UNIVERSITY OF NAIROBI

SYSTEMS ASSOCIATED WITH WET SPELLS OVER KENYA DURING THE USUALLY DRY DECEMBER-FEBRUARY SEASON

BY

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DECLARATION

This dissertation is my original work and has not been presented for examination in any other University:

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DEDICATION

I dedicate this dissertation to my beloved family: My husband **Mr. Julius Leley** and our son, **Mr. Ivan Kiprotich.**

ABSTRACT

Most socio-economic activities in Kenya are rain-dependent with the occurrences of floods and droughts inflicting miseries at many locations year after year. Most of the rains in Kenya are experienced within two major rainy seasons every year and are centred on March-May and October-December. A third rainfall peak is observed at some locations in western Kenya in June-August. The months of late December to early February are however dry in most locations across the country.

The main objective of this study was to investigate the climate systems that may be associated with extremely wet conditions that are sometimes observed during the usually dry December-February (DJF) season in Kenya. The datasets used in this study included monthly and daily rainfall data for 32 seasons from DJF 1981/82 to 2012/13. Other datasets are wind downloaded from European Centre for Medium range Weather Forecasting (ECMWF), historical tropical cyclone (name, track, and dates they occurred), Sea Surface Temperature downloaded from National Oceanic and Atmospheric Administration (NOAA), and Madden Julian Oscillation (MJO) proxy values from Bureau of Meteorology (BoM) website. The data were subjected to several analyses including percent anomaly and correlation analysis.

The results from the study indicated that during DJF, wet conditions are observed during warm El Niño Southern Oscillation (ENSO) seasons regardless of the Indian Ocean Dipole (IOD) phase though the intensity increases during a positive IOD phase. The intraseasonal rainfall characteristics showed that although wet conditions spread throughout the DJF season, the highest amounts of rainfall is received during specific dekads. For example, during 1989/90 and 2012/13 DJF seasons, the rainfall received during the third dekad of December accounted for 61% and 70% of the long term mean respectively. These peak rainfall occurrences were associated with tropical cyclones occurring in the South West Indian Ocean. This study further observed that MJO's contribution to rainfall during DJF of the ENSO neutral seasons is insignificant. Results from this study provided information that can be used in water use planning through water harvesting for irrigation, disaster risk reduction by incorporating tropical cyclones in seasonal weather forecasting, among others in support of sustainable livelihoods and national development.

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Thanks to the **Almighty Lord** for seeing me through my university education this far and successive completion of this Masters dissertation. May His Holy Name be glorified forever. I would also like to take this earliest opportunity to thank my supervisors, **Prof. Laban Ogallo,** Director of IGAD Climate Prediction and Applications Centre (ICPAC), **Dr. Wilson Gitau and Dr. Alfred Opere** of Department of Meteorology at University of Nairobi (UoN) in Nairobi, Kenya, for their continuous guidance and encouragement. I cannot forget to thank the director of ICPAC for awarding me a scholarship to pursue this Master's Degree.

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LIST OF ACRONYMS

CPC	Climate Prediction Centre
DJF	December-January-February
ECMWF	European Centre for Medium range Weather Forecast
EEA	Equatorial East Africa
ENSO	El Niño Southern Oscillation
GHA	Greater Horn of Africa
GHACOFs	Greater Horn of Africa Climate Outlook Forums
ICPAC	IGAD Climate Prediction and Applications Centre
IGAD	Inter-Governmental Authority on Development
IOD	Indian Ocean Dipole
IRI	International Research Institute
ITCZ	Inter-Tropical Convergence Zone
JJA	June-July-August
MAM	March- April-May
MJO	Madden Julian Oscillation
NOAA	National Oceanic and Atmospheric Administration
OLR	Outgoing long wave Radiation
OND	October- November-December
PCA	Principal Component Analysis
RMM	Real time Multivariate MJO
SE/NE	South easterlies/North easterlies

SOI	Southern Oscillation Index
SOND	September-October-November-December
SST	Sea Surface Temperature

CHAPTER ONE

INTRODUCTION

1.0 Background

Climate over Kenya exhibits high variability in both space and time with frequent recurrences of floods and droughts that have far reaching impacts. Accurate weather prediction and early warning is, therefore, of great essence if life and property are to be safeguarded from the impacts of adverse weather. Climate forecasting practice has involved the use of both dynamical and statistical models at both regional and national levels. IGAD Climate Prediction and Applications Centre (ICPAC) have over the years organized Greater Horn of Africa Climate Outlook Forums (GHACOFs) which focus on seasonal forecasts for the Greater Horn of Africa. The forecasts have helped various sectors in the region to put necessary measures to reduce the effects of adverse weather.

Although most parts of Eastern and North Eastern Kenya are characterized by arid and semi-arid climate, with high space-time variability in rainfall, droughts are often preceded by floods. Since most economic activities over these areas are rain-dependent, they are highly affected during these seasons, and hence hindering economic growth (Gitau, 2011). In other cases, lack of pasture for livestock often results into conflicts among pastoralist communities. This has therefore, called for skillful weather prediction and early warning to ensure that necessary precautions are put in place and destruction of life and property reduced.

Kenya has two distinct rainy seasons: March to May (MAM), which is usually referred as the long rainfall seasons, and October to December (OND), which is the short rainfall season. Parts of western Kenya receive substantial amount of rainfall in June to August (JJA) while December to February (DJF), is generally dry over all part of Kenya. In some years however, the dry season of December to February (DJF), has received very heavy rainfall that often extends into the long rainy season of MAM. Some of these wet events have been linked to El-Niño (Nyakwada, 2009; Muhati *et al.,* 2007). Recent studies have however revealed that not all El-Nino conditions do lead to too much and extended rainfall in Kenya and many parts of Eastern Africa. El

Niño Southern Oscillation (ENSO) is a fundamental quasi-periodic ocean-atmosphere system feature with a period of at most 8 years (Rasmusson and Carpenter, 1983). Some rainfall anomaly extremes have had a close relationship with ENSO. Ropelewski and Halpert (1987) carried out a study on the relationship between the Southern Oscillation Index (SOI) and the global rainfall and found out that during El Niño years, abnormally wet conditions were expected even when the statistical association between SOI and Kenya rainfall was weak. Ogallo (1988) in his study showed that ENSO explains about 50% of variance in the Kenya rainfall. Other studies that have focused on the relationship between ENSO and East African rainfall include Shisanya *et al*. (2011).

In certain cases, extended wet conditions have been observed even with no major El Niño event. Some of the recent studies have also linked rainfall anomalies over the region to IOD (Ashok *et al*., 2001 and Owiti *et al.*, 2008). Some studies have tried to diagnose the characteristics of dry and wet spells during the rainy seasons over Kenya. Sharma (1996) studied the linkages of these spells with large scale circulation patterns and attributed the rainfall patterns over western and eastern parts of Kenya to moist easterly winds flowing from the Indian Ocean and the effect of the Rift valley highlands and westerly winds respectively. Similar results were obtained by Pohl and Camberlin (2006) and Omeny *et al*. (2008).

1.1 Statement of the Problem

During the dry season, natural resources like water and vegetation, especially for pastoralists, are highly stressed. These in many cases have resulted into conflicts among the affected communities. The increasing population and decreasing fertility of agricultural lands among other factors have increased the poverty level in Kenya. These socio-economic challenges have led to large scale deforestation in search of fertile farm lands. Deforestation and destruction of the limited environmental resources have somehow led to the changing climate, which is manifested in the form of floods and droughts. Occurrences of unusual wet spells with flash floods occurring during the dry season can be very destructive to livelihoods and socio-economic systems.

Occurrence of wet spells during the dry season also has positive impacts. These spells can help to reduce water stresses that are normally common during this season. Thus, if prediction of such wet spells and timely early warning information is provided, such information can be used for local drought and flood management and support of local disaster risk reduction strategies.

Previous studies on rainfall characteristics have focused on monthly, interannual, and seasonal time scales with little focus on combined seasonal and intraseasonal scales. Furthermore, the studies on intraseasonal scales have mainly concentrated on MAM and OND. From the current patterns of rainfall, however, it has been observed that the DJF season occasionally exhibits wet conditions, which can be of benefit to rain dependent sectors. It is, therefore, prudent to understand the systems and processes that cause the unusual December–February rainfall events over Kenya so that people can be able to properly utilize the available water resources to reduce water stress challenges that are associated with high rainfall variability in space and time.

This study, therefore, aims to address the intraseasonal rainfall distribution and provide knowledge on the dominant systems that may be associated with wet spells over Kenya during the December to February dry season.

1.2 Objective of the Study

The main objective of this study is to investigate climatic systems that may be associated with occasional wet spells that are observed over Kenya during the usually dry December to February season.

The specific objectives of the study are to:

(i) Identify anomalously wet years during the December- February (DJF) seasons;

(ii) Determine the distribution and the characteristics of the unusual wet spells during the DJF season;

(iii) Investigate the climate systems that may be associated with the unusual wet spells during the DJF season.

1.3 Justification of the Study

Climate over Kenya is quite variable in both space and time; in the recent times, several changes have been experienced in rainfall distribution and amounts especially on seasonal time scales. Above normal rainfall has been received in areas known to receive normal rainfall during the main rainfall seasons in the country and vice versa. When rainfall characteristics suddenly change, rain dependent activities are highly impacted (Usman and Reason, 2004). Heavy rainfall for the agricultural sector, for example, may lead to loss of yields depending on the stage of the crops. Too wet conditions during harvesting may destroy agricultural products such as maize.

Therefore, it is prudent to understand the factors that cause these variations especially on intraseasonal time scales. Although the December-February season over Kenya is usually a dry season, there are few cases where unexpected rains have been experienced. These cases include the 1997/98 where the short rains extended into February 1998 (Latif *et al.*, 1999). These wet spells were attributed to variations on ocean-atmosphere interactions. However, no detailed study has been undertaken to understand the drivers of the unusual wet spells in DJF season.

The knowledge of expected wet spells during the DJF season will help farmers to take advantage of rains that can fall during the DJF season, to grow early maturing crops. Alternatively, this water can be harvested and used for irrigation during dry periods. This enhances food security in the country.

The focus of this study would, therefore, be to investigate the specific systems that may be associated with wet spells observed during the DJF season and by extension enhance knowledge of the future weather/climate predictability when such systems prevail. Understanding the cause of these wet spells during the DJF season will help improve the knowledge of weather/climate patterns and help reduce loss of lives and property, enhance food security and promote economic development. It will also help forecasters give timely and early warning that can help various sectors such as water, agriculture, energy, health among others in planning

1.4 Area of Study

The area of study is Kenya, which is positioned at the east of the Congo basin and the west of the Indian Ocean. Kenya lies approximately between 5° S and 5° N latitudes, and 34° E and 42° E longitudes. It borders Tanzania to the South, Uganda and Lake Victoria to the west, South Sudan to the North West, Ethiopia to the North, Somalia and the Indian Ocean to the eastern side.

1.4.1 Geographical Features and Rainfall Climatology of the Region

The country has vast geographical features consisting of mountains, escarpments, forests, and lakes, among other features. The water bodies that are found within the area of study include Lake Victoria; which is shared by Uganda, Tanzania and Kenya, L. Turkana and L. Naivasha among other inland lakes. The presence of the Rift Valley System that runs from the north to the south across the country and the Turkana Low-level jet provide an environment where both local and global systems interact to create a climate that is quite variable in space and time. Deserts (e.g. Chalbi), Mountains (e.g. Mt. Kenya) and plateaus are other features found in the country. These features highly contribute to the type of rainfall received in the various parts with those lying along the coastal region experiencing convectional rainfall, and those in the highlands experiencing relief rainfall. Figure 1 shows the area of study with some of the dominant physical features.

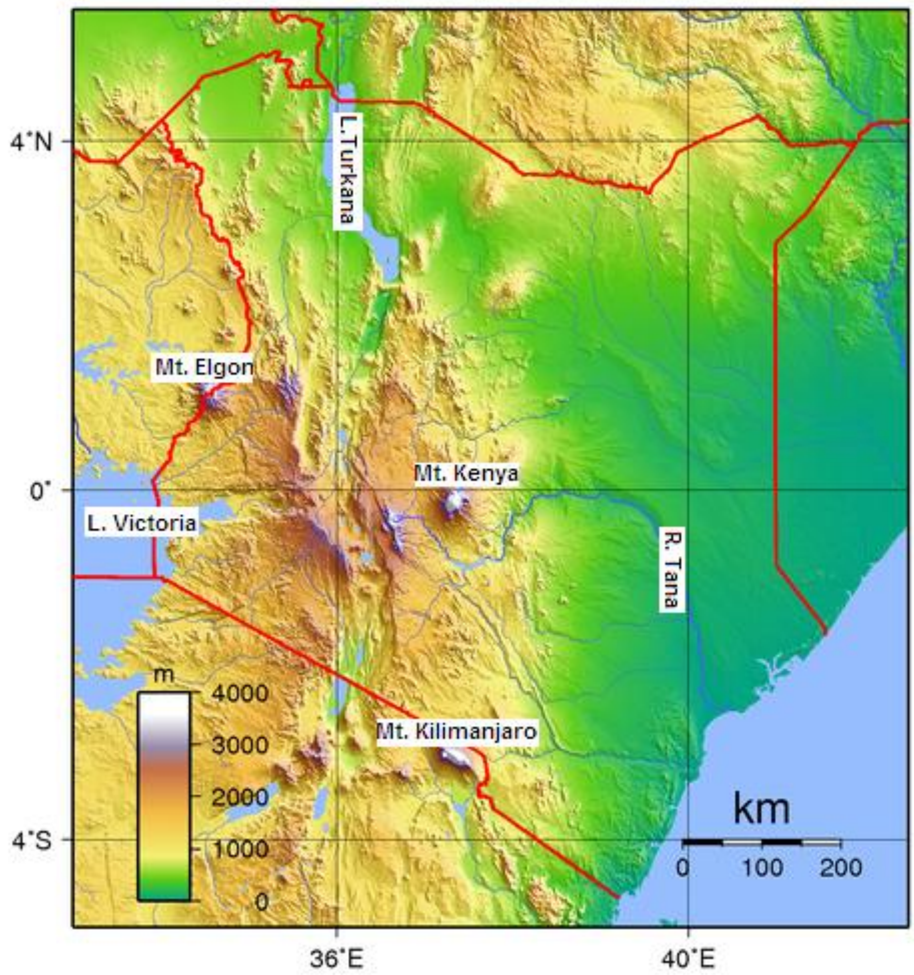


Figure 1: The study region showing altitude (M) and major Lakes and mountains. (Source: https://www.google.com/search?q=topography+kenya+map>)

Rainfall over Kenya varies significantly with some areas like the western parts experiencing longer rainfall seasons. Mt. Kenya and Kilimanjaro, and northwest of Lake Victoria are areas which receive high rainfall annually. The driest regions, which receive less than 400 mm annual mean, are mainly in the northeastern part of the country. The desert areas in the Northern part generally receive less than 200 mm with only small portions of Kenya receiving a little above 800 mm (Nicholson, 1996). Generally; the mountainous regions in the country receive the highest rainfall annually. The seasonal mean vary from one season to another over the country. The seasonal mean of the usually dry December to February is shown in Figure 2.

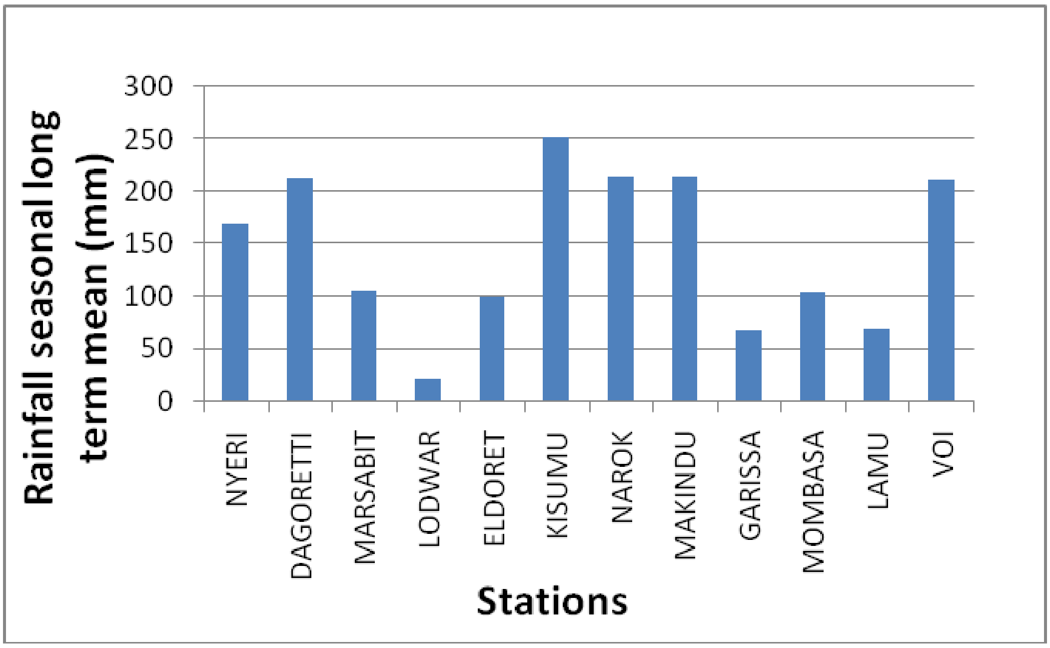


Figure 2: December to February rainfall seasonal long term mean (mm) for stations over Kenya

A larger part of the country experiences a bimodal seasonal rainfall distribution, with the maximum occurring in the two ITCZ transition seasons. Few other areas including part of western Kenya experience a third rainfall maximum during July-August. These rainfall distributions in the country are observed in different times and the peaks for unimodal, bimodal or trimodal distributions are also observed at different times of the year. This is attributed to the complex nature of the systems that cause rainfall over the various locations of interest. Some of these climatic systems are discussed in the next section.

