Interannual Variability of Seasonal Rainfall and Associated Circulations over Gambella, Ethiopia

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To cite this article:

Waza Mulualem Abera, Wang Wen. Interannual Variability of Seasonal Rainfall and Associated Circulations over Gambella, Ethiopia. *International Journal of Environmental Monitoring and Analysis*. Vol. 9, No. 3, 2021, pp. 67-95. doi: 10.11648/j.ijema.20210903.13

Received: April 14, 2021; **Accepted:** June 7, 2021; **Published:** June 16, 2021

Abstract: Ethiopia composes diversified topographic structures; undulated plateaus and mountains, rugged valleys and plains. The highlands and ever-green portions of the country are fringed by the Sahara and Arabian deserts as well as East African arid climates. This study investigates the spatial and temporal seasonal (June-September [JJAS]) rainfall variability and the associated circulation patterns over Ethiopia. The study utilized ten daily station gridded rainfall, monthly SST, Outgoing Longwave Radiation (OLR) and zonal and meridional wind at various levels for 1983-2015. Statistical methods employed include EOF, composite and correlation analysis. The three leading EOF analysis revealed 57.8% that the first and second PC modes over Gambella are associated with ENSO and IOD variability. Wind and velocity potential revealed that wet (dry) years were characterized by convergence (divergence) in the lower level and divergence (convergence) at the upper level, implying rising (sinking) motion over the study area and western Indian Ocean. During normal (wet) years, maximum intensity of westerlies was generally observed at 850 hPa level, while easterlies were dominant at the upper level. There exists a significant correlation between JJAS rainfall and Nino3.4 for ENSO with r value (-0.56) but insignificant for (DMI) IOD with r value (-0.11). A cold (warm) summer SST over the central equatorial Pacific is associated with more (less) rainfall over Ethiopia. This shows that both ENSO and IOD modes have influence on rainfall variability during main rainy season. The findings of this and related studies is crucial to the development, planning and mitigation of all rainfall dependent activities.

Keywords: Rainfall, *Kiremt*, ENSO, IOD, Extremes, Wind, SST, Ethiopia

1. Introduction

Climate change characterized by increased in annual temperatures, changes in rainfall patterns threatens food security in low-income and agriculture-based economies [14]. Regional climate change variations in can be high, considerable spatial and temporal variations between climatically different stations [11].

Agriculture is the most dominant sector of Ethiopia's economy, contributing 42 to 45% of gross domestic product (GDP) and 80% of employments [8]. The sector is currently challenged mainly by climate related hazards. According to the [23], drought and flood are very common climate change-related hazards in Ethiopia, with

significant drought events occurring every 3 to 5 years. Rainfall in Ethiopia shows large variations across time and space, due to the complex topography and varying latitude of the country [20, 21]. This complex spatio-temporal variability of rainfall over Ethiopia is also linked to variations in sea surface temperatures (SSTs) over the Indian, Pacific and Atlantic Oceans [12], and the interseasonal and interannual variation of the strength of the monsoon over the Arabian Peninsula [18, 19]. A more complete understanding the spatial seasonal variation of these SST-to-rainfall teleconnections is very important to produce reliable weather and climate forecasts for users.

The spatial and temporal distribution of climatological rainfall in Ethiopia is largely controlled by the Inter Tropical Convergence Zone (ITCZ) [12]. The movement and intensity

of the African ITCZ varies from year to year, causing most of the interannual variability of seasonal rainfall over Ethiopia [12, 19]. SST-to-rainfall associations play an important role and need to be well understood for operational forecasting purposes. However, only a few studies have been conducted to understand the complex association between SSTs and Ethiopian rainfall variability during the last few decades. Most of these have focused on the predictability of June–September rainfall ‘*Kiremt*’, [5, 10] and [3, 13]. These and other related studies, such as [30] and [12] suggest that the interannual rainfall variability during this season is ultimately controlled by the El Niño–Southern Oscillation (ENSO) and the Indian Ocean, where warming/cooling events are associated with deficit/excess of rainfall over the central and northern half of the country. A few of these studies [19, 5] also reported the presence of some correlation between SSTs over the southern Atlantic Ocean and Gulf of Guinea and Ethiopian June–September rainfall. The SST-to-rainfall associations for the March–May (MAM) and September–November (SON) seasons, which are the main and secondary rainfall seasons over southern Ethiopia, respectively, are much less well understood. Only [6]. Has used the SST anomalies from the Atlantic, Indian and Pacific Oceans to predict the MAM rainfall. Although no study has been conducted for the southern Ethiopian September–November season, available studies conducted for the wider region of

Equatorial East Africa [17] show that anomalous warming (cooling) over the equatorial East Pacific and Indian Ocean are associated with enhanced (suppressed) rainfall amounts in this wider region.

Therefore, it is imperative to investigate the association of the tropical SSTs and wind features with *Kiremt* rainfall and avail the information for further use in forecasting and analysis of *Kiremt* season rainfall over Gambella regional state. This work is crucial for planning and designing Gambella Regional state’s climate variability adaptation, water resources management, agriculture practice, hydroelectric power generation among others.

2. Data and Methods

2.1. Area of Study

Ethiopia is characterized by diverse climatic conditions ranging from humid to semi-arid environments. Its climate system is largely determined by the seasonal migration of the ITCZ and a complex topography. Mean annual rainfall distribution ranges from a maximum of more than 2,000 mm over the south-western highlands to a minimum of less than 300 mm over the south-eastern and north-eastern lowlands. The mean annual temperature varies widely, from lower than 15°C in the highlands to more than 25°C in the lowlands.

Figure 1. Map of study area Gambella; Weredas, Ethiopia Elevation.

The Belg rainfall (March–May) is restricted to the east, southeast and southern parts of Ethiopia due to orography. Additionally, a meridional arm of the ITCZ, induced by the difference in heat capacity between the land surface and the

Indian Ocean produces rainfall over the southwestern Ethiopia in February and March [20]. During *Kiremt*, the Arabian and the Sudan low pressure ITCZ moves to the extreme northern Ethiopia along 15° N due to mountainous topography over

central part of Ethiopia. During September–November, the rain-fall over Ethiopia retreats towards the south following the southward migration of ITCZ. During winter season (December– February), the ITCZ is located well south of Ethiopia and the country predominantly falls under the influence of dry warm and cool northeasterly winds.

Gambella region (Figure 1) is located in the western tip of the country and has common borders with Sudan in the West, South and North, the Regional state of the South Nations Nationalities and People Regional States in the south and East, with The Regional state of Oromia in the North and East.

2.2. Data and Methodology

2.2.1. Data

The data used include global SSTs, winds (Zonal and Meridional), Relative humidity, stream function, sea level pressure, velocity potential, vertical velocity, outgoing longwave radiation and a selection of climate indices (i.e. Niño 3.4 and Dipole Mode Index [DMI]).

Two observed monthly rainfall data were utilized: adjusted rain fall reconstruction data sets were taken from the Ethiopia National Meteorology Agency (NMA) and gridded data from the Global Precipitation Climatology Center's (GPCC). GPCC dataset runs from 1901 to present. The data is discussed in detail by Schneider et al. (2011). GPCC data set has a resolution of $2.5^\circ \times 2.5^\circ$.

