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Rainfall variability and meteorological drought in the Horn of Africa

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सार – 1901 से 2010 तक की अवधि में अफ्रीका के हार्न क्षेत्र में वर्षा की आधारभूत विशेषताओं ओर सूखे की जाँच की गई है। सूखे की परिवर्तनशीलता का अध्ययन करने के लिए मानक वर्षण सूचकांक (SPI) का उपयोग किया गया है जिसमें मुख्यरुप से तीन महीने की मानक वर्षण सूचकांक को लिया गया है। ऋतुनिष्ठ वर्षण की परिवर्तनशीलता के प्रबल माध्यम का विश्लेषण आनुभविक आर्थोजोनल कार्य विश्लेषण के निष्पादन से किया गया है। ग्रिडिड ऑकड़े जलवायु अनुसंधान एकक (CRU) से लिए गए है और ये 1901 से लेकर 2010 तक की अवधि के है। होआ (HoA) में प्रबल रुप से बाय-मॉडल वर्षा वितरण समय पर मार्च से मई और अक्तूबर से दिसंबर में पाया गया| पहले ईजीनवैक्टर (EOF1) के स्थानिक घटक से चला है कि मार्च से मई और अक्तूबर से दिसबंर का ऋतुनिष्ठ वर्षण क्रमशः नकारात्मक और सकारात्मक लोडिगंस से प्रभावित है। (EOF1) से स्पष्ट होता है कि मार्च से मई ओर अक्तूबर से दिसंबर की ऋतुनिष्ठ वर्षा की परिवर्तनशीलता क्रमशः 34.5% ओर 58.9% है। EOF2, 3 ओर 4 सकारात्मक रुप से पहले से ही प्रभावित है जो दो ऋतुओं मे ऋतुनिष्ठ वर्षण परिवर्तनशीलता का कुल 25% कम होने को स्पष्ट करता है| अक्तूबर से दिसंबर की ऋतुनिष्ठ वर्षा के साथ पिछले दो दशकों में अत्याधिक नकारात्मक विसंगति देखी गई जो मार्च से मई की ऋतु की अपेक्षा अत्यधिक विसंगति दिखा रही थी| मार्च से मई की ऋतु की अपेक्षा अक्तूबर से दिसंबर के मौसम में 9% अधिक सूखे की घटनाएं रिकॉर्ड की गई है| इन दोनों मौसमों में शुष्कता के सामान्य, भीषण ओर अत्याधिक भीषण की बारम्बारता की घटना एक समान थी| ये परिवर्तन क्षेत्रीय मॉडल वैधता के लिए अच्छा आधार प्रदान करने के साथ ही साथ होआ (HoA) में सूखे के प्रमुख क्षेत्रों ओर प्रोजेक्शन अध्ययन मानचित्रण का कार्य करता है।

ABSTRACT. Basic rainfall characteristics and drought over the Horn of Africa (HoA) is investigated, from 1901 to 2010. Standard Precipitation Index (SPI) is used to study drought variability, mainly focusing on 3-month SPI. The dominant mode of variability of seasonal rainfall was analyzed by performing Empirical orthogonal functions (EOF) analysis. Gridded data is sourced from Climate Research Unit (CRU), spanning from 1901 to 2010. The HoA experiences predominantly bimodal rainfall distribution in time; March to May (MAM) and October to December (OND). The spatial component of the first eigenvector (EOF1) shows that the MAM and OND seasonal rainfalls are dominated by negative and positive loadings, respectively. The EOF1 explain 34.5% and 58.9% variance of MAM and OND seasonal rainfall, respectively. The EOF2, 3 and 4 are predominantly positive, explaining less than 25% in total of the seasonal rainfall variance in the two seasons. The last two decades experienced the highest negative anomaly, with OND seasonal rainfall showing higher anomalies as compared to MAM season. The OND season recorded 9% more drought events as compared to MAM season. The frequency of occurrence of moderate, severe and extreme dryness was almost the same in the two seasons. These results give a good basis for regional model validation, as well as mapping out drought hotspots and projections studies in the HoA.

Key words – Rainfall, Drought, EOF, SPI, Horn of Africa.

1. Introduction

Rainfall occurrence and distribution remains among important weather aspects that affect many people in the Horn of Africa (HoA) and Africa at large. This is so, since most economies in the region are reliant on rain-fed agriculture, energy production and other related sectors (Ngetich *et al*., 2014; Ongoma, 2013; Funk *et al*., 2008; Lyon, 2014). Thus, understanding the occurrence of extreme rainfall events in the HoA is of great importance to the region.

Drought has negative impacts on most of the countries, with developing countries such as those in the HoA being affected the most. According to reports by IPCC (2012), changes in climate over recent decades continue to cause impacts on natural and human systems globally. The impacts of the recent climate-related extremes such as floods and droughts show significant vulnerability and exposure of some ecosystems ranging from coastlines, marine environments, arid and semi-arid regions and many human systems. For instance, following the recent 2010/11 drought that affected Kenya, Somalia, and parts of Ethiopia, approximately ten million people were affected, leading to over 250 000 deaths in Somalia alone (Checchi and Robinson, 2013).