1.4.2 Systems Influencing Rainfall over Kenya

The spatial and temporal variation of rainfall over Kenya is influenced by global, regional, and local systems. Studies have shown that the diurnal changes in the Kenya rainfall is highly determined by the mesoscale flows, synoptic scale flows, and their interactions (Mukabana and Pielke, 1996). These synoptic scale flows include subtropical anticyclones, westerly and easterly waves, monsoons, tropical cyclones, regional and global modes of variability, and jet streams.

1.4.2.1 Inter-Tropical Convergence Zone

Inter-Tropical Convergence Zone (ITCZ) is a narrow band of low pressure in which air masses moving equator-wards from the southern and northern hemispheres converge. This zone is characterized by high humidity, heavy precipitation, deep cloudiness, slow winds, and low pressure. The ITCZ over Kenya is complex, as it comprises of both zonal and meridional arms. The converging westerly and easterly winds from the Indian Ocean and the Atlantic Ocean respectively form the meridional arm.

The zonal (East-West) arm of the ITCZ moves North-South and brings rainfall in the areas it passes. The general passage of the ITCZ over Kenya has been known as the main factor causing rains during the MAM and OND seasons (especially in western Kenya and the Rift valley). A north-south pattern of rainfall is experienced due to the movement of the ITCZ, with most rainfall occurring during the MAM season (Nicholson, 1996). ITCZ is, therefore, the main synoptic system known to control the East African seasonal rainfall (Asnani and Kinuthia, 1979; Asnani, 2005).

1.4.2.2 Monsoons

Monsoons are low-latitude winds, which seasonally change direction. Depending on where the monsoon flows from (land (winter), water (summer)), they cause drastic changes in temperature and precipitation patterns on the area they affect. Monsoons are mainly caused by differential heating causing land-ocean pressure differences. Due to high temperature difference between land and water in the tropical region, monsoon winds are majorly confined to this region.

Kenya experiences two monsoonal circulations; the Southeast (SE) and Northeast (NE) monsoons. Okoola (1999) found out that these monsoons are experienced when the ITCZ is away from Kenya hence bringing little rainfall. The NE monsoon occurs during the DJF season originating from Arabian Peninsula and curves south of Equator to become a north westerly wind. During this season, this monsoon drives dry continental air to Kenya hence, it is associated with little or no rainfall. The SE monsoon on the other hand occurs during the JJA season and emanates from the south Indian Ocean with cool and moist properties due to the Mascarene highs. Reaching the north of equator, this monsoon re-curves to become south westerly flow. These two monsoons flow parallel to the coast and are diffluent in the low levels.

1.4.2.3 El-Niño Southern Oscillation

El-Niño is the anomalous warming of the central and eastern equatorial Pacific Ocean, where the sea surface temperature anomalies are of magnitudes greater than 0.5. If this anomalous condition persists for five or more months, the condition is termed as an El-Niño episode. Various studies have shown that there exist a relationship between East Africa rainfall and El-Niño (Ogallo and Suleiman, 1987; Muhati *et al*., 2007). Since El-Niño shows a peak in late December, its effect is highly felt during the short rains extending to the DJF season.

The El Niño Sea Surface Temperature (SST) changes cause key global weather and climate fluctuations and have significant consequences on water, health, food security, and energy sectors. On July 5, 2012 the NOAA Climate Prediction Center (CPC) and the International Research Institute for Climate and Society (IRI) declared that the consensus forecast, which was obtained from over 25 ENSO forecast models from major forecasting centers in the world reflects increased chances of 55 percent for a weak to moderate El Niño event beginning in August-September 2012 and continuing through early 2013 (Fewsnet, 2012). The El Nino, however, died off in November. The most devastating El Niño, which was felt worldwide, occurred in 1997/98. Flooding leading to loss of lives and property was experienced in many countries over the Greater Horn of Africa (Latif *et al*., 1999).

Other studies on the relationship between global climate systems and the total rainfall during the long rainfall season over Kenya have shown that there is no significant correlation especially with both atmospheric and oceanic components of ENSO. Weak positive rainfall anomalies are manifested on the onset of El Niño conditions and negative anomalies are experienced at the decaying El Niño phase. Therefore, the relationship between the long rains season and ENSO is still not clear although it has been reported that analyzing a month to month relationship gives better understanding of this season (Mutai and Ward, 2000)

1.4.2.4 Indian Ocean Dipole

This is a mode of climate variability that involves ocean and atmosphere interaction. The Indian Ocean Dipole (IOD), which is the difference between the sea surface temperature anomalies of the western and South eastern equatorial Indian ocean is taken from (50° E-70° E, 10° S-10° N) and (90°E-110° S, 10° S-0 °) respectively. Past studies (Saji *et al.,* 1999; Saji and Yamagata, 2003b; Owiti, 2005; Owiti *et al.,* 2008) have shown that the anomalous warm sea surface temperatures are sometimes experienced over the western Indian Ocean and cold SSTs over the Eastern region. This condition has been found to have a great influence on the rainfall over the East Africa region. Reason (2001) in the study over the Southern Africa showed that the winds from the Indian Ocean are influenced by IOD SST anomalies especially on the amount of moisture that is pushed to the region. IOD is said to be positive if the western Indian Ocean is warmer than the Eastern side, and vice versa. The positive phase of IOD is known to be of great influence on the rainfall condition over the East and South Africa region. It activates atmospheric convection and leads to enhanced rainfall during the rainy season and wet spells during the dry season. This phase causes an anomalous cooling of SST in the eastern tropical Indian Ocean and brings droughts in the Indonesian and Australian region. On the other hand, the negative phase involves high SSTs in the eastern Indian Ocean, which brings more rainfall to Australian and Indonesian region and less is experienced over the East African countries. Studies have also shown that just like ENSO, the IOD may induce unusual circulation and rainfall pattern in countries beyond the proximity of the Indian Ocean.

Owiti *et al.* (2008) analyzed the evolution phases of IOD, and showed that it starts developing in April and reaches the peak in October or November and starts decaying in January. This therefore implies that the SST anomalies pattern experienced during IOD events has a strong signal on the East African climate system during the OND rainfall season, hence indicating that some of the extreme events that have been experienced over the region have a close relationship with the negative and positive phases of IOD.

1.4.2.5 Intra-seasonal Oscillation

Intra-seasonal oscillation studies, which relate to tropical Africa and its adjacent oceans, include that of Zhu and Wang (1993). Madden Julian oscillation (MJO) is the major source of intra-seasonal variability over the region. Several studies have been done and it has been found that there exist eastward-propagating convective perturbations, which affect the Equatorial East Africa (EEA) region and generate rainy spells. The Madden Julian oscillation has a significant impact leading to enhanced rainfall over East Africa when it is in phases 2 and 3 during MAM and depressed rainfall when in Phases 5 and 6 during OND season (Omeny, 2006). A good number of these studies, however, have focused on its contribution during the short and long rainy seasons.

Changes on intra-seasonal oscillations in relation with MAM rainfall was studied by Okoola and Camberlin (2003), they used rainfall pentads, NCEP global reanalysis, and OLR datasets. They found that there exist intra-seasonal oscillations, which move across Equatorial East Africa and has a periodicity of 40-50 days. The study also showed that there are two or more active convection events for most seasons and one event for seasons with less rainfall. Omeny (2006) showed that strong configuration of 700hpa and 200hpa winds, and highly negative values of OLR occur during the phase 2 of MJO hence a clear indicator that East Africa rainfall at intra seasonal time scale is influenced by MJO.

The passage of MJO and its influence on the spatial extent of rainfall can be statistically analyzed by using Real time Multivariate MJO (RMM) indices (Zhang, 2013). The RMM index, which was first done by Wheeler and Hendon (2004) gives a real time signal that best describes MJO. These RMM indices also show the phases of MJO and the geographical location as shown in Figure 3.

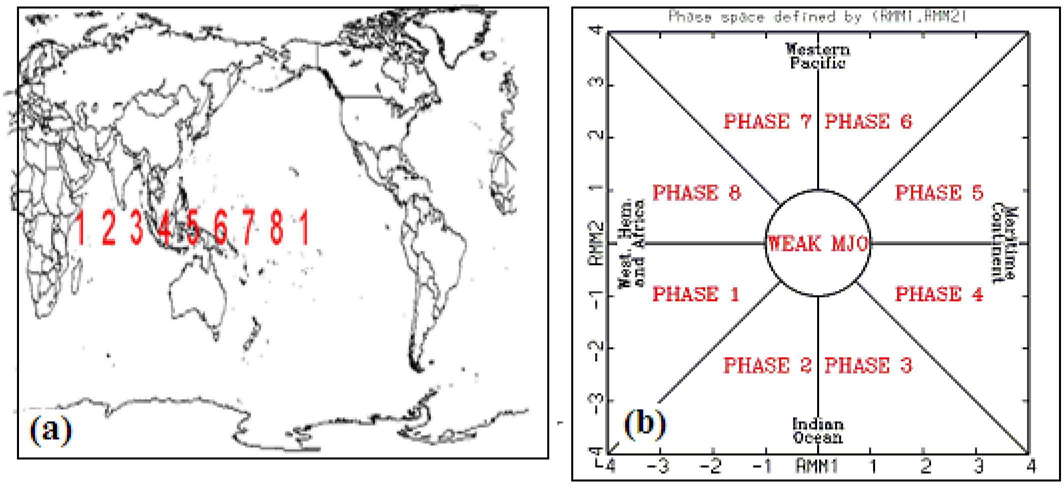


Figure 3: (a) Approximate locations of the MJO centre of convection and (b) RMM Index phases 1-8 (Source: Donald *et al.*, 2004)

1.4.2.6 Tropical Cyclones and Storms

A tropical cyclone is an intensified low pressure zone with minimum wind speed of 119 km/h while tropical storm is an area of low pressure with maximum wind speed of 117 km/h. A tropical cyclone is characterized by a counter-clockwise rotation in the Northern Hemisphere (NH) and a clockwise rotation in the Southern Hemisphere (SH). Its formation is favored by sea surface temperatures of at least 26.5° C. A fully developed cyclone shows a centre characterized by sinking winds, which forms an ‘eye’. This centre has calm weather free of clouds. Outside this eye is the ‘eyewall’, which has the highest wind speeds, rising air, cloudiness, and heavy precipitation (Zehnder, 2013). Cyclones’ season over South West Indian Ocean (SWIO) spans from October to May with peaks in January and February. A cyclone would in most cases decay when it strikes land due to lack of moisture that is a source of latent heat of condensation that provides the energy for its propagation.

Tropical cyclones and storms have both male and female names; the naming is done by regional bodies in charge of the respective basins. A number of names to be used for six years are proposed by the different countries’ members of the body in charge of the cyclone basin, and must meet specific criteria such as being short, easily understood when broadcast, culturally sensitive, and should not pass across unintended meaning (Landsea and Dorst, 2010). The name of a very destructive cyclone is retired once used. The cyclones and storms forming over the South West

Indian Ocean has greater influence on the rainfall over countries in the East Africa region compared to those over the East Indian Ocean (Elsberry, 2006). Tropical cyclones may cause rainfall during a dry season and suppresses during a rainfall season (Omondi, 2010).

1.4.2.7 Quasi-Biennial oscillation

Indeje and Semazzi (2000) examined the relationship between March –May seasonal rainfall anomalies over eastern Africa and the lower equatorial stratospheric zonal winds from 1964–1995. Spatial correlation patterns were studied to understand the climatic association between regional rainfall and equatorial stratospheric zonal wind at the interannual time scale. Results showed that during march-May, there is a significant positive simultaneous and non-zero lag correlations between lower equatorial stratospheric zonal wind and rainfall over parts of East Africa. Significantly high correlations (+ 0.8) were found over the western regions of eastern Africa. Furthermore, these month to month associations were observed to be outstanding during lag than in the simultaneous correlations and were observed after June preceding the onset of the March to May seasonal rainfall. The December–February season were observed to have the weakest relationship.

1.5 Mesoscale Systems Causing Rainfall

These are small scale weather systems covering a horizontal distance of between 5 km and 1000 km and periods of at most 1 day. Many mesoscale systems over Kenya are as a result of its location close to the ocean, availability of many mountains and valleys, and the many inland lakes. Some episodes of heavy precipitation can be attributed to these local systems. Examples of these systems include sea/land breezes, low level jets, rain bands, thunderstorms, gap winds, convergence zones, orographic lifting, and organized convective systems, among others.

Precipitation associated with orography is quite complex because orographic lifting can either trigger convection or destabilize the flow such that the convective cells are entrenched in a smooth ascending flow. Due to this problem associated with orographic flow, the amount and distribution of rainfall is highly affected in the area of interest causing a series of spells. It is therefore, essential to understand other processes that play a role in orographic lifting especially in areas where mountains are in direct contact with moist and unstable flows, which may cause forced lifting if synoptic conditions are favorable (Buzzi and Foschini, 2000)

Studies by Indeje *et al*. (2001) showed that orography plays a crucial role in influencing the occurrence of rainfall over many places in East Africa. This implies that the interaction between varying large scale flows and mesoscale circulations highly contribute to the spatial distribution of rainfall. Other mesoscale features like land and sea breezes, occur due to the difference in heat holding capacities of land and water (Luis *et al*., 2010). Water has a high specific heat capacity hence little temperature change while land warms faster during the day. The winds from the relatively cold lake move to the warm land, where the pressure is low. During the night hours, the ocean cools off slowly while the land cools fast creating low pressure in the warm lake. This makes the cold air from the land to flow into the lake forming a land breeze. Over Kenya, these mesoscale features occur along the coastal region and in Lake Victoria.

Oettli and Camberlin (2005) studied the influence of topography on rainfall distribution over North eastern Tanzania and southern Kenya and found that areas over the eastern parts of the mountain are wetter during OND season but remain dry during the monsoon season. This was attributed to slopes and changes in seasonal atmospheric circulation over the area of study.

Disastrous wet spells as a result of mesoscale convective system were experienced in Burkina Faso in 2009. Heavy down pour was experienced and in 10 hrs, the system caused floods in the capital city affecting 150 000 people with 9 deaths and loss of property and infrastructure (Poan, 2013). Similar systems also caused flash floods in Niger.

Surface forcings also have a great influence on the initiation of convection and mature storms. Vegetation forcing for example, cause divergence over cool boundary layer over a forested area hence generating convergence and cloud formation over a warm clear land surface. Since most surface forcings are stationary, they are more predictable and cause high rainfall over the area where they are stationed (Garcia-Carreras *et al.*, 2010).

CHAPTER TWO

LITERATURE REVIEW

This chapter is divided into two sections; past studies that have been carried out to help understand the characteristics of wet and dry spells over Kenya and other African countries, and the systems that were attributed to observed wet and dry spells in the past years.

2.1 Studies on the Characteristics of Wet Spells

Many researchers have examined the space-time characteristics of rainfall over the East Africa region especially during the principal rainfall seasons. Studies on the characteristics of wet and dry spells for the rainfall seasons over East African countries have been done by different people and the results differed depending on the areas of study. Tilya and Mhita (2007) studied the temporal and spatial characteristics of wet and dry spells in Tanzania during the rainfall seasons. They used the threshold of 1.0 mm of daily rainfall for a wet spell and observed that the frequency of 1 day wet spells at unimodal and bimodal locations were high in all locations and reduced smoothly as the season progressed. The longest wet spell of 25 days was observed during March-May season in the areas experiencing two rainfall seasons. Areas receiving unimodal rainfall had the longest wet spell of 28 days. The study also showed that wet spells lasting for over 10-days occurred during peak rainfall months and were seen to dominate in highlands and areas close to large water bodies like Lakes Tanganyika and Victoria and the Indian Ocean coast. Similar results had been found by Alusa and Gwage (1978) and Ogallo and Chillambo (1982).

Gitau (2005) studied the characteristics of wet and dry spells during the rainfall seasons over Kenya, using the thresholds of 1.0 mm, 3.0 mm and 5.0 mm to define a wet day, he found that the frequency of wet spells of 1 day were the most dominant for all the three thresholds. The study also showed that increasing the length of wet spells decreased the frequency of the spells. Longer spells were found to be dominant in wet parts of the country, except for few wet years which had wet spells in dry places known for episodic events. Further results showed that the conditional probability for the occurrence of wet spells of a given length decreased for all thresholds with increase in the length of the spell. Trend analysis results for some locations showed that on interannual timescales, there is a significant trend of wet and dry spells and rainfall amounts. A significant decreasing trend for 1.0 mm wet spells was observed in Nairobi during the long rains season. Results on wavelet band analysis showed 3 bands of spells of less than 10 days, 10-20 days and between 20 and30 days. The study showed that the 20-30 days wavelet band was as a result of the influence of MJO (Krishnamurti and Ardunary, 1980; Sikka and Gadgil, 1980; Kripalani *et al*., 2004)

Ochola and Kerkides (2003) in their study used Markov chain simulation model and found that in areas experiencing a bimodal rainfall pattern in the Kano plains of Kenya, the length of a critical dry spell was 14 days during the 'long rains' season and for the 'short rains' season, the longest dry spell was 12 days. The same study showed that the longest wet spells during the long rains and short rains season were 12 and 8 days respectively.

Ambenje *et al.* (2001) carried out an analysis on the frequency of days with rainfall above some amount and the trend of seasonal precipitation over countries in South and Eastern Africa. Using four seasons, the frequency of wet days of rainfall above 1 mm, 12.5 mm, 25.4 mm, 50.8 mm and 100 mm were studied. The results obtained showed that over the equatorial Africa, the frequency of those days receiving seasonal precipitation above certain thresholds tend to increase over the semi-arid and the coastal regions to the east and decreased in western parts, which are more humid. The increase in the semi-arid and the coast were prominent from September to November and DJF seasons. These characteristics were found to be as a result of the warm phase of ENSO.

Ngigi *et al.* (2005) studied the occurrence of dry spells over upper Ewaso Ng'iro and showed that there is a high probability of up to 80 % for 10 days and 20 days dry spell occurrence during the long and short rainfall seasons. Gitau *et al*. (2013) studied the spatial coherence of intraseasonal rainfall variation over equatorial east Africa during the MAM and OND rainfall seasons. The study showed that at sub-regional levels, the number of wet days and seasonal rainfall totals showed the highest spatial coherence. More coherence for other components was seen during the shot rains season than the long rains season.

