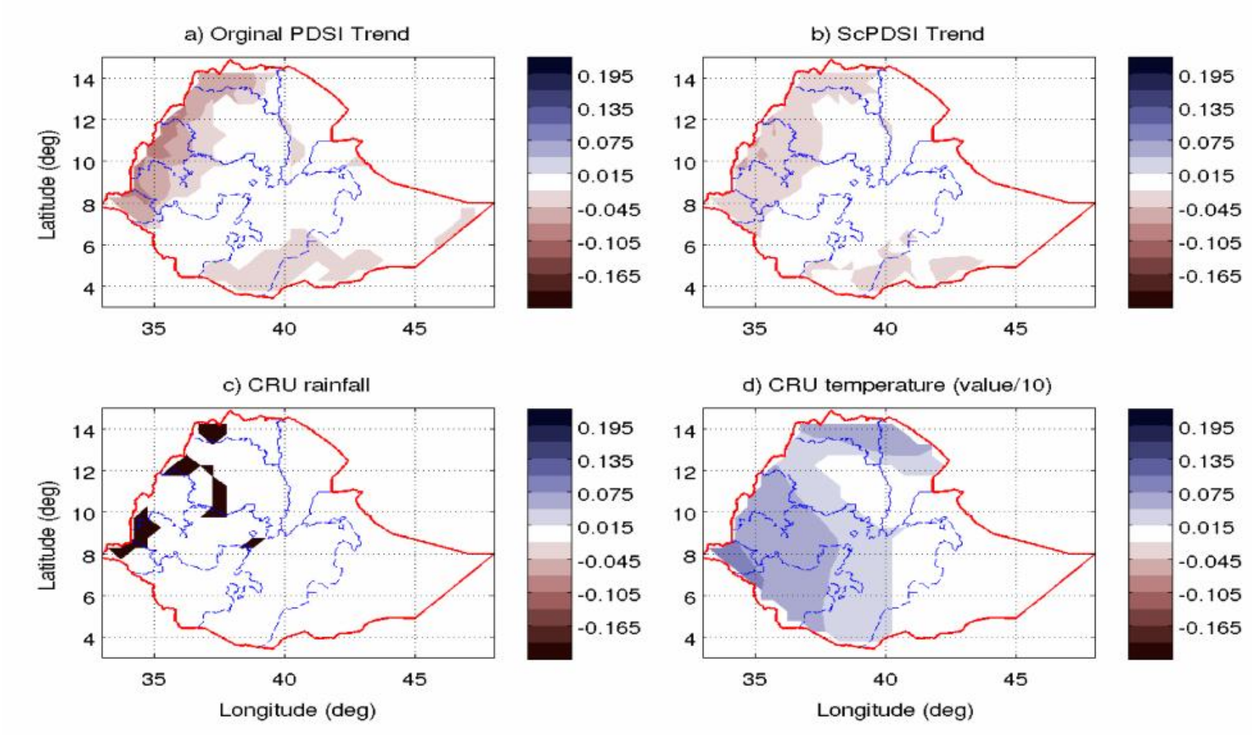

Figure 3.2 summer session drought, temperature and rainfall spatial distributions by using PDSI and ScPDSI from 1901-2014.

Using the PDSI and ScPDSI computed for different periods in the CRU dataset. In figure 3.2a; indicated that the drought distribution of the study area using original PDSI, the northern and north west part of the country were dry in the study period 1901-2014. In figure 3.2c, North West and some portion of Amhara and Tigray negative rainfall anomaly were observed but other part was normal. The trend shows that western and northern part of Ethiopia the distribution of drought increase with time. In summer season figure 3.2d, the temperature decreases compare to spring but western and northern part remains the same with spring. Eastern part of the study area temperature was normal in summer but the distribution or the trend shows the decreasment of rainfall with time.