Recent studies (Boyd *et al*., 2013; Shongwe *et al*., 2011; IPCC, 2007) have shown that extreme rainfall events, especially droughts continue to increase both in frequency and intensity over the Great Horn of Africa (GHA) making the populations in the region vulnerable to effects of climate variability and change. Recent droughts are documented over the years 1999-2001, 2005-2006 and 2010-2011 that affected many parts of the East Africa (Mwangi *et al*., 2014). The results showed that El-Niño Southern Oscillation (ENSO) plays a significant role in determining the monthly and seasonal rainfall patterns over East African (Ongoma *et al*., 2015). This happens in the background of reducing rainfall in the region (Christensen *et al*., 2007; Lyon and DeWitt, 2012; Yang *et al*., 2014; Liebmann *et al*., 2014; Maidment *et al*., 2015; Funk *et al*., 2015; Tierney *et al*., 2015; Nicholson, 2016; Wakachala *et al*., 2015). Maidment *et al*. (2015) reported a decrease in the March-May (MAM, 'long rains') seasonal rainfall over East African by 14 to 65 mm/yr per decade. Tierney *et al*. (2015) investigated the cause of the reducing trend of the 'long rains' and noted that the reduction had anthropogenic influence with the rainfall pattern was synchronous with the global and regional warming. However, the rainfall situation is likely to reverse by the end of the current century, going by the recent climate projections (Shongwe *et al*., 2011; Yang *et al*., 2014; Tierney *et al*., 2015). All the studies agree that the increase in rainfall will be more in October-December (OND, 'short rains') season as compared to 'long rains'.

The understanding of occurrence of droughts and its diagnosis alone is not enough. Knowledge on the frequency and intensity of droughts is equally essential in projection studies that help in planning purposes, especially in water resources management and utilization. This can best be realized by utilizing long-term, accurate and reliable datasets. Muller (2014) studied adaptation to climate change and management of drought in HoA and recommended facilitation of timely access to weather forecast products, early response funding mechanisms and technical support especially for farmers to minimize the related socioeconomic losses.

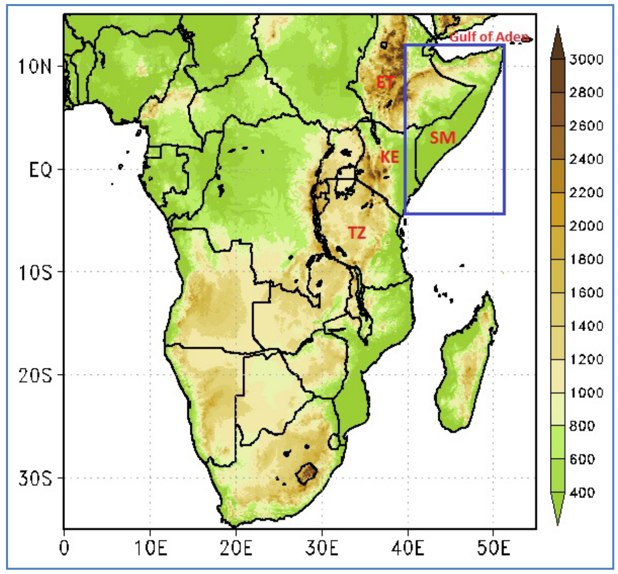


Fig. 1. A map showing topography of a section of Africa

This study investigates the variability of drought over HoA using gridded data from Climate Research Unit (CRU). The output of this study presents the first long-term trend analysis of droughts in the HoA. The results will form a resourceful reference material in climate vulnerability studies and drought projections in the HoA.

The remaining parts of this work are arranged as: Section 2 - Data and methodology, Section 3 - Results and discussion and Section 4 - Conclusion and recommendations of the study, followed by the Acknowledgement and References.

2. Data and Methodology

2.1. *Area of Study*

This study considers HoA as countries mainly comprising of Somalia, Djibouti and eastern Ethiopia, bounded within longitude 40.75° E and 51.75° E and latitude 2° S to 12.25° N (Fig. 1).

The study area is enclosed by a rectangle [Indigo colour]. ET, KE, SM and TZ represent Ethiopia, Kenya, Somalia and Tanzania, respectively

The HoA is characterized by unique rainfall regime, with its annual rainfall being lower than the entire equatorial Africa (Hoerling *et al*., 2006). The region is

TABLE 1

Classification of SPI Values (McKee *et al.*, 1993)

SPI class	Drought category
≥2.0	Extremely Wet
1.5 to 1.99	Very Wet
1.0 to 1.49	Moderately Wet
-.99 to .99	Near Normal
-1.0 to -1.49	Moderately Dry
-1.5 to -1.99	Severely Dry
≤ -2	Extremely Dry

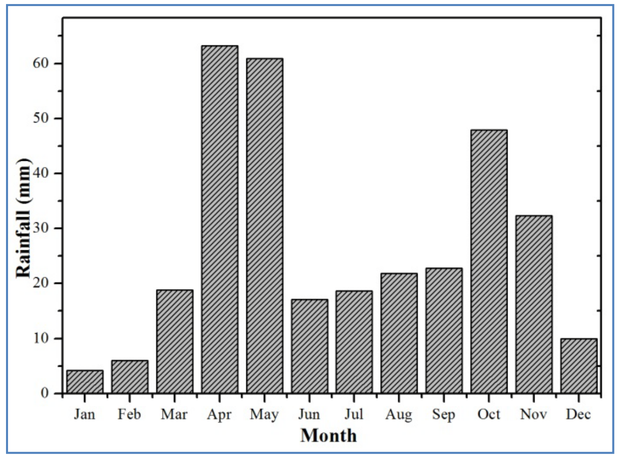


Fig. 2. Annual rainfall cycle over the Horn of Africa based on 1901-2010 monthly dataset

