EVALUATING THE ROLE OF INDIAN OCEAN DIPOLE ON SEASONAL RAINFALL PERFORMANCE OVER ETHIOPIA

By

Kedir Kemal

A THESIS SUBMITTED TO APPLIED PHYSICS PROGRAM SCHOOL OF APPLIED NATURAL SCIENCE

PRESENTED IN PARTIAL FULFILLEMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN PHYSICS (METEOROLOGY)

OFFICE OF GRADUATE STUDIES ADAMA SCIENCE AND TECHNOLOGY UNIVERSITY

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Acronomy

ASL…………………………………Above Sea Level

CHIRPS…………………………..…Climate Hazards Group InfraRed Precipitation with Station

CPT…………………………………Climate Predictability Tool

DMI………………………………… Dipole Mode Index

ENSO………………………………..El-Niño/SouthernOscillation

FEWSNET…………………………..Famine Early Warning Systems Network

ITCZ…………………….………… Inter-tropical Convergence Zone

IO……………………………………..Indian Ocean

IOD……………………………..……Indian Ocean Dipole

NMA…………………………………National Meteorological Agency

NMSA ……………………………….National Meteorological Service Agency

SO……………………………………Southern Oscillation

SPSS…………………………………Statistical Package for Social Sciences

SST…………………………………..Sea Surface Temperatures

SSTA ………………………………..Sea Surface Temperature Anomaly

TAMSAT ………………………..…Tropical Applications of Meteorology using SATellite

TIO…………………………………..Tropical Indian Ocean

TPO…………………………………Tropical Pacific Ocean

USGS………………………………...United States Geological Survey

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Abstract

Inter-seasonal rainfall variability over the Ethiopia was investigated with respect to Indian Ocean Dipole (IOD) and Indo-Pacific (IOD-ENSO). For better understanding of the nature of IOD and El Niño/Southern Oscillation (ENSO) influences on short rains, it is important to check the amplitude variation particularly during the years when flood or drought happened. The impact of IOD and ENSO were well investigated with the help of statistical analysis method. Statistical correlation between the IOD index and the global sea level pressure anomalies demonstrates that loadings of opposite polarity occupy the western and the eastern parts of the Indian Ocean. Besides the simple correlation method and a partial correlation technique were also used to show exclusive relationship between two variables while excluding influence arising from another independent variable. In order to make in-depth analysis, we considered parts of the country where Belg and Kiremt are the main rainy seasons. During *Bega* season*, the country also receives less mount of rainfall but often very unseasonal that disturb harvesting season. We found that during bega season, rainfall performance over the country is clearly influenced by Indian Ocean Dipole (IOD) and/or ENSO. In contrast, during March-May, there is no clear inter-relation exist between seasonal rainfall and SST pattern in the Indian Ocean. As the result, the short rainy season over the country is not linearly related with selected extreme event of IOD years. The association between El Niño and positive IOD phases is much stronger than the association between La Niña and negative IOD during September to November. Further analysis is therefore required to pinpoint how the formation of strong SST anomalies over Indian and Pacific Oceans to explain seasonal rainfall variability, which in turn improves localized climate prediction over the country.*

1. Introduction

1.1 Background of the Study

Rainfall variability in Ethiopia has significant effects on rain-fed agriculture and hydro power generation. Thus, understanding its association with slowly varying global Sea Surface Temperatures (SSTs) is potentially important for prediction purposes (Mekonnen et al. 2016). ENSO is known to affect oceanic and atmospheric circulation patterns of the Indian Ocean through three different teleconnection processes. One is an atmospheric teleconnection that modulates the thermodynamic fluxes at the sea surface (Klein et al. 1999; Yulaeva and Wallace 1994; Alexander et al. 2002), forcing basin wide SST anomalies following an ENSO event. The second process involves off-equatorial Rossby waves excited by ENSO-induced wind stress (Xie et al. 2002). The slow westward propagation of these Rossby waves prolongs the ENSO influence on Indian Ocean SSTs seasons after ENSO's demise. The third process involves the propagation of sea level anomalies from the western Pacific into the southeastern Indian Ocean (Clarke and Liu 1994; Wijffels and Meyers 2004), affecting SSTs there and consequently rainfall over northwestern Australia (Meyers 1996; England et al. 2006).

In recent years, the Indian Ocean has been discovered to have a much larger impact on climate variability than previously thought (Friedrich et al. 2009). For instance, Saji et al. (1999) found that the coupled ocean-atmosphere phenomenon evolves with an east-west dipole in the SST anomaly, and named it the Indian Ocean Dipole (IOD). The changes in the SST during the IOD events are found to be associated with the changes in the surface wind of the central equatorial Indian Ocean. In fact, winds reverse direction from westerlies to easterlies during the peak phase of the positive IOD events when SST is cool in the east and warm in the west.

These changes in surface winds and oceanic conditions are coupled with the changes in the atmospheric convection through either convergence or divergence of the moist air. The convection in the eastern Indian Ocean is suppressed during the positive IOD events, where as the convection in the central and western Indian Ocean is enhanced.

Using a simple Matsuno-Gill type model, Saji and Yamagata (2001) have also shown that the atmospheric linear response to such changes in the heat source of the eastern Indian Ocean strengthens the easterly wind anomalies, which in turn are responsible for the evolution of the SST dipole. The conditions are just opposite during a negative IOD event (e.g., Ansell et al. 2000).

Dynamically consistent evolution of correlations is found in anomalies of the surface winds, currents, sea surface height and sea surface temperature. Anomalous changes of the Walker circulation provide a necessary driving mechanism for anomalous moisture transport and convection over the coastal East Africa. The seasonal rainfall in the equatorial eastern Africa and most part of eastern and southern half of Ethiopia is characterized by double peaks. This semiannual signal is basically related to the seasonal meridional migration of the Inter-tropical Convergence Zone (ITCZ) across the equator. Amount of rainfall is larger during the season of long rains from April through May, as compared to that of the short rains from October through November (e.g. Hastenrath et al. 1993).

The surface winds are easterlies south of the equator in the eastern and central Indian Ocean but veer northwestward towards the East Africa during both transition seasons. The regional veer coincides with development and retreat of the boreal summer monsoon and leads to moisture convergence over the East Africa, enhancing the atmospheric convection and rainfall there. Although the averaged rainfall amount is larger during the long rains than during the short rains, the latter show more interannual variability (Hastenrath et al. 1993; Black et al. 2003; Clark et al. 2003) and have larger impact on the society through changes of the regional hydrological cycle.

Until quite recently, it was generally accepted that the influence of the Indian Ocean (IO) on climate variability, beyond its probable impact on the monsoons, was not appreciable. This view has changed profoundly recently, particularly since 1997, with new evidence indicating an important climatic role of IO sea surface temperature (SST) both within the region and in other sectors of the globe (Friedrich et al. 2009).

By many measures, 1997 was an extraordinary year for the IO and countries on its rim. Record rainfall was observed in East Africa during October and November. Severe flooding in Somalia, Ethiopia, Kenya, Sudan, and Uganda caused several thousand deaths and displaced hundreds of thousands of people (Friedrich et al. 2009).

On the other side of the IO, Indonesia suffered severe droughts at the same time, and wild fires broke out of control on several of its islands. The smoke and haze they generated caused severe health problems in Indonesia and surrounding countries (Friedrich et al. 2009). Not all of these climatic anomalies were due to the El Niño of the century; unusual conditions in the tropical IO made them worse.

1.2 Statement of the Problem

The analysis of observed data and model results reveals that the influence of IOD on short rains is overwhelming as compared to that of ENSO; the correlation between ENSO and short rains is insignificant when IOD influence is excluded (Swadhin et al. 2005). In consistent with the observational findings, the model results show a steady evolution of IOD prior to extreme events of short rains (Pascale D. 2005). The model results nicely augment the observational findings and provide us with a physical basis to consider IOD as a predictor for variations of the short rains (Gualdi et al. 2003). This is demonstrated in detail using the statistical analysis method.

IOD events are often triggered by ENSO but can also occur independently, subject to eastern tropical preconditioning. Over the past decades, Indian Ocean (IO) sea surface temperatures and heat content have been increasing, and model studies suggest significant roles of decadal trends in both the Walker circulation and the Southern Annular Mode. Prediction of IO climate variability is still at the experimental stage, with varied success (Friedrich et al. 2009).

Recent model studies suggest that Indian Ocean SST modulates atmospheric convection and circulation, exerting a significant influence on the ENSO (Yu et al. 2004; Wu and Kirtman 2004; Annamalai et al. 2005). In a series of articles, Saji and Yamagata (2002), using a partial correlation analysis, have demonstrated that the enhancement of the East African rain is dominated by the positive IOD rather than El Niño.

The statistical analyses reported prior to the introduction of the IOD mode did not recognize this degeneracy of two climate modes. Therefore, those analyses inherit part of the IOD influence on short rains as an apparent positive relation between ENSO and short rains. Even the co-occurrence of IOD and ENSO (e.g. as in 1997) does not necessarily suggest that ENSO influences short rains through IOD (Gualdi et al. 2003). This is because the IOD can evolve independently of the ENSO as in 1961, 1967 and 1994 (Saji et al. 1999; Webster et al. 1999; Anderson et al. 1999; Yamagata et al. 2002, 2003, 2004; Behera et al. 2003a; Saji and Yamagata 2003a). So the impacts of IOD on short rain over the study area have been analyzed.

1.3 Objectives of the study

This work has its own general and specific objectives.

1.3.1 General objective

The general objective of this study is to determine the role of Indian Ocean Dipole on seasonal rainfall performance over Ethiopia.

1.3.2 Specific Objective

1. To assess the challenges of reasoning the main triggering factors behind year to year short rainy season fluctuation over Ethiopia for the period of 1981 to 2016.
2. To analyze the role of Indian Ocean Dipole on seasonal rainfall performance over Ethiopia.
3. To quantify the severity of climatic extremes based on the level of Indian Ocean Dipole impacts on seasonal rainfall performance over Ethiopia.

The thesis is organized as follow: In chapter 1, Background of short rain variability that is influenced by Indian Ocean Dipole, Statement of the problem, the general and specific objective of the study is presented.

In chapter 2, Literature review related to short rain variability, the Indian Ocean Dipole, El Nino Southern Oscillation is discussed. Furthermore, the impacts of Indian Ocean Dipole and Enso condition on short rains are presented.

In chapter 3, the data and methodology of the study is presented. This chapter contains four sections. The frist section discussed about the location and background of the study area. The second section includes type and source of the data. The third section discussed about Method of data analysis. The fourth section includes the location of the twelve homogeneous rainfalls Region.

In chapter four the result and discussion of the thesis is presented. The Evolution of Indian Ocean Dipole with interaseasonal variability of short rains, dominant IOD impact on short rains variability and IOD connection with extreme events of short rains. Furthhermore, simple and partial correlation for Bega and Belg seasons also discussed.   Finally, the conclusion and summary of the thesis presented in chapter 5.

2. Literature Review

2.1 Theory of the short rains variability

Earlier studies have attempted to link the variability in the Tropical Pacific Ocean (TPO) to the rainfall variability of the region (Ropelewski and Halpert 1987; Ogallo 1988; Ogallo et al. 1988; Hastenrath et al. 1993; Mutai and Ward 2000). In a previous study, Deser and Wallace (1987) showed that the major negative swings of the Southern Oscillation that occurred in 1963 and 1977 were not accompanied by strong El Niño events. Hence, they concluded that the El Niño and Southern Oscillation are more loosely coupled than numerous past studies would suggest.

Based on the analyses of available observed data, they suggested that during high SO phase the pressure is high (low) in the western (eastern) during October-November. Concomitantly they also found that strong westerlies sweep the equatorial zone of the basin and the surface waters in western Indian Ocean are cold that suppress the atmospheric convection. It has been generally believed that the short rains increase (decrease) during the warm (cold) ENSO events. In an earlier study Hastenrath et al. (1993) found that the causality of short rains anomalies are strongly related to the Southern Oscillation (SO), i.e. the atmospheric component of ENSO.