The complex nature of Lake Victoria basin in terms of weather systems and orography gives a unique rainfall regime. Nguatha (1984) analyzed the rainfall characteristics over this basin with more interest on the frequency of occurrence of wet and dry spells of different lengths. Using thresholds of 1.0 mm and 5.0 mm for a wet day, the results showed that for each selected station, the frequency of wet and dry spells fell off exponentially from the shortest duration to the longest. The areas close to Lake Victoria experienced more frequent wet and dry spells of short duration while areas far from the lake like Kericho, experienced wet spells of longer durations. A number of stations received longer dry spells than wet spells of 1.0 mm. This shows that close to the lake, the rainfall received is in form of storms, which last for a short time of few minutes to few days while areas far from the lake receive continuous rainfall for over a week (Nguatha, 1984).

Bamanya (2007) in his study on the intraseasonal characteristics of daily rainfall over Uganda during the wet seasons examined the distribution and frequency of dry and wet spells. He focused on the spatial and temporal patterns during strong El Niño and IOD years. Results from this study showed that there was a high frequency of occurrence for 1 day wet/dry spell all over the country and exponentially reduced with an increase in the length of the spells. Long duration wet spells were observed over areas close to large water bodies and highlands. The study also showed that the conditional probability of these spells decrease from 1 day spell to longer spells. Results from wavelet analysis showed 3 bands of less than 10, 10-20 and 20-32 days for the Uganda rainfall seasons.

2.2 Studies of Systems Causing Wet Spells

Different climate variability modes have been used as indices to show the characteristics of the climatic conditions of an area of interest. These indices are known to cause different rainfall patterns including wet and dry spells. Owiti *et al.* (2008) studied the evolution of the IOD and the role of Indian Ocean SSTs in the East African rainfall. Considering the wettest and driest years during the MAM and OND seasons, the study showed a significant correlation between OND rainfall and IOD values and insignificant relationship during MAM rainfall seasons.

Gitau (2011) used ocean gradients among other predictors and found out that there exists a relationship between these gradients and the East Africa rainfall. The study showed that the 925 mb level wind signal persists from December to February and becomes weak in March-April. This Index showed an inverse relationship with rainfall totals, mean frequency of wet spells of 3 or more days, mean rainfall intensity, and the number of wet days. The zonal wind at 200 mb crossing the equatorial Africa into Atlantic Ocean was found to persist from July to December. There was a significant inverse relationship between this index and the wet days and the seasonal totals over the coastal Kenya and Tanzania. This was also experienced over the northern Kenya with the 3 day wet days. On the other hand, western and northwestern Tanzania, and southern Uganda showed a positive relationship.

The study further showed that the relationship between large scale signals and the intraseasonal wet spells during the long rains season was mainly from specific humidity and atmospheric fields of meridional and zonal components of wind. On the other hand, short rains were highly linked to SSTs.

Ward and Mutai (2000) carried out a study on the cause of wet spells in East Africa and came up with a conclusion that there exist an eastward migrating synoptic disturbance, which moves into East Africa and has a close relationship with westerly near-surface wind anomalies. These wind anomalies tend to develop 5 days before the onset of rainfall over the Greater Horn of Africa (GHA). They also noted that at this time, anomalous near surface easterlies tend to strengthen over the Indian Ocean hence enhancing the onshore component of the SE and NE trades. Jury and Mpeta, (2001) studied the evolution and pattern of East Africa's intraseasonal rainfall and the tele-connections with the regional circulations. They used OLR anomalies and winds at 850 hPa and showed that there exist an eastward propagation coupled with local circulation and convection. There were other quasi-stationary features observed with the westward propagating features being short-lived and weak. The intra-seasonal convective systems, which pass across the continent with small amplitudes showed an eastward propagation towards the Indian Ocean with increasing amplitudes. They also found that the MJO and strong equatorial convection favors wet conditions over this region and the western part of the Indian Ocean although drier conditions are experienced in much of the sub-tropical Africa.

Pohl and Camberlin (2006) studied the influence of the MJO on the rainfall amounts over the Equatorial East Africa during the March-May and October-December season. They noted that the wet spells observed in the region are entrenched in large scale zonal flow anomaly patterns along the equatorial region displaying an eastward movement. They further found that these wet spells have a high correlation with the MJO cycle, showing an out of phase relationship between the coastal areas and the highlands. MJO phases that cause wet spells in the Highland (western) areas are those linked with the development of large scale rising motions in the Indian Ocean region, the phases causing wet spells over the coastal (eastern) region are as a result of suppressed deep convection over the Indian Ocean. These contrasting weather patterns observed in the two regions during the opposite MJO phases are highly correlated with the pressure gradient between the Atlantic and the Indian Oceans. It was observed that most wet days in the western parts are preferentially occurring during particular MJO phases. Similar results were also obtained by Omeny *et al*. (2008). Although the MJO occurs after 30-60 days, this study mainly focused on the rainfall seasons with no consideration on its influence during the dry season.

Pohl and Camberlin (2006) further noted that during the MAM and OND seasons, precipitation is highly influenced by the MJO although the responses are spatially different. They also showed that the eastern and western regions of Kenya show an out of phase relationship such that when the western region is wet, the eastern region is dry and vice versa. These characteristics were attributed to topographical influence and the large scale zonal gradients of mean sea level pressure (MSLP) of the Indian and Atlantic Oceans. High rainfall amounts received over the western region was attributed to deep convection accompanied by ascending motions from 700-200 hPa levels. Considering the lower troposphere, advection of moisture from the Congo basin is said to trigger wet spells. Other studies on the impacts of MJO on rainfall in different parts of the globe are found in Julia *et al.* (2012); Yoneyama *et al*. (2013); Amanda and Rapp (2014); and Kiladis *et al.* (2014).

Other studies by Rui and Wang (1990), which used pentad outgoing long wave radiation (OLR) and the derived 200 and 850 hPa wind divergence from the European Centre for Medium range Weather Forecasting showed a dynamic structure of intra-seasonal convection anomalies along the tropics. This was confirmed by the studies by Mpeta (2001) who obtained the same observations. Murakami (1988), Anyamba (1992) and Matarira and Jury (1992) in their studies, which contrasted the meteorological structure of the intra-seasonal wet and dry spells over Zimbabwe, discussed intra-seasonal variability in the African sector but did not describe the evolution of synoptic-scale forcing and its relationship to local convection experienced during dry seasons.

Several studies have provided evidence of some large-scale interactions between the Indian Ocean and the overlaying atmosphere and indications of climatic consequences (Saji *et al.,* 1999; Webster *et al.*, 1999; Hastenrath, 2002; and Hastenrath et *al*., 2004). These studies related the Indian Ocean temperature distribution to increase/ decrease in rainfall over East Africa/ Indonesia. Webster *et al.* (1999) indicated that there is little statistical relationship between the IOD and El Niño; this is because the dipole has been observed to occur in both non-El Niño and El Niño years. This further explains why above normal rainfall can be achieved when the IOD is highly positive in a non-El Niño year.

A similar study over Tanzania was done by Kabanda and Jury (2000) who used ECMWF gridded meteorological data to diagnose the mechanisms that influence the intra-seasonal variability during the short rains and explained the synoptic processes that are responsible for development and sustenance of intense wet spells. The composite anomaly patterns obtained for major wet spells showed the presence of a strengthened anticyclone over the Southwest Indian Ocean and related westward moisture fluxes. There is also a northeast fluxes from the Arabian Sea, such that a line of confluence is maintained and moist unstable air uplift is sustained over northern Tanzania. This rising air is compensated by sinking motions occurring over the south Indian Ocean before the wet spell and over India during the event. Convection over the region is enhanced by an increase in upper westerlies in the equatorial band, which improve convective outflow.

Kenya lies within the tropics and most of the rainfall observed is from deep convective clouds, some extending to tropopause. Satellites show these clouds as regions of low OLR and cold temperatures. Nyakwada (2009) studied the relationship between rainfall and OLR, and based on Principal Component Analysis (PCA), results obtained showed similarities in temporal and spatial characteristics of rainfall and OLR. However, better results were obtained when areal average records were used compared to point station data.

The study on the midtropospheric circulation patterns associated with wet and dry episodes over Equatorial East Africa (EEA) by Okoola (1999) used ECMWF reanalysis datasets by analyzing the synoptic features. Using wind datasets for a dry and a wet year during the rainy seasons, the study showed that there exists a cyclonic circulation in the southern part of Madagascar; that produces a southerly flow moving through the Mozambique Channel. These southerlies then turn to westerlies at between about 10° S and the Equator. During this flow transition, the EEA experiences wet spells. It further showed that wet events occurring in the EEA during Northern hemisphere summer are as a result of westerly anomalies between the equator and the 10^{o} S latitude, and southerly winds below this latitude to about 30^{o}. Studies by Pohl *et al.* (2005) on topology of pentad circulation anomalies over eastern Africa-western Indian Ocean region and their relationship with rainfall showed that wind anomaly patterns associated with MJO were dominant.

The inter-annual rainfall variation in East Africa is linked to changes in the global SSTs over the Indian Ocean, and equatorial Pacific basins (Indeje *et al.*, 2001). The IOD and coupled IOD-ENSO interaction have hence been linked to the wettest periods experienced over the region like the case of 2006 long rains season (Bowden and Semazzi, 2007). Rainfall variability due to effects of IOD is nearly as strong as that associated with ENSO (Saji and Yamagata, 2003a) and because strong tropical rainfall anomalies may affect subtropical regions through stationary Rossby-wave propagation (Hoskins and Karoly, 1981), it is more likely that IOD events have quantifiable and major impacts on climate in the sub-tropics. A study by Saji and Yamagata (2003a) showed that there exist a positive correlation between IOD events and surface air temperature anomalies in both the southern and northern subtropics, with the southern subtropics being more strongly associated with IOD events.

The influence of tropical easterly waves on the East Africa rainfall has been studied in detail by Asnani (1993). These easterly waves are westward propagating perturbations moving within an easterly current. They are related to the formation of tropical cyclones and display different characteristics depending on the stage of development (formation, enhancement or decay). Passage of an easterly wave over an area is recognized by the change in the weather condition and surface pressure. Another study by Kabanda (1999) showed that convection is increased when upper level westerlies within the equatorial band increase. This impact is felt in Uganda and western Kenya during July and August.

Tropical cyclones influencing weather over Kenya and the neighboring countries always form in the West Indian Ocean. They form in regions of high Coriolis force, which help to generate a cyclonic circulation. These intense depressions occur during certain times of the year and have different names depending on the region they occur. In Australia for example, they are called Willy-Willy, and Southwest Indian Ocean, they are referred to as cyclones. In the southern hemisphere the peak of formation of cyclones is in January-February, and they are associated with severe weather, which in many cases leads to loss of life and property. Although these systems rarely hit the East African coastal region, there are few cases like 1972 and 1984 where they struck the coast and caused a lot of rainfall in northern Kenya. However, the location, track, and season of the cyclones highly affect how the cyclone influences the rainfall. It can cause an increase or a reduction on the amount of rainfall over a region of interest depending on the season they occur (Omondi, 2010; Dare, 2012).

A study by Camberlin and Wairoto (1997) on the daily wind anomalies associated with wet and dry spells over Kenya showed that for the two main rainfall seasons, there is a significant relationship between winds and rainfall. The study showed that between the 500 and 850 hPa levels, there are strong easterlies, which result into little rainfall or dry conditions over the country especially during the long rains season. Divergent wind anomalies are observed in the lower troposphere during the short rainfall season. The western part of Kenya experience wet conditions when the there is anomalous convergence and the prevailing winds are predominantly westerly. The results obtained further showed that wet spells observed in the eastern part of the country are not associated with westerlies but rather easterlies during the short rainfall season.

Nyakwada *et al.* (2009) in their study on the Atlantic-Indian Ocean Dipole and its influence on East African seasonal rainfall used wind composite anomaly for MAM, and SOND with extreme negative and positive categories of the sea surface temperature gradient modes, and showed that negative values of SSTs gradient modes are associated with easterly wind anomalies in equatorial central Indian Ocean and westerlies over East Africa and equatorial West Indian Ocean during MAM. This wind pattern favors enhanced rainfall over East Africa through interaction of the easterly wind currents flowing from the Indian Ocean and the Congo air mass. During SOND, the study showed that the extreme negative values of SST gradient modes have high relationship with southerly surface winds in the south-eastern Atlantic Ocean, and Western and southern Indian Ocean. These results confirmed those obtained by Anyah *et al*. (2006).

A study by Zorita and Tilya (2002) on the variability of rainfall and its links to large scale systems in northern Tanzania during the March-May showed that there exist a linkage between the zonal thermal contrast between the East African land and the Indian Ocean and the rainfall received during March and April while the May rainfall is associated with meridional thermal contrast between the Asian continent and the Indian Ocean.

From the available literature, it should be noted that many studies have put more focus on systems influencing rainfall during the main rainfall seasons (MAM and OND). It is also clear that most studies have analyzed these systems on inter-annual and seasonal timescales. This study, therefore, aims to fill the gap of intra-seasonal analysis during the DJF season.

CHAPTER THREE

DATA AND METHODS

This chapter gives the description of the datasets, which were used together with the methodologies adopted in this study in order to achieve the objective of the study as outlined in Section 1.2.

3.1 Data

The datasets used in the study included daily and monthly gauge rainfall data, Madden Julian Oscillation (MJO) proxy indices, Tropical cyclones tracks, Sea surface temperature, ENSO indices, and wind data. The following are detailed descriptions of these datasets.

3.1.1 Rainfall Data

Both daily and monthly gauged rainfall amount for the 12 representative stations over Kenya were used. The monthly rainfall data spans for 32 years, from 1981 to 2013. The 12 representative stations were derived from ICPAC's regional homogenous rainfall zones that have been used in many previous studies and seasonal forecasting during rainfall seasons (Omeny, 2006).

Table 1 show the name and the geographical location of the stations used while Figure 3 shows the distribution of the gauge stations and the near-homogeneous zones for the study area. This network of stations was taken as the most representative for the daily data. These data were obtained from IGAD Climate Prediction and Application Centre (ICPAC), and the Kenya Meteorological Services.

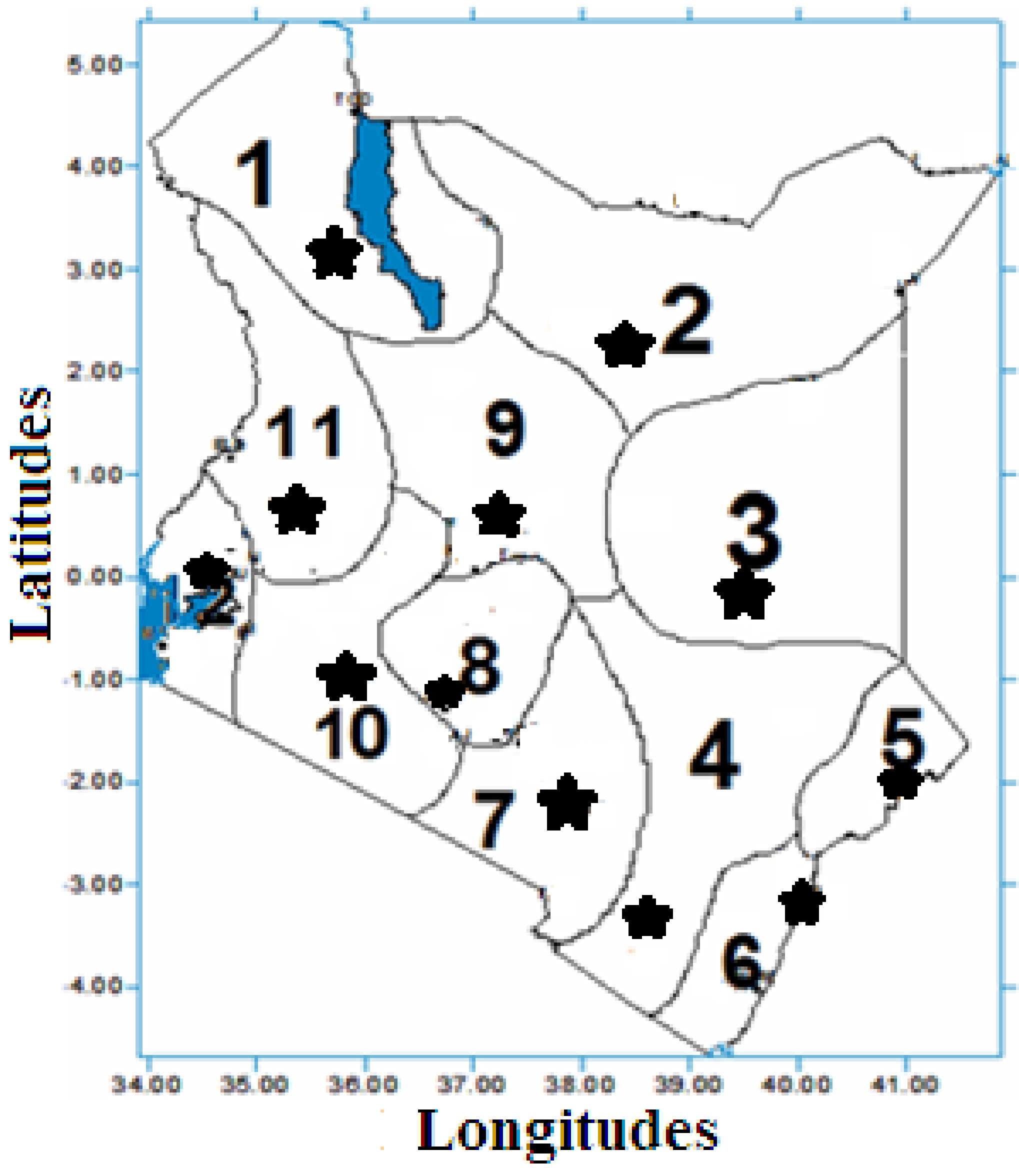


Figure 4: A map of Kenya showing near-homogeneous climatic zones over Kenya for December-February (DJF). The stars show the approximate locations of the stations used (Source: ICPAC, 2010).