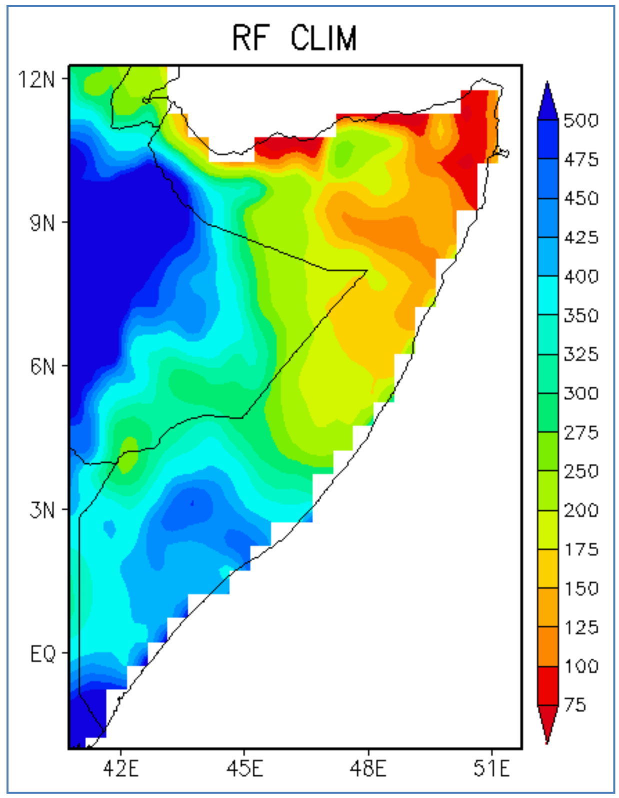


Fig. 3. Annual rainfall climatology over Horn of Africa. The RF CLIM is an acronym for rainfall climatology

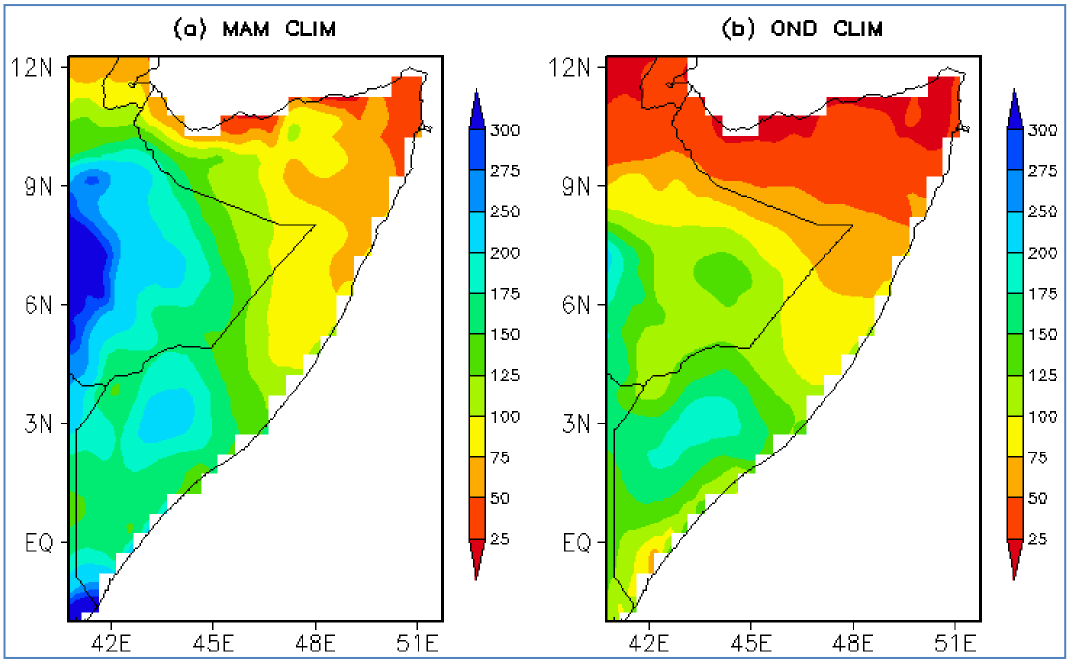
mainly arid and semi - arid (ASAL); experiencing northeasterly monsoons in December to February and south-west monsoon during May to October in response to the overhead sun. The daily and seasonal weather of the region is mainly influenced by the Inter-Tropical Convergence Zone (ITCZ). The ITCZ passes the Equator twice in a year; the passages of the ITCZ coincide with the two distinct rainy seasons experienced in the area (Liebmann *et al*., 2012). In Somalia, the two rain seasons are locally referred to as *Gu* and *Deyr*. During the rainy period, the atmospheric pressure is high in the subtropical latitudes of the Sahara and southern Africa, and there is often a movement of air masses from the high-pressure belts towards the trough of low pressure in the equatorial region. The rainfall in the area exhibits high spatiotemporal variability, linked to varying orography ranging from mountains, plateaus and valleys. Studies show that the large maritime bodies such as Lake Victoria and the Indian Ocean, and the vast moist Congo forest moderate rainfall performance in the HoA (Nyakwada, 2009; Indeje *et al*., 2001; Oettli and Camberlin, 2005). The El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) mainly influences the inter-annual variability of rainfall in the region (Ogallo *et al*., 1988; Indeje *et al*., 2000; Behera *et al*., 2005; Liebmann *et al*., 2014). The impact of the two is higher on 'short rains' as compared to 'long rains'.

2.2. *Data*

The monthly gridded data covering the region was sourced from Climate Research Unit (CRU), spanning from 1901 to 2010. The data is gauge-based, gridded at 0.5° by 0.5° resolution. The data is discussed in detail by Harris *et al*. (2014). The dataset was preferred over other datasets since it was found to reproduce rainfall better than other datasets in the region (Ongoma and Chen, 2017). The data has been applied successfully in previous studies in the region (Maidment *et al*., 2015; Omondi *et al*., 2014; Shongwe et al., 2011; Schreck and Semazzi, 2004; Anyah and Semazzi, 2006).

2.3. *Methodology*

Rainfall variability was investigated using trend analysis as well as Empirical Orthogonal Function (EOF).