The dipole like sea surface temperature anomaly (SSTA) characterizing the IOD was mentioned in a few research articles on TIO variability (Reverdin et al. 1986; Flohn 1987; Nicholls 1989; Hastenrath et al. 1993; Meyers 1996) since the 1980s. However, these anomalous conditions in the TIO have gained wider notice since the recent occurrence of two strong events: that of 1994 (Meyers 1996; Behera et al. 1999; Reppin et al. 1999; Vinayachandran et al. 1999) and that of 1997 (Chambers et al. 1999; Webster et al. 1999; Yu and Rienecker 1999; Murtugudde et al. 2000). In case of 1994 there is large debate about whether it is in El Niño or not. Many IOD literatures follow Meyers et al. (2007) classification for IOD. In this classification in 1994 IOD was positive while ENSO was categorized as neutral event. Webster et al. (1999) argued that ocean-atmosphere coupling in 1997-1998 was not associated with big 1997-1998 El Niño, as drought in Indonesia and flood over East Africa was larger than what was anticipated for ENSO event.

2.2 The Indian Ocean Dipole

The Indian Ocean Dipole (IOD) is defined by the difference in sea surface temperature between two areas (or poles, hence a dipole) – a western pole in the Arabian Sea (western Indian Ocean) and an eastern pole in the eastern Indian Ocean south of Indonesia (Fig 1). The IOD affects the climate of Australia and other countries that surround the Indian Ocean Basin, and is a significant contributor to rainfall variability in this region. A positive IOD period is characterised by cooler than normal water in the tropical eastern Indian Ocean and warmer than normal water in the tropical western Indian Ocean. Conversely, a negative IOD period is characterised by warmer than normal water in the tropical eastern Indian Ocean and cooler than normal water in the tropical western Indian Ocean (Australian Government Bureau of Meteorology, 2012).

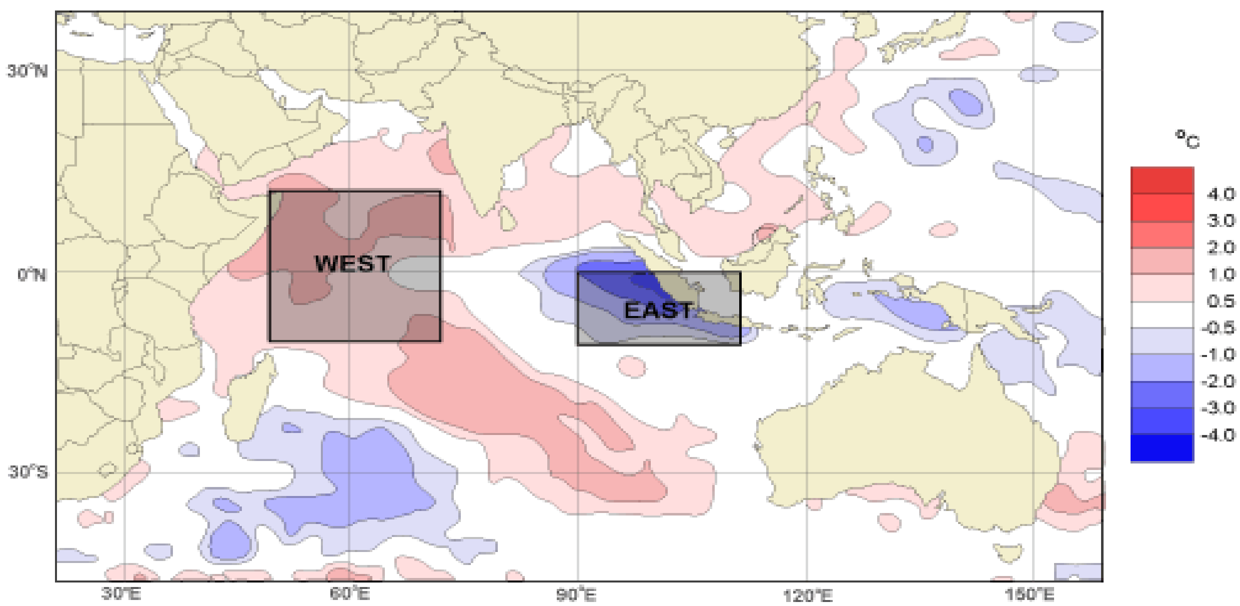

Fig 1) Map shows departures from average Indian Ocean surface temperatures .The east and west poles of the IOD are marked with black boxes.

Following Saji et al. (1999), the Dipole Mode Index (DMI) is defined as the SST anomaly difference between the western (50°E-70°E, 10°S-10°N) and eastern (90°E-110°E, 10°S-Eq) tropical Indian Ocean. When the DMI is positive then, the phenomenon is refereed as the positive IOD and when it is negative, it is refereed as negative IOD. Since, IOD is a coupled ocean-atmosphere phenomenon it can also be represented by any other atmospheric (pressure, OLR) or oceanographic (sea surface height) as well. The changes in the SST during the IOD events are found to be associated with the changes in the surface wind of the central equatorial Indian Ocean.

In fact, winds reverse direction from westerlies to easterlies during the peak phase of the positive IOD events when SST is cool in the east and warm in the west. Saji et al. (1999) showed that an east-west dipole mode in the sea surface temperature (SST) anomalies of the tropical Indian Ocean is coupled to the surface zonal winds. They also showed that the SST dipole is significantly correlated with the rainfall variability over the two poles. The rainfall over East Africa (Indonesia) is increased (decreased) during a positive (negative) IOD event. The East African region receives above (below) normal rainfall during positive (negative) IOD events.

2.3 El Niño – Southern Oscillation (ENSO)

El Niño–Southern Oscillation is an irregularly periodical variation in winds and sea surface temperatures over the Tropical eastern Pacific Ocean, affecting much of the tropics and subtropics. The Tropical Pacific Ocean and atmosphere swings, or oscillates, between warm, cool and neutral phases on a timescale of a few years. These changes in the Pacific Ocean and its overlying atmosphere occur in a cycle known as the El Niño–Southern Oscillation (ENSO). The atmosphere and ocean interact, reinforcing each other and creating a 'feedback loop' which amplifies small changes in the state of the ocean into an ENSO event. When it is clear that the ocean and atmosphere are fully coupled an ENSO event is considered established.

Even in a neutral state, temperatures in the Pacific Ocean vary from east to west. For example, the western Pacific 'warm pool' in the tropical Pacific has some of the warmest large-scale ocean temperatures in the world (Australian Government Bureau of Meteorology, 2012). During an ENSO event, ocean temperatures become warmer than usual or cooler than usual at different locations, which are reflected in ocean temperature gradients. The most important driver of ENSO is these temperature gradients across the Pacific, both at the surface and below the surface, particularly at the thermocline. El Niño and La Niña events are a natural part of the global climate system. They occur when the Pacific Ocean and the atmosphere above it change from their neutral ('normal') state for several seasons. El Niño events are associated with a warming of the central and eastern Tropical Pacific (Fig 2), while La Niña events are the reverse (Fig 3), with a sustained cooling of these same areas. During an El Niño event, trade winds weaken or may even reverse, allowing the area of warmer than normal water to move into the central and eastern tropical Pacific Ocean. During a La Niña event, the Walker Circulation intensifies with greater convection over the western Pacific and stronger trade winds.

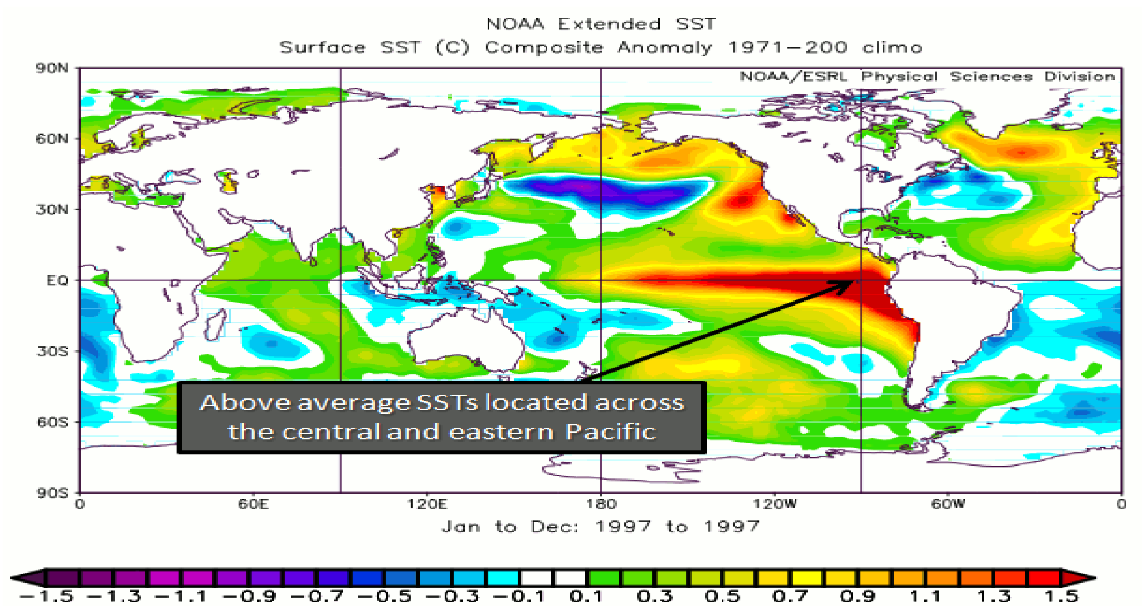

Fig 2) the warm phase (El Niño) of the ENSO cycle features warmer than normal SSTs across the central and eastern equatorial pacific.

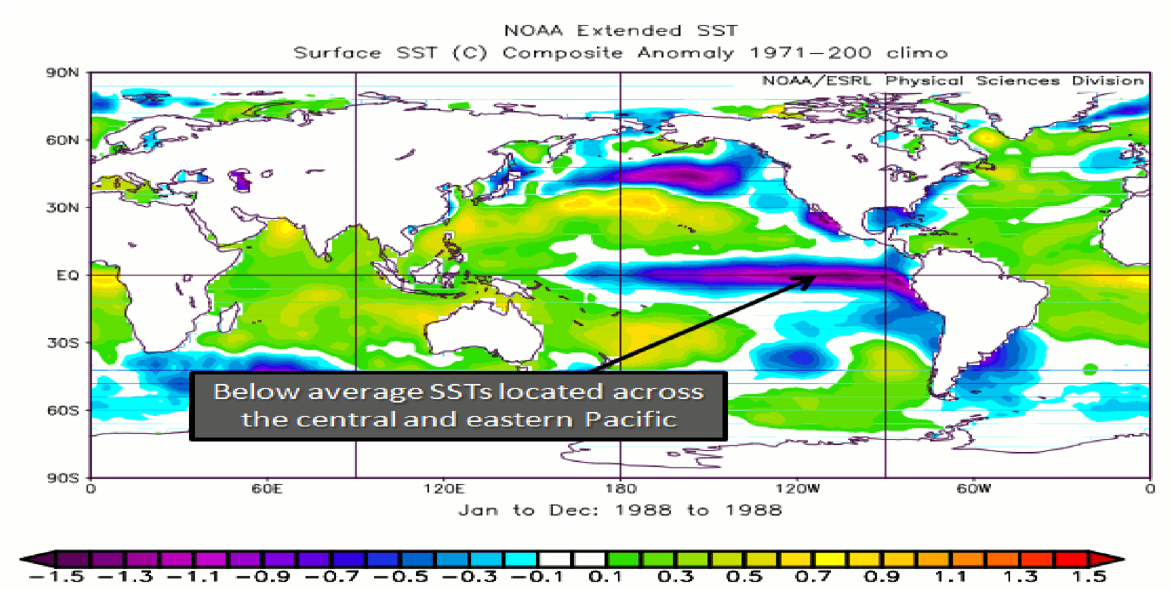

Fig 3) the cold phase (La Niña) of the ENSO cycle features warmer than normal SSTs across the central and eastern equatorial pacific.

2.4 IOD versus ENSO impact on the short rains

Like ENSO, the change in temperature gradients across the Indian Ocean results in changes in the preferred regions of rising and descending moisture and air. In scientific terms, the IOD is a coupled ocean and atmosphere phenomenon, similar to ENSO but in the equatorial Indian Ocean. It is thought that the IOD has a link with ENSO events through an extension of the Walker Circulation to the west and associated Indonesian throughflow (the flow of warm tropical ocean water from the Pacific into the Indian Ocean) (Australian Government Bureau of Meteorology, 2012). Hence, positive IOD events are often associated with El Niño and negative events with La Niña. When the IOD and ENSO are in phase the impacts of El Niño and La Niña events are often most extreme over Australia, while when they are out of phase the impacts of El Niño and La Niña events can be diminished.