Table 1: Location Details of the Rainfall Stations Used in the Study

Zone	Station	Latitude (°)	Longitude (°E)	Elevation (m)
1	Lodwar	3.12 N	35.62	566
2	Marsabit	2.32 N	37.98	1219
3	Garissa	0.47 S	39.63	128
4	Voi	3.4 S	38.57	579
5	Lamu	2.27 S	40.9	9
6	Mombasa	4.03 S	39.62	57
7	Makindu	2.28 S	37.83	1000
8	Dagoretti	1.3 S	36.75	1798
9	Nyeri	0.5 S	36.97	1768
10	Narok	1.13 S	35.83	1890
11	Eldoret	0.53 N	35.28	1036
12	Kisumu	0.1 S	34.58	1146

3.1.2 Wind Data

This study also utilized the once daily full resolution ECMWF Re-Analysis (ERA)-Interim wind data (0600hrs) from the European Centre for Medium range Weather Forecast (ECMWF). The spatial resolution is 0.75^0 latitude by $0.75\ ^0$ longitude for the lower and upper levels (850 and 200mb). It is in this part of the atmosphere (between 850 and 200mb) that active weather is exhibited. 850 mb gives a level where the surface has no much influence on the wind speed and direction. These data between 25°S and 25°N latitude and 15°E and 60°E longitude for the study period were downloaded from the ECMWF data server.

Over East Africa, Murakami and Sumathipala (1989), Mukabana and Pielke (1996), Okoola (1999), and Gitau *et al*., (2014), among others have successfully used the ECMWF datasets for various studies. Evaluation of NCEP/NCAR, NCEP-CFSR, ERA-interim, ERA-40 against sounding observations over Tibetan plateau and Ireland have shown that ERA-interim has a better representation of the actual sounding observation (Mooney *et al*., 2011; Bao and Fuqing, 2013). Studies by Lin *et al.* (2014)

compared the skills of five re-analysis datasets (ERA-40, ERA-Interim, NCEP-2, Modern-Era Retrospective Analysis for Research and Applications (MERRA), and Japanese 25-yr Reanalysis Project (JRA-25)), showed that ERA-Interim has the highest skill in reproducing the climatology of Global monsoons. These researchers have shown that the ERA-Interim re-analyses were good approximations of the real flow fields. ERA-Interim also has higher resolution compared to other re-analysis datasets.

3.1.3 Madden Julian Oscillation

Daily Madden Julian Oscillation (MJO) dataset for the period of study were downloaded from Bureau of Meteorology (BoM) Australia website. This dataset consist of daily Real time Multivariate MJO 1 (RMM1) and Real time Multivariate MJO 2 (RMM2) indices. These RMM values are the first two Empirical Orthogonal Functions (EOFs) of the combined fields of near-equatorially-averaged 850 hPa zonal wind, 200 hPa zonal wind, and the satellite-observed outgoing longwave radiation (OLR) data (Wheeler and Hendon, 2004). The OLR is an indicator of convective areas while winds show the propagation of MJO. These RMM values were earlier used by Omeny *et al.* (2008) in their study on the relationship between MJO and rainfall over East Africa during the main rainfall seasons and proved as a good indicator for MJO. These indices are therefore used as an MJO proxy in the current study to determine its relationship with daily rainfall during the otherwise dry season of December-February.

3.1.4 Historical Tropical Cyclones and Storms

Tropical cyclones and storms occurring over the South West Indian Ocean were used in this study. Tropical cyclones developing in this part of the Indian Ocean are tracked by the Regional Specialized Meteorology Centre (RSMC) La Réunion. The track, name, and dates of occurrence of tropical cyclones occurring from December to February were downloaded from the South West Indian Ocean cyclone portal. This cyclone data also give the intensity of each of the cyclone.

3.1.5 Sea Surface Temperature

Daily high resolution Sea Surface Temperature (SST) over the south west Indian Ocean (between 25° S and 8° N latitude and 30° E and 65° E longitude) for the period of study was downloaded from the National Oceanic and Atmospheric Administration (NOAA) website. The horizontal resolution for this data is 0.25° latitude and 0.25° longitude. Sea surface temperatures have been used in many studies to show its correlation with seasonal rainfall (Nyakwada, 2009). Over the Greater Horn of Africa, SSTs over the Indian Ocean and Atlantic Ocean have been used as rainfall predictors for seasonal forecasting.

3.1.6 El Niño Southern Oscillation and Indian Ocean Dipole Indices

Historical El Nino southern oscillation (ENSO) indices were obtained from the Climate Prediction Center (CPC) website. The ENSO indices for 32 years used in this study were separated for El Niño, La Niña, and Neutral phases for the period of study. India Ocean Dipole (IOD) indices on the other hand were obtained from ICPAC. These IOD data were also categorized into positive, neutral and negative phases. Negative IOD phase have an index less than -0.4 while positive phase have an index greater than 0.4, values between these positive and negative indices are considered neutral.

3.2 Methodology

Before the rainfall data were subjected to any analyses, missing data were estimated and homogeneity test undertaken to test the quality of the data. Details of these are discussed in the subsequent sections.

3.2.1 Estimation of Missing Rainfall Data and Homogeneity Test

Many long-term meteorological data have a number of gaps where data were not recorded. This problem among others has been the major drawback in research. The missing data should be filled with the highest precision and their quality tested in order to provide reliable near-homogeneous series. Missing data can be filled by using regression, correlation, and arithmetic mean methods. Only stations (Eldoret 4%, Voi 2%) with less than 10% of missing monthly data were filled using correlation and arithmetic mean method shown in Equation 1. Details if this method is documented in De Silva *et al*. (2007). There were no missing daily data.

$$x_i = x_o \frac{\overline{x_i}}{\overline{x_o}} \quad \text{..............................} \ (1)$$

In Equation 1, χ_i is the estimated data, X_o is the data of the station with highest correlation with station whose data is missing, while $\overline{x_o}$ represents the mean value for the station with complete data. $\overline{x_i}$ is the mean value for the station with missing data.

The single mass curve method was used to assess the quality of all data. A straight line is obtained for homogeneous records. Other patterns reflect heterogeneous records and to adjust these records, double mass curves are often used (Omondi, 2010).

3.2.2 Determination of Anomalous Wet Seasons

In order to achieve the first specific objective, major wet December-February seasons within the study period were identified. This was obtained by first normalizing the seasonal rainfall and converting to percentage by using Equation 2.

$$X_t = \frac{100X_{tj}}{\bar{X}_j} \quad \text{........................... (2)}$$

Where X_t is the percent of mean, X_{tj} is the seasonal rainfall total, while $\bar{X}_j$ represent the seasonal long term mean for 30 years (1981-2010). The X_t values thus obtained were used to define the above normal, near normal and below normal rainfall categories (Table 2).

Table 2: Classification of Rainfall Anomaly Categories

Scenario type	**Anomaly range (%)**
Above Normal	$X_t>125$
Near Normal	$75<X_t<125$
Below normal	$X_t<75$

3.2.3 Definition of a wet day and Determination of Wet Spells

In order to meet the second specific objective of this study as outlined in Section 1.2, the first step is to delineate the wet and dry spells. Different authors have adopted different thresholds to define a wet spell depending on the aspect of the spells being considered. Most recent studies have defined wet and dry spells locally such that a wet (dry) spell of length **i** is a sequence of **i** wet (dry) days preceded and followed by a dry (wet) day (Gitau, 2011). Further, some studies have adopted a number of thresholds to define a wet day (Ambenje *et al*., 2001; Gitau, 2005; Tilya and Mhita, 2007; Bamanya, 2007). Ambenje et al. (2001) for example, used 5 different thresholds (1 mm, 12.5 mm, 25.4 mm, 50.8 mm and 100 mm). Although a wet spell definition by Gitau (2011) have been widely used over the Greater Horn of Africa region, the current study adopts the criteria earlier used by Pena and Douglas (2002) such that a wet day is defined as a day when at least 35 % of the stations recorded at least 1mm of rainfall, and a wet spell is defined as a sequence of wet days. A local definition of a wet day is a day in which a station received rainfall of at least 1 mm. This 1 mm threshold was used to ensure that the sample size of the data remain substantially enough for analysis given that DJF is a dry season and that higher thresholds would reduce the sample size. This threshold was earlier adopted by Frei *et al*. (2003).

3.2.4 Space-time Characteristics of Wet Spells

Identifying wet spells that occur within a season and selecting areas where they dominated was done by tallying the number of stations that recorded 1 mm of rainfall or more for each day within the season. This distribution was plotted in a graph for easy counting. The days that met the criteria for a wet spell as outlined in sub-section 3.2.3 were analyzed. During the whole season, the month which had a large number of wet days was identified and the dominant space-time patterns delineated. Areas where such spells were dominant were also noted. These areas were the Western highlands (Eldoret), South Rift valley (Narok), Coast (Lamu and Mombasa), Lake Victoria basin (Kisumu), Central highlands (Nyeri and Dagoretti), North eastern (Garissa), South western low lands (Makindu and Voi), and Northwestern area (Turkana).

3.2.5 Correlation Analysis

Correlation analysis technique gives the simple relationship between two variables. In this study, this analysis was used to assess the extent of association between daily rainfall and the Madden Julian Oscillation (MJO) over Kenya. In order to categorize the MJO amplitude and phases, the method used by Wheeler and Hendon (2004) was adopted. This method was developed based on Empirical Orthogonal Function (EOF) analysis of average zonal winds at 850 and 200 hPa and outgoing Longwave Radiation (OLR). The two leading EOFs namely RMM1 and RMM2 values were used in this study. The correlation between MJO indices (RMM1 and RMM2) and daily rainfall for each of the stations were computed for DJF season. This was done for the periods when MJO was active in all the phases (when the amplitude was equal to or greater than 1). This method was earlier used by Omeny *et al.* (2008). Given the number of observations as N, then the correlation coefficient showing the relationship between variables **x** and **y** was computed using Equation 3**.** To test for the significance of the calculated correlation coefficients, the student t test was used. This is given in Equation 4.

$$r = \frac{\sum_{i=1}^{N}(x_i - \overline{X})(Y_i - \overline{Y})}{\left[\sum_{i=1}^{N}(x_i - \overline{X})^2 \sum_{i=1}^{N}(Y_i - \overline{Y})^2\right]^{1/2}} \qquad \text{.....................(3)}$$

$$t = r\sqrt{\frac{N-2}{1-r^2}} \qquad \text{.. (4)}$$

Where **r** is the correlation coefficient between X and Y, X and Y are daily rainfall and RMM values respectively, N is the total number of observations, $\overline{X}$ and $\overline{Y}$ are the rainfall and RMM long term mean respectively.

The values of **t** obtained using this technique was then compared with the tabulated value such that **t** is significant (insignificant) if it is greater (lower) than the tabulated value at 95% level of significance.

3.2.6 El Niño Southern Oscillation and Indian Ocean Dipole Events

ENSO events, which are known to develop over the Pacific Ocean, are felt globally due to the response by the Indian and Atlantic Oceans. The three ENSO phases namely El Niño, La Niña, and Neutral phases have significant effects on the rainfall characteristics over Kenya and other East African countries. In the current study, all the wet seasons were grouped into three categories according to the prevailing ENSO phases. After grouping these seasons, further analysis was done for IOD phases during these wet seasons. IOD is a phenomenon of the Indian Ocean and hence have significant influence in the rainfall characteristics over East Africa. In this study, wet seasons associated with El Niño coupled with positive, negative and neutral IOD phases were identified and analyzed. This was also done for other wet seasons associated with La Niña and neutral ENSO phases.

3.2.7 Sea Surface Temperature, Tropical Cyclones, and Wind Vector Patterns

Daily Sea Surface Temperatures (SSTs) downloaded from the National Oceanic and Atmospheric Administration (NOAA) were averaged and plotted for days when tropical cyclones occurred in the South West Indian Ocean (SWIO). The SSTs from NOAA were chosen for this study because they are readily available in daily time steps. The mean SSTs during the time of occurrence of cyclones were plotted to determine whether the minimum temperatures (26.5° C) required for cyclone formation were achieved.

The daily wind vectors were downloaded from the ECMWF website. Mean daily wind vectors were plotted for the days when tropical cyclones occurred in the SWIO. The strength and orientation of winds were analyzed to identify whether there were areas of confluence or difluence hence the observed weather patterns. Winds originating from the Indian Ocean or the Congo basin carry substantial amounts of moisture that can precipitate over the area of study. Areas where convergence occurs, experience upward motion resulting to cloud formation and precipitation if there is enough moisture and condensation nuclei (Okoola, 1999). During the time of occurrence of the cyclones, the space-time patterns of the winds at 850 mb and 200 mb levels were individually investigated.

CHAPTER FOUR

RESULTS AND DISCUSSION

This chapter discusses the results that were obtained when various methods as outlined in Section 3.2 were applied. Results of quality control analysis are discussed first.

4.1 Data Quality Control Results

The few missing data in the representative stations were estimated using the correlation and mean ratio method as indicated in Section 3.2.1. Examples of homogeneity test done by use of single mass curves are presented in Figures 5, and 6. All the data showed that a single straight line could be fitted on cumulative rainfall amounts for any station. This is an indication of the degree of homogeneity of the data being used in this study. These quality controlled data formed the foundation of all analyses that were carried out in this study.

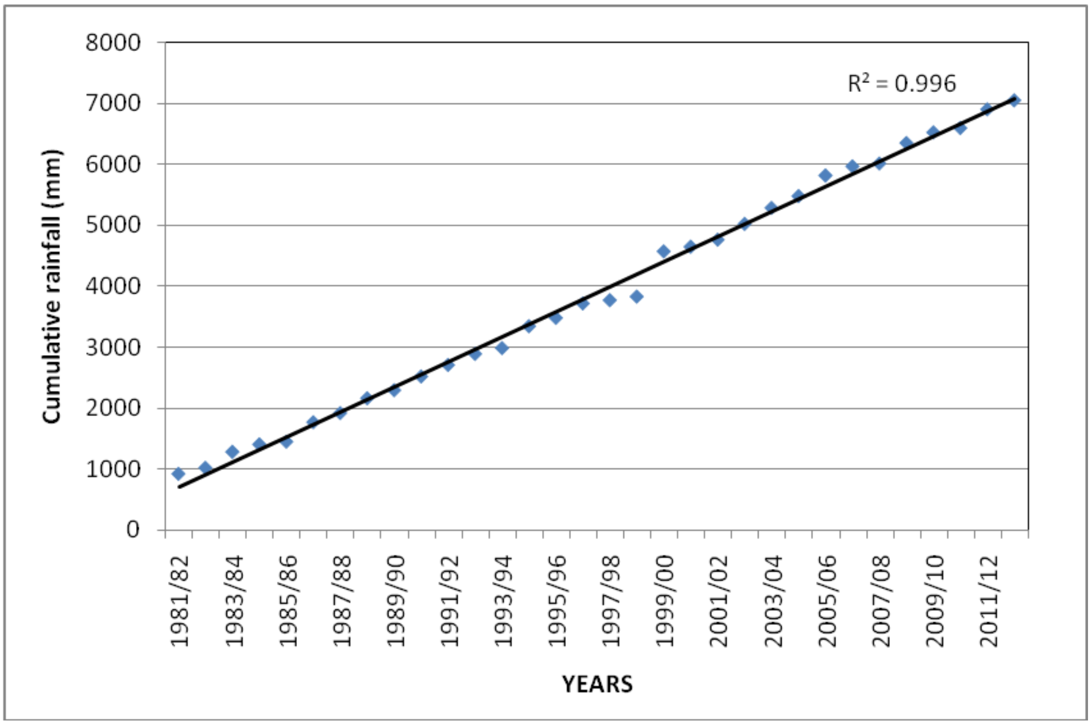


Figure 5: Cumulative December-February (DJF) seasonal rainfall totals (mm) over Voi in South western lowlands of Kenya.

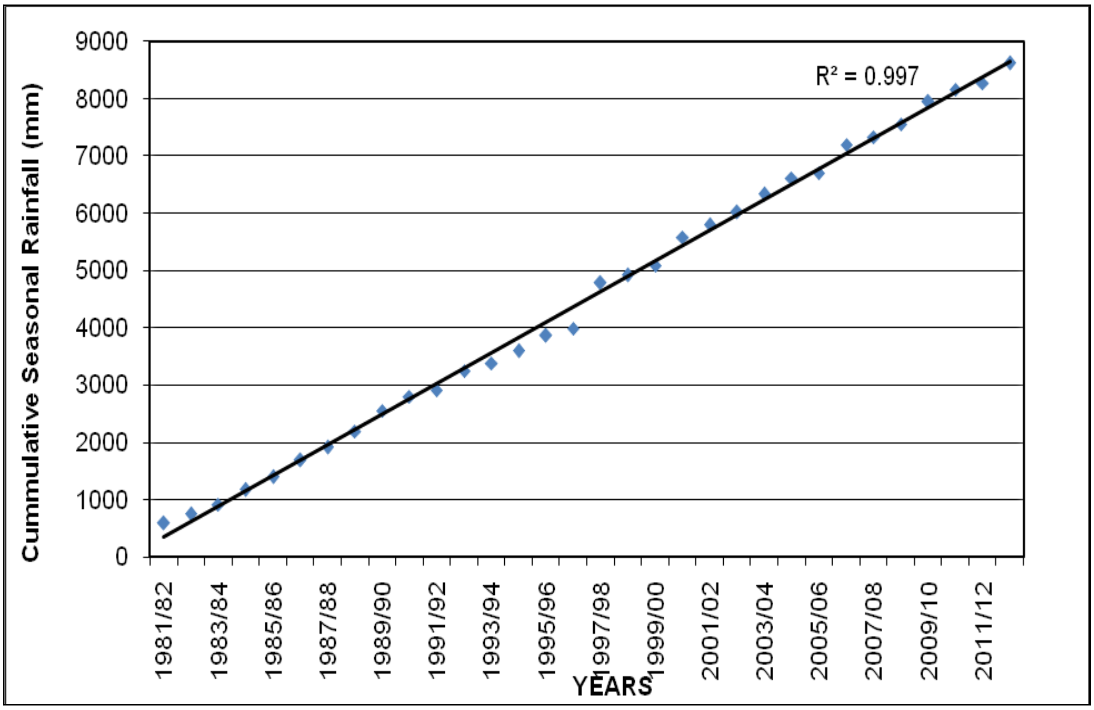


Figure 6: Cumulative December-February (DJF) seasonal rainfall totals (mm) over Kisumu in the Lake Victoria basin.