In annually the distribution of drought, temperature, and rain fall as shown in figure 3.3

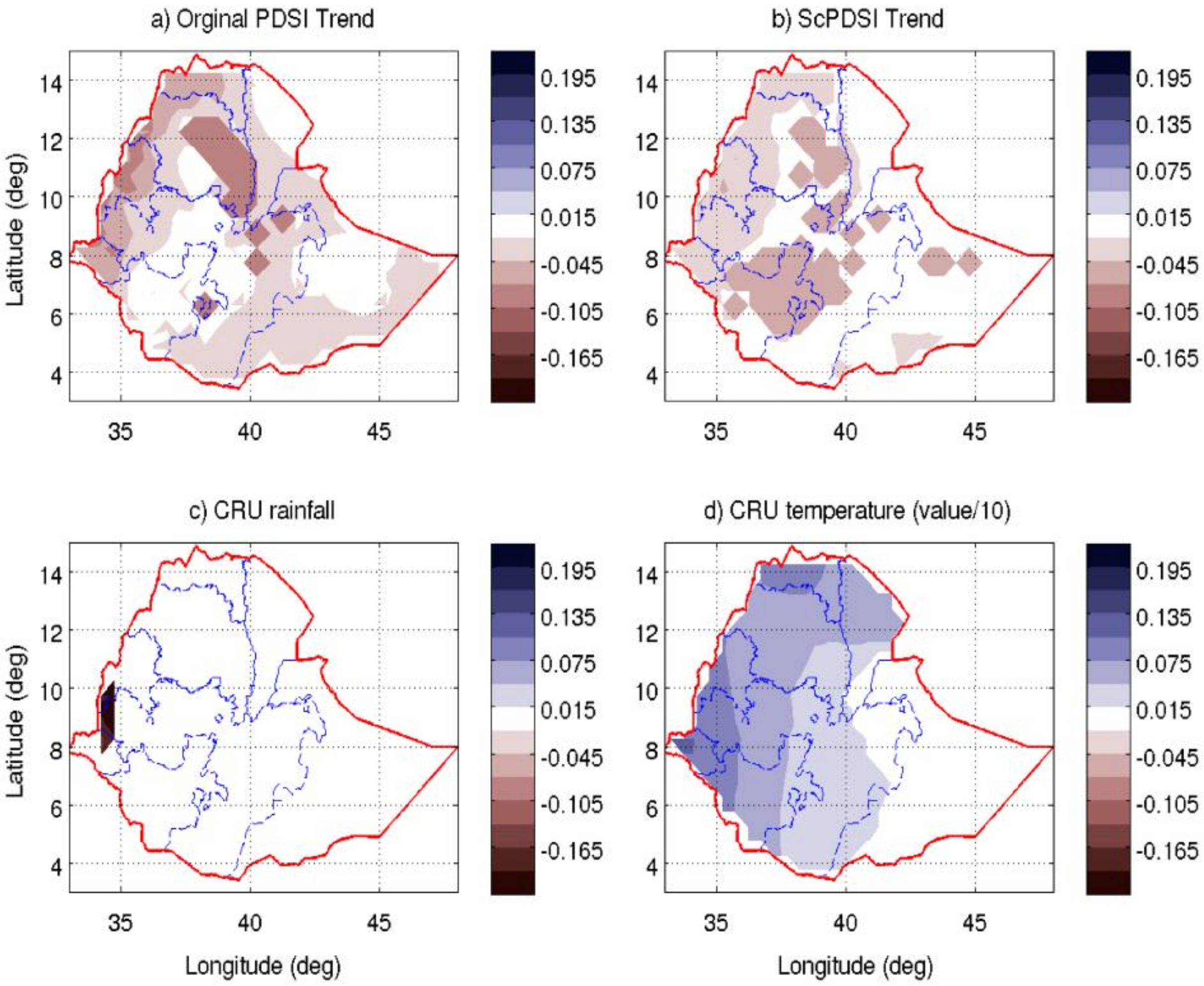

Figure 3.3 Annual drought, temperature, and rainfall trends on spatial distributions by using original PDSI and ScPDSI from 1901-2014.