Figs. 4(a&b). Seasonal rainfall climatology over Horn of Africa

The trend analysis considered decadal changes in seasonal rainfall. The EOF technique is used to identify and verify dominant modes of the inter-annual rainfall variability. Variability considered in this study is based on seasonal mean data for the seasonal rainfall. In the calculation, EOF analysis involves computation of the Eigen modes for a correlation matrix based on the normalized rainfall data for each season for all grid points over the HoA stacked into a single vector. A detailed discussion on EOF technique is given by Lorenz (1956). This methodology has been successfully applied in related studies over the larger eastern Africa (Ogwang *et al*., 2016).

Standard Precipitation Index (SPI) is used to measure the severity of extreme rainfall events, with emphasis on drought. The SPI, developed by McKee *et al*. (1993), has widely been used in the monitoring of drought on multiple timescales; 1-, 3-, 6-, 12- and 24- month. This approach has been used widely globally such as in China (Zhai and Feng, 2009), in India (Pal and Al-Tabbaa 2011; Joseph, 2014), in Ethiopia (Belayneh *et al*., 2014), in Chad and Somalia (Okonkwo, 2011), and in Kenya (Opiyo *et al*., 2015; Onyango, 2014), among others. In the assessment of the performance of drought indices over East Africa, Ntale and Gan (2003) reported that SPI is more suitable as compared to Palmer Drought Severity Index (PDSI) and Bhalme - Mooley index (BMI). The index is preferred over other indices because it is only based on rainfall and it is easy to compute. It calculates the rainfall of a given year, respect to historical records and then uses probabilities to tell whether the rainfall of that year is more or less than the median rainfall of the historical dataset. The index is discussed in detail by WMO (2012) and McKee *et al*. (1993). The SPI values were calculated using the version 6 of the program developed by National Drought Mitigation Center (NDMC), in the United States of America. The program; SPI_SL_6.exe, is freely available on their website at http://drought.unl.edu/MonitoringTools/DownloadableSPIProgram.aspx.

The classification system presented in Table 1 was applied by McKee *et al*. (1993) to categorize drought according to SPI intensities. A drought is thus said to occur at a given time when the SPI is persistently negative, getting to $\leq$ -1.0.

This study adopted 3-month SPI because it reflects short- and medium- term moisture state and gives a seasonal estimation of rainfall (WMO, 2012).

3. Results and Discussion

3.1. *Rainfall Characteristics*

3.1.1. *Rainfall Climatology*

The annual rainfall cycle is important in weather studies; the rainfall seasonality affects the timing of many agricultural activities including farm preparations, planting, weeding, harvesting, and drying the produce sequentially. In animal husbandry, it dictates silage

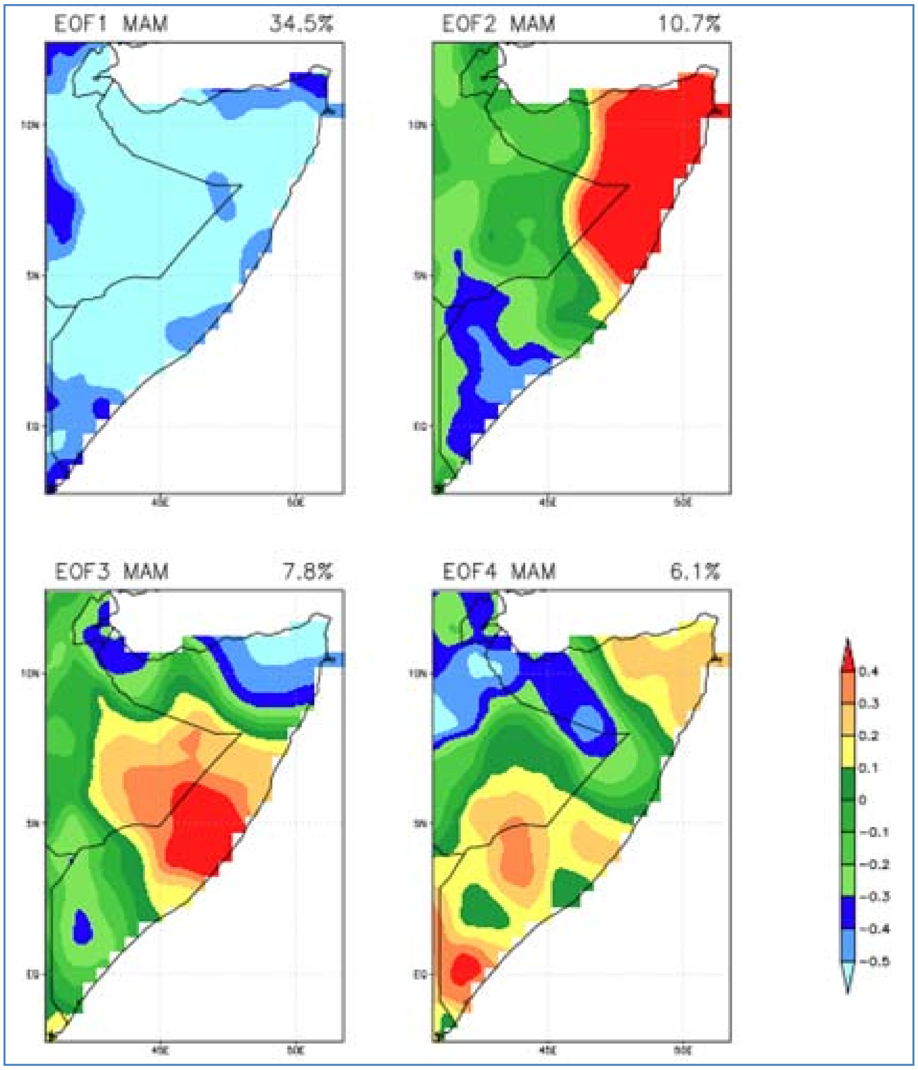


Fig. 5. The first four spatial EOF modes explaining variance in MAM seasonal rainfall, 1951- 2010