4.2 Results for Determination of Wet Seasons

The focus of this section was to determine wet seasons, which in this case are those which were categorized in the near normal and above normal categories as per Table 2. These categories were chosen to ensure that the arid and semi arid areas that are known to be very dry during the DJF season are included when significant rainfall was recorded.

Figures 7 shows the percent of normal for these wet seasons indicating when different El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) phases prevailed.

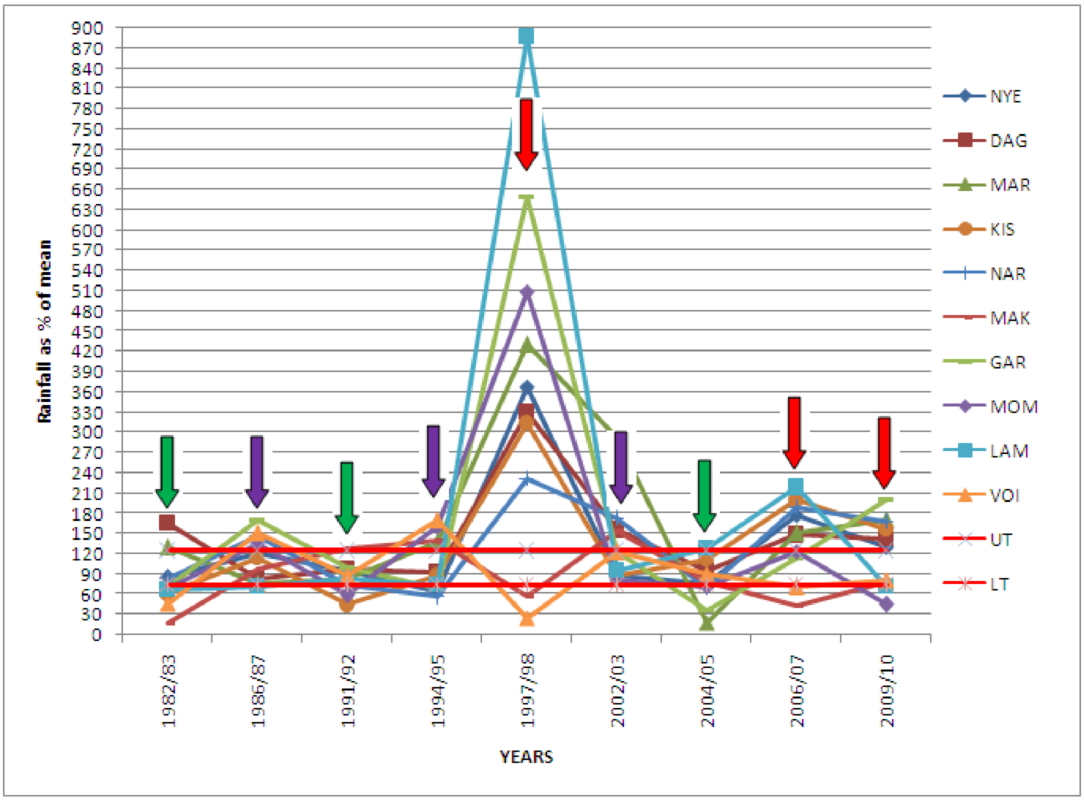


Figure 7: Percentage distribution of DJF rainfall for wet seasons over the various stations with prevailing warm ENSO coupled with negative IOD (Green arrows), Positive IOD (Red arrows), and Neutral IOD (Purple arrows) showing the lower tercile (LT) and upper tercile (UT) for below normal and above normal rainfall categories respectively.

From the results in Figure 7, it is noted that seasons with prevailing El Niño events coupled with positive IOD showed above normal rainfall being received in many parts of the country except the south west lowlands (makindu) and part of the coastal region (Mombasa). The seasons when IOD was negative generally received below normal rainfall in various parts of the country while when IOD was neutral, the distribution showed that a majority of areas received normal to above normal rainfall. Spatial map for rainfall over the country expressed as a percentage of the long term mean (LTM) in seasons when an El Niño event coupled with positive IOD occurred is shown in Figure 8. The distribution shows that almost the whole country records wet conditions when El Niño event is coupled with positive IOD.

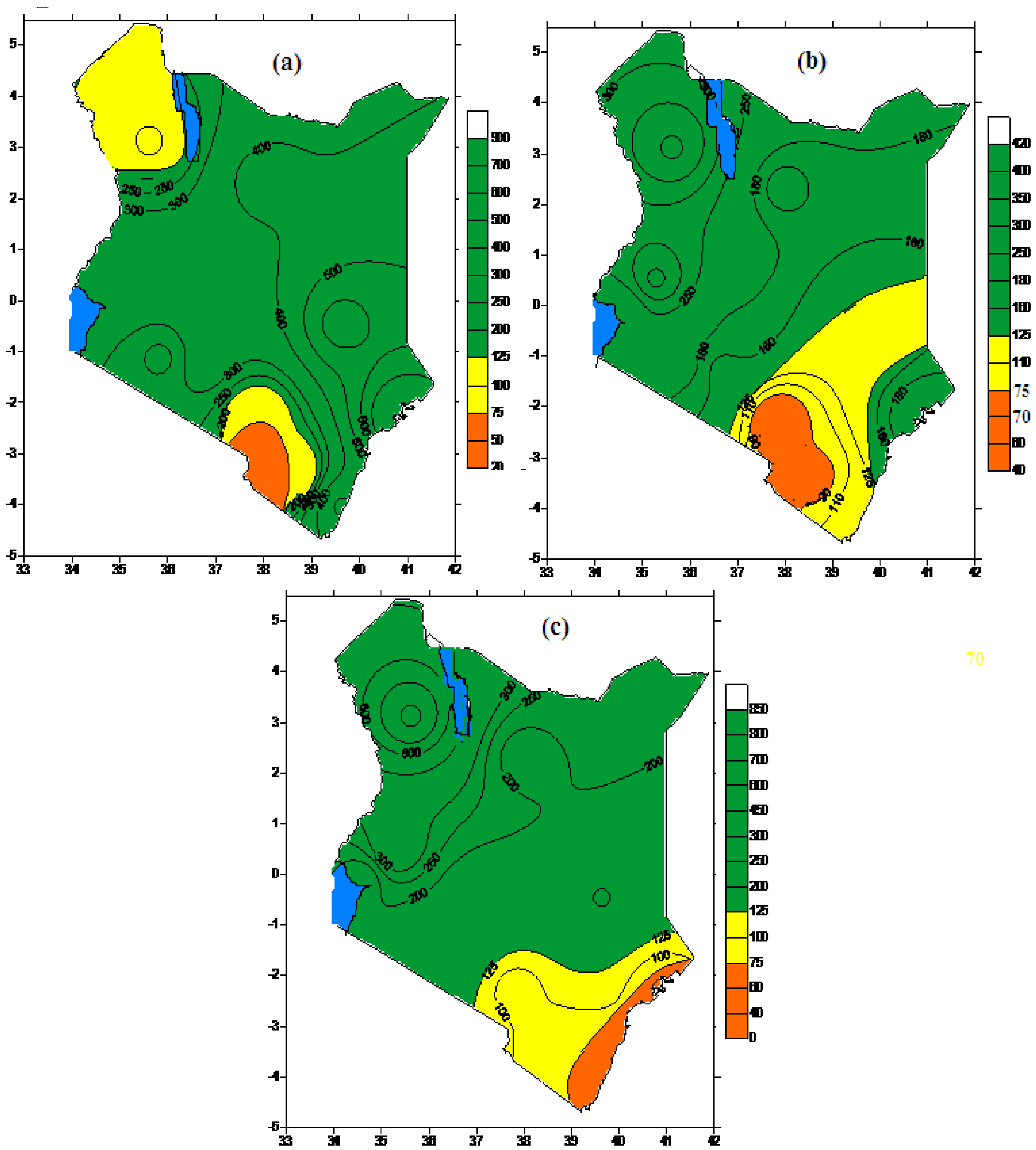


Figure 8: Rainfall received over Kenya during the DJF season expressed as a percentage of the LTM during (a) 1997/98, (b) 2006/07, and (c) 2009/10 when El Niño was coupled with positive IOD. Orange colour shows below Normal, Yellow shows near Normal, and Green shows above Normal rainfall categories.

Figure 9 shows the percent of normal for wet seasons indicating when different El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) phases prevailed. The results displayed in Figure 9 show that seasons when La Niña events coupled with positive or negative IOD occurred, there is no clear seasonal rainfall distribution; stations randomly receive below normal to above normal rainfall in different seasons (2000/01, 1988/89). Seasons experiencing neutral ENSO events coupled with both positive (neutral) IOD show that all stations except parts of the coastal region (South west lowlands, and north eastern) receive normal to above normal rainfall. The spatial maps showing the rainfall distribution during ENSO neutral seasons coupled with neutral and positive IOD are shown in Figure 10.

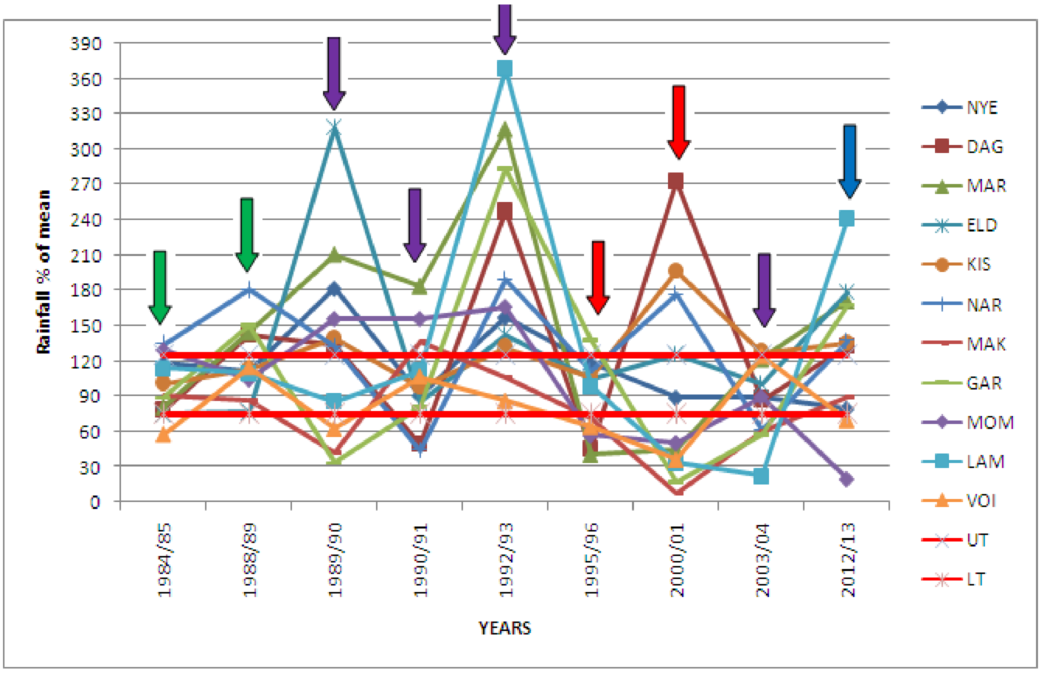


Figure 9: Percentage distribution of DJF rainfall for wet seasons with prevailing cool ENSO phases coupled with Negative IOD (Green arrows) and positive IOD (Red arrows) and neutral ENSO phase coupled with positive IOD (Blue arrow) and Neutral IOD (Purple arrows). (LT) and (UT) are lower (less than 75%) and upper (more than 125%) tercile respectively.

Studies on the effects of ENSO and IOD on rainfall during MAM and OND seasons have been done by Owiti *et al. (*2008). The results they obtained showed that positive IOD during warm ENSO enhances rainfall over East Africa during OND. The results obtained in the current study confirm the results obtained by Owiti *et al.* (2008) even though the season was different. Their study, however did not consider rainfall distribution during ENSO neutral seasons.

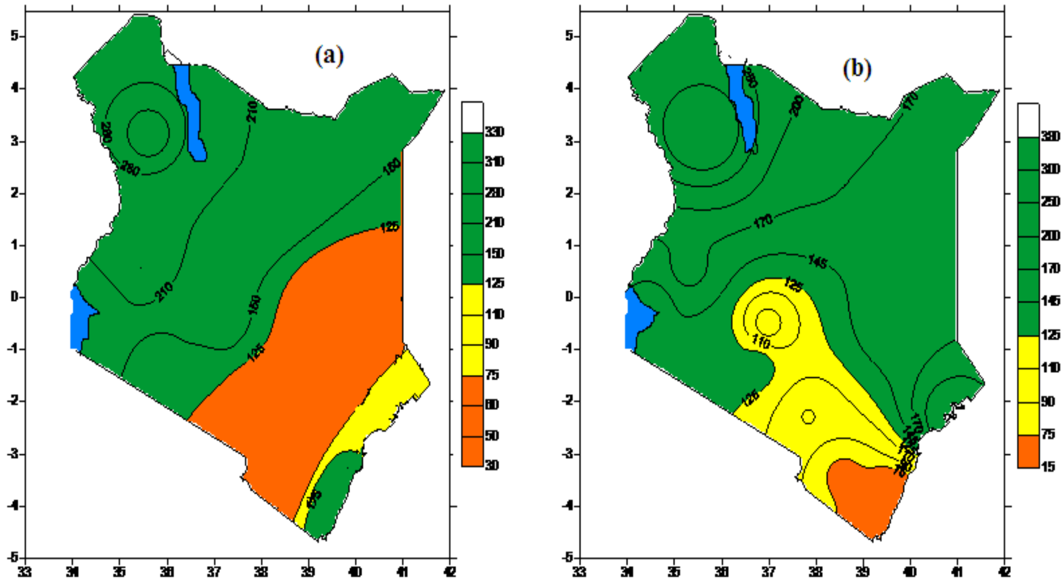


Figure 10: Rainfall received over Kenya during the DJF season expressed as a percentage of the LTM during (a) 1989/90 (b) 2012/13 when Neutral ENSO was coupled with (a) Neutral and (b) positive IOD. Orange colour shows Below Normal, Yellow shows Near Normal, and Green shows Above Normal.

Figure 11 shows the spatial distribution of DJF rainfall season expressed as a percentage of the long term mean when El Niño is coupled with negative IOD. The distribution shows that the Central highlands is always wet, with parts of the coast (Mombasa) remaining dry. Other parts of the country do not show consistent pattern of rainfall amounts received.

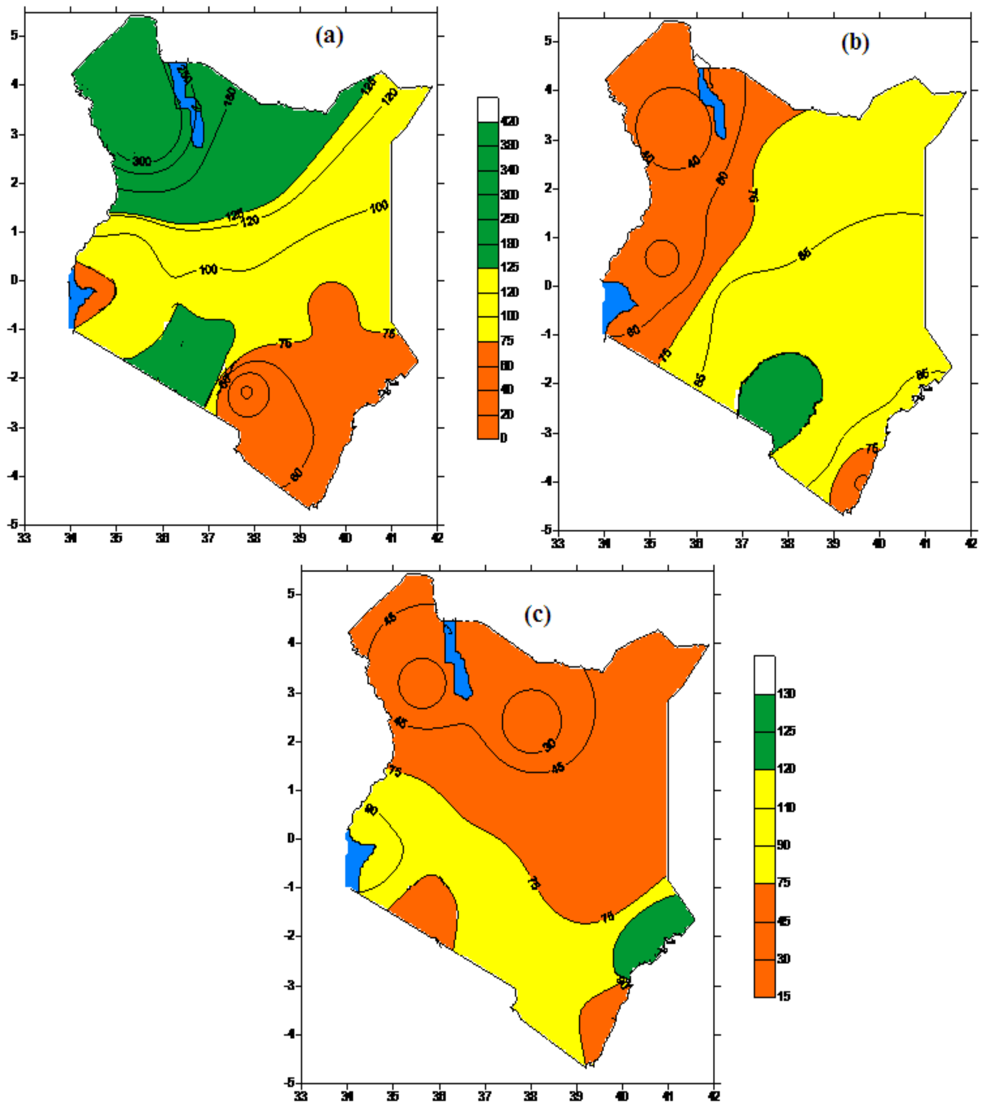


Figure 11: Rainfall received over Kenya during the DJF season expressed as a percentage of the LTM during (a) 1982/83 (b) 1991/92, and (c) 2004/05 when El Niño was coupled with negative IOD. Orange colour shows Below Normal, Yellow shows Near Normal, and Green shows Above Normal rainfall categories.