Table 1. List of rainfall stations and their coordinates.

No.	Station name	Longitude	Latitude
1	Abobo	34.6	7.9
2	Fugnido	34.2	7.4
3	Gambella	34.6	8.2
4	Lare	33.6	8.2
5	Baro bonga	34.9	8.2
6	Gog	34.3	7.4
7	Hukuna	34.7	7.9
8	Iliadura	34.2	8.1
9	Itang	34.2	8.1
10	kumi	35.2	7.2
11	Gnengnang	33.4	8.2
12	Puchala	34.1	7.4
13	pukadi	34.3	7.9
14	Pukumo (Akado)	34.2	8.1
15	Ruchi	34.2	7.5
16	Solan	34.4	8.2
17	Jor	34	7.6
18	koben	34.8	8.1
19	Meti	35.2	7.2
20	Dima	35	7.2

Based on data availability, quality and relative length of time, 20 stations (Table 1) were selected for the study with a reasonably good geographic distribution in the study area. The data is for the period 1983 – 2015, with a resolution of $0.1^\circ \times 0.1^\circ$.

The SST data for 1983-2015 used in this study is the Extended Reconstructed Sea Surface Temperature (ERSST) version 3b from the National Oceanic and Atmospheric Administration/National Climate Data Center. This data are available with resolution of $2.5^\circ \times 2.5^\circ$ latitude/longitude.

The NCEP/NCAR reanalysis data used include the zonal and meridional wind components, stream Function specific humidity, and velocity potential. The Outgoing Long wave radiation (OLR) data used in the study was obtained from the Climate Prediction Center (CPC), spanning from 1974 onwards with a resolution of $2.5^\circ \times 2.5^\circ$. For this study, a box $[0-60^\circ \text{E}$ and 10°S to $30^\circ \text{N}]$ was considered and OLR and SST data were similarly extracted for further analysis.

Nino 3.4 index was used in the study to describe the ENSO variability and that helped to verify the correlation between ENSO and IOD. The DMI was used in this study to quantify the Indian Ocean Dipole (IOD) [1, 17]. The SST data is available from Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST).

2.2.2. Methodology

This study utilized different methods: these methods Empirical Orthogonal Function (EOF), Correlation, Composite Analysis, t-test, coefficient of variation (CV), Standardized Precipitation Index (SPI), and Mann-Kendall's trend test.

Table 2. Excess and deficit of JJAS rainfall years selected for composite analysis.

Wet years	Dry years
1983	1984
1986	1989
1988	1997
1996	2000
2007	2002
2012	2015

3. Results and Discussions

The spatial rainfall distribution over the country varies according to the migration of ITCZ. In January the ITCZ is in the southern hemisphere in this month there is no any convection system over the country. February, march, April and May the main rainy season for south and southeast part of the country. The southern half of the country receives relatively high rainfall totals due to its proximity to the movement of ITCZ during Belg (FMAM) (Figure 3b). Over southwest parts of the country uninterrupted rainy season continue more than eight months. The main rainfall season spans from April to November over most parts of the southwestern Ethiopia. When the ITCZ shifts northwards, southern and southeastern regions remain dry throughout the *Kiremt* season, with seasonal rainfall totals of less than 300 mm (Figure 3a). In the study area *Kiremt* total rainfall receives from 600 to 1200 mm (Figure 3a).

From Figure 4 the *Kiremt* seasonal rainfall of the region in the lower elevation varies from 600 – 700 mm, in south west, west and central parts of the region. At higher elevation it ranges from 700-900mm, in central, north east and eastern parts of the region. Rainfall generally increases with elevation, from the lower elevation in the western part of the region 600 mm to at higher altitudes it ranges from in northeast and eastern parts of the region over 900 mm in *kiremt* season in the escarpment. Generally rainfall increased

from west to east part of the region. The most important weather systems that cause rainfall over Gambella Region

are northward migration of ITCZ and the development of Tropical Easterly Jet (TEJ) and its persistence [9].

Figure 2. Spatial precipitation distribution of monthly climatology (mm) based period 1983-2015 over Ethiopia.

Figure 3. Spatial Precipitation distribution of seasonal climatology (mm, 1983-2015) over Ethiopia.

Figure 4. JJAS spatial rainfall (mm) distribution over Gambella, 1983-2015.

Figure 5. (A) The first spatial mode EOF1 (27.0% of Variance) and (b) its corresponding time series.

3.1. Empirical Orthogonal Function Analysis

As the purpose of EOF analysis is to determine several functions that describe most of the variance in the data by defining the dominant modes using eigenvectors. And since the eigenvector corresponding to the largest eigenvalue of the covariance matrix is referred to as the leading EOF and the eigenvector associated with the second largest eigenvalue of the covariance matrix is referred to as the second EOF and soon. Figures (5-7) show the first three dominant modes of

variability of JJAS rainfall over the study region respectively. These three EOFs explain 57.8% of the total variance based on the stations data for 32 years used to build the eigenvectors. Figure 5(a) shows the spatial pattern of the leading eigenvectors (EOF1) of JJAS seasonal rainfall. It explain the positive loading all over the Region with depicting strong seasonal rainfall variability in the Western, central and northeastern part of the Region, while the weak positive loading is observed in the southern, north western and the central part of the region.

The area of positive loading is an indicator of high variability of rainfall in those areas and the low and negative loading is an indicator of less variability of rainfall in particular areas. It is evident that JJAS rainfall mostly occurs in eastern and north eastern part of the region and it is uniform with the average seasonal rainfall contributions to

annual rainfall totals in Table 5. This is consistent with the JJAS season long term mean over Gambella. Figure 5(b) shows the first EOF PC time series. PC1 had five (5) years of wet such as 1985, 1990, 1993, 2000 and 2004, whereas 4 dry years occurred in 1986, 1987, 1998 and 2007. The recent extreme dry and wet year's are 1986 and 1987, respectively.

Figure 6. (a) The 2nd spatial mode-EOF2 (16.9% of variance) (b). Its corresponding time series.

Figure 7. (a) The 3rd spatial mode-EOF3 (13.9% of variance) (b). Its corresponding time series.

Figure 6(a) shows the spatial pattern of the second eigenvectors (EOF2) of JJAS seasonal rainfall. It explain the two phases (i.e. positive and negative) loading over the region with the Positive loading in the southwest, south and pocket areas of northeast and southeast part of the region, while the negative loading is found in the western, northern and the pocket area of central part of the Region. As it is

explained, the area with positive loading is an indicator of high variability (suppress) of rainfall in those areas and the negative loading is an indicator of less variability (enhance) of rainfall in particular areas. EOF2 strongly agree with the theory that JJAS rainfall mostly occur in central, eastern and north eastern part of the region. Figure 7(b) shows the second EOFPC time series. PC2 had five (5) years of wet such as

1987, 1996, 1998, 2004, 2012 and (5) dry years are 1983, 1991, 1997, 1999 and 2007.

Because of its high percentage of variance (variability) than other EOFs, EOF 1 is referred to be a dominant mode and were taken in to consideration for the study of the circulation anomaly mechanisms were discussed.