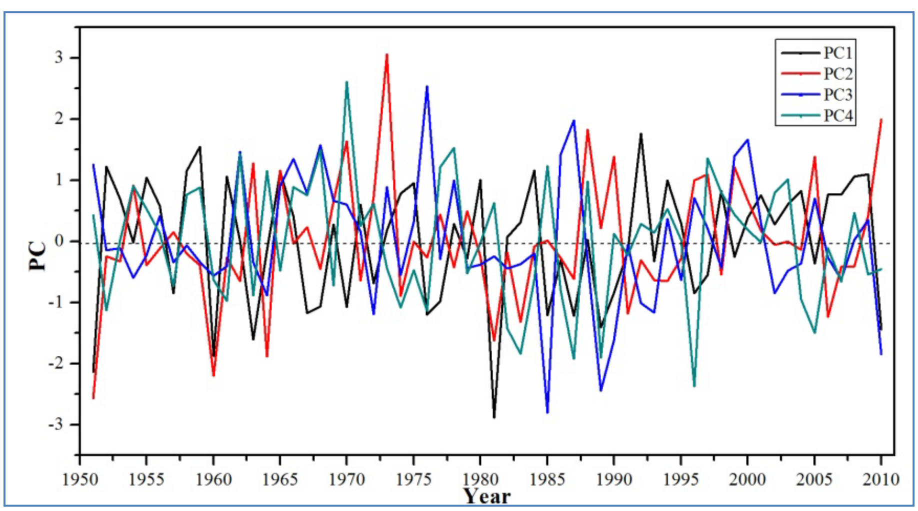


Fig. 6. Principal component (PC1-4) corresponding to EOF1- 4 for MAM seasonal rainfall presented in Fig. 5

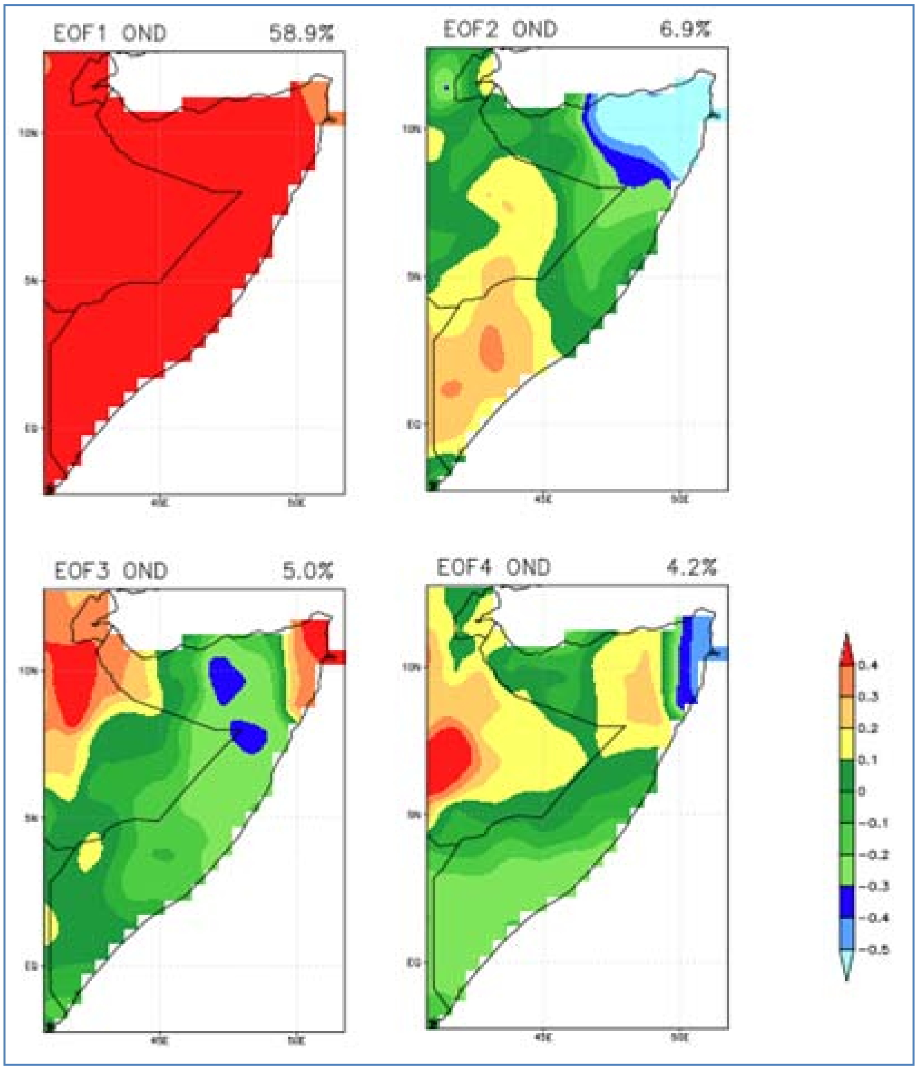


Fig. 7. The first four spatial EOF modes explaining variance in OND seasonal rainfall, 1951-2010