Consequently, recent studies tried to compare the fractional influence of IOD and ENSO on short rains (Saji and Yamagata 2003b; Black et al. 2003; Clark et al. 2003; Behera et al. 2003b).

Recent studies reported some of these exceptional short rains events (Saji and Yamagata 2003b; Black et al. 2003; Behera et al. 2003b; Yamagata et al. 2004). One typical case is the record-breaking floods in 1961, which did not coincide on a negative SO phase. During that year, the Pacific Ocean condition was quite normal but the Indian Ocean condition was reportedly abnormal (Reverdin et al. 1986). The unique variability in the Indian Ocean has recently been reorganized as an inherent ocean-atmosphere coupled mode (e.g. Saji et al. 1999; Webster et al. 1999; Yamagata et al. 2003, 2004), which is now widely accepted as IOD mode. In view of this new mode, the focus has been shifted to the Indian Ocean for understanding variability of the short rains (Saji and Yamagata 2003b; Black et al. 2003; Behera et al. 2003b; Clark et al. 2003; Yamagata et al. 2004).

Most of the variability in the model short rains is linked to the basin-wide large-scale coupled mode, which is known as the Indian Ocean Dipole in the Tropical Indian Ocean. The IOD short rains relationship does not change significantly in a model experiment in which the ENSO influence is removed by decoupling ocean and atmosphere in the tropical Pacific (Swadhin et al. 2005). The partial correlation analysis of the model data demonstrates that a secondary influence of ENSO comes from a regional mode located near the African coast. In a negative SO phase the ocean-atmosphere condition becomes opposite and western Indian Ocean and the East African region receives abundant rainfall (Swadhin et al. 2005).

This hypothesis contributed to deepening of our appreciation about the simultaneity of some ENSO events and floods and droughts associated with the short rains but failed to provide a unified viewpoint that can explain all the extreme events as acknowledged in Hastenrath and Polzin (2003).

Comparatively the ENSO influence in that region is quite different from a conventional view. Once we remove the IOD influence from the composite, the pure ENSO influence becomes even opposite in East Africa (Saji and Yamagata 2003b; Yamagata et al. 2004); El Niño (La Niña) produces a negative (positive) anomaly in short rains. Quite interestingly, this contrasts with Clark et al. (2003).

Unlike the basin-wide surface warming (cooling) that is related to warm (cold) ENSO, the dipole mode is rooted in subsurface equatorial ocean dynamics (e.g., Murtuggude et al. 2000; Rao et al. 2002, 2004; Feng et al. 2001; Shinoda et al. 2003) and appears to be inherent in the Indian Ocean. Recent teleconnection studies also reveal the unique influence of IOD on many parts of the globe (Ashok et al. 2001; Guan and Yamagata 2003; Saji and Yamagata 2003b; Zubair et al. 2003; Yamagata et al. 2004). Therefore, it is natural to expect that the IOD has a significant influence on short rains in the neighboring East Africa.

The recent finding about the relative influence of IOD and ENSO on short rains is not surprising. About 30% of positive IOD events co-occur with El Niño events (Rao et al. 2002). It is noticed that this percentage of co-occurrences varies marginally depending on SST data products. Nevertheless, we found that the percentage of IOD events independent to ENSO is always higher than that of the percentage of co-occurrences irrespective of SST data set (Swadhin et al. 2005).

3. Data and Methodology

3.1 Study Area

Ethiopia is located along 3°N latitude – 14°N&33°E – 48°E longitude, with an area of about 1.02 million square km. It is a country of geographical contrasts, varying from as much as 116 m (381 ft) below sea level in the Danakil depression to more than 4,600 m (15,000 ft) above sea level in the mountainous regions. The climate of the country varies from humid to arid zones. The mean annual rainfall ranges from 2400 mm over south western portion, to as little as 500 mm, over northeastern and southeastern low lands (Kassa F, 2015). Ethiopia is the most populous landlocked country in the world and the second-most populous nation in the African continent. Ethiopia covers 1,000,000 square kilometers of land and 104,300 square kilometers of water, making it the 27th largest nation in the world with a total area of 1,104,300 square kilometers. Its proximity to the Middle East and Europe puts the country on a strategic position to enhance international trade.

It is a country of great geographical diversity. It has high and rugged mountains, flat-topped plateaus, deep gorges, valleys and vast rolling plains. A large part of the country comprises of high plateaus and mountain ranges with precipitous edges dissected by rushing streams that are tributaries of famous rivers like the Abay (the Blue Nile). As the country is located within the tropics, its physical conditions and variations in altitude have resulted in great diversity of terrain, climate, soil, flora and fauna.

In Ethiopia there are three seasons, based on climatological means of rainfall and temperature. These seasons are locally known as Bega, Belg and Kiremt (Degefu, 1987; Gissila et al, 2004).

Generally, mean maximum temperature is higher from March to May and mean minimum temperature is lower from November to December as compared to other months. The lowest mean minimum temperature mostly occurs over the highlands of the country. Most of the highlands experience mean minimum temperature as low as 0^oc from November to January while the higher mean minimum temperature (20^oc - 30^oc) is observed over the Danakil depression, the south-eastern and the western lowlands of the country and the highest mean maximum temperature ($45\ ^oc$) is found over the Danakil depression .

The government's long-term economic development strategy – Agricultural-Development-Led-Industrialization (ADLI) – is geared to the transformation of the economic structure. The strategy involves an export-led external sector, and internal emphasis on agriculture to supply commodities for exports, domestic food supply and industrial output, and expand markets for domestic manufacturing. The development strategy is supported by an economic reform program developed in cooperation with the World Bank and the International Monetary Fund (IMF) and by a series of structural adjustment programmes.

3.2 Data Collection

Monthly observed rainfall data was used for the period from 1981 to 2016 in the study area. In getting data there are several approaches available in order to collect reliable and valid information. The Climate Hazards group Infrared Precipitation with Stations (CHIRPS) dataset builds on previous approaches to 'smart' interpolation techniques and high resolution, long period of record precipitation estimates based on infrared Cold Cloud Duration (CCD) observations. It was developed to support the United States Agency for International Development Famine Early Warning Systems Network (FEWS NET). CHIRPS has been explicitly designed to fill the gap, providing blended gauge-satellite precipitation estimates that cover most global land regions and have a fairly low latency and low bias. The CHIRPS station blending procedure is a modified inverse distance weighting algorithm that has several unique characteristics. CHIRPS data is available from 6-hourly to 3-monthly aggregates. Almost all data has an 0.05° × 0.05° degree spatial resolution (Chris Funk et al. 2015). The method use in collecting the data is from global data base.

Intensity of the IOD is represented by anomalous SST gradient between the western equatorial Indian Ocean (50E-70E and 10S-10N) and the south eastern equatorial Indian Ocean (90E-110E and 10S-0N) (Source: http://www.bom.gov.au/climate/iod/). This gradient is named as Dipole Mode Index (DMI). When the DMI is positive then, the phenomenon is refereed as the positive IOD and when it is negative, it is refereed as negative IOD. This dataset can be downloaded in a netcdf format. Since IOD is a coupled ocean-atmosphere phenomenon, it can also be represented by any other atmospheric (pressure, OLR) or oceanographic (sea surface height) as well.

The observed Niño-3.4 index is derived from the HadlSST data. We define an index for short rains by averaging the gridded rainfall data over the area (170^oW-120^oW, 5^oS-5^oN). (Source: http://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Nino34/).The sources of other data include academic books, internet search, scientific articles, journals and regional and global climate data centers among others.

3.3 Method of Data Analysis

In this study, we employed SPSS and Microsoft excels tools to analyses our data set. Simple correlation analysis technique, the relationship between rainfall anomalies and DMI were analyzed for extreme IOD years. To quantify the strength of the relationship, we calculated the correlation coefficient by:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 3.1$$

Where, r is simple linear correlation coefficient exists between two variables x_i is independent variable (DMI) for ith year and y_i is dependant variable for ith year (in this case, rainfall anomalies). The value of r always lies between -1 and +1 and quantifies the direction and strength of the linear association between the two variables. The sign of the correlation coefficient indicates the direction of the association. The magnitude of the correlation coefficient indicates the strength of the association. A value of the correlation coefficient close to +1 indicates a strong positive linear relationship (i.e. one variable increases with the other). A value close to -1 indicates a strong negative linear relationship (i.e. one variable decreases as the other increases). A value close to 0 indicates no linear relationship.

Besides, the simple correlation method, a partial correlation technique also used to show exclusive relationship between two variables while excluding influence arising from another independent variable (Yamagata et al. 2002). Partial correlation indicates the strength and direction of a linear relationship between two continuous variables whilst controlling for the effect of one or more other continuous variables. In this case, DMI is used as independent variable and rainfall anomalies as dependant variable by controlling the effect of correlation between Niño-3.4 and rainfall anomalies for co-occurrence years. Although the partial correlation does not make the distinction between independent and dependent variables, the two variables are often considered in such a manner.

For example, the partial correlation between DMI and rainfall anomalies, while excluding the influence that arises owing to correlation between Niño-3.4 and rainfall anomalies (Saji and Yamagata 2003b; Yamagata et al. 2004), is defined as follows:

$$r_{13.2} = (r_{13} - r_{12} \,.\, r_{23}) / \sqrt{(1 - r^2_{12})} \sqrt{(1 - r^2_{23})} \quad \ldots\ldots\ldots\ldots\ldots\ldots \; 3.2$$

where r_{13} is the correlation between DMI and rainfall anomalies, r_{12} is the correlation between DMI and Niño-3.4 index and r_{23} is the correlation between Niño-3.4 and rainfall anomalies. We also use a tercile method, which is a set of data arranged in order with values that partition the data into three groups, each containing one-third of the total data. The historical data (1981 to 2016) is arranged in order from the lowest to the highest and then the data is partitioned into three equal groups. The lowest third of the data values which are defined as the lowest tercile represents below normal rainfall, the middle third of the values which are the middle tercile represents normal rainfall and the upper third of the values which are the upper tercile represents above normal rainfall categories. Representations of these findings using diagram, tables and charts are used to ensure easy and quick interpretation of data. Prior to data undertaking data anlaysis, all sets of data are properly checked for completeness and consistency.

3.4 Homogeneous rainfall regions

Averaging gauges over large areas is important for increasing the signal to noise ratio, however, care must be taken in places where, there is high spatial variation. Rainfall over East Africa in general and Ethiopia in particular exhibits high spatial variation (Diro 2008; Tsidu 2012). Therefore, it is necessary to divide the country into homogeneous rainfall zones.

Several attempts have been made to regionalize spatial variation rainfall of Ethiopia into homogeneous rainfall zones. For example, Gissila et al. (2004) divided the country into five homogeneous rainfall zones for the summer (Kiremt) season. Whereas Diro et al. (2008 and 2011) modified these classifications and produced six rainfall zones. The differences existed between these two works were emerged due to variations in number of stations used and seasons. The analyses are based on monthly rainfall totals from three date sets of NMA. These are; 162 meteorological stations, merged station-satellite rainfall data (Dinku et al., 2011) extracted at the locations of the 162 stations, and the same data extracted at 717 randomly selected rainfall grid points. The latter two data sets cover the period 1983-2010.

Monthly rainfalls recorded over 162 meteorological stations for the period 1951-2009 were investigated to examine the spatial and temporal rainfall patterns in Ethiopia. Mean annual and seasonal rainfall were computed, and their spatial patterns are analyzed. After applying Principal Component Analysis (PCA) and Canonical Analysis (CA) on monthly rainfall over Ethiopia, and considering the country's intra-annual rainfall variability, climatological patterns and topography of the country, fourteen homogeneous rainfall regions were identified. However, when rainfall station-based classifications were compared with results from merged station-satellite rainfall data, the homogenous rainfall Regimes became twelve Diriba (2013).

Homogeneous rainfall of Ethiopia has many advantages. Firstly, it is constructed based on high quality rainfall data, both at point stations and merged station- satellite rainfall estimates at finer spatial resolution. Secondly, all parts of Ethiopia are fairly represented. Thirdly, the merged data set represents the more recent inter-annual variability of rains than the station-based data. The merging of pocket places such as southern exit of Rift Valley, areas bordering with Djibouti and southern highlands with the neighboring regions is made based on the knowledge of local topography and climate. Figure 4 therefore, contains twelve homogeneous rainfall regions in Ethiopia. For this study, we adopt the work of Diriba K. (2013) as working platform of homogeneous rainfall Regimes.