3.2. Classification of Wet and Dry Years

Based on the EOF analysis, wet and dry years were

identified from the temporal variability (PCs) of EOFs. Although the method gives a good result, it isn't convenience for that instead SPI method which is specifically for identifying wet and dry years was used in this study Figure 8(a) gives the interannual variability of JJAS rainfall over the country. This was used for analyzing the wet and dry events when performing composite analysis method. The identification of dry and wet years was based on the inter-annual standardized rainfall anomaly.

Figure 8. (a) Temporal series of the areal average JJAS rainfall over Ethiopia and at (b) Gambella, Ethiopia.

From table 3; that the years 1984, 1987, 1997, 2002 and 2015 recorded below normal rainfall; dry years while 1988, 1998, 1999, 2007 and 2010 experienced above normal rainfall; wet year. The remaining years in between 1983 and 2015 received normal rainfall.

Table 3. JJAS flood/drought years in the period 1983-2015 and the respective standardized anomaly over Ethiopia.

Standardized Anomaly	Event	Years
2.0 and more	Extremely wet	1988
1.5 to 1.99	Very wet	2007, 2010
1.0 to 1.49	Moderately wet	1998, 1999
-0.99 to 0.99	Near normal	1983, 1985, 1986, 1989, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 2000, 2001, 2003, 2004, 2005, 2006, 2008, 2009, 2011, 2012, 2013
-1.0 to -1.49	Moderately dry	1984, 1997, 2002, 2014
-1.5 to -1.99	Severely dry	1987, 2015
-2.0 and less	Extremely dry	-

From Figure 8a and Table 3, show that the *kiremt* seasonal standardized rainfall over Ethiopia in the year from 1983 up to 2015. Most of the wet and dry years are occurred with La Nina and El Niño years correspondingly except year 1984. The year 1984 was the worst driest year in the history of Ethiopia even though occurred with upper level 200hPa easterlies (TEJ). The years such as 1984, 1987, 2002 and 2015 was dry and selected for composite analysis for further work. The wet years like 1988, 1998, 1999, 2007 and 2010 also selected for wet years composite analysis work. In addition to this in the Figure: 9b, and Table 4, showed that the *kiremt* seasonal standardized rainfall over gambella south western part of Ethiopia, in the year from 1983 up to 2015.

Most of the wet and dry years are occurred with La Nina and El Niño years correspondingly except year 1984. The year 2002 was the worst driest year in the used time series in gambella, Ethiopia. The years such as 1984, 1989, 1997, 2000, 2002 and 2015 was dry and selected for composite analysis for further work. The wet years like 1983, 1986, 1988, 1996 and 2007 also selected for wet years further analysis.

From Table 4 the years 1984, 1989, 1997, 2000, 2002 and 2015 are recorded below normal rainfall; dry years while 1983, 1986, 1988, 1996, 2007 and 2012 experienced above normal rainfall; wet year. The remaining years in between 1983 and 2013 received normal rainfall.

Table 4. JJAS flood/drought years in the period from 1983-2015 and the respective standardized anomaly over gambella region.

Standardized Anomaly	Event	Years
2.0 and more	Extremely wet	1988
1.5 to 1.99	Very wet	2007
1.0 to 1.49	Moderately wet	1983, 1986, 1996 and 2012
-0.99 to 0.99	Near normal	1985, 1987, 1990, 1991, 1992, 1993, 1994, 1995, 1998, 1999, 2001, 2003, 2004, 2005, 2006, 2008, 2009, 2010, 2011, 2013, 2014
-1.0 to -1.49	Moderately dry	1984, 1989, 1997 and 2000
-1.5 to -1.99	Severely dry	2015
-2.0 and less	Extremely dry	2002

3.3. Standardized Precipitation Index Analysis

Figure 9. Three month SPI at dry years (a) 1984 and (b) 2002 spatial JJAS rainfall over Gambella region.

From Figure 9 (a) year 1984 were most parts of the region affected by drought. From the SPI value category the red color showed that moderately dry in most stations except barabonga, dima, kumi and meti stations have yellow color which means near normal category according to SPI value class. In Figure 9 (b) year 2002 was almost all the stations are under drought with different anomaly types the western and northwestern part of the region which has red color the SPI value category is

extremely dry in year 2002. The stations represented by yellow color which have SPI value category is severely dry conditions. The stations which have green color the SPI value category is moderately dry conditions. Generally year 2002 were the most extremely dry year over gambella region compared to year 1984 and other drought years. Major droughts occurred during 1983 and 2002 across gambella, which affected over 80% of the study area.

Figure 10. Three month SPI, Severity of drought during 1984 and 2002 over different zones of gambella region.

A 3-month SPI reflects short - and medium-term moisture conditions and provides a seasonal estimation of precipitation. From Figure (10) year 1984 and 2002 the region was under drought except pocket areas such as Dima,

Kumi and Meti stations in the year 1984. From Figure (8b and 11) the temporal and spatial drought pattern year 2002 was the worst driest year in the history of gambella regional state of Ethiopia.

Figure 11. Three month SPI JJAS rainfall temporal patterns over Gambella region.

3.4. Annual and Seasonal Rainfall Regimes

Rainfall in the study area is generally high that varies slightly from 1172.5 mm at Jor to 1801.7 mm at Meti (Table 5). The *kiremt* contributes largely to the annual rainfall totals in all stations. However, its contribution varies from 551.3 to 894.2 mm which accounts for 47.1 to 62.7% each and every station.

Belg rainfall also makes a considerable contribution to the annual rainfall totals in some areas such as low at Lare (22.0%), Kumi (29.9%) and high at Meti (30.5%). Similarly, in the Amhara regional state of Ethiopia, *kiremt* and *belg* rainfall had contributed 55-85% and 8-24%, respectively to the annual rainfall totals [2]. The coefficient of variation in most stations revealed that rainfall in the region has moderate inter-annual variability (Table 6). The result indicated that annual rainfall at Meti ($CV < 9\%$) less variable and at Jor ($CV < 17\%$) was moderately variable. Moreover, *kiremt* rainfall variability for most stations was also moderate ($CV_{\text{nearly}} < 26\%$). In agreed, [2] reported moderate inter annual variability of *kiremt* rainfall in the Amhara regional state of Ethiopia. Considering the direct effect of *kiremt* rainfall on agricultural production, moderate variability could tremendously useful to the livelihood of the farming community in the region. Likewise, *belg* rainfall in the region showed moderate inter annual variability ($CV < 30\%$). Comparing the seasonal variability of rainfall in the region, *belg* rainfall is more variable than the *kiremt* rainfall. [21] noted that the rainfall variability over the central high land of Ethiopia during the

kiremt season was associated with the equatorial eastern Pacific sea level pressure, the southern oscillation index and the sea surface temperature (SST) over the tropical eastern Pacific Ocean. These authors further noted that the SST over the tropical eastern Pacific Ocean is negatively correlated with *kiremt* rainfall. The rainfall reliability almost in all seasons are range from 74 to 90% as moderate to high stability.

Table 5. Average seasonal rainfall contributions to annual rainfall totals in Gambella; from 1983-2014.