Annually observation of drought distribution in original PDSI indicated that North West part and half of Amhara region expanded drought occurrence with time and with high magnitude. Exception south Somali and Afar region major part of Ethiopia were dry. Shown figure 3.3c, rainfall distribution except western part is normal but temperature distribution is increase under considerable eastern part, so the cases of drought in the study area were the positive anomaly of temperature.

Figure 3.3b expressed by ScPDSI the trend shows that North West part of the country was dry but not heave with compared that of south west, central and half of Amhara region. Major part of the country the distribution of drought in ScPDSI completely difference with that of PDSI. Except south east part of country annual temperature was increase with time. Annual rain fall of country nearly the same except small portion of western part Ethiopia. The trends of rainfall of the country nearly the same but the trend of drought is being increase because of increasing temperature.

Drought frequencies in original PDSI and ScPDSI

The 14 year interval of droughts in PDSI & ScPDSI stated from 1901 to 1956 year.

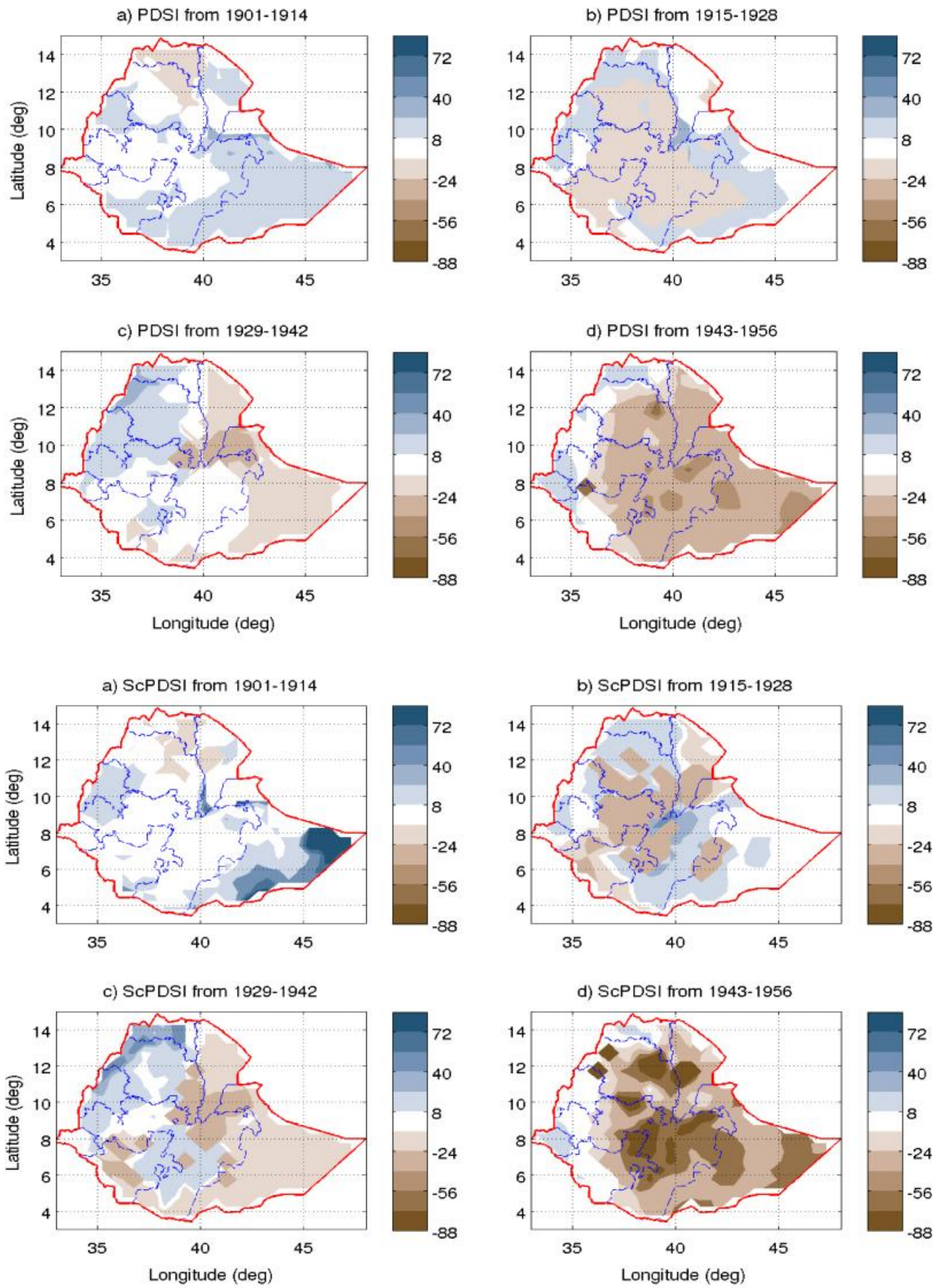

Figure 3.4 the frequency of dry/wet event months per total months using CRU datasets original PDSI and ScPDSI with 14 years interval from 1901 to 1956.

During the first quarter of the study period (figure 3.4a; 1901-1914), in the case of PDSI northern portions of the country were dry but not much, while the south and south east portions were observed positive anomaly precipitation. In the case of ScPDSI south east was very wet compare with that of original PDSI others are similar under considerable its magnitude.

In the second quarter PDSI (figure 3.4b; 1915-1928), the spatial pattern of drought continued to some expansion in central parts of country but with some extent wet conditions in the Northern, north west, south east parts were observed. There is significant drought anomalies were seen over the central and south west regions of the country. In the second quarter insignificant difference between PDSI and ScPDSI.

In the third quarter (figure 3.4c; 1929-1942) the south east and eastern part of the country dry anomalies was evident but Northern and North West part of the country again wet conditions expand towards the central part. In the case of ScPDSI western part of Oromia is wet but in PDSI being normal; south nation nationality and peoples becomes dry but not much in PDSI. Central and northern part little difference had been observed between ScPDSI and PDSI. In the fourth quarter (figure 3.4d; 1943-1956) in this division except western and few northern part all are dry. In the fourth quarter there is no significant difference between ScPDSI and PDSI except the magnitude is increase in the case of ScPDSI in central part of country.

On the other hand the left 14 year period divisions stated in figure 3.5 shown below.