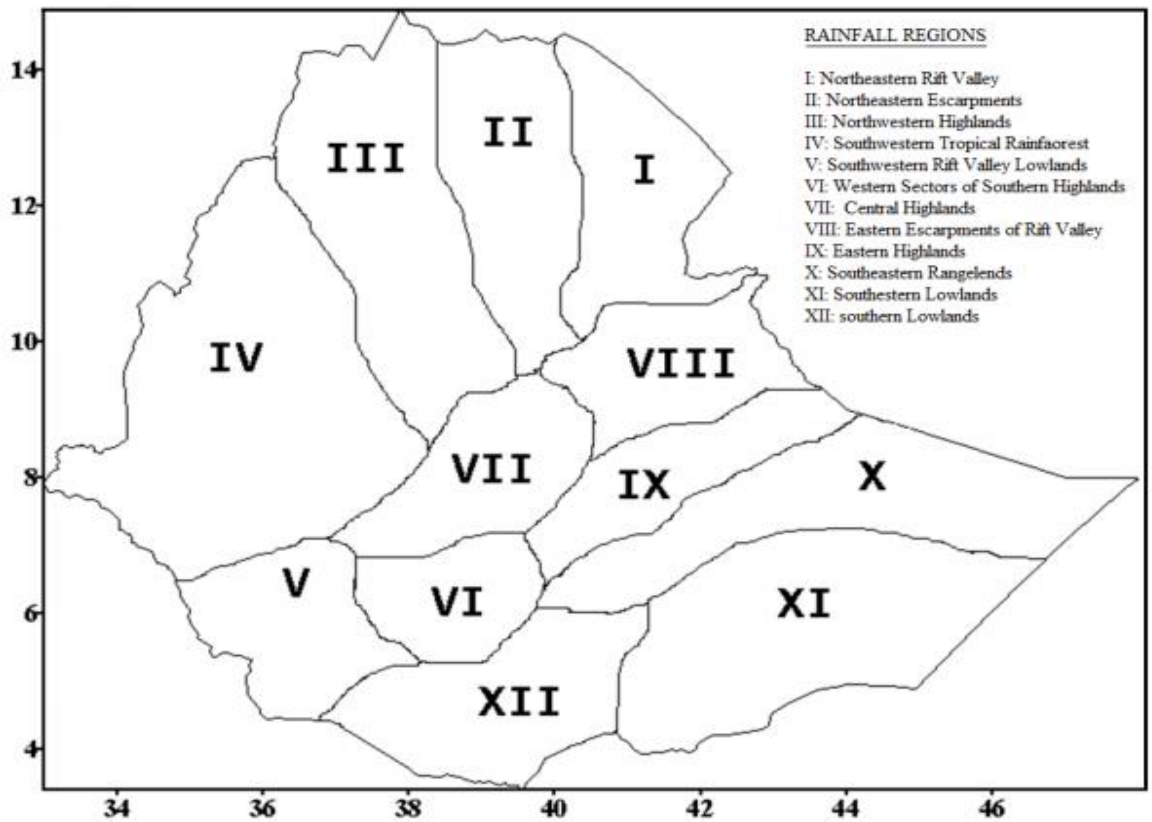

Fig 4) Homogeneous rainfall regions in Ethiopia based on outputs from stations, merged station-satellite rainfall data and knowledge of local climate and topography. In the classifying rainfall patterns into homogeneous regions, more information was used from station-satellite merged rainfall data. Roman number was used to represent each homogeneous rainfall region on the map of Ethiopia (Courtesy of Diriba K, 2013).

4. Results and Discussions

In Ethiopia there are three climatic seasons, which are locally known as Bega, Belg and Kiremt (Degefu,1987; Gissila et al, 2004). Bega (autumn) which is dry and cool season, spans from October to January and Belg (spring) is lasting from February to May. Kiremt (summer) which is wet and cools that cover most part of the country spans from June to September.

4.1 Evolution of the IOD

The seasonality of DMI is complicated. Usually IOD events mature in Autumn with a peak in October. However, although many events mature in Autumn, some events mature in summer. Some events start in spring and mature in summer, then decay in autumn, but the majority of events start in summer, and peak in autumn. IOD events tend to peak between August and October (Ahmed A. Shaaban 2015).

For this reason the analysis of Dipole Mode Index (DMI) is done from May to November monthly anomaly for the period of 1981 to 2017 that shows the positive IOD and Negative IOD event. The positive IOD years from strong to weak intensity are 1997, 1994, 2006, 1982, 2015 where as Negative IOD years includes 2016, 1998, 1996, 1992, 2010 (Table 1 and Fig 5). Australian Government Bureau of meteorology web page indicates that IOD index greater than +0.4^{o}C positive IOD years where as less than -0.4^{o}C is categorized as negative IOD years.

Table 1) Intensity of monthly Indian Ocean Dipole (IOD) SST anomaly difference between the western (50°E-70°E, 10°S-10°N) and eastern (90°E-110°E, 10°S-0°S) tropical Indian Ocean. anomaly from May to November months within 1981 to 2017.

Rank based on DMI value	Positive IOD Years	DMI values	Negative IOD Years	DMI values
1st	1997	1.08	2016	-0.67
2nd	1994	1.04	1998	-0.62
3rd	2006	0.58	1996	-0.60
4th	1982	0.52	1992	-0.48
5th	2015	0.45	2010	-0.45
6th	1991	0.44	1990	-0.38
7th	2007	0.38	1984	-0.37
8th	2011	0.34	1989	-0.35
9th	2008	0.33	2001	-0.30
10th	2003	0.30	2005	-0.27

Three rare consecutive IOD events occurred during 2006, 2007, and 2008. The interesting thing about these three events is that they were all positive, which broke the IOD biennial property based on (Behera et al. 2008; Du et al. 2012; Iskandar et al. 2013). The short lived IOD events during 2007-2008 were due to the triggering of down-welling Kelvin waves by the MJO (Rao et al. 2008; Yan et al. 2012). The down-welling Kelvin wave moves eastward toward the coast deepening the thermocline so ending the IOD event.

It has been believed that surface cooling (warming) near the African coast following an above (below) normal Indian monsoon year causes below (above) normal short rains. The present analysis has started from doubting the above link among the short rains, Indian summer monsoon and ENSO.

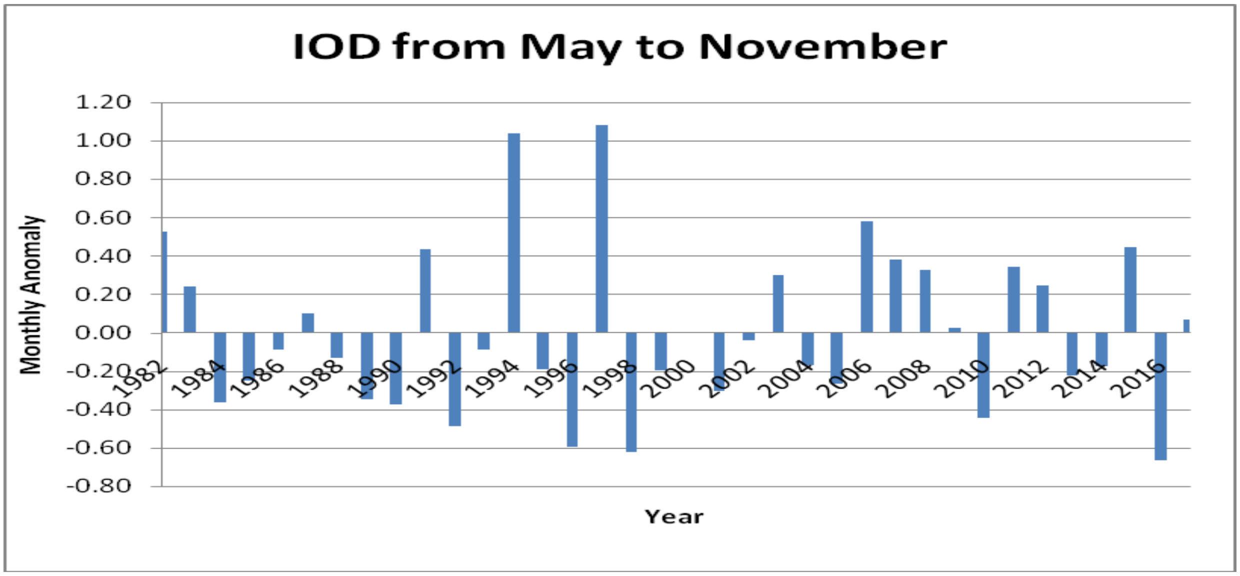

Fig 5) Intensity of the Indian Ocean Dipole from May to November is represented by anomalous SST gradient between the western equatorial Indian Ocean (50E-70E and 10S-10N) and the south eastern equatorial Indian Ocean (90E-110E and 10S-0N).

4.2 Interseasonal variability of the short rains

Performances of short rainy season in Ethiopia were analyzed for all twelve homogeneous rainfall regions. For example, on homogeneous rainfall Region I during the study period above normal rainfall for bega season was recorded in 1992, 1997, 2000, 2008, 1996 and 1998 where as below normal rainfall was recorded in 1981, 2001, 2012, 2007, 2017, 1986 and 1990. During Belg season above normal rainfall was recorded in 1993, 1987, 2016, 1996, 1995 and 1989 where as below normal rainfall was observed in 1999, 2008, 2009, 1984, 2000 and 2011 (Table 2). For the rest of homogeneous rainfall Regions the results of short rain variability were summarized from Tables 6 to 15 on Appendix A.

Table 2) Tercile probability for below and above normal rainfall for both Bega and Belg seasons for Homogeneous rainfall region I. The bold asterisks are the selected IOD years.

Bega Season For Region I				Belg Season For Region I			
Year	Tercile for Below Normal	Year	Tercile for Above Normal	Year	Tercile for Below Normal	Year	Tercile for Above Normal
1981	2.70	2009	67.57	1999	2.70	2005	67.57
2001	5.41	2013	70.27	2008	5.41	**2006***	**70.27**
2012	8.11	2002	72.97	2009	8.11	1983	72.97
2007	10.81	1993	75.68	1984	10.81	**1982***	**75.68**
2017	13.51	2011	78.38	2000	13.51	2017	78.38
1986	16.22	**1982***	**81.08**	2011	16.22	1986	81.08
1990	18.92	1999	83.78	2002	18.92	1985	83.78
2010*	**21.62**	**1998***	**86.49**	**1994***	**21.62**	1989	86.49
1988	24.32	**1996***	**89.19**	**2015***	**24.32**	1995	89.19
1987	27.03	2008	91.89	2007	27.03	**1996***	**91.89**
1985	29.73	2000	94.59	**1992***	**29.73**	**2016***	**94.59**
1994*	**32.43**	**1997***	**97.30**	**1998***	**32.43**	1987	97.30
		1992*	**100.00**			1993	100.00

4.3 Dominant IOD impact on short rains variability

The role of Indian Ocean Dipole on bega and belg seasons over Ethiopia was indicated by the bold years with asterisks (Table 2, 3 and from 6 to 15). During Bega season, for instance above normal rainfall were observed on homogeneous rainfall Regions I in 1992, 1997, 1996, 1998 and 1982 but in 2010 and 1994 below normal rainfall was observed (Table 2). In contrast, on Regions II in 1994, 2010 and 2016 IOD year shows below normal rainfall and in 2006, 1998, 1991, 1996, 1982, 1992 and 1997 IOD years above normal rainfall (Table 3). On Region III in 1994, 2010, 1996 and 2016 indicate below normal rainfall but in 2006, 1998, 1982, 1992 and 1997 shows above normal rainfall. On Region IV in 1991 and 2010 show below normal rainfall where as in 2015, 1998, 1982, 1992, 2006 and 1997 indicates above normal rainfall. On Region V in 2010 and 1996 show below normal rainfall but in 1982, 2015, 2006 and 1997 IOD years above normal rainfall. On Region VI in 1994, 2010 and 1991 show below normal rainfall but in 2016, 1992, 1998, 1982 and 1997 indicates above normal rainfall (Table 6 to 9).