Stations	Annual (mm)	Kiremt (mm)	Belg (mm)
Abobo	1486.5	836.2 (56.3%)	356.8 (24.0%)
B/Bonga	1497.6	894.2 (59.7%)	368.2 (24.5%)
Dima	1445.4	551.3 (38.1%)	483.2 (33.4%)
Fugnedo	1416.5	767.5 (54.2%)	353.0 (24.9%)
Gambella	1401.5	835.0 (59.6%)	334.4 (23.9%)
Gog	1447.5	776.0 (53.6%)	364.0 (25.1%)
Hukuna	1485.0	836.2 (56.3%)	355.3 (23.9%)
Iliadura	1283.0	780.9 (60.9%)	286.2 (22.3%)
Itang	1285.4	781.5 (60.8%)	291.1 (22.6%)
Jor	1172.5	685.0 (58.4%)	275.9 (23.5%)
Koben	1404.8	834.0 (59.4%)	334.3 (23.8%)
Kumi	1735.4	818.3 (47.1%)	519.5 (29.9%)
Lare	1189.6	745.5 (62.7%)	263.9 (22.0%)
Meti	1801.7	861.9 (47.8%)	548.8 (30.5%)
Gnengnang	1285.9	783.1 (60.9%)	290.8 (22.6%)
Puchala	1327.7	729.4 (54.9%)	334.7 (25.2%)
Pukadi	1372.3	784.2 (57.1%)	327.0 (23.8%)
Pukumo	1314.6	795.5 (60.5%)	299.0 (22.8%)
Ruchi	1394.2	772.8 (55.4%)	341.3 (24.5%)
Solan	1342.8	808.9 (60.2%)	310.5 (23.1%)

Table 6. Coefficient of variation for annual, Kiremt and Belg rainfall and reliability Values for the period 1983–2014 in Gambella.

Stations	Annual CV	Reliability for Annual (%)	Kiremt CV	Reliability for Kiremt (%)	Belg CV	Reliability For Belg (%)
Abobo	11.6	88.4	14	86	20	80
B/Bonga	11.9	88.1	10.1	89.9	20.3	79.7
Dima	13.6	86.4	25.4	74.6	18	82

Stations	Annual CV	Reliability for Annual (%)	Kiremt CV	Reliability for Kiremt (%)	Belg CV	Reliability For Belg (%)
Fugnedo	13.5	86.5	16.8	83.2	18.2	81.8
Gambella	12.1	87.9	11.2	88.8	18.8	81.2
Gog	13	87	16.2	83.8	19.4	80.6
Hukuna	11.4	88.6	14	86	20.3	79.7
Iliadura	14.1	85.9	14.1	85.9	26	74
Itang	13.6	86.4	13.4	86.6	21.9	78.1
Jor	16.3	83.7	19.7	80.3	24.8	75.2
Koben	11.5	88.5	10.6	89.4	20.9	79.1
Kumi	9.3	91.7	14.3	85.7	13.9	86.4
Lare	15.4	84.6	16.9	83.1	24.7	75.3
Meti	8.4	91.6	12.7	87.3	13	87
Gnengnang	13.6	86.4	13.5	86.5	21.7	78.3
Puchala	13.1	86.9	16	84	19.3	80.7
Pukadi	12.8	87.2	14.9	83.1	19.5	80.3
Pukumo	13.5	86.5	13	87	21.8	78.2
Ruchi	12.7	87.3	16	84	17.5	82.5
Solan	12.6	87.4	12.2	87.8	20.1	79.9

3.5. Annual and Seasonal Rainfall Trend Analysis

The results of statistical analysis at 95% confidence level for annual rainfall data using Mann-Kendall test have both positive and negative trends. The results obtained for rainfall series indicated that all stations have showed positive trends for annual rainfall series. Positive value of Sen's slopes indicates an upward or increasing trend in all over the stations in the time series (Table 7). 11 stations out of 20 have statistically significant. Annual rainfall trend analysis is not statistically significant. Findings from national and regional level rainfall trends analysis reported both increasing and decreasing trends [15, 16]. Similarly, [15] who reported that analysis of the historical rainfall records in North and Central Ethiopia revealed that there has been trend of decreasing rainfall. However, the trend analysis of annual rainfall showed that rainfall remained more or less constant when averaged

over the whole country for 1951 to 2006 [14]. [10] Confirmed that regional variations can be much larger, and considerable spatial and temporal variations may exist between climatically different stations. The main season (June to September) season revealed negative trends at Kumi, Lare and Meti while positive at the rest of 17 stations. *Kiremt* shows non-significant trend at 0.05%. This season contributes the largest amount of rainfall to annual rainfall (Table 5). Similarly, seasonal rainfall trend analysis result from March to May season which showed negative trend in Dima and Lare with statistically insignificant (Table 7). However, analysis of seasonal rainfall trend analysis for the period of (1983 to 2014) shows rising trend for March to April at Gog and Fugnedo the trend is statistically significant at 0.05. The other stations are statistically insignificant except the decreasing trend in Dima and Lare. Rising trends of March to April rainfall provided moisture for main season land preparation.

Table 7. Trends of Annual and seasonal rainfall totals in gambella; Ethiopia for the period 1983-2014.

Stations	Annual		Kiremt season		Belg season	
	Z MK P value	Slope	Z MK P value	Slope	Z MK P value	Slope
Abobo	0.007 *	9.3	0.38ns	1.8	1.0ns	1.65
B/Bonga	0.12ns	6.2	1.0ns	2.2	0.38ns	1.64
Dima	0.08ns	5.8	0.77ns	0.9	0.77ns	-0.17
Fugnedo	0.01*	10.1	0.38ns	1.9	0.04*	2.02
Gambella	0.02*	7.6	1.0ns	3.2	1.0ns	3.29
Gog	0.008*	9.6	0.7ns	1.3	0.04*	2.11
Hukuna	0.007*	9.2	0.38ns	1.8	1.0ns	1.6
Iliadura	0.06ns	5.7	0.38ns	1.0	1.0ns	0.22
Itang	0.07ns	5.3	0.38ns	0.5	1.0ns	0.48
Jor	0.03*	7.0	0.38ns	1.8	0.38ns	0.5
Koben	0.01*	6.5	0.77ns	1.5	0.38ns	0.89
Kumi	0.12ns	4.7	0.77ns	-1.8	1.0ns	1.19
Lare	1.0ns	0.7	0.38ns	-1.5	0.77ns	-0.45
Meti	0.26ns	3.3	0.77ns	-2.5	1.0ns	1.10
Gnengnang	0.06ns	5.3	0.38ns	0.46	1.0 ns	0.5
Puchala	0.04*	9.9	0.77ns	3.0	1.0ns	0.9
Pukadi	0.006*	9.1	0.77ns	1.8	0.77ns	1.3
Pukumo	0.07ns	5.2	0.38ns	0.8	1.0ns	0.24
Ruchi	0.002*	10.0	0.77ns	2.1	0.77ns	1.58
Solan	0.03*	5.7	0.77ns	1.4	0.77ns	0.4

ZMK is Mann-Kendall trend test, Slope (Sen's slope) is the change (mm)/annual; ns is non-Significant trend at 0.05 and *indicates significant trend at 0.05 Significant level.