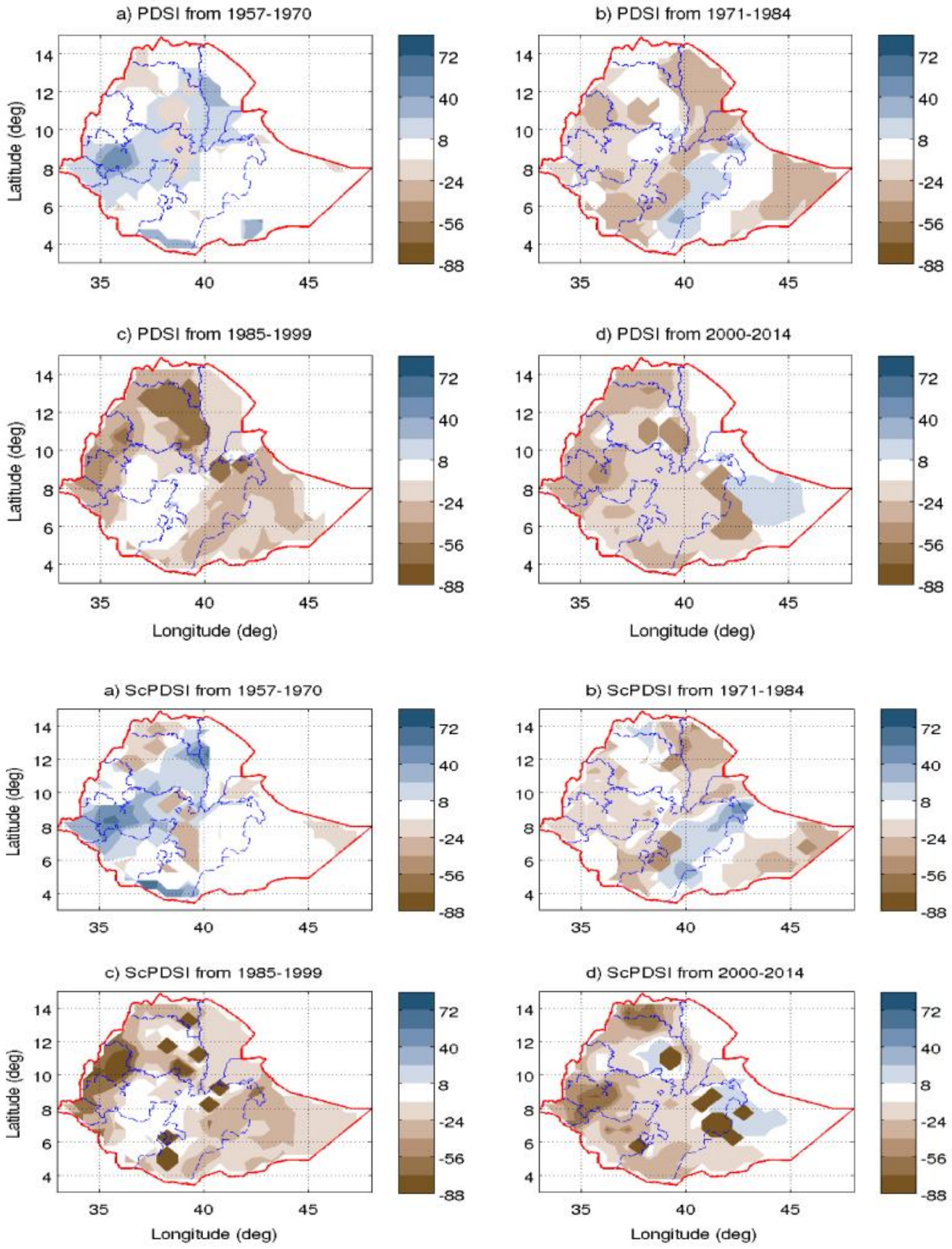

Figure 3.5 the frequency of dry/wet event months per total months of using CRU datasets original PDSI and ScPDSI with 14 years interval from 1957 to 2014.

During the first quarter of the left study period (figure 3.5a, 957-1970) in the case of PDSI central and northern portion of Ethiopia were dry but not higher magnitude. West and east part of central Ethiopia had been very wet but major parts of the country were normal. In these division has insignificance difference between ScPDSI and PDSI except eastern Somali.

In the second quarter (figure 3.5b, 1971-1984), drought rapidly expanded throughout the country except some parts of Oromia was wet. Amhara, some parts of southern Ethiopia, Somali and Tigray were normal. In the second division has also insignificant difference but in the case of magnitude PDSI greater than ScPDSI.

The third quarter of the study period (figure 3.5c, 1985-1999), major part of the study area were drought under considerable southern nations, nationality and people and far eastern Somali. Half parts of Amhara, Northern Oromia and few portions of Tigray regions severe drought were observed. In PDSI northern part is very dry others nearly the same with ScPDSI. The latest period (figure 3.5d, 2000-2014), major part of the study area were dry except eastern part in specific region. Central Somali becomes wet but some part of Amhara, eastern Oromia severe drought had been observed. In ScPDSI central Amhara in western part is wet, in eastern part is very dry. In central part nearly normal but in PDSI light drought were observed.

The PDSI could be used to generate such rainfall estimation images from as far back as the data goes. On the basis of the results of PDSI a quantitative definition of a drought event was adopted, only to include drought events, likely to cause a significant downturn in, for example, farm income over a prolonged period. Therefore, in our analysis, a drought event is a period in which the PDSI is continuously negative and reaches a value of -2.0 or less.