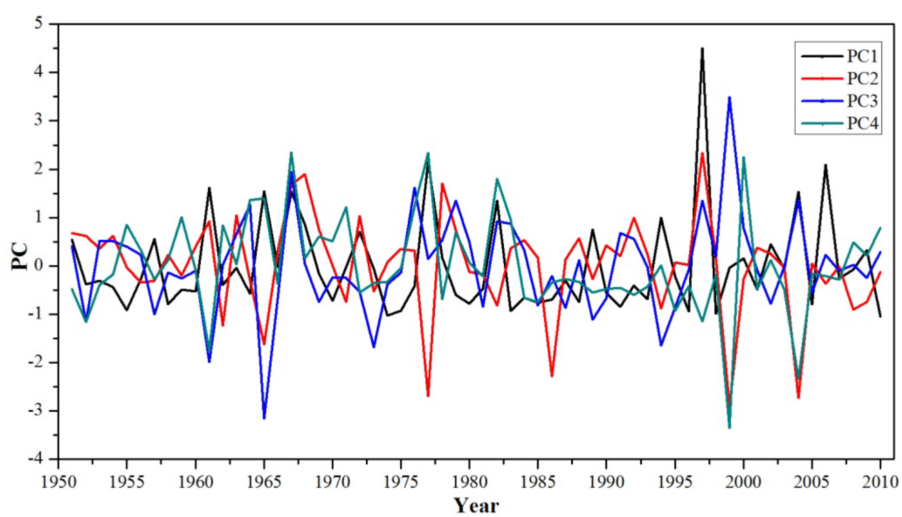
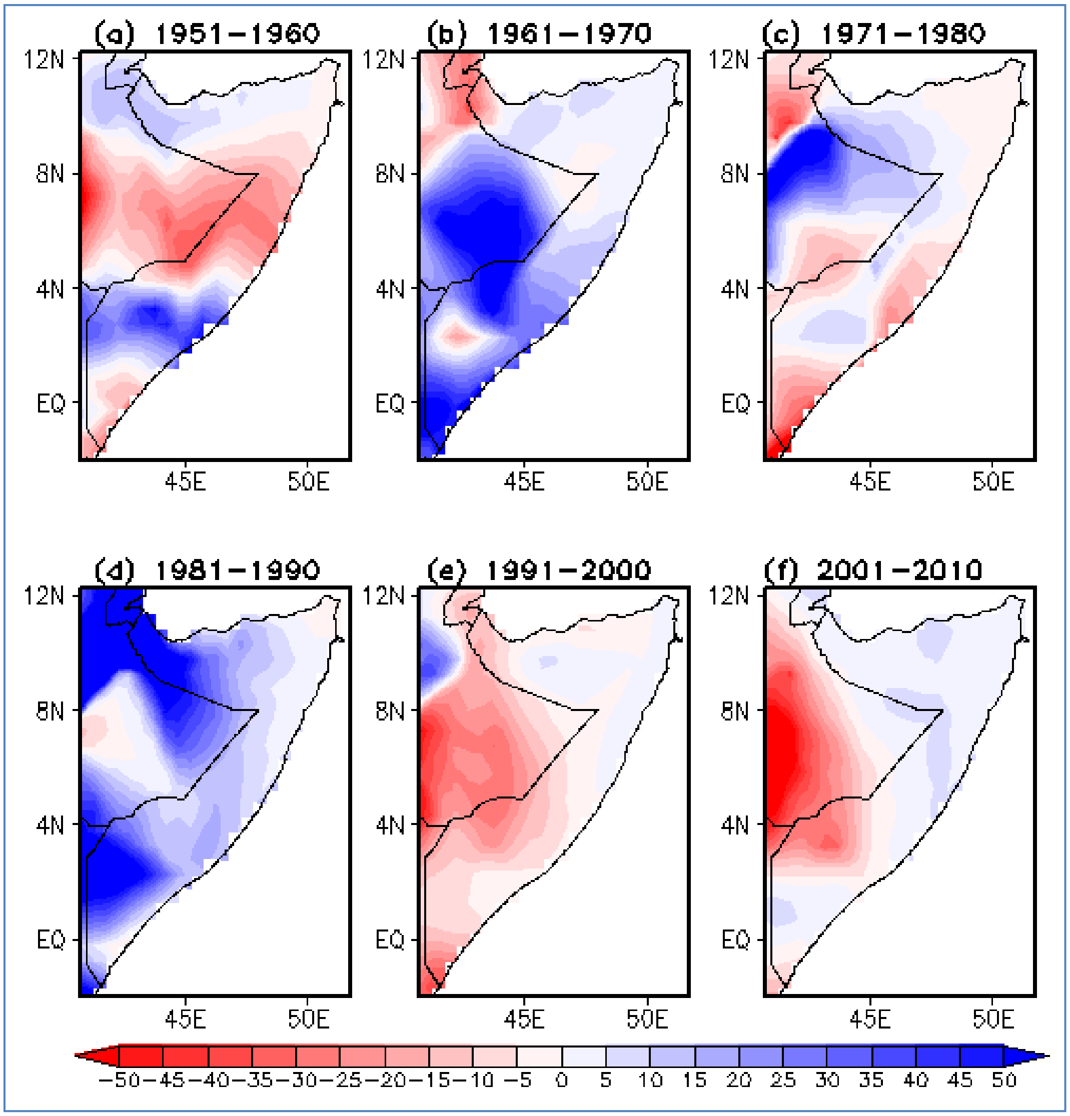


Fig. 8. Principal component (PC1-4) corresponding to EOF1- 4 for OND seasonal rainfall presented in Fig. 7