3.6. Rainfall Kiremt Season and Mean Circulation Systems

Figure 12 (a) show the location of Semi-permanent high pressure areas such as Azores High over North West coast of Africa, St. Helena and Mascarene high pressure centers over southern Atlantic and Indian Oceans during JJAS seasons. The intensification of the southern hemisphere high-pressures and the orientation of the main mountain ridges boosts moisture fluxes and hence wide spread rainfall over Ethiopia [11]. According to [4], from the end of June, because of the deepening in the Indian monsoon low further east, the south-westerly flow associated with the Indian south west monsoon spills over the Ethiopian high lands to reach the southern Red Sea, where it channeled until it joins the main Indian monsoon flow in the Arabian Sea. [7], explored the formation of low-level jet (LLJ) during the northern hemisphere summer over western Indian Ocean, bordering to the East African coast (Figure 12b). He further documented that over eastern Africa coast the low-level jet streams centered at about 1-1.5km and lie in the middle

of the day time convective layer. Low-level wind flows with its score centered in 850hPa over the Indian Ocean partly intrude in to the Ethiopian highlands while the large portion of this feature forms strong southwesterly flow to wards south Asia during the northern hemisphere summer season (Figure 12b). For Ethiopia's JJAS rainy season, low level flows play vital role in transporting moisture in to the country. During the June-September rainy season, the African Easterly Jet is depicted at 600hPa although its direct impact on Ethiopia's summer rain has not yet known (Figure 12c). Figure 12d shows the mean subtropical westerly jets and tropical easterly jet. TEJ originates from Southeast Asia as part of the Indian summer monsoon, with the maximum winds found in July-August at 150hPa near 10-15°N over Sudan, with velocities decreasing from 25 to 10m/s from east to west Sudan [18]. It plays an important role in facilitating deep cloud formation and steering monsoon cloud clusters, which are formed over the Arabia region in to the Ethiopian high grounds.

Figure 12. Climatology of June-September from 1983-2015, a) sea level pressure (mb), b) 850mb vector wind (m/s), c) 600mb vector wind (m/s) and d) 150mb vector wind (m/s). Shaded is magnitude of wind vector in m/s.

3.7. Typical Characteristics of Tropical SSTs During the Kiremt Season

The seasonal SST analysis depicted in Figure 13 indicates that the SSTs in the tropics have zonal distribution of temperature in most areas of the oceans. Meridional temperature distributions are observed over

south West Atlantic and Pacific Oceans around the southern tips of South America and Africa. The meridional SST distribution increases in size as the season progresses and during September it reaches its maximum extension. The SSTs in the tropics range from 16°C to 30°C. The relatively cooler SSTs with value around 16°C are found in the south eastern parts of the Pacific and

Atlantic Oceans around western tips of Southern Africa and South America in the southern hemisphere where the meridional SST temperature distribution is observed. The warmest SSTs are found in the northern Indian Ocean,

North West Pacific and equatorial Atlantic Ocean. The temperature in these areas range from 26°C to 30°C in all months of the *Kiremt* season. These patterns of tropical SSTs are shown in Figure 13.

Figure 13. Mean spatial distribution of SST (°C) during JJAS climatology (1983–2015).

NOAA (2013) defines ENSO state (e.g., ElNiño or LaNiña) as a departure from normal of the sea surface temperature (SST) in the Niño3.4 region of magnitude 0.5°C or more, lasting for at least five running three-month periods over the tropical Equatorial Pacific Ocean. The main ENSO signals found during the northern summer (Camberlin 2009), at which time a negative correlation is found with the Niño3.4 index, depicting lower than normal rainfall in the years of higher SSTs in the eastern equatorial Pacific (i.e., El Niño years). It is argued that each ENSO state (El Niño, neutral or La Niña) had its own influence on the rainy or dry season. From Figure 15 (a) the eastern and central pacific

ocean the sea surface temperature is ranging from -1.0 to -2.0°C, in western Indian ocean the SST varies from -0.5 to 0°C and in the south eastern equatorial Atlantic ocean has the value from 0.5 to 1.0°C in La Nina years. The sea surface temperature also described by the solid (dashed) lines positive (negative) values in Figure 14(a) and (b) respectively. In Figure 14(b) the sea surface temperature varies accordingly opposite to La Nina years. Over eastern and central Pacific Ocean value varies from 1.0 to 1.5°C, in western Indian ocean the SST varies from 0 to 0.5°C and while the SST over in south eastern equatorial Atlantic ocean the value varies from -1.0 up to 0°C.

(a) JJAS SST deg(c) La Nina years anomaly

(b) JJAS SST deg(c) El Nino years anomaly

Figure 14. SST composite anomalies (°C) a) for La Nina and b) El Niño years during June to September (1983–2015).

3.8. Circulation Anomaly Patterns Associated with Wet and Dry Events of JJAS Rainfall Season

3.8.1. Sea Surface Temperature

Figure 15. SST in contours and shaded area is for t test values during wet years (a); dry years (b) and composite years (wet-dry) (c). The red (blue) color indicate the significant (insignificant) region meaning warming (cooling) based on 95% of confidence level.

Sea-surface temperature (SST) is one of the important parameters related to the global ocean atmosphere system that plays a major role in studies of air-sea heat exchange and circulation pattern. On inter-annual scales, Indian Ocean, Atlantic Ocean and Pacific Ocean are known to affect East African rainfall directly [8]. Therefore, given this significance of SSTs in the global climate, the predictability in the tropics rely critically on accurate of SST patterns and trends since these Oceans have a direct effect on East Africa. Figure 15(a) shows that during wet years, Eastern and central pacific SST cold tongue and the west IO are neutral but near to the central and eastern IO which means that over those areas, SSTs are cold (cool) while over North and south east Atlantic Ocean, SSTs are warm (hot). Even though it shows that the areas are not too significant, but due to the presence of cold temperatures over the regions, the air becomes stable which is favorable for moisture transport over the study region the trade winds

are stronger than normal years. In Figure 15(b) the systems are completely changed the central pacific and near to the eastern Indian Ocean have warm core rising motion over this areas but in northern and south eastern equatorial Atlantic Ocean have a cold tongue high pressure area. In this case the trade winds are weaker than normal years because of this the moisture transport to the study area are deficient (divergent) system are developed. In Figure 15(c) the system is similar to the wet years in Figure 15 (a). The difference between wet and dry years composite analysis the trade winds are very much strongest than any other years, it is like La Nina years the study areas get excessive rainfall in this years because of the systems are more intensified anomalously in the south east pacific ocean high pressure with steep slope thermocline line and also high pressure in eastern Indian Ocean. These systems give excess precipitation over the study area and may occur floods in many parts of the country.

Figure 16. SST anomaly for dry years (a) 1984; (b) 2002 and (c) wet year 1988 (broken line is negative and solid lines are positive regions).