An analysis of the prevailing oceanic conditions during the wet seasons is summarized in Table 3. The summary shows that out of the 32 (DJF 1981/82 to 2012/13) seasons used in this study, only 18 were wet with 9 being associated with the warm ENSO phase; 4 and 5 seasons were associated with cool and neutral ENSO phases respectively.

Table 3: Summary of Characteristics of Prevailing ENSO and IOD Phases during Wet Seasons

ENSO	Warm phase (El Niño)			Cool phase (La Niña)			Neutral phase		
IOD	+ve	-ve	Neut	+ve	-ve	Neut	+ve	-ve	Neut
WET SEASONS	1997/98 2006/07 2009/10	1982/83 1991/92 2004/05	1986/87 1994/95 2002/03	1995/96 2000/01	1984/85 1988/89	-	2012/13	-	1989/90 1990/91 1992/93 2003/04
TOTAL	**3**	**3**	**3**	**2**	**2**	**0**	**1**	**0**	**4**
	9			**4**			**5**		

Past studies have noted that warm El Niño Southern Oscilation (ENSO) events occasionally enhances sea surface temperatures over the central south Indian Ocean and causes cooling over the south west Indian Ocean (Jury, 1993; Ho *et al*., 2006). During these warm ENSO seasons, more tropical cyclones tend to form in the east of South Indian Ocean. Seasons in which El Niño and La Nina events prevailed were hence not further analyzed in this study. Further analysis were done for ENSO neutral seasons to understand the intraseasonal rainfall characteristics and their causes during the DJF season.

In conclusion, this study has indicated occurrence of wet conditions during DJF and showed that during warm ENSO seasons, wet conditions prevail regardless of the Indian Ocean Dipole (IOD) phase although they are enhanced during positive phase of IOD. During Neutral ENSO phase, wet conditions are observed when both Neutral and positive IOD phases prevail but a high intensity is observed when IOD phase is positive.

4.3 Intra-seasonal Characteristics of Rainfall during Neutral ENSO Seasons

In order to achieve the second specific objective of this study outlined in Section 1.2, ENSO neutral seasons were analyzed. Results obtained from Section 4.2 show that ENSO neutral conditions mainly resulted in wet conditions over most parts of the country. El Niño episode in most cases are associated with extended rainfall seasons (Ross *et al.*, 1998). On a normal situation the cessation of OND rainfall is expected to cease in November. Though wet conditions have been observed during the ENSO neutral phase, the causes of the wet spells observed have rarely been studied. The observed wet spells are thus the subject of study in this sub-section.

The intra-seasonal characteristics of rainfall for two DJF seasons were studied separately. The two ENSO neutral seasons were chosen for neutral and positive IOD phases from the first and the last decades of the 32 seasons used in the study. Using the definition of wet day explained in Sub-section 3.2.2, the time series showing the distribution of wet and dry days over the various stations are shown in Figures 12 (a) and 13 (a).

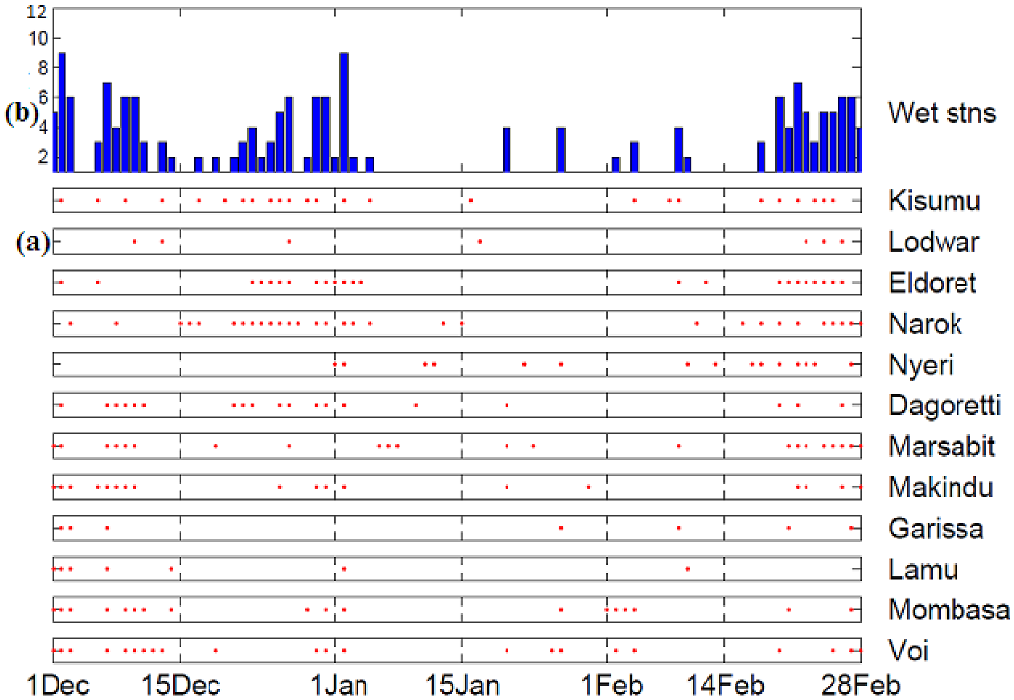


Figure 12: (a) Distribution of wet and dry days during the DJF season in 1989/90 over the various stations used in the study. A red dot indicates a wet day, and (b) Frequency of stations recording a wet day.

Figure 12 (a) shows the distribution of wet days during DJF 1989/90 season. It is evident that many wet days were observed in most of the stations, for example Kisumu, Eldoret and (Narok). Garissa, Lodwar and Lamu are three areas that received the least number of wet days. Voi received a number of wet days during the early part of the season. During the months of December and February, many wet days were observed countrywide. Figure 12 (b) shows the frequency of stations that recorded a wet day, from this figure, the three wet spells were obtained.

Table 4 shows the three main wet spells considered for analysis for DJF 1989/90 and the cumulative rainfall received in the various stations with the contribution of each spell to the long term mean. It is noted that on average, the first, second and third spells contributed a total of 29 %, 61% and 50% of the long term mean respectively. It was also noted that during the first spell, parts of south west lowlands (Makindu) and the coastal region (Mombasa and Lamu) received more than 50% of rainfall long term mean.

Table 4: The cumulative rainfall received in each of the three wet spells identified during DJF 1989/90 over the various stations. The value in the brackets shows the cumulative rainfall received during each spell expressed as a percentage of the long-term mean for the DJF season.

Stations	**Cumulative rainfall received during**		
	Wet spell 1 (1-14 Dec 1989)	**Wet spell 2** (17 Dec 1989- 5 Jan 1990)	**Wet spell 3** (17-28 Feb 1990)
Kisumu	30.8 (12)	131.5 (52)	130.9 (52)
Lodwar	6 (28)	41.5 (193)	20.9 (98)
Eldoret	5.6 (6)	155.9 (156)	135.6 (136)
Narok	16.1 (8)	235.5 (110)	115.8 (54)
Nyeri	0 (0)	34.6 (20)	71.8 (42)
Dago	44.8 (21)	203.2 (95)	27.6 (13)
Marsabit	24 (23)	14.2 (13)	131.6 (123)
Makindu	111.5 (54)	44.2 (21)	80.5 (38)
Garissa	6 (9)	0 (0)	12.9 (19)
Lamu	51.4 (74)	4.2 (6)	0 (0)
Mombasa	67.6 (65)	49.3 (47)	9 (7)
Voi	94.5 (45)	31.2 (15)	35.9 (17)
Average % of LTM	**29%**	**61%**	**50%**

The intra-seasonal rainfall distribution during the DJF 2012/13 rainfall was also studied and the results were as shown in Figure 13 (a). Results show that many wet days were observed during December with few isolated wet days in the first dekad of January. A number of wet days were also observed from the end of January to early February. The highest number of wet days was recorded over Kisumu, Eldoret, Nyeri and Dagoretti, Makindu, Marsabit, and Narok. Figure 13 (b) shows the frequency of stations that recorded wet days; this frequency plot was used to define the wet spells shown in Table 5**.** Results show that the second spell occurring during the third dekad of December has the highest average contribution of the long term mean (70%). Stations over the coastal and south west lowlands remained dry during the third spell. The first and third spells contribute an average of 39% and 11% of the long term mean respectively.

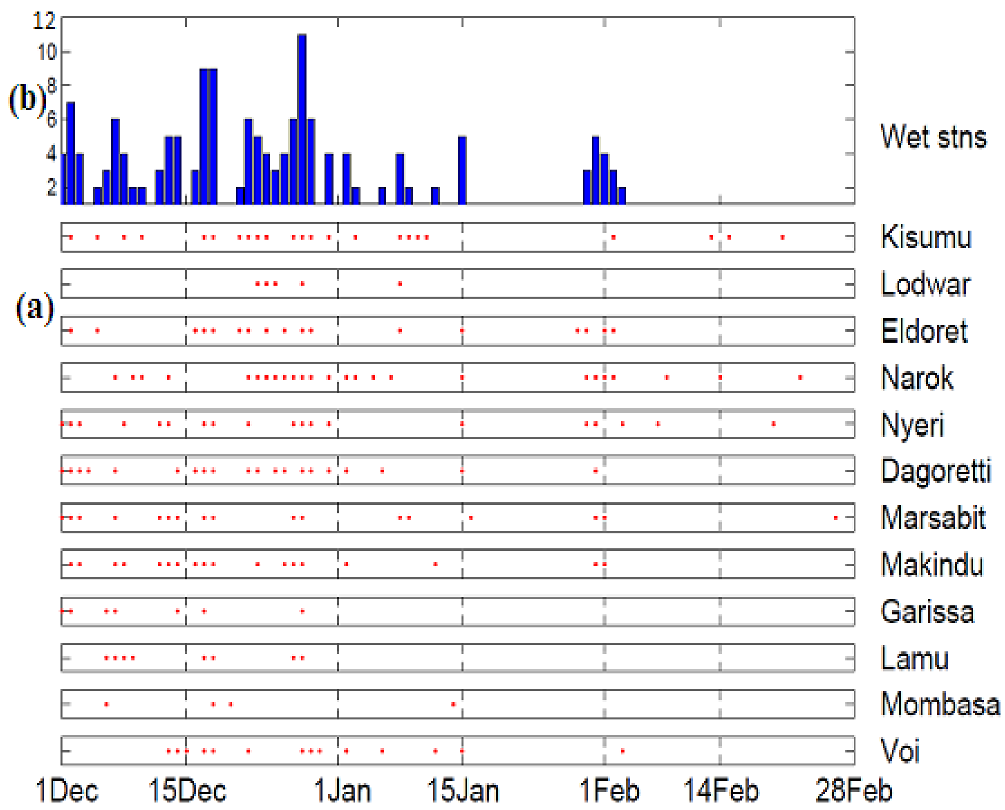


Figure 13: (a) Distribution of wet and dry days during the DJF 2012/13 season over the various stations used in the study. A red dot indicates a wet day, and (b) Frequency of stations recording a wet day.

Table 5: The cumulative rainfall received in each of the three wet spells identified during DJF 2012/13 over the various stations. The value in the brackets shows the cumulative rainfall received during each spell expressed as a percentage of the long-term mean for the DJF season.

Stations	**Cumulative rainfall received during**		
	Wet spell 1 (1-18 Dec 2012)	**Wet spell 2** (21Dec 2012 - 2 Jan 2013)	**Wet spell 3** (29 Jan- 2 Feb 2013)
Kisumu	62.5 (24)	215.1 (85)	18.6 (7)
Lodwar	0 (0)	72.7 (340)	0 (0)
Eldoret	13.6 (12)	89.2 (89)	45 (45)
Narok	36.1 (19)	126.8 (52)	61.7 (29)
Nyeri	52.6 (32)	23.7 (14)	28.7 (17)
Dago	77.1 (35)	186.6 (88)	9.8 (5)
Marsabit	127 (120)	7 (7)	30.8 (29)
Makindu	111 (52)	46.7 (22)	9.2 (4)
Garissa	53.6 (78)	12.4 (18)	0 (0)
Lamu	41.3 (59)	63.9 (92)	0 (0)
Mombasa	10.6 (10)	0 (0)	0 (0)
Voi	65.1 (31)	69.2 (32)	1 (1)
Average % of LTM	**39%**	**70%**	**11 %**

In conclusion, the intraseasonal rainfall characteristics during these seasons showed that a large number of wet days were recorded in Eldoret, Kisumu, Nyeri and

Dagoretti and Narok with a few wet days in Makindu and Voi. Garissa and Lamu received the least number of wet days. Interestingly, it is further observed that the highest amount of rainfall is always received during the second spell that occurred during third dekad of December. On average, this spell alone contributed 61% and 70% of the long term mean for the DJF season during 1989/90 and 2012/13 respectively. It was also noted that in the third spell, Lamu, Mombasa, Voi, Garissa, and Lodwar remained dry during 2012/13 DJF season.

4.4 Systems Influencing Rainfall During Neutral ENSO DJF Seasons

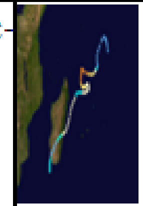
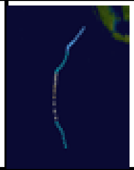
In order to address the last specific objective of this study, two systems that rainfall occurrence may be attributed to during the DJF season were analyzed independently. These systems are tropical cyclones/ storms and the Madden Julian Oscillation (MJO).

4.4.1 Tropical Cyclones Occurring During the DJF 1989/90 season

The DJF season in 1989/1990 experienced tropical cyclones occurring in the South West Indian Ocean. Their tracks and dates of occurrence with other characteristics are shown in Table 6. It can be noted that most stations received significant amounts of rainfall during the periods in which tropical cyclones occurred.

The occurrence of cyclones during the DJF 1989/90 season was such that two to three cyclones coincided during some days (Table 6). From the second dekad of December to the first dekad of January for example, two cyclones had formed concurrently and it was during this period that the highest cumulative rainfall over several stations was received as compared to other periods with cyclone activities. The rainfall received during these three dekads were significantly high and occasionally contributed up to 100% of the rainfall received in a station during the spells in which they occurred. On average, the rainfall received during the occurrence of these cyclones accounted for 97% of the long term mean for all the stations used in this study. However, it should be noted that cyclones Dety and Cezare, contributed the least average percentage of the long term mean (at most 10%).