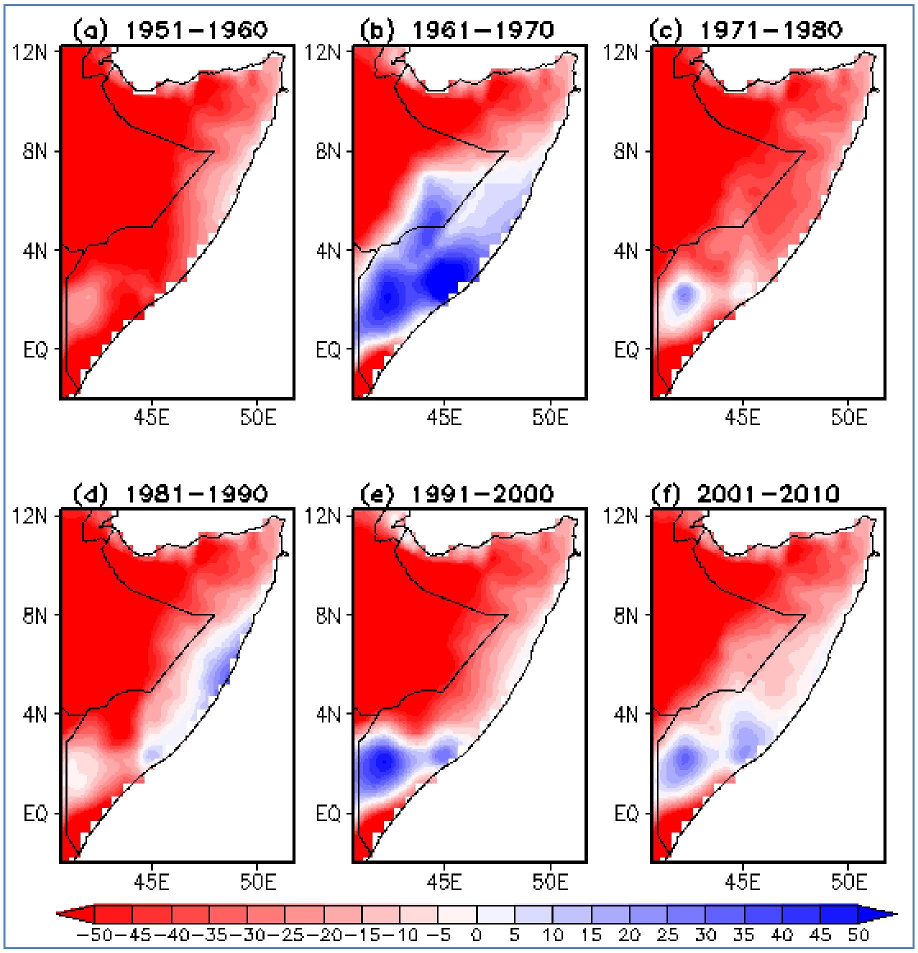


Figs. 9(a-f). Decadal March - May rainfall anomaly relative to 1901-2010 rainfall over Horn of Africa

preparation, watering points, and nomadic movements. The expected annual bimodal rainfall cycle is depicted in the rainfall over HoA (Fig. 2). The MAM and OND seasons contribute approximately 44% and 28% of the annual rainfall experienced in the HoA. The MAM rainfall and OND rainfall have peaks in April and October, respectively. Although, recent observations indicate the April peak is slowly shifting towards the month of May (Wakachala *et al.*, 2015). The least rainfall, coinciding with the driest period, is recorded in the months of December - January - February. This period coincides with north-easterly monsoons, traversing in the great deserts, which are normally dry and hot, leading to the observed low rainfall.

The annual rainfall climatology over HoA is displayed in Fig. 3. The rainfall decreases from the west to the north-eastern part of the study area, ranging from about 550 to 50 mm, respectively.

The annual rainfall is further split into seasonal climatology in Figs. 4(a&b). Generally, in both seasons, the rainfall over the study area increases from northeast to the west, ranging from slightly $\leq$ 50 mm to $\geq$ 300 mm, in the respective areas. More rainfall is recorded during the MAM season as compared to OND season. During OND season, almost half of the region records less than 100 mm of rain, with the south-western parts of the region recording the highest rainfall at about 200 mm. The OND season is, however,



Figs. 10(a-f). Decadal October - December rainfall anomaly relative to 1901 – 2010 rainfall over Horn of Africa

crucial as it serves as a major season over some parts and reduces the dry period in between the MAM episodes. Somali come off a dry country with average annual rainfall of 324 mm.

3.1.2. *Rainfall variability*

The spatial components of the first to fourth eigenvectors (EOF1 - 4) of MAM and OND rainfall seasons are presented in Figs. 5 and 7, respectively. Their corresponding principal components (PC1 - 4) are shown in Figs. 6 and 8, respectively. In the MAM season, the EOF1 explains 34.5% of the total variance, exhibiting negative loadings over the entire region. The EOF 2, 3 and 4 explain 10.7%, 7.8% and 6.1% of the total variance, respectively. Positive loadings dominated the last three EOFs. Analysis of the corresponding principal components (PC1 - 4) to EOF1 - 4, with emphasis on PC1, shows that the severest drought was witnessed around 1981/1982.

In the OND season, a positive loading dominates over the entire region, explaining 58.9% of the total rainfall variance. The dominance of the positive loadings characterizes the second, third and fourth EOFs. The three EOFs; EOF1, 2 and 3, explain approximately 15% of the OND rainfall variance. These results closely agree with the observation by Ogwang *et al*. (2016) in September - November (SON) over Uganda. PC1 shows that the severest drought in OND season was recorded around 2007/2008. The observation corroborates the report by Nicholson (2016) that drought prevailed during much of the period; 2008-2011, resulting in extreme food scarcity and deaths.

Figs. 9 and 10 show the decadal rainfall anomaly for MAM and OND seasons, respectively. In MAM season, during the last six decades, it is evident that the last two decades have experienced the highest reduction in rainfall, about the long term mean. The decrease in rainfall in the last 20 years is significant [Figs. 9(a-f)]. In the earlier