The positive SST events happen during dry years over both oceans. The implication of this is that, JJAS rainfall over the country are mainly influenced by Pacific (eastern and central), Indian (Western and eastern) Ocean SSTs and South eastern equatorial Atlantic ocean SSTs. Unlike other oceans (the Pacific and Atlantic), the Indian Ocean is bounded by a mass of land in the north. In order to have a closer view of the anomaly pattern of SST associated with wet and dry events, two dry years: 1984 and 2002, and a wet year (1988) were considered and the anomaly patterns of SST displayed over the Pacific ocean, Atlantic ocean and Indian Ocean, Figure 16(a) and (b) for dry years and (c) is for wet year respectively. Anomaly analysis in the SSTs during wet and dry Kiremt seasons indicated that the SSTs have distinct changes in their patterns from their normal pattern. SSTs either get colder or warmer than the long term mean temperature or show changes in their normal patterns. During the 1984, the subsequent Kiremt season failed and this condition caused the most catastrophic famine in the country's history. Areas in the northeast, northwest and northern parts of the country were heavily affected by the drought and also most parts of Gambella region were under moderately dry drought category. The SST anomaly assessment during 1984 Kiremt season. This can be seen from Figure 16 (a), the eastern parts of the South east equatorial Atlantic Ocean were warmer from the normal condition by up to 1.5°C . Cooler than normal SSTs were also observed in the western Indian Ocean that persisted during the 1984 Kiremt season. And also the cooler than normal SST condition which was observed in the central and eastern equatorial Pacific Ocean in this Kiremt season. Figure 17(b) displays results which are similar to the composite anomaly patterns Figure 18(b), where the sea surface temperature anomaly associated with the dry year, Figure 17 (b) was characterized by positive anomaly values (warm water) over the western Indian Ocean, eastern and central equatorial Pacific Ocean and south western and eastern Atlantic Ocean. The negative anomaly (cool water) over the southern Indian Ocean, North East of Pacific and North Atlantic Ocean. Figure 16(c) displays results which are similar to the composite anomaly patterns (Figure 17a), where the sea surface temperature anomaly associated with the Wet year, Figure 16(c) was characterized by negative anomaly values (cool water) over the western Indian Ocean, eastern and central Pacific ocean SST up -2.0°C and positive anomaly (warm pool of water) over the eastern Indian Ocean, south east and south west Atlantic ocean is warm, 0.6 to 0.8°C .

3.8.2. Wind Anomaly Patterns

Figure 17 shows wind circulation during wet and dry years. During wet years, the wind flow near the surface is mainly westerly over Ethiopia. A stronger westerly anomaly winds from Atlantic accompanied by humid Congo air mass flowing in to the country are generally warm and moist. The wind components; the zonal and meridional components of

anomalous 850 hPa winds develops a weaker anomalous cyclonic circulation (Figure 18a) during wet years over the Eastern equatorial Atlantic Ocean, Sharan desert and Yemen or Arabian land while high pressure occurred over central Indian Ocean.

Cold and moist air mass transported from south east equatorial Atlantic Ocean which bears westerlies and south easterly winds from Indian Ocean that favor rainfall formation over Ethiopia. At high level, winds are easterlies which develop anti-cyclonic circulation over the region the results showed sinking motion due to divergence at high level (Figure 18c). These westerlies wind at low level during wet years converge with south easterlies wind from Indian Ocean over the country. This agrees the north ward shift of ITCZ during wet years. Convergence at low level gives rise to vertical stretching, whereas divergence results in vertical shrinking, which suppresses convection due to subsidence. The situation reverses during dry years (Figure 17b). Low pressure developed over central Indian ocean, even though winds are moving from Arabian sea coming with moist air, it cross over the country with strong wind speed which means that all moist air are taken away which causes the region to become dry. In Figure 17d, during dry years winds at high level are westerlies. The Figure 17e and f are showing that the difference between wind differences wet and dry years the shaded are significant areas under statistical test over 0.05 levels. Figure 17 e, wind difference between wet and dry at 850hPa (Figure 17f), wind difference between wet and dry at 200hPa.

Wind and Velocity Potential Anomaly Patterns during Dry Year 1984

At low level, winds are easterlies for dry years at 850hPa in Figure 17(b) but the system is quite different in Figure 18(a) the high pressure system develop over Yemen and Arabian land it sinks down over the northern part of Ethiopia and low pressure was seen in eastern Indian ocean. The north easterly wind that stands from Yemen and Arabian land brings warm and dry air mass over most part of the country and there was north easterly flow over the region. In other part of the country such as south and south east had westerlies (wind) air mass flow which favors the transport of cold and moist air over this part of the country. In Figure 18 (b) high level 200hPa dry year 1984. Which showed easterlies flow occurred which is not expected in dry year. This year showed it is anomalous year than other dry year weather systems. The system is changed because of the anomalous warming in south eastern equatorial Atlantic Ocean in Figure 16 (a). This condition shows that the transport of moisture from the south western Indian Ocean is hampered by weak winds at this Kiremt season. In low level 850hPa the divergence area was in western side of Indian Ocean. While in the upper level at 200hPa the winds were easterly that means divergent in the upper level. Even though the season was in La Nina condition. This year was dry and totally

anomalous year for kiremt season rainfall over Ethiopia. In Figure 18 (a) at the 850hPa level, during 1984, relatively stronger easterlies were observed along approximately latitude 10°N and also along latitude 6°N with weaker variable flow in between. Maximum intensity of 3.7 ms⁻¹ was observed near the point 8°N, 40°E. A minimum in wind intensity is located at the point 5°N, 36°E within the region of study. A closed circulation is observed around this point of minimum wind intensity with weak westerlies to the south and relatively stronger easterlies to the north. Also, during the dry year a local anticyclone was observed in the winds near the point 7°N,

45°E. This local anticyclone seems to be a feature for the dry years. Two years were considered for further investigation, one wet year (1988) and a dry year (1984), Table 3) in order to depict the sinking/rising motion associated with the anomalous patterns of velocity potential/divergence (convergence) during a wet and a dry year. Figure 18 (c) reveals that in the dry year, the anomaly pattern was characterized by divergence over the western Indian Ocean, including the study area and the equatorial Pacific Ocean (at 850hPa), whereas at 200hPa, Figure 18(d), the regions experienced convergence in the upper level over the western Indian ocean.

Figure 17. Composite wind anomaly vectors for; wet years at (a) 850hPa; (c) 200 hPa; dry years at (b) 850hPa; (d) 200 hPa difference of wet and dry years (e) 850; (f) 200 hPa. Shaded are significant areas under statistical test at 0.05 levels.

over the study area. Negative anomalies over the equatorial central and eastern Pacific and positive anomalies over the Indian Ocean and East Africa indicate a Walker-Cell like response to the SST pattern with upward anomalies over the warm SST in the Pacific and balancing downward anomalies over the whole Indian Ocean [22]. This pattern already indicates that there are westerly wind anomalies in upper levels over Africa. Figure 19 (d) shows a very similar circulation anomaly in dry Kiremt seasons, the negative

(downward) velocity potential anomalies directly over Ethiopia indicate a direct effect of the cell-like circulation anomaly on Kiremt rainfall via the deficits of convection, similar to subsidence anomalies. The anomaly fields of velocity potential at 850 hPa (200 hPa) shows (convergence) divergence over the western Indian Ocean, in the region between 50°E, 90°E and 20°N, 20°S and (divergence) convergence over the central pacific ocean in region between 120°W, 170°W and 20°N, 20°S, among others.