Table 6: DJF 1989/90 Tropical cyclones showing their (a) Names, track, date of occurrence and (b) Cumulative rainfall received during the period they occurred, percentage of spell and long term mean(LTM)

(a) Cyclones observed during DJF 1989/90			(b) Cumulative rainfall received													
Name	Date	Track		Kis	Lod	Eld	Nar	Nyer	Dag	Mars	Mak	Gar	Lam	Mom	Voi	Average
Alibera	14Dec-5Jan		cum	131.5	41.5	155.9	241.6	34.6	203	27.4	44.2	0	11.7	54.9	31.6	
			% of spell	100	100	100	102.5	100	100	192	100	0	278	111	101	125
				52	194	156	113	20.5	95.5	25.8	20.6	0	16.8	52.7	14.9	69
Baomavo	29De-9Jan		cum	77.6	0.4	84.9	67.7	34.6	116	13.4	40.3	0	4.2	49.2	11.4	
			% of spell	59	1	54.5	28.7	100	57	94	91	0	100	99.8	36.5	65.6
			% of	30.8	1.8	85	31.7	20.5	54.6	12.6	18.8	0	6	47	5.4	29
Dety	30Jan-11Feb		cum	49.4	0.2	20.7	4.3	3.8	0	1.4	1.1	1.6	4.1	46.7	17.4	
			% of spell	This cyclone occurred outside the spell period												
			%LTM	19.6	0.9	20.8	2	2.2	0	1.3	0.5	2.3	5.7	44.8	8.2	10
Cezara	31Jan-11Feb		cum	49.4	0.2	20.7	4.3	3.8	0	1.4	0.8	1.6	4	46.7	17.4	
			% of spell	This cyclone occurred outside the spell period												
			%LTM	19.6	0.9	20.8	2	2.2	0	1.3	0.4	2.3	5.7	44.8	8.2	10
TOTAL			Cum	258.5	42.1	261.5	313.6	39	319	42.2	85.6	1.6	20	150.8	60.4	
			LTM	102	197	262	148	23	150	39	40	2	29	145	29	97

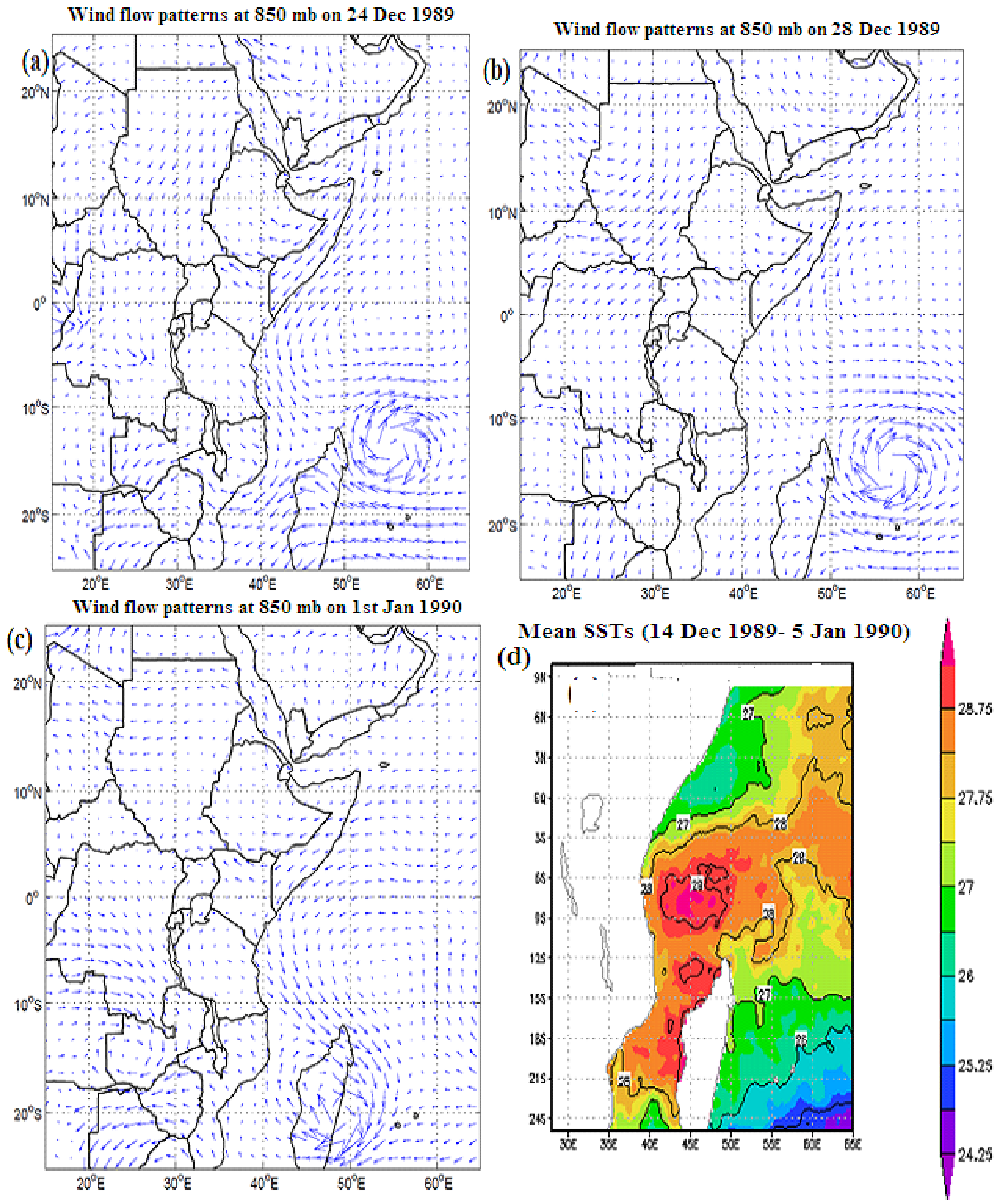


Figure 14: (a) (b) and (c) Wind patterns at 850mb level during different days since cyclone Alibera fully developed to when it started decaying (d)Average sea surface temperature (° C) when tropical cyclone Alibera occurred.

Tropical cyclone Alibera developed on 14th Dec 1989 as a low pressure area, and formed a well defined eye on 24th December (Figure 14 (a)); the surface winds were mainly north easterlies from Indian Ocean through Somalia, winds flowing over the Somalia coast re-curved to north westerlies over the Kenyan coast. Divergence occurred over the North eastern (Garissa) but decelerating winds were observed over the Central highlands (Nyeri and Dagoretti) and South Rift Valley (Narok). This resulted in the heavy rainfall observed over the Lake Victoria basin (Kisumu) and the Central highlands extending to South Rift valley. On 28th December the cyclone moved south and caused divergence over most parts of the country leaving it dry (Figure 14 (b)). Towards the end of the spell, the cyclone hit Madagascar and winds flowed from land to the Ocean (Figure 14 (c)). The average sea surface temperatures when tropical cyclone Alibera developed over the South West Indian Ocean was above 26.5° C within the area it developed (Figure 14 (d)).

The upper level winds over Kenya on the other hand were mainly South easterlies when the tropical cyclone fully developed, and when it finally struck the land (Figure 15 (a) and (c)). On 28th December, the upper level winds were dominantly easterlies (Figure 15 (b)). The rains received over the coastal region (Mombasa) were as a result of North Easterlies recurving to the Ocean over the coast; the decelerating winds over the Lake Victoria basin caused heavy rains while the north eastern part of Kenya (Garissa), which was dominated by high speed dry winds from Somali diverging over the same area remained dry.

Tropical cyclone Dety developed on 30th January 1990, north east of Madagascar. With a maximum peak of 130km/h, it has little influence on rainfall over Kenya. This cyclone occurred outside the period of selected spells and contributed only 10% of the long term mean rainfall (Table 6). On 6th of January, the cyclone was fully developed and the weak surface winds observed over the Lake Victoria basin (Kisumu) and part of the coast (Mombasa) and south west lowlands (Voi) resulted in little precipitation (Figure 16 (a)). As the cyclone decayed, surface winds had grown stronger and dry conditions were experienced in most parts of the country (Figure 16 (b)). The upper level wind patterns showed low speed south westerlies and south easterlies flowing to Ethiopia when the cyclone fully developed (Figure 16 (c)), and dominant easterlies as it began to decay (Figure 16 (d)). The average sea surface temperature was higher than the minimum required temperature over a large area within the South West Indian Ocean (Figure 17).

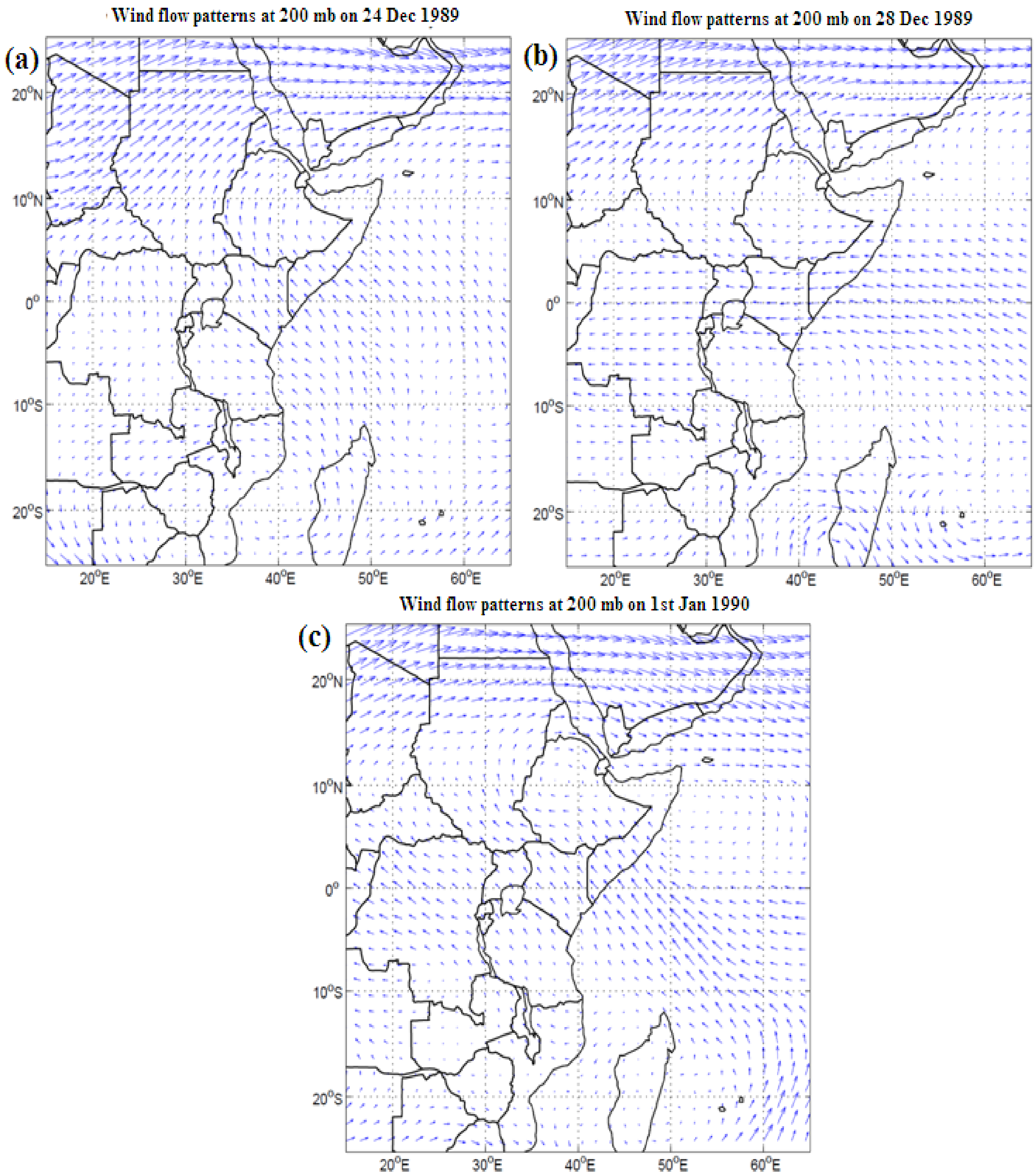


Figure 15: Wind patterns at 200mb level when tropical cyclone Alibera fully developed (a), when it moved southwards (b), and when it started decaying (c).

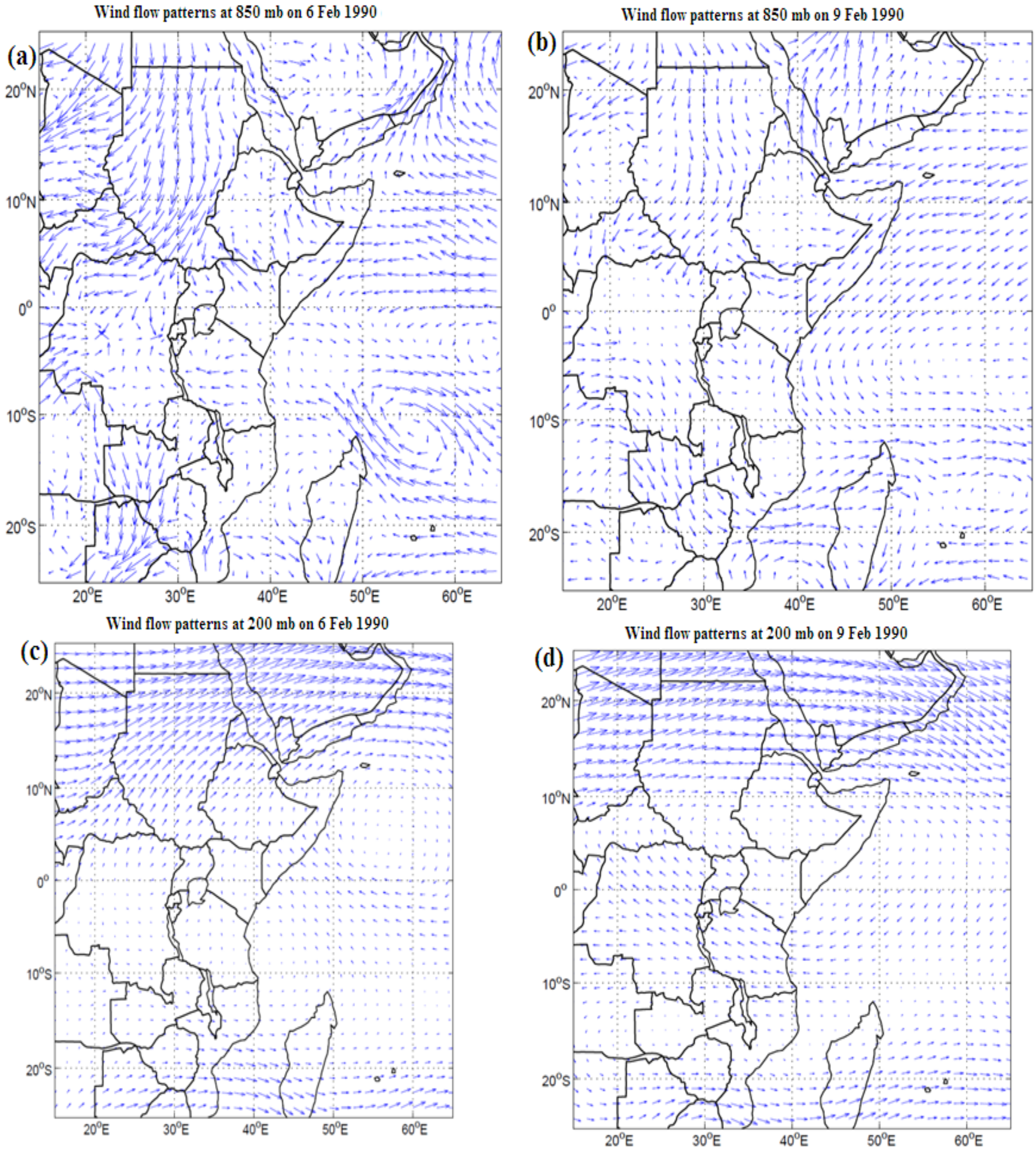


Figure 16: (a) and (b) Wind patterns at 850mb, (c) and (d) Wind patterns at 200mb level when tropical cyclone Dety fully developed and when it started to decay.

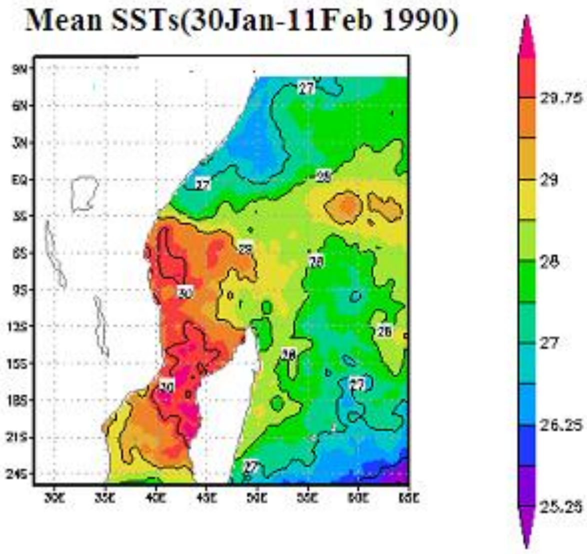
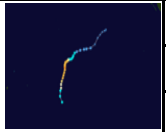
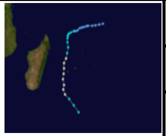
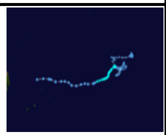
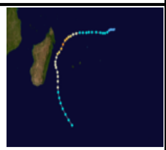
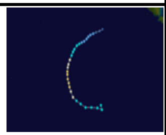
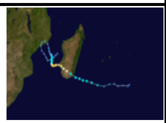


Figure 17: Mean sea surface temperature (° C) over the South West Indian Ocean from 30 Jan to 11 Feb 1990 when tropical cyclone Dety developed.

4.4.2 Tropical Cyclones Occurring During 2012/13 DJF season

During the DJF 2012/13 season, there were 6 tropical cyclones observed in the South West Indian Ocean. The period of occurrence and the amount of rainfall received in various locations throughout this period among other features are displayed in Table 7. From the table, it can be seen that the cyclones occurring in the Indian Ocean had significant effect on the amount of rainfall received in the country. Occurrence of tropical cyclone Felleng for example, which developed on 26th January and decayed on 3rd February brought a lot of rainfall inland with no rains received in the eastern, parts of South west lowlands and Coastal areas. South Rift valley (Narok) received the highest amount of cumulative rainfall of 61.7 mm.

Table 7: DJF 2012/13 Tropical cyclones showing their (a) Names, track, date of occurrence and (b) Cumulative (CUM) rainfall received during the period they occurred, percentage of spell and the long term mean (LTM)

(a) Cyclones observed			(b) Cumulative rainfall												
Name	Date	Track		**Kis**	**Eld**	**Nar**	**Nye**	**Dag**	**Mars**	**Mak**	**Gar**	**Lam**	**Mom**	**Voi**	**AVE**
Claudia	6-13 Dec		CUM	21.5	0	35.8	21	2.5	24	57	24	35	8.7	5.2	
			% spell 1	34	**0**	**99**	**40**	**3**	**19**	**51**	**45**	**85**	**82**	**8**	**42**
			%LTM	**8.5**	**0**	**17**	**12**	**1.2**	**22.6**	**26.6**	**35**	**50.3**	**8.4**	**2.5**	**18**
Dumile	29-6 Jan		CUM	43.3	20	43	14	19	0	5	0	0	0	45	
			% spell 2	**19.7**	**20**	**32.2**	**29**	**8.6**	**0**	**3.8**	**0**	**0**	**0**	**34**	**18**
			% LTM	**17.2**	**20.1**	**20.1**	**8.3**	**8.9**	**0**	**2.3**	**0**	**0**	**0**	**21**	**14**
Emang	12-17 Jan		CUM	0	2.32	43	20	2.9	9	17	0	0	9	16	
			% spell	**This cyclone developed outside the spell periods**											
			%LTM	**0**	**3**	**20**	**12**	**2**	**8.4**	**8**	**0**	**0**	**8**	**8**	**9**
Felleng	26-3 Feb		CUM	18.61	47.2	61.7	29	9.8	31	9.2	0	0	0	0	
			% spell 3	**100**	**105**	**100**	**101**	**100**	**101**	**100**	**0**	**0**	**0**	**0**	**101**
			% LTM	**7.3**	**47**	**29**	**17**	**5**	**29**	**5**	**0**	**0**	**0**	**0**	**20**
Gino	11-15 Feb		CUM	8	0	1.1	0	0	0	0	0	0	0	0	
			% spell	**This cyclone developed outside the spell periods**											
			% LTM	**2.8**	**0**	**0.5**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**
Haruna	18-24 Feb		CUM	5.8	0	19	7.3	0	0	0	0	0	0	0	
			% spell	**This cyclone developed outside the spell periods**											
			% LTM	**2.3**	**0**	**8.9**	**4.3**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**5**
TOTALS			CUM	**96.7**	**70**	**204**	**91**	**34**	**64**	**88**	**24**	**35**	**17**	**66**	
			% LTM	**38**	**70**	**95**	**54**	**16**	**60**	**41**	**35**	**50**	**17**	**31**	**46**

From the results in Table 7, the occurrence of cyclones over the South Western Indian Ocean during this period had significant effect in terms of rainfall quantity. Unlike the 1989/90 season though, which received up to 241.6 mm as the highest cumulative rainfall when a cyclone occurred, the highest rainfall amount was 61.7mm over the south Rift valley (Narok). It is worth noting that the short rains in Narok extend to the March to May long rainfall season. SSTs and wind circulation patterns at 850 and 200mb levels were analyzed for two cyclones Claudia and Felleng, which had intensity greater than 135km/h.