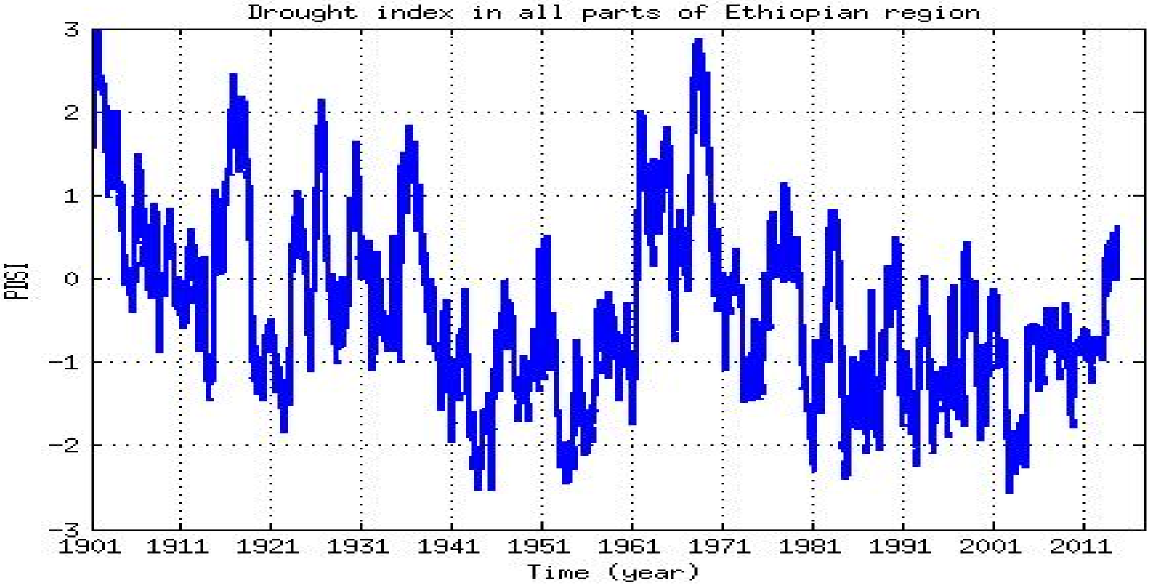

Figure 3.6 temporal averages of the PDSI mean values based on the monthly series during the study period (1901-2014) in Ethiopia.

The figure illustrates frequencies and durations of droughts and dry/wet spells as measured by the PDSI for 10 years interval. The temporal variability of drought in the study area from 1901 to 2014, Positive numbers indicate wet conditions and negative numbers correspond to dry spells and droughts. The figure 3.6 shows that the country experienced droughts of different severity and duration every decade for the presented period. Very dry drought spells (PDSI=-2 to -2.99) per decade observed three times during in the 1941-1950, four times in 1951-1960, five times in 1980-1990, two times in 1991-2000 and three times in 2001-2010 period. Thus, during the study period the northern and North West parts of the country should reveal the precipitation deficit and positive signal of the temperature anomaly relatively more than the other areas. This condition apparently has been caused by global surface warming as a complementary cause to the precipitation deficit particularly after 1940. Extreme drought was observed in 1981-1987 and 2001-2004. Socio-economic and environmental sections were seriously damaged due to this rainfall deficit, and obviously Ethiopia was hit by the most intense drought event in the 3 year period 2002-2004 (Masih, 2014).

CONCLUSION AND RECOMMENDATION

Positive numbers indicate wet conditions and negative numbers correspond to dry spells and droughts. The figure 3.6 shows that the country experienced droughts of different severity and duration every decade for the presented period. Very dry drought spells (PDSI=-2 to -2.99) per decade observed three times during in the 1941-1950 period, four times in 1951-1960, five times in 1980-1990, two times in 1991-2000 and three times in 2001-2010. Also the study showed that the highest frequencies of temperature significant observations were related to spring (March-May) and the highest frequency of precipitation is related to summer (June-September). This study shows that, the increment of temperature is the real cause of drought in Easter Ethiopia and the deficiency of precipitation is the real case of drought in western Ethiopia. I have found that the occurrences of drought in Ethiopia were irregular in frequency. Climate change has diverse economical social and political problems, this can be overcome by great effort of the government and the community shared responsibilities. Researchers should be go further study in these environmental conditions and tell their results to the policy makers. The occurrence of drought in the country is irregular in frequency so we should be study this factors.

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