Figure 19. Composite anomaly of velocity potential ($\times 10^6 \text{ m}^2 \text{ s}^{-1}$)/divergence (convergence) for wet years (a) 850hPa and (b) 200 hPa; for dry years (c) 850hPa and (d) 200 hPa. The solid (dashed) lines indicate (convergent/divergent) ascending/descending) motion contours intervals $0.4 \times 10^6 \text{ m}^2 \text{ s}^{-1}$. Shaded are significant at 0.05.

3.8.4. Pressure Vertical Velocity

Vertical velocity in Figure 20 describes the rising and sinking of air underlying surface characteristics over the study region. Figure 20(a) shows that during wet years at a fixed longitude 40°E, respectively, the region was characterized by negative vertical velocity or omega that means positive vorticity advection from lower level to upper

level, that there is ascending motion in western, southwestern and northern part of Ethiopia, which enhance the formation of precipitation over the region. During dry years Figure 20(b) and the region in the northern and south western part of the country was characterized by positive vertical velocity from low to upper level that there is descending motion which subsidence of the air mass formation positive omega and negative vorticity advection ridge (high pressure) area.

Figure 20. Vertical Velocity Anomalies; wet years (a) and dry years (b) at a fixed longitude 40°E . The red/ blue significant/insignificant area. The dashed (solid) lines show ascending (descending) motion. Negative (positive) values indicate upward (downward) motion. Contour interval 0.002 and units are in pas^{-1} .

Figure 21. Mean Sea Level Pressure (a) for wet years and (b) for dry years from 1983-2015, Units are in hPa.

3.8.5. Mean Sea Level Pressure

An extensive area of negative mean sea level pressure (MSLP) anomalies are centered over south western and western Indian Ocean and the East African coast and also extend west to the south of Africa during wet year case (Figure 21(a)). The reduced MSLP extends to the west across

the South Atlantic and to the north over the Arabian Peninsula, India, and central Asia. In contrast, positive MSLP anomalies occur over the eastern equatorial Indian Ocean associated with the cold SST tongue. Geostrophic theory [9] suggests that a near-surface low (high) will be generated in response to the warm (cool) SST forcing. This agrees with the analysis done in Figure 16.

Results show that during wet years Figure 21(a), Mascarene High (Indian Ocean high) weakens due to the presence of low pressure in the region (25°S – 50°S and 40°E – 110°E) and aligns itself in the zonal orientation. Moisture from Indian Ocean is freely transported (by easterly winds) into East Africa during wet years. And because of low pressure at East African coast. The area experience a lot of activities (convection) favored for rain formation. As the western pole is cooled from the western

side, the negative MSLP anomaly disappears from the western side during dry years. This is accompanied by the motion and extension of the positive MSLP anomaly toward the east of Indian Ocean. during dry years (Figure 21(b), Mascarene High intensifies and aligns itself in the southeast - northwest orientation, stretching up to the continent, which in turn inhibits the influx of moisture from Indian Ocean into east Africa by influencing the air flow.

3.8.6. Outgoing Long Wave Radiation

Figure 22. The OLR (Wm^{-2}) (a) for wet years and (b) for dry years from 1983-2015.

During this period, values of OLR below 240 Wm^{-2} are observed at longitude 10°E to 40°E (Figure 22). The axis of minimum OLR values starts at about 25°N , 35°E in the east and passes through the points of Equator, 10°E ; 50°E and then runs equator wards ending at the point 18°N . This axis of minimum OLR values marks the mean position of ITCZ during each month over the region. Thus, the ITCZ may be placed to the north of the equator in the east of 10°E and north of the equator between longitudes 5°S and 15°N . It is noted that the lowest OLR values ($< 240 \text{ Wm}^{-2}$) are centered near the point 5°N , 20°E during this period. From the area less than $< 240 \text{ Wm}^{-2}$ white shaded it is observed those areas have small values during June to September. The region of low OLR values starts to move northwards in the month of June to August. Noteworthy during this period is the wet zone over the study region. This wet zone is defined by the 210 Wm^{-2} white shaded. Emanating from this wet zone is a

'tongue' of low values of OLR with an axis along about 35.5°E and touching the 210 Wm^{-2} . This 'tongue' of low values of OLR is therefore important to the rainfall climatology of the study region.

For the 'long-rains' season in order to delineate the major years with low/high convective activity. These OLR which indicates low OLR values corresponding to anomalously wet years during 1988, while high OLR values representing dry years occurred during 1984. This OLR has also been able to delineate the years 1988 and 1984 as extremely wet/dry years. However, during the years of 1988 and 1984 OLR anomalies over the region had similar magnitudes but of opposite signs. The years 1988 and 1984 have been selected as the major anomalously wet and dry years within the study period. Positive value indicate that the OLR is above the mean value, in other words a dry spell and negative OLR means a wet spell.

Figure 23. Outgoing Long Wave Radiation (a) for wet year 1988 and (b) for dry year 1984 from (1983-2015); units are in w/m^2 .

3.8.7. Inter Tropical Convergence Zone

From Figure 24(a-d) the ITCZ position is over the North Africa. The surface air temperature over 15 degrees north of the Equator is varies 25°C to 30°C . The low pressure systems intensify over this region. The ITCZ, is a belt of low pressure which circles the Earth generally near the equator where the trade winds of the Northern and Southern Hemispheres come together. It is characterized by convective activity which generates often vigorous thunderstorms over large areas. It is most active over continental land masses by day and relatively less active over the oceans. The position of the ITCZ varies with the seasons, and lags behind the sun's relative position above the Earth's surface by about 1 to 2 months, and

correlates generally to the thermal equator. Since water has a higher heat capacity than land, the ITCZ propagates poleward more prominently over land than over water, and over the Northern Hemisphere than over the Southern Hemisphere. In July and August, over the Atlantic and Pacific, the ITCZ is between 5 and 15 degrees north of the Equator, but further north over the land masses of Africa and Asia. In eastern Asia, the ITCZ may propagate up to 30 degrees north of the Equator. In January, over the Atlantic, the ITCZ generally sits no further south than the Equator, but extends much further south over South America, Southern Africa, and Australia. Over land, the ITCZ tends to follow the sun's zenith point. Where the trade winds are weak, the ITCZ is characterized by isolated

Cumulus (Cu) and Cumulonimbus (Cb) cells. However, where the trade winds are stronger, the ITCZ can spawn a solid line

of active Cb cells embedded with other cloud types developing as a result of instability at higher levels.

Figure 24. ITCZ for June (a), July (b), august (c) and (d) September climatology from 1983-2015 and (e) January; (f) July daily precipitation climatology.

Figure 25. Spatial CORR over gambella region JJAS rainfall with a) Niño 3.4 and b) DMI. Stations with different correlation coefficient (r) value and significant at 95% confidence level ($p < 0.05$).