During Belg season on homogeneous rainfall Regions I among the selected IOD years in 1994, 2015, 1992 and 1998 below normal rainfall was observed where as in 2016, 1996, 1982 and 2006 above normal rainfall was observed (Table 2). On Region II in 1994 and 1991 shows below normal rainfall but in 2016, 1997, 2006, 1982 and 1996 shows above normal rainfall (Table 3). On Region III none shows below normal rainfall where as in 2006, 2015, 2016, 1997 and 1996 above normal rainfall. On Region IV in 1982 and 1998 shows below normal rainfall but in 2010, 2015, 1997, 1994, 1991, 1996 and 2016 shows above normal rainfall. On Region V in 1982, 2016 and 1992 shows below normal rainfall but in 1994, 2006, 1996 and 2010 shows above normal rainfall. On Region VI in 2015 and 1994 shows below normal rainfall but in 1998, 2006, 2016, 1996 and 2010 shows above normal rainfall (Table 6 to 9).

During bega season on Region VII also among the selected IOD years in 1994 and 2015 show below normal rainfall where as 1992, 1998, 1982 and 1997 show above normal rainfall. On Region VIII only 2010 show below normal rainfall but in 1996, 1998, 1992, 1982 and 1997 show above normal rainfall. On Region IX in 2010, 2015 and 1996 shows below normal rainfall where as 1992, 2006, 1998, 1982 and 1997 shows above normal rainfall. On Region X in 2010, 1991, 1996 and 2016 shows below normal rainfall but in 1994, 2006, 1982 and 1997 shows above normal rainfall. On Region XI in 1991, 2010, 1996, 2016, 1998 and 1992 shows below normal rainfall but in 2015, 1994, 1982, 2006 and 1997 shows above normal rainfall. On Region XII in 2010, 1991 and 1996 shows below normal rainfall where as in 2015, 1982, 2006 and 1997 shows above normal rainfall (Table 10 to 15).

During belg season on Region VII for selected IOD years in 1994 and 1997 shows below normal rainfall but in 2006, 1996, 2010 and 2016 shows above normal rainfall. On Region VIII in 2015, 1992 and 1994 shows below normal rainfall but in 2010, 1982, 2016 and 1996 shows above normal rainfall. On Region IX only in 2015 shows below normal rainfall but in 2016, 1982, 1996 and 2010 shows above normal rainfall. On region X, XI and XII only in 1992 shows below normal rainfall. On Region X in 1991, 1996, 1982 and 2010; on Region XI in 1997, 1994, 2010, 1998 and 1982, on Region XII in 2006, 1996, 1982 and 2010 shows above normal rainfall (Table 10 to 15).

For all homogeneous rainfall Regions the 1997 year is an extraordinary year that shows above normal rainfall for bega rainy season as stated by many scholars (Table 2, 3 and from 6 to 15). For belg season the role of IOD on rainfall distribution is low as compare to bega season for most part of homogeneous rainfall Region. Especially, on homogeneous rainfall Region III, IX, X, XI and XII the role of IOD during belg season for below normal condition is almost none.

Table 3) Tercile probability for below and above normal rainfall for both Bega and Belg seasons for Homogeneous rainfall region II. The bold asterisks are the selected IOD years.

Bega Season For Region II				Belg season For Region II			
Year	Tercile for Below Normal	Year	Tercile for Above Normal	Year	Tercile for Below Normal	Year	Tercile for Above Normal
2001	2.70	**2006***	**67.57**	1999	2.70	**2016***	**67.57**
1994*	**5.41**	2009	70.27	2009	5.41	**1997***	**70.27**
1986	8.11	**1998***	**72.97**	2013	8.11	1983	72.97
1981	10.81	**1991***	**75.68**	2008	10.81	**2006***	**75.68**
1990	13.51	**1996***	**78.38**	2004	13.51	2005	78.38
1985	16.22	2014	81.08	1988	16.22	2017	81.08
2010*	**18.92**	1999	83.78	2007	18.92	2014	83.78
2016*	**21.62**	2008	86.49	**1994***	**21.62**	1995	86.49
1984	24.32	**1982***	**89.19**	2002	24.32	**1982***	**89.19**
2007	27.03	2013	91.89	**1991***	**27.03**	1985	91.89
2003	29.73	2000	94.59	1984	29.73	1987	94.59
2005	32.43	**1992***	**97.30**	2001	32.43	**1996***	**97.30**
		1997*	**100.00**			1993	100.00

4.4 Indian Ocean Dipole and ENSO Interaction

An IOD events that co-occur with ENSO events include in 1982, 1991, 1994, 1997, 2006 and 2015 (-positive IOD event co-occur with El Nino event) and 1984, 1989, 1998, 2010 and 2016 (negative IOD event co-occur with La Nina event) where as non co-occur year is only in 1992

(Fig 6). In 1994 there is some El Nino condition with greater intensity in positive IOD condition but in 2007 and 2011 positive IOD conditions co-occur with La Nina condition. In 2016 small La Nina condition co-occurs with greater intensity negative IOD condition.

However, in 1982, 1994 and 1997 IOD was coincident with warm phase ENSO (Ahmed A. Shaaban 2015). There is large debate about whether 1994 in El Niño or not. Many IOD literatures follow (Meyers et al. 2007) classification for IOD; in this classification the 1994 is positive IOD and neutral ENSO event. The biggest IOD event was in 1997, the second biggest event was in 1961 (Saji et al. 1999) reported two important features of the IOD.

Webster et al. (1999) argued that ocean-atmosphere coupling in 1997-1998 was not associated with big 1997-1998 El Niño, as drought in Indonesia and flood over East Africa was larger than what was anticipated for ENSO event. Such argument may not be enough to indicate that the precipitation was due to the IOD because response of the precipitation to El Niño is not linear; also several other factors can influence precipitation.

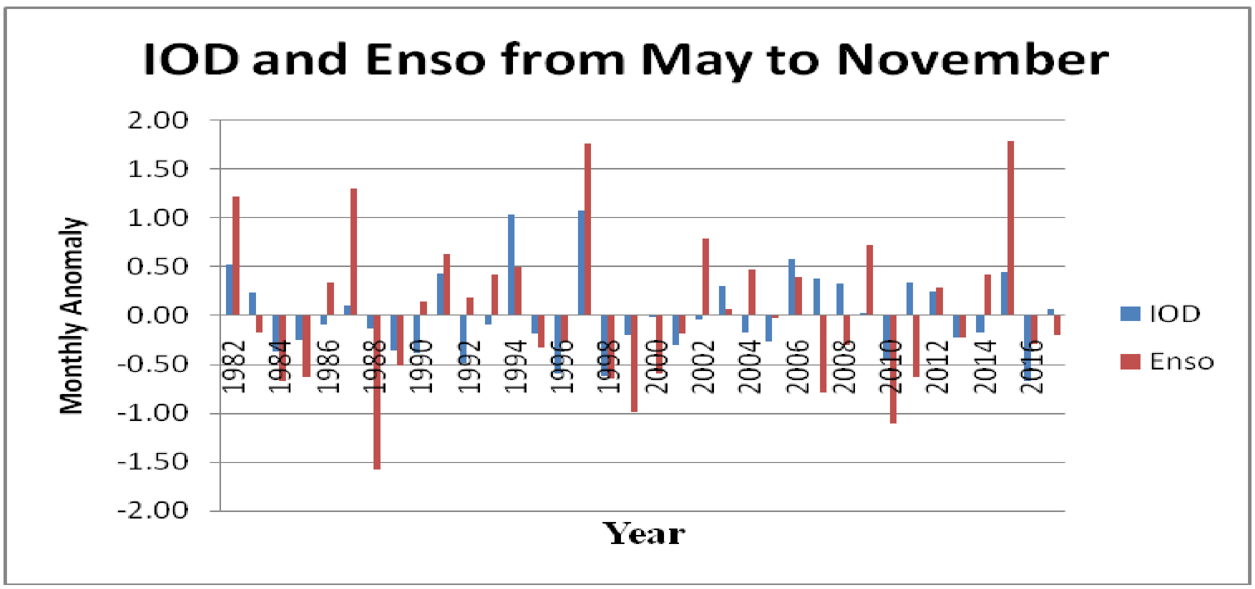

Fig 6) Intensity of the Indian Ocean Dipole from May to November is represented by anomalous SST gradient between the western equatorial Indian Ocean (50E-70E and 10S-10N) and the south eastern equatorial Indian Ocean (90E-110E and 10S-0N) and Enso condition.

4.5 IOD connection with extreme events of short rains

4.5.1 Simple correlation for Bega Season

The simple correlation coefficients exist between observed rainfall data and DMI for selected IOD years from 1981 to 2017 and for the period of May to November months were computed for each homogeneous rainfall Region of the country. For Zero month lag, the selected positive IOD years have significant correlation coefficients on homogeneous rainfall Regions IV, V, VII, X, XI and XII (Table 4 and Fig 7) but the negative IOD years have no better correlation coefficients on all homogeneous rainfall Regions (Table 4 and Fig 8).

For one month lag, positive IOD years have significant correlation coefficients on all homogeneous rainfall Regions except on region I and IX (Table 4 and Fig 7) where as on negative IOD years only region IV, VII and XI have significant correlation coefficients (Table 4 and Fig 8). For two month lag, positive IOD years have significant correlation coefficients on region II, III, IV, VI, VII, VIII and XII (Table 4 and Fig 7) but the negative IOD years have significant correlation coefficients on all homogeneous rainfall Regions except on region V, X, XI and XII (Table 4 and Fig 8). The result of the analysis indicates that one month lag have better correlation coefficients than zero and two month lag for selected positive IOD years.

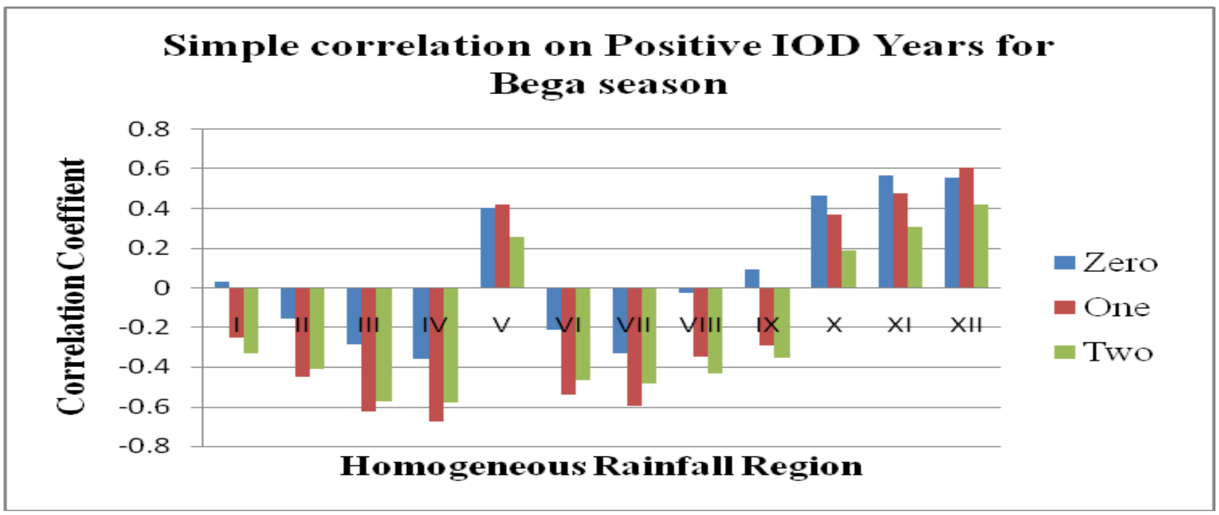

Fig 7) simple correlation between Indian Ocean Dipole (IOD) and observed rainfall from May to November months for 1981 to 2017 on Positive IOD years for all homogeneous rainfall Region.

Table 4) Summary of simple and partial correlation between Indian Ocean Dipole (IOD) and observed rainfall from May to November months for 1981 to 2017 selected IOD years for all homogeneous rainfall Region.