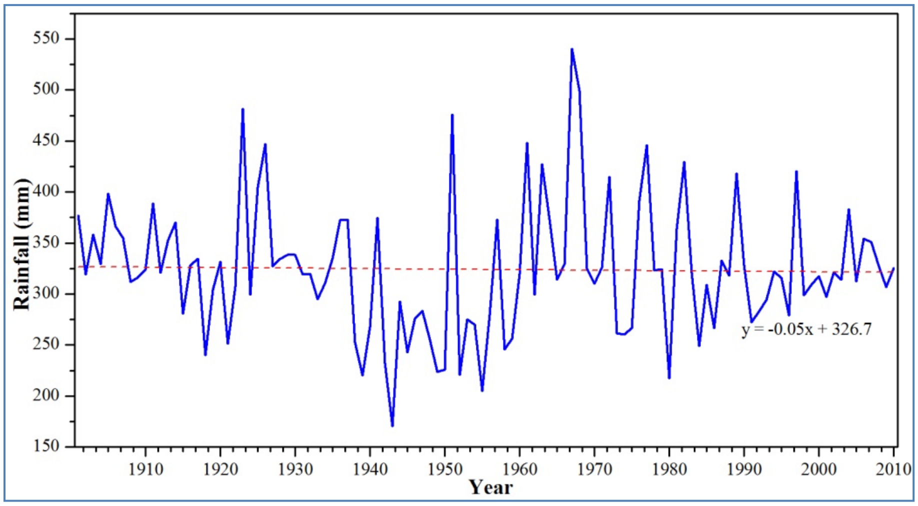


Fig. 11. Inter-annual variability of annual rainfall over Horn of Africa

TABLE 2

Decadal mean rainfall and anomaly from the long term mean

Decade	Mean Rainfall (mm)	Anomaly from LTM (mm)
1901-1910	345.6	21.6
1911-1920	325.2	1.2
1921-1930	352.9	28.9
1931-1940	306.6	-17.4
1941-1950	257.6	-66.4
1951-1960	292.2	-31.8
1961-1970	386.5	62.5
1971-1980	323.1	-0.9
1981-1990	333.7	9.7
1991-2000	311.2	-12.8
2001-2010	329.4	5.4

decades of the 1950s to 1970s showed a significant increase in the rainfall with time. It is worth noting that the areas that experience the highest rainfall climatologically are the same sector that are witnessing a higher reduction in rainfall as compared to other regions. On the other hand, the period between 1981 and 1990 recorded the highest positive anomaly in the last half of the 20th century.

In comparison to MAM seasonal rainfall, the OND season recorded the higher reduction in rainfall between 1951 and 2010 [Figs. 9(a-f) and 10(a-f)]. The decrease in rainfall during both seasons leads to the overall decline in rainfall as observed in recent studies by Liebmann *et al*. (2014) and Yang *et al*. (2014).

The long-term annual rainfall mean (LTM) over HoA is 324 mm. Statistics show that 1961-1970 was the wettest decade while 1941-1950 was the driest (Table 2). In the last half of the 20th century, 1991- 2000 recorded the least amount of rainfall. The observation is in agreement with the report made by Nicholson (2016) over the entire eastern Africa.

Fig. 11 gives the interannual variability of annual rainfall over HoA. The rainfall shows a negative linear trend with a negative gradient of -0.05. High temporal variability characterizes the rainfall with a cycle of about 5 to 8 years. The results corroborate the recent findings by Nicholson (2016) over the entire eastern Africa.

TABLE 3

Probability of recurrence of seasonal; March-May, drought over Horn of Africa

SPI	Category	Number of times in 110 years	Severity of event
0 to -0.99	Mild dryness	37	1 in 3 years
-1.00 to -1.49	Moderate dryness	10	1 in 11 years
-1.5 to -1.99	Severe dryness	4	1 in 28 years
< -2.0	Extreme dryness	3	1 in 37 years

TABLE 4

Probability of recurrence of seasonal; October-December, drought over Horn of Africa

SPI	Category	Number of times in 110 years	Severity of event
0 to -0.99	Mild dryness	45	1 in 2 years
-1.00 to -1.49	Moderate dryness	9	1 in 12 years
-1.5 to -1.99	Severe dryness	4	1 in 28 years
< -2.0	Extreme dryness	1	1 in 110 years

Nicholson (2016) looked into the recent rainfall conditions over eastern Africa considering 1998-2014 period, and observed anomalously low rainfall since 2008.

3.2. *Drought characteristics*

Understanding the pattern of the past droughts is essential in the projection of similar events in future. The frequency of drought events gives the possible severity of drought events. The OND season experiences more drought incidents as compared to drought incidences in MAM season (Tables 3 and 4). The drought cases in OND and MAM seasons stand at 59 and 54, respectively, in the past 110 years. The cases in OND outnumber MAM seasons events by approximately 9%. Rainfall failure in OND season leads to long term drought since the season if followed by a relatively dry season; January and February, as compared to June-September in the case for MAM season.

Drought frequencies are observed to decrease with increase in extremity is dryness in all seasons. The cases of moderate, severe and extreme dryness were almost the same in both seasons. Interestingly, one instance of severe dryness was reported during OND season as compared to 3 incidences in MAM season.

4. Conclusion and recommendation

Horn of Africa rainfall characteristics and drought variability during 1901-2010, has been investigated using reanalyzed data from Climate Research Unit (CRU). The region receives low seasonal rainfall generally as compared to other equatorial regions. The highest rainfall recorded during MAM and OND seasons reaches 300 and 200 mm, respectively. The northeastern and southwestern areas record the lowest and highest rainfall respectively. The dominant modes of variability of seasonal rainfall were identified by performing empirical orthogonal function (EOF) analysis. The spatial component of the first eigenvector (EOF1) shows that the negative and positive loadings dominate MAM and OND seasonal rainfall respectively. The EOF1 explain 34.5% and 58.9% variance of MAM and OND seasonal rainfall, respectively.

The OND has experienced the highest negative anomaly as compared to MAM seasonal rainfall. The western and southwestern parts of the region, which climatologically receive high rainfall, show the highest negative anomaly. The rainfall pattern in last two decades affirms the observation made in previous studies that rainfall is currently reducing over the entire GHA. OND season record more drought instances/cases as compared to MAM season.

The information herein presents a good basis for carrying out projection studies of drought and related events. Owing to the high variability of rainfall in the region, there is need to carry out sub-regional variability of rainfall and drought using observed rainfall data, where available, to achieve the best results.

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