3.9. Correlation Analysis

Correlations between regional JJAS rainfall and indices (Niño 3.4, DMI) were investigated. From Figure 25a) stations which had light green color the correlation coefficient value -0.20 which means that this part of the region JJAS rainfall had weak downhill (negative) linear relationship with warm phase of ENSO. This part of the region had statistically insignificant correlation at 95% confidence level ($p < 0.05$). Other part of the region which have the correlation coefficient value from -0.33 to -0.59 had from weak downhill (negative) linear relationship to moderate (strong) downhill (negative) linear relationship with warm phase of ENSO. This part of the region had statistically significant correlation at 95% confidence level ($p < 0.05$). Specially areas which had the correlation value at -0.59 such as south eastern part of the region statistically significant with negative downhill at warm phase of central and eastern equatorial Pacific Ocean. Generally showed that the regional JJAS rainfall had negative correlation with the warm sea surface temperature in central and eastern equatorial pacific ocean at (Niño3.4 region 5°S-5°N, 170°-120° W) (Figure 25a). Therefore, the sea surface temperature over central and eastern equatorial pacific is warm the JJAS rainfall over the region will decrease anomalously, the reverse is true. In Figure 26b) showed that the correlation between JJAS rainfall over Gambella region stations and DMI the red color which had -0.29 correlation coefficient value weak downhill (negative) linear relationship with the warm western Indian ocean. The red shaded color stations such as Kumi, Meti, Dima and Gog had negative and statistically insignificant correlation at 95% confidence level

($p < 0.05$). the remaining stations which had the correlation value from 0.16 to 0.39 shaded colors yellow and light green weak uphill (positive) linear relationship with statistically insignificant correlation at 95% confidence level ($p < 0.05$), except stations such as Gambella town and Barobonga which have weak uphill (positive) linear relationship with statistically significant correlation at 95% confidence level ($p < 0.05$) the warm phase of the western Indian ocean. Generally most of the stations had weak uphill (positive) correlation coefficient value with statistically not significant with the warm sea surface temperature in western equatorial Indian Ocean at (DMI region 10°S - 10°N, 50°-70° E and 10°S - 0°N, 90°-110° E).

For June–September (hereafter JJAS), which is the main rainfall season over most parts of the country, also locally known as Kiremt, I found strong and statistically significant rainfall negative correlations with Nino 3.4 that SSTs over the equatorial central and east Pacific while weak not significant negative downhill correlation with DMI. The sea surface temperature are used for operational forecasts by the National Meteorological Agency of Ethiopia. I find that correlations with the IOD are statistically non-significant, the interannual rainfall variability in JJAS for gambella, South west part of Ethiopia associated modes of SST (Nino 3.4 and IOD) (Figure 26a, b) It is clear that interannual rainfall variability in these region is strongly influenced by the SSTs anomalies over the equatorial central and east Pacific and Indian Oceans. The negative correlations of rainfall over Gambella, Ethiopia in the JJAS season with ENSO (Nino 3.4) is stronger downhill ($r = -0.56$) than with the IOD ($r = -0.11$), in this study composites significant SST anomalies are mostly limited to the central and eastern Pacific Ocean.

Figure 26. Gambella, Ethiopia JJAS rainfall (RF) and (a) Nino 3.4 with $r = -0.5641$; (b) DMI with correlation coefficient (r) of -0.1095 . At 95% level of significance ($p < 0.05$).

Figure 27. CORR JJAS rainfall and SST (a) pacific ocean and (b) Indian ocean SST from 1983-2015.

Figure 27a shows the correlation patterns of global SSTs against the average rainfall for Gambella, Ethiopia for the JJAS rainfall season. The correlation between SST anomalies in Pacific Ocean and JJAS rainfall (Figure 27a) show strong negative loading in the central and eastern part of the Pacific Ocean. The findings agree with previous studies with the suggestions that the inter-annual SST oscillation in the tropical Pacific Ocean is connected to the changes in the atmospheric circulation and precipitation over a large portion of the globe. The anomalous SST over the equatorial central and east Pacific exerts some control over this region during JJAS. It is evident that the occurrence of drought and excessive rainfall over this region is somewhat associated with warm (El Nino) and cold (La Nina) events, respectively. The effect of ENSO on the onset and length of the Ethiopian Kiremt (June–September) season has also been reported [18]. The warming/cooling event is strongly linked with reduced/enhanced TEJ and EALLJ wind systems, and associated with deficit/excessive rainfall amounts over Gambella south west part of Ethiopia. Figure 27b shows the correlation patterns of global SSTs against the average rainfall for Gambella for the JJAS rainfall season. Spatial patterns of the correlations that were obtained between JJAS rainfall and Oceans SST are given in Figure (27a, b). As shown in Figure 27b, the JJAS precipitation is negatively correlated with western Indian Ocean. This weak downhill correlation indicates that when there is more than normal precipitation over the region, the western Indian Ocean SST tends to become less than normal. The Figure 27b revealed that the increased rainfall is associated with below normal SST in the western Indian Ocean and above average SST in the eastern part of the Ocean. It is evidence from Figure 27b, that the rainfall over the region is associated with west to east SST gradient over the Indian Ocean. This gradient is referred as IOD measured by DMI. This results agrees with the study done [10] and [18], this effect is exerted by weakening/intensifying the Mascarene high in response to the warming/cooling of the southern Indian Ocean, affecting the easterly flow on its northern flank, the moisture flux into East Africa, and then reducing/enhancing rainfall over Ethiopia. The findings of my study, therefore, support this view.

4. Summary and Conclusions

In this chapter the large scale atmospheric and oceanic controls on Kiremt rainfall have been studied and the main points are summarized below. For Kiremt, in most cases excess (deficit) year rainfall are associated with:

- 1) The three leading EOF analysis revealed 57.8% that the first and second PC modes over Gambella are associated with ENSO and IOD variability with variance.
- 2) Wind and velocity potential revealed that wet (dry) years were characterized by convergence (divergence)

in the lower level and divergence (convergence) at the upper level, implying rising (sinking) motion over the study area and western Indian Ocean.

- 3) During (wet) years, maximum intensity of westerlies was generally observed at 850hPa level, while easterlies were dominant at the upper level.
- 4) There exists a significant correlation between JJAS rainfall and Nino3.4 for ENSO with r value (-0.56) but insignificant for (DMI) IOD with r value (-0.11).
- 5) A cold (warm) summer SST over the central equatorial Pacific is associated with more (less) rainfall over Ethiopia.
- 6) A stronger (weaker) EALLJ leads to more (less) moisture from southern Indian Ocean penetrating in to east Africa and hence giving rise to more (less) favorable conditions for high rainfall.
- 7) A stronger (weaker) Tropical Easterly Jet (TEJ). A stronger (weaker) jet implies a strong (weak) divergence associated with the jet and hence more (less) convective activity over Ethiopia.
- 8) A stronger (weaker) easterly anomaly from Indian Ocean. The easterlies in the Indian Ocean are associated with the Arabian High, the Arabian High in turn may be associated with the Azores High

Acknowledgements

The authors are appreciative to all data centers that provided the datasets used in this study free of charge. The authors are indebted to NUIST for providing research supportive environment.

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