Homogeneous Region	Lag of Month	Simple Correlations		Partial correlation	
		Positive IOD	Negative IOD	Positive IOD	Negative IOD
I	Zero	0.032	-0.241	0.100	-0.225
	One	-0.254	0.125	-0.196	0.133
	Two	-0.332	0.522**	-0.281	0.471*
II	Zero	-0.153	-0.224	-0.064	-0.218
	One	-0.450**	0.254	-0.379*	0.234
	Two	-0.412*	0.571**	-0.362	0.525**
III	Zero	-0.284	-0.199	-0.198	-0.197
	One	-0.624**	0.331	-0.571**	0.284
	Two	-0.574**	0.580**	-0.541**	0.537**
IV	Zero	-0.360*	-0.072	-0.251	-0.123
	One	-0.674**	0.399*	-0.629**	0.318
	Two	-0.579**	0.540**	-0.554**	0.488*
V	Zero	0.407**	0.132	0.369*	0.073
	One	0.423*	0.090	0.335*	0.011
	Two	0.257	0.318	0.172	0.286
VI	Zero	-0.210	0.001	-0.118	-0.049
	One	-0.540**	0.361	-0.507**	0.291
	Two	-0.467**	0.542**	-0.452*	0.491*
VII	Zero	-0.329*	-0.150	-0.228	-0.167
	One	-0.597**	0.376*	-0.531**	0.327
	Two	-0.486**	0.580**	-0.441*	0.537**
VIII	Zero	-0.028	-0.280	0.030	-0.268
	One	-0.345*	0.199	-0.291	0.200
	Two	-0.434*	0.562**	-0.390*	0.514*
IX	Zero	0.092	-0.100	0.172	-0.147
	One	-0.289	0.225	-0.265	0.181
	Two	-0.356	0.410*	-0.337	0.342
X	Zero	0.468**	0.136	0.439**	0.085
	One	0.371*	-0.270	0.285	-0.236
	Two	0.188	-0.212	0.124	-0.154
XI	Zero	0.567**	0.206	0.516**	0.162
	One	0.477**	-0.417*	0.398*	-0.364
	Two	0.308	-0.274	0.248	-0.235
XII	Zero	0.557**	0.138	0.498**	0.100
	One	0.610**	-0.337	0.541**	-0.283
	Two	0.424*	-0.308	0.369*	-0.203
*. Correlation is significant at the 0.05 level (2-tailed).					
**. Correlation is significant at the 0.01 level (2-tailed).					

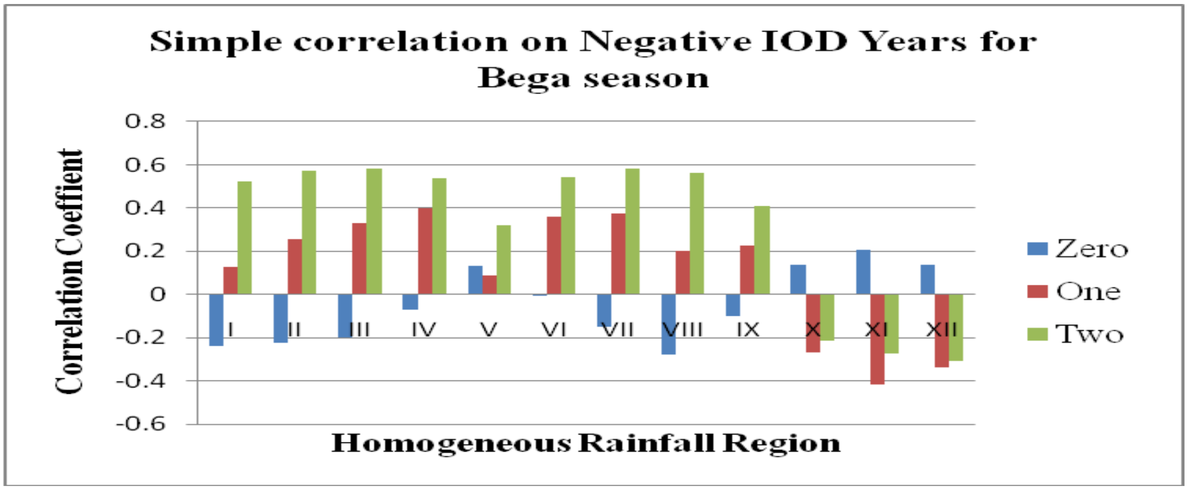

Fig 8) Simple correlation between Indian Ocean Dipole (IOD) and observed rainfall from May to November months for 1981 to 2017 on Negative IOD years for all homogeneous rainfall Region.

4.5.2 Partial correlation for Bega Season

For zero month lag, the results of partial correlation for positive IOD years from May to November have significant correlation coefficients on region V, X, XI and XII (Table 4 and Fig 9) but the negative IOD years have not significant correlation coefficients on all homogeneous rainfall Regions (Table 4 and Fig 10).

For one month lag with positive IOD years the significant correlation coefficients observed on all homogeneous rainfall Region except on I, VIII, IX and X (Table 4 and Fig 9) but the Negative IOD year have no significant correlation coefficients on all region (Table 4 and Fig 10). For two month lag, positive IOD years have the significant correlation coefficients on region III, IV, VI, VII, VIII and XII (Table 4 and Fig 9) and the negative IOD year on region I, II, III, IV, VI, VII and VIII have significant correlation coefficients (Table 4 and Fig 10).

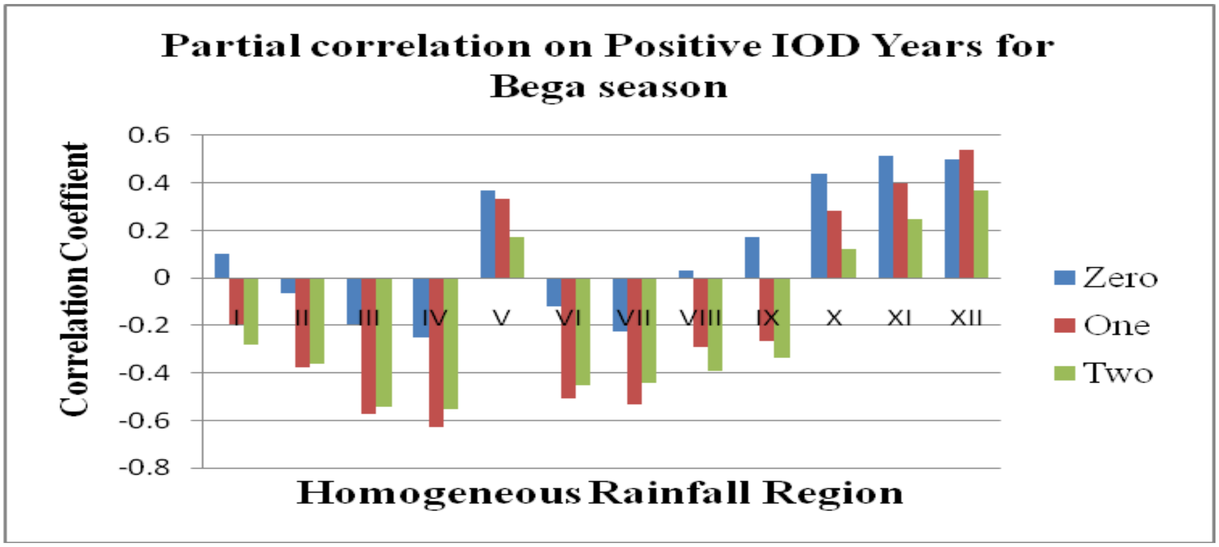

Fig 9) Partial correlation between Indian Ocean Dipole (IOD) and observed rainfall from May to November months for 1981 to 2017 on Positive IOD years for all homogeneous rainfall Region.

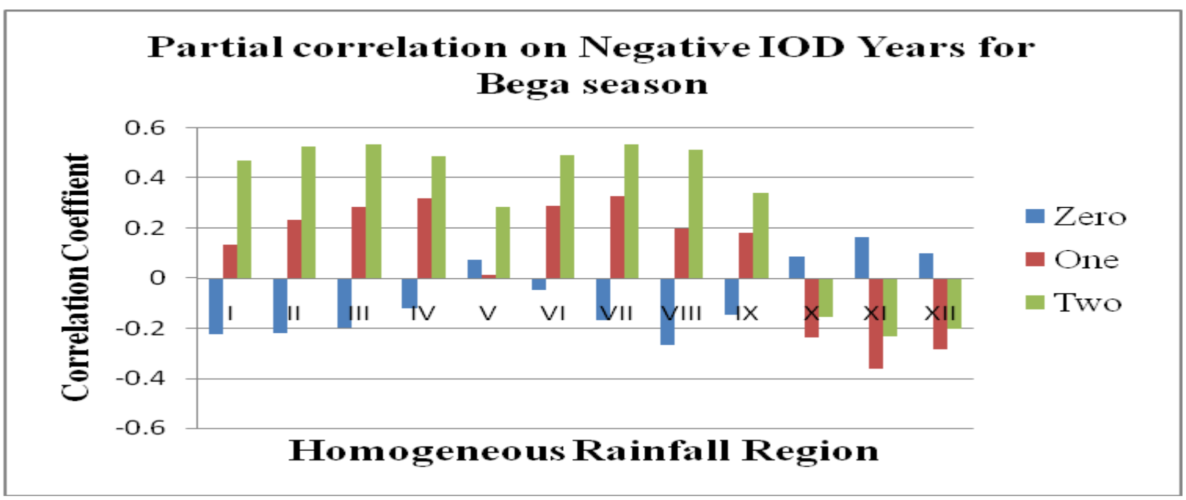

Fig 10) Partial correlation between Indian Ocean Dipole (IOD) and observed rainfall from May to November months for 1981 to 2017 on Negative IOD years for all homogeneous rainfall Region.

4.5.3 Simple and Partial correlation for Belg Season

Simple and partial correlations during belg season for positive IOD years have no significant correlation on all homogenous rainfall Regions of Ethiopia for both zero and one month lag but for negative IOD years only the homogenous rainfall Regions IV, VI and VII have significant correlation for both zero and one month lag (Table 5 and Fig 11 to Fig 14) .

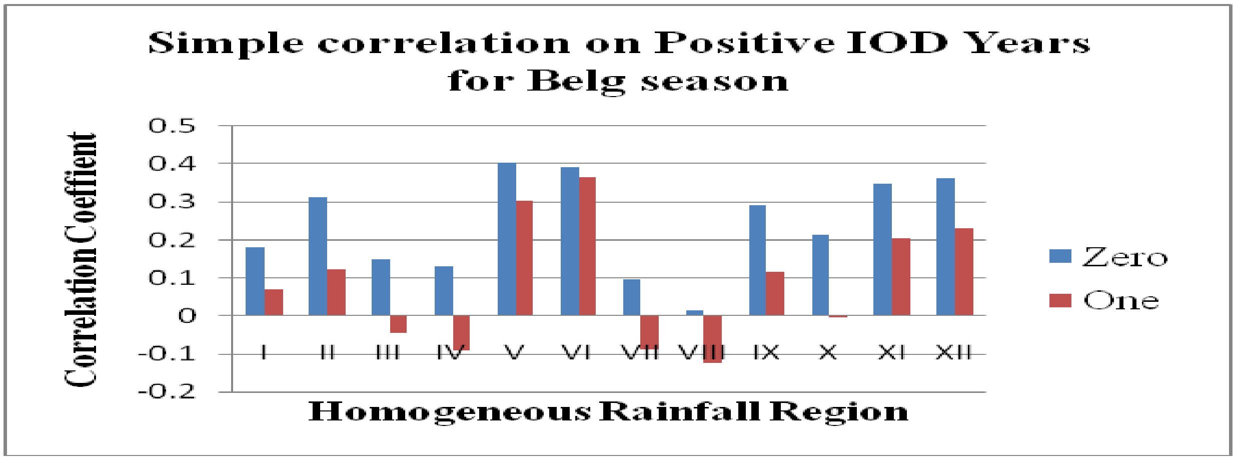

Fig 11) Simple correlation between Indian Ocean Dipole (IOD) and observed rainfall from February to May months for 1981 to 2017 on Positive IOD years for all homogeneous rainfall Region.

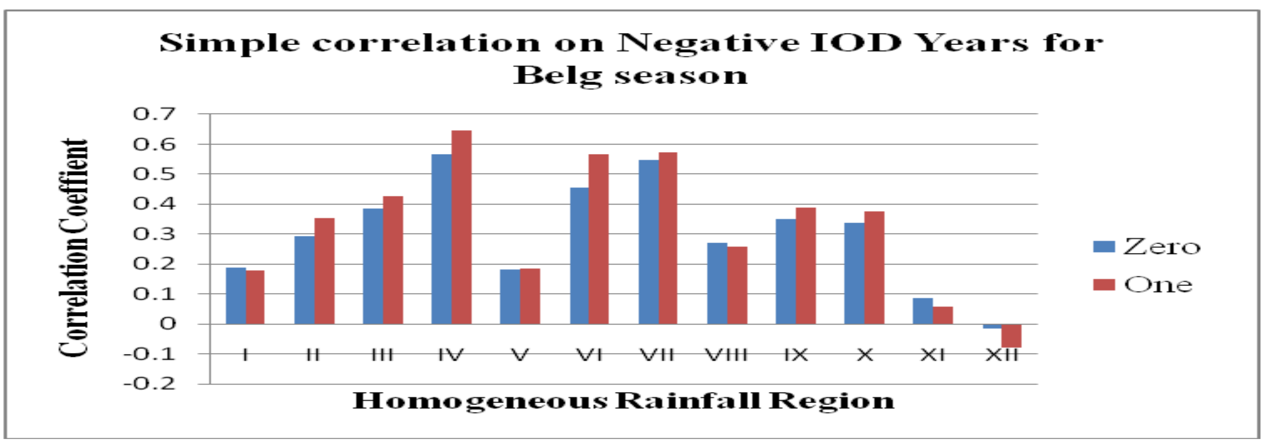

Fig 12) Simple correlation between Indian Ocean Dipole (IOD) and observed rainfall from February to May months for 1981 to 2017 on Negative IOD years for all homogeneous rainfall Region.

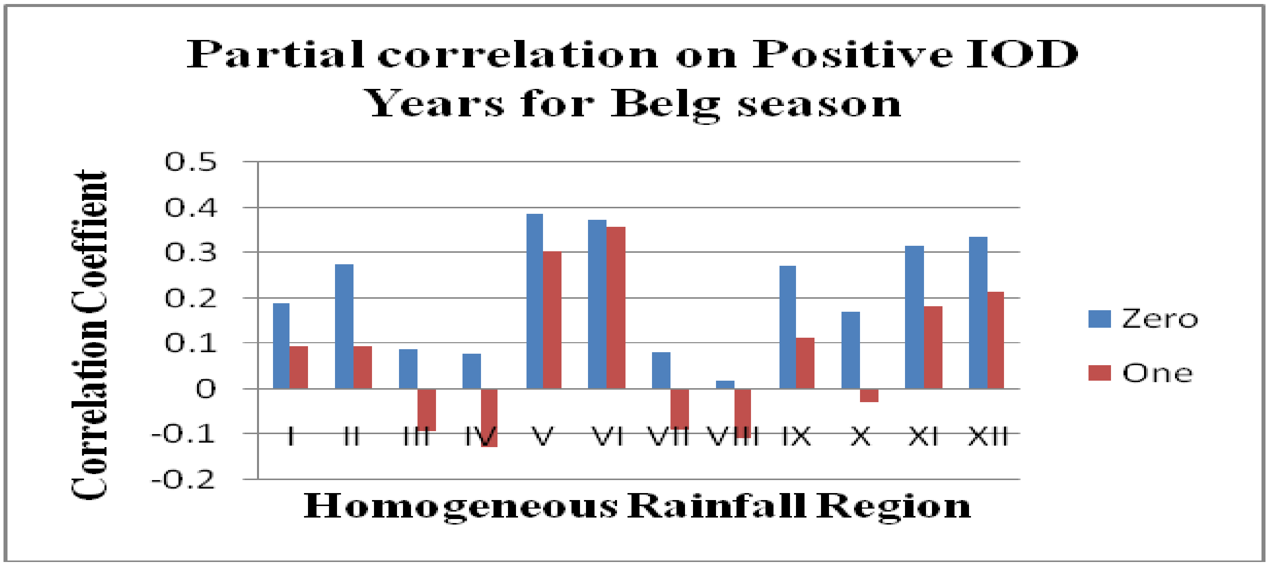

Fig 13) Partial correlation between Indian Ocean Dipole (IOD) and observed rainfall from February to May months for 1981 to 2017 on Positive IOD years for all homogeneous rainfall Region.

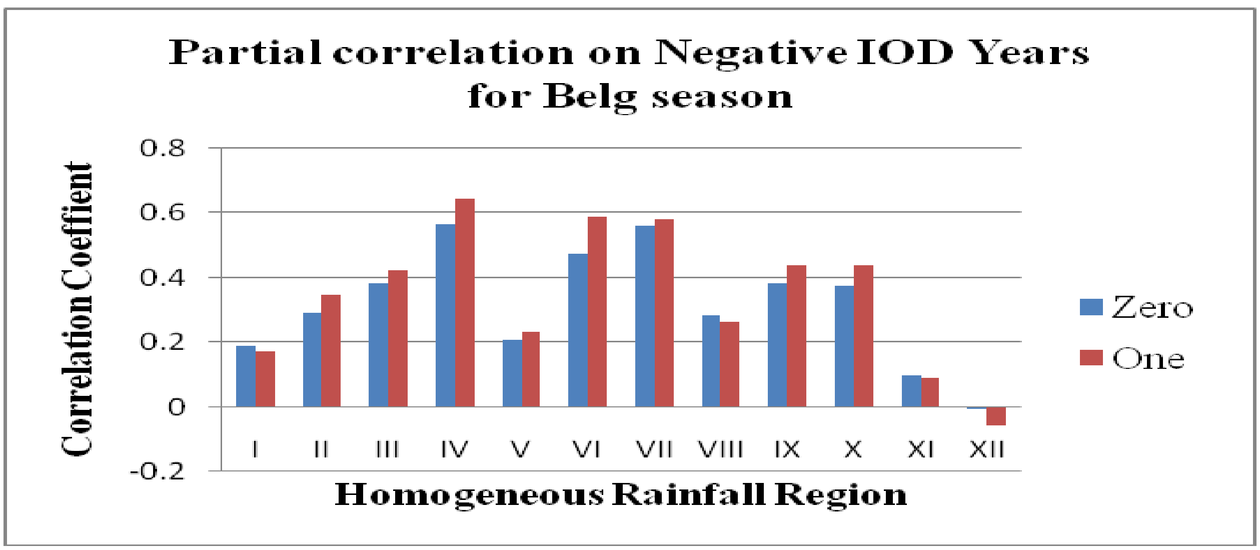

Fig 14) Partial correlation between Indian Ocean Dipole (IOD) and observed rainfall from February to May months for 1981 to 2017 on Negative IOD years for all homogeneous rainfall Region.

Table 5) Summary of simple and partial correlation between Indian Ocean Dipole (IOD) and observed rainfall from February to May months for 1981 to 2017 selected IOD years for all homogeneous rainfall Region.

Homogeneous rainfall Region	Lag of Month	**Simple Correlations**		**Partial correlation**	
		Positive IOD	Negative IOD	Positive IOD	Negative IOD
I	Zero	0.181	0.187	0.189	0.187
	One	0.069	.0 .177	0.093	0.173
II	Zero	0.313	0.292	0.276	0.292
	One	0.122	0.352	0.094	0.349
III	Zero	0.148	0.385	0.088	0.385
	One	-0.044	0.426	-0.092	0.423
IV	Zero	0.130	0.566**	0.080	0.567*
	One	-0.092	0.647**	-0.127	0.645*
V	Zero	0.403	0.182	0.386	0.207
	One	0.305	0.184	0.303	0.232
VI	Zero	0.393	0.456*	0.374	0.475*
	One	0.364	0.565*	0.359	0.591*
VII	Zero	0.097	0.548*	0.081	0.560*
	One	-0.090	0.574*	-0.089	0.583*
VIII	Zero	0.013	0.272	0.019	0.284
	One	-0.125	0.257	-0.109	0.266
IX	Zero	0.293	0.349	0.273	0.384
	One	0.115	0.388	0.115	0.437
X	Zero	0.212	0.338	0.172	0.374
	One	-0.004	0.377	-0.028	0.439
XI	Zero	0.348	0.085	0.316	0.099
	One	0.203	0.059	0.184	0.089
XII	Zero	0.363	-0.014	0.335	-0.005
	One	0.231	-0.078	0.216	-0.057
*. Correlation is significant at the 0.05 level (2-tailed).					
**. Correlation is significant at the 0.01 level (2-tailed).					

5. Conclusions and Summaries

The analysis of rain-fall data, Indian Ocean Dipole and Enso condition based on statistical analysis method demonstrated that it is possible to explain those abnormal years of short rains once we take into account the intrinsic zonal variability related to IOD. The 1994 and 1997 are typical IOD years in the Indian Ocean (Fig 5 and Table 1). The challenges faced on both short rainy seasons for the study area are not linearly related with all selected IOD years for all homogenous rainfall regions. The 1997 which is the frist extreme IOD event results the highest rainfall amount through the country during Belg season (Table 2, 3 and from 6 to 15).

The role of Indian Ocean Dipole on both short rainy seasons over the country is observed on most of homogenous rainfall Region. Not all types of El Niño events aid in triggering positive IOD event (Fig 6). Most positive IOD events are associated with wet outcomes and most negative IOD events are associated with below average precipitation especially on south and south east of the country. But not all negative precipitation anomalies are associated with negative DMI value. The association between DMI and flood is stronger than the association between DMI and dry conditions (Table 2, 3 and from 6 to 15).

The severity of climatic extremes based on the level of Indian Ocean Dipole impacts on seasonal rainfall performance over the country is quantified using a simple and partial correlation analysis. The simple correlations analyses from May to November are more significant for positive IOD years on South and South East of the country for zero month lag. It is also significant on Tigray, Amhara, Benishangul-Gumz, Gambella, Centeral & West Oromia, Eastern part of SNNP and South and South East part of Somali Regional States for one month lag. For two month lag it is more significant on West Tigray, Centeral and West Ahmara, Benishangul-Gumz, Centeral & West Oromia and East SNNP Regional States. The negative IOD years show significant correlation on Afar, Tigray, Ahmara, Benishangul-Gumz, Central, West & East Oromia and East SNNP Regional States only for two month lag. But, zero and one month lag do not show more significant correlation to all part of the country for negative IOD years. Positive IOD years influence more than negative IOD years by simple correlation analysis during bega season on most part of the county (Table 4).

The correlation pattern is further examined by using a partial correlation method to establish the relation unique to IOD events. The partial correlation analysis of the data demonstrates that more significant correlation for positive IOD years on West Tigray, Central & West Ahmara, Benishangul-Gumz, East SNNP, Central & West Oromia and West of Somali Regional States for one month lag. It is also more significant on South and South East of the country for zero month lag. For two month lag the correlation is significant on West Tigray, Central & West Ahmara, Benishangul-Gumz and West Oromia Regional States for two month lag. The negative IOD years is more significant on Tigray, East Ahmara and Central Oromia Regional States for two month lag. In contrast, correlation coefficients that are partial to ENSO did not show any significant values on the country for zero and one month lag (Table 4). We find that all coefficients of both simple correlation and partial correlation in the model are comparable to those in the observation.

During Belg season simple correlation of positive IOD years did not show any significant correlation on the country for zero and one month lag. But the negative IOD years is more significant on West Ahmara, Benishangul-Gumz and West Oromia Regional States for zero and one month lag. The Partial correlation did not correlate significantly on the country for both positive IOD years and negative IOD years for zero and one month lag (Table 5).

Generally the Indian Ocean Dipole plays a significant role during bega season on most part of the country. The positive IOD year had more significant role than negative IOD year by both simple and partial correlation on the country. The influence of Positive IOD year covers most part of the country during bega season for one month lag that is analyzed by simple correlation. The negative IOD year is significant after two month from the occurrence of IOD condition on most part of the country.

The correlation between DMI and rainfall during belg season indicates less significant than during bega season for both simple and partial correlation on most of the homogeneous rainfall Region.

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Appendix 1

Table 6) Tercile probability for below and above normal rainfall for both Bega and Belg seasons for Homogeneous rainfall region III. The bold asterisks are the selected IOD years.

Bega Season For Region III				Belg season For Region III			
Year	Tercile for Below Normal	Year	Tercile for Above Normal	Year	Tercile for Below Normal	Year	Tercile for Above Normal
1984	2.70	2004	67.57	1986	2.70	1989	67.57
1990	5.41	1993	70.27	2003	5.41	**2006***	**70.27**
1995	8.11	1987	72.97	2009	8.11	1985	72.97
2003	10.81	**2006***	**75.68**	2004	10.81	2011	75.68
1994*	**13.51**	1988	78.38	1988	13.51	**2015***	**78.38**
2010*	**16.22**	2013	81.08	2012	16.22	2008	81.08
1996*	**18.92**	**1998***	**83.78**	1990	18.92	**2016***	**83.78**
2007	21.62	2014	86.49	2002	21.62	**1997***	**86.49**
2002	24.32	**1982***	**89.19**	1999	24.32	1987	89.19
1985	27.03	**1992***	**91.89**	2013	27.03	1993	91.89
1986	29.73	1999	94.59	1984	29.73	2017	94.59
2016*	**32.43**	2000	97.30	1983	32.43	**1996***	**97.30**
		1997*	**100.00**			2014	100.00

Table 7) Tercile probability for below and above normal rainfall for both Bega and Belg seasons for Homogeneous rainfall region IV. The bold asterisks are the selected IOD years.

Bega Season For Region IV				Belg season For Region IV			
Year	Tercile for Below Normal	Year	Tercile for Above Normal	Year	Tercile for Below Normal	Year	Tercile for Above Normal
1984	2.70	2013	67.57	1986	2.70	**2010***	**67.57**
1981	5.41	2008	70.27	2003	5.41	**2015***	**70.27**
1986	8.11	1989	72.97	2002	8.11	**1997***	**72.97**
1985	10.81	2000	75.68	1988	10.81	**1994***	**75.68**
2007	13.51	**2015***	**78.38**	2004	13.51	1993	78.38
1991*	**16.22**	1988	81.08	**1982***	**16.22**	2017	81.08
1990	18.92	2014	83.78	1983	18.92	2007	83.78
2010*	**21.62**	1999	86.49	**1998***	**21.62**	**1991***	**86.49**
1995	24.32	**1998***	**89.19**	1984	24.32	1985	89.19
2011	27.03	**1982***	**91.89**	1990	27.03	2008	91.89
2005	29.73	**1992***	**94.59**	2009	29.73	**1996***	**94.59**
2003	32.43	**2006***	**97.30**	2005	32.43	**2016***	**97.30**
		1997*	**100.00**			2014	100.00

Table 8) Tercile probability for below and above normal rainfall for both Bega and Belg seasons for Homogeneous rainfall region V. The bold asterisks are the selected IOD years.

Bega Season For Region V				Belg season For Region V			
Year	Tercile for Below Normal	Year	Tercile for Above Normal	Year	Tercile for Below Normal	Year	Tercile for Above Normal
1981	2.70	2004	67.57	1984	2.70	1993	67.57
1985	5.41	2014	70.27	2000	5.41	1995	70.27
2010*	**8.11**	2000	72.97	2008	8.11	**1994***	**72.97**
1986	10.81	2009	75.68	1999	10.81	1985	75.68
1996*	**13.51**	2013	78.38	**1982***	**13.51**	1981	78.38
1984	16.22	2008	81.08	1988	16.22	2013	81.08
1990	18.92	**1982***	**83.78**	2009	18.92	2014	83.78
1988	21.62	**2015***	**86.49**	2004	21.62	**2006***	**86.49**
2007	24.32	1989	89.19	**2016***	**24.32**	1987	89.19
1995	27.03	2002	91.89	1983	27.03	**1996***	**91.89**
1987	29.73	2011	94.59	2017	29.73	2005	94.59
2005	32.43	**2006***	**97.30**	**1992***	**32.43**	1990	97.30
		1997*	**100.00**			**2010***	**100.00**

Table 9) Tercile probability for below and above normal rainfall for both Bega and Belg seasons for Homogeneous rainfall region VI. The bold asterisks are the selected IOD years.

Bega Season For Region VI				Belg season For Region VI			
Year	Tercile for Below Normal	Year	Tercile for Above Normal	Year	Tercile for Below Normal	Year	Tercile for Above Normal
1994*	**2.70**	2014	67.57	2009	2.70	**1998***	**67.57**
1981	5.41	2013	70.27	1984	5.41	**2006***	**70.27**
1984	8.11	**2016***	**72.97**	1999	8.11	2001	72.97
1990	10.81	2004	75.68	2008	10.81	1995	75.68
1985	13.51	2008	78.38	1988	13.51	2005	78.38
1986	16.22	1999	81.08	2000	16.22	**2016***	**81.08**
2012	18.92	1989	83.78	2012	18.92	1993	83.78
1995	21.62	**1992***	**86.49**	2004	21.62	1990	86.49
2007	24.32	**1998***	**89.19**	2002	24.32	1983	89.19
2010*	**27.03**	1993	91.89	**2015***	**27.03**	2014	91.89
1991*	**29.73**	2009	94.59	2003	29.73	**1996***	**94.59**
1987	32.43	**1982***	**97.30**	**1994***	**32.43**	**2010***	**97.30**
		1997*	**100.00**			1987	100.00

Table 10) Tercile probability for below and above normal rainfall for both Bega and Belg seasons for Homogeneous rainfall region VII. The bold asterisks are the selected IOD years.

Bega Season For Region VII				Belg season For Region VII			
Year	Tercile for Below Normal	Year	Tercile for Above Normal	Year	Tercile for Below Normal	Year	Tercile for Above Normal
1984	2.70	2005	67.57	1999	2.70	1989	67.57
2017	5.41	1993	70.27	2009	5.41	2001	70.27
1994*	**8.11**	2014	72.97	2008	8.11	1981	72.97
1990	10.81	2004	75.68	1988	10.81	**2006***	**75.68**
2012	13.51	2000	78.38	**1994***	**13.51**	2005	78.38
2015*	**16.22**	2013	81.08	2002	16.22	1986	81.08
1981	18.92	2008	83.78	2012	18.92	**1996***	**83.78**
1995	21.62	**1992***	**86.49**	2000	21.62	1990	86.49
1986	24.32	1999	89.19	**1997***	**24.32**	1993	89.19
1987	27.03	2009	91.89	1984	27.03	**2010***	**91.89**
2011	29.73	**1998***	**94.59**	2013	29.73	1983	94.59
1985	32.43	**1982***	**97.30**	2004	32.43	**2016***	**97.30**
		1997*	**100.00**			1987	100.00

Table 11) Tercile probability for below and above normal rainfall for both Bega and Belg seasons for Homogeneous rainfall region VIII. The bold asterisks are the selected IOD years.

Bega Season For Region VIII				Belg season For Region VIII			
Year	Tercile for Below Normal	Year	Tercile for Above Normal	Year	Tercile for Below Normal	Year	Tercile for Above Normal
2012	2.70	**1996***	**67.57**	1999	2.70	2005	67.57
2017	5.41	2004	70.27	2009	5.41	1986	70.27
1981	8.11	2013	72.97	2008	8.11	1981	72.97
2001	10.81	2014	75.68	2000	10.81	1995	75.68
1984	13.51	1993	78.38	2011	13.51	1983	78.38
1986	16.22	**1998***	**81.08**	**2015***	**16.22**	**2010***	**81.08**
1988	18.92	2000	83.78	2002	18.92	**1982***	**83.78**
1985	21.62	1999	86.49	**1992***	**21.62**	1990	86.49
1990	24.32	2009	89.19	2012	24.32	**2016***	**89.19**
2011	27.03	2008	91.89	1984	27.03	**1996***	**91.89**
2010*	**29.73**	**1992***	**94.59**	**1994***	**29.73**	1989	94.59
1995	32.43	**1982***	**97.30**	2007	32.43	1993	97.30
		1997*	**100.00**			1987	100.00

Table 12) Tercile probability for below and above normal rainfall for both Bega and Belg seasons for Homogeneous rainfall region IX. The bold asterisks are the selected IOD years.

Bega Season For Region IX				Belg season For Region IX			
Year	Tercile for Below Normal	Year	Tercile for Above Normal	Year	Tercile for Below Normal	Year	Tercile for Above Normal
1984	2.70	2000	67.57	2009	2.70	**2016***	**67.57**
2017	5.41	2004	70.27	2000	5.41	1986	70.27
2010*	**8.11**	2014	72.97	2008	8.11	1993	72.97
2012	10.81	**1992***	**75.68**	1988	10.81	1990	75.68
1981	13.51	1999	78.38	**2015***	**13.51**	**1982***	**78.38**
1986	16.22	1993	81.08	2011	16.22	2005	81.08
1985	18.92	**2006***	**83.78**	2012	18.92	1995	83.78
1990	21.62	2013	86.49	1999	21.62	1981	86.49
2011	24.32	2009	89.19	2002	24.32	1985	89.19
1995	27.03	2008	91.89	2004	27.03	1983	91.89
2015*	**29.73**	**1998***	**94.59**	2003	29.73	1987	94.59
1996*	**32.43**	**1982***	**97.30**	1984	32.43	**1996***	**97.30**
		1997*	**100.00**			**2010***	**100.00**

Table 13) Tercile probability for below and above normal rainfall for both Bega and Belg seasons for Homogeneous rainfall region X. The bold asterisks are the selected IOD years.

Bega Season For Region X				Belg season For Region X			
Year	Tercile for Below Normal	Year	Tercile for Above Normal	Year	Tercile for Below Normal	Year	Tercile for Above Normal
2010*	**2.70**	1987	67.57	2017	2.70	1983	67.57
1984	5.41	**1994***	**70.27**	1984	5.41	2007	70.27
1991*	**8.11**	1989	72.97	2004	8.11	**1991***	**72.97**
1986	10.81	2004	75.68	2002	10.81	1995	75.68
1996*	**13.51**	2002	78.38	2000	13.51	**1996***	**78.38**
2003	16.22	2001	81.08	2008	16.22	1989	81.08
2005	18.92	2008	83.78	2009	18.92	2013	83.78
2016*	**21.62**	2014	86.49	**1992***	**21.62**	1986	86.49
1990	24.32	2000	89.19	2011	24.32	1985	89.19
1988	27.03	2013	91.89	1999	27.03	1981	91.89
1985	29.73	**2006***	**94.59**	2003	29.73	**1982***	**94.59**
1981	32.43	**1982***	**97.30**	2014	32.43	1987	97.30
		1997*	**100.00**			**2010***	**100.00**

Table 14) Tercile probability for below and above normal rainfall for both Bega and Belg seasons for Homogeneous rainfall region XI. The bold asterisks are the selected IOD years.

Bega Season For Region XI				Bega Season For Region XI			
Year	Tercile for Below Normal	Year	Tercile for Above Normal	Year	Tercile for Below Normal	Year	Tercile for Above Normal
1991*	**2.70**	2008	67.57	1984	2.70	1986	67.57
2010*	**5.41**	2009	70.27	2017	5.41	**1997***	**70.27**
1986	8.11	2004	72.97	**1992***	**8.11**	**1994***	**72.97**
2005	10.81	**2015***	**75.68**	2011	10.81	**2010***	**75.68**
1996*	**13.51**	2014	78.38	2008	13.51	**1998***	**78.38**
1984	16.22	2002	81.08	2001	16.22	1988	81.08
2016*	**18.92**	**1994***	**83.78**	1999	18.92	1995	83.78
1998*	**21.62**	2011	86.49	2000	21.62	**1982***	**86.49**
1983	24.32	2000	89.19	2002	24.32	1989	89.19
1988	27.03	2013	91.89	2009	27.03	2013	91.89
2003	29.73	**1982***	**94.59**	2004	29.73	1981	94.59
1992*	**32.43**	**2006***	**97.30**	2014	32.43	1985	97.30
		1997*	**100.00**			1987	100.00

Table 15) Tercile probability for below and above normal rainfall for both Bega and Belg seasons for Homogeneous rainfall region XII. The bold asterisks are the selected IOD years.

Bega Season For Region XII				Bega Season For Region XII			
Year	Tercile for Below Normal	Year	Tercile for Above Normal	Year	Tercile for Below Normal	Year	Tercile for Above Normal
2010*	**2.70**	2009	67.57	1984	2.70	**2006***	**67.57**
1984	5.41	1989	70.27	2017	5.41	**1996***	**70.27**
1991*	**8.11**	2012	72.97	2011	8.11	1995	72.97
1990	10.81	2000	75.68	1999	10.81	2005	75.68
1986	13.51	2002	78.38	2000	13.51	1985	78.38
2005	16.22	**2015***	**81.08**	2008	16.22	1989	81.08
1981	18.92	2004	83.78	1983	18.92	2003	83.78
1985	21.62	2013	86.49	2004	21.62	**1982***	**86.49**
1996*	**24.32**	2008	89.19	**1992***	**24.32**	1987	89.19
1988	27.03	**1982***	**91.89**	2009	27.03	**2010***	**91.89**
1999	29.73	**2006***	**94.59**	2001	29.73	2013	94.59
1995	32.43	2011	97.30	2002	32.43	1990	97.30
		1997*	**100.00**			1981	100.00