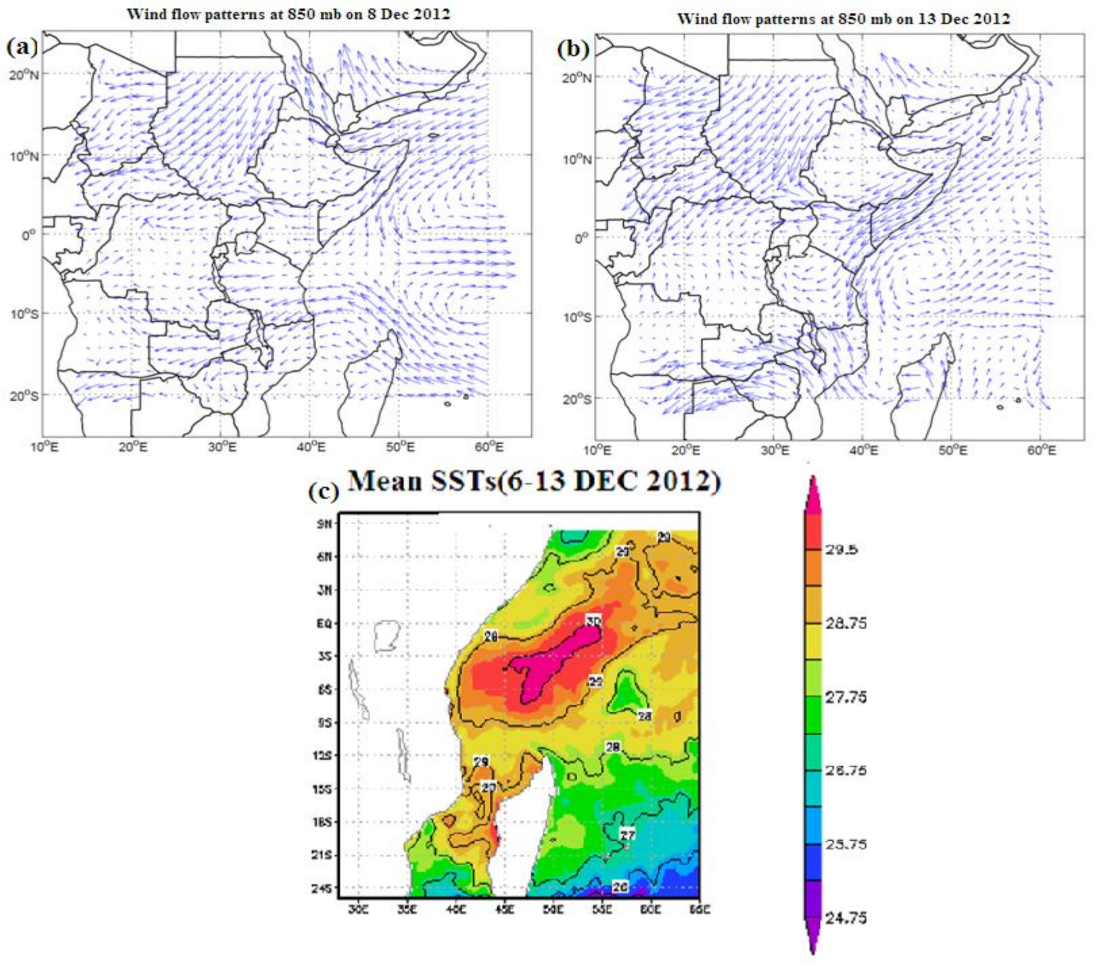


Figure 18: Wind pattern at 850mb when tropical cyclone Claudia (a) fully developed (b) when the cyclone decayed, and (c) Average sea surface temperature (° C) from 6th to 13th Dec 2012 when intense tropical cyclone Claudia developed.

When intense tropical cyclone Claudia occurred, the surface winds over the ocean when it clearly developed showed converging NE and SE over the ocean, which then became westerlies and easterlies over the Ocean and land (Kenya and Tanzania) respectively (Figure 18 (a)). By the time it decayed, the surface flow was dominantly north easterly with an area of divergence over the Kenyan coast (Figure 18 (b)). The average SSTs were warmer than the minimum required temperature over the area where the cyclone formed (Figure 18 (c)). The upper level winds on the other hand were north easterlies over Kenya when the cyclone formed and easterlies changing to south easterlies as it decayed as shown in Figure 19 (a) and (b) respectively.

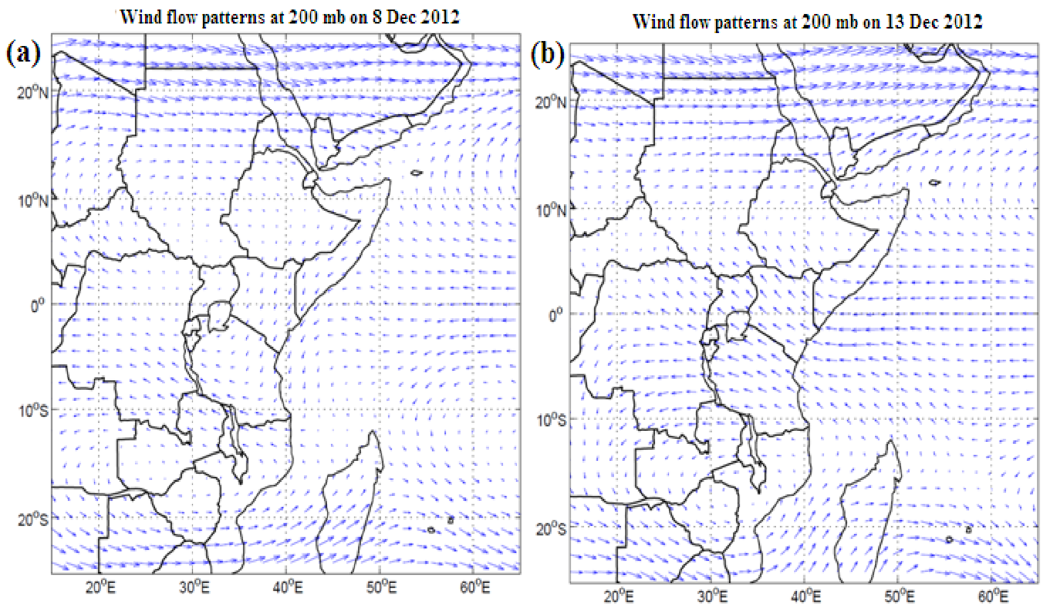


Figure 19: (a) Wind patterns at 200mb level when tropical cyclone Claudia developed and (b) wind patterns at 200mb level when the cyclone decayed.

Similarly, when intense tropical cyclone Felleng developed a well defined eye, the surface winds were dominantly north easterlies diverging over Garissa to northerlies and finally to North westerlies over the Ocean and south easterlies flowing to South Sudan. There is also an area of convergence in the Lake Victoria basin extending to North western Tanzania (Figure 20 (a)).

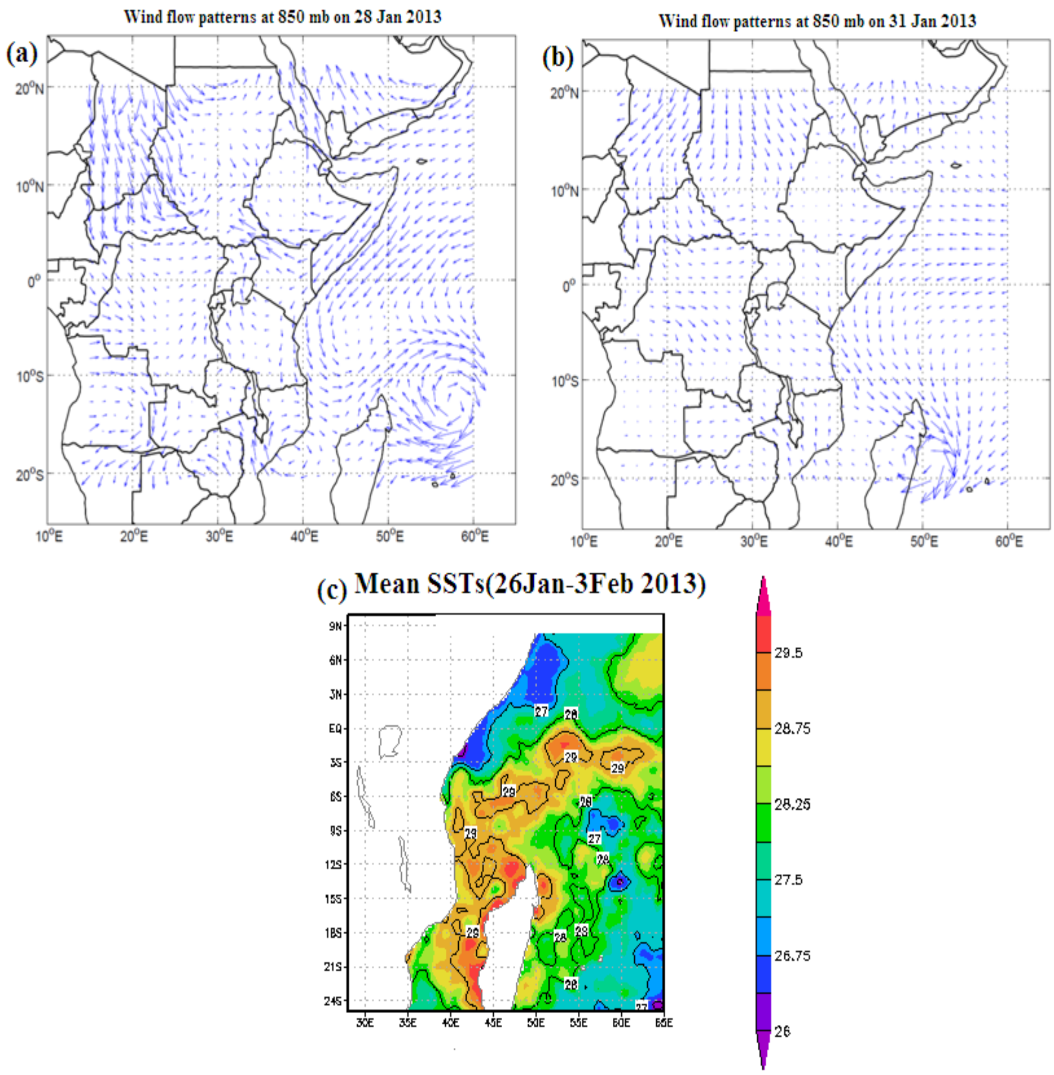


Figure 20: Wind vector patterns at 850 mb when intense tropical cyclone Felleng developed (a), when the cyclone decayed (b) and, (c) Mean Sea Surface Temperatures (° C) for the whole period when intense tropical cyclone Felleng occurred.

The upper level winds were mainly easterlies and south easterlies over Kenya as shown in Figure 21 (a) and (b) respectively.

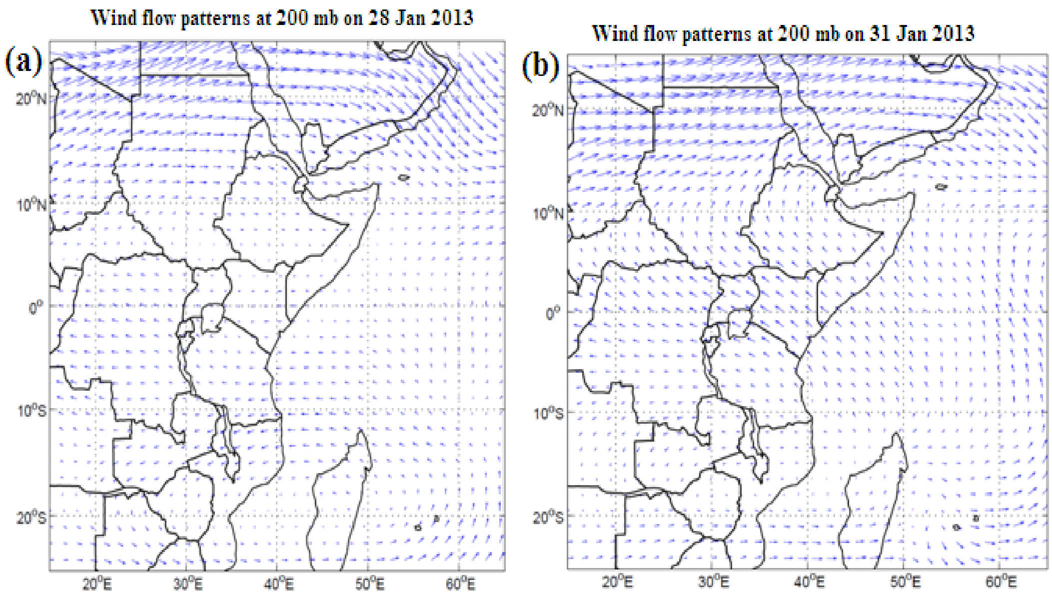


Figure 21: Upper level wind patterns when intense tropical cyclone Felleng (a) developed, and (b) when the cyclone decayed.

This study has for the first time analyzed the influence of tropical cyclones / storms on rainfall during DJF season over Kenya. The average Sea surface temperature during the cyclone periods were more than the 26.5° C the threshold required for the formation of a cyclone. The results obtained show that the cumulative rainfall received over the stations used in this study has a relationship with the strength, and track of a tropical cyclone. Intense tropical cyclones with high intensity of more than 135km/h occurring close to the East African coast have high impact on rainfall over Kenya compared to tropical cyclones and storms with intensity less than135km/h and those occurring far east of South West Indian Ocean.

During the DJF 1989/90 season, tropical cyclones Alibera and Baomavo that occurred at the beginning of the season had the highest impact on rainfall while intense tropical cyclone Claudia and Felleng in 2012/13 DJF season had a great significance on the rainfall received in terms of distribution and stations cumulative, respectively. Comparing the amount of rainfall received to the long term mean, results show that the average percentage of cyclone contribution to the long term mean is quite significant. During the DJF 1989/90 season, the cyclones that occurred contributed an average of more than 97% of the long term mean rainfall. The cyclones that occurred during the DJF 2012/13 season contributed an average of about 50% of the long term mean. The major cities of Mombasa, Kisumu, and Nairobi (Dagoretti) received the least percentages of the long term mean. The reasons for this observed pattern were however not clear.

In conclusion tropical cyclones occurring in the South Western Indian Ocean during the DJF season have been identified as the major contributors of extreme wet spells that are occasionally observed during this otherwise dry DJF season. For example during DJF 1989/90 and 2012/13 seasons, it was noted that tropical cyclones contributed to over 50% of the rainfall's long term mean.

4.3.3 MJO influence on the intra-seasonal rainfall

Madden Julian Oscillation (MJO) affects rainfall over different regions globally depending on the active phase. MJO is considered active if its amplitude is equal or greater than 1 (Omeny *et al*., 2008). The current study first analyzed the influence of MJO throughout the season when it was active in all the 8 phases in order to identify the phases in which MJO influences rainfall over Kenya during the DJF season.

During the seasons analyzed, the correlation between Real time Multivariate MJO 1 (RMM 1) and Real time Multivariate MJO 2 (RMM 2) values on one hand and daily rainfall on the other hand was done and the results showed a significant relationship between RMM values and rainfall in phases 1, 3, 7 and 8 (Table 8). Unlike the out of Phase relationship between the eastern and western areas as seen during MAM and OND, the areas with significant correlation coefficients are quite scattered (During Phase 8, the correlation coefficients showing the relationship between RMM values and rainfall are significant over Eldoret, Makindu, and Nyeri, while in Phase 7, they are significant over Makindu and Garissa. In Phase 3, they are significant over Kisumu and Eldoret and finally in Phase 1, they are significant in Kisumu, Lodwar and Nyeri). The correlation coefficients obtained are shown in Table 8, while the phase diagram showing the location of MJO during OND 1989 and January-March (JFM) 1990 are shown in Figures 22 (a) and (b).

Table 8: Correlation coefficient values between RMM1 and RMM2 on one hand and daily rainfall, the values in red are significant at 95% significance level.

	RMM 1								RMM 2							
	1	2	3	4	5	6	7	Phase8	Phase1	2	3	4	5	6	7	
KISM	0.54	0.23	-0.47	-0.05	0.35	0.12	-0.33	-0.04	-0.47	0.22	0.07	0.21	-0.22	0.08	-0.32	0.18
LOD	0.06	0.53	-0.20	-0.06	0.24	0.00	0.00	0.17	-0.43	0.23	-0.10	0.20	-0.26	0.01	0.01	-0.22
ELD	0.23	0.24	-0.61	-0.09	0.15	0.01	-0.01	-0.13	0.09	-0.07	-0.14	-0.32	-0.24	0.01	-0.17	0.51
NAROK	0.20	-0.29	-0.18	-0.07	0.25	0.21	-0.32	-0.43	0.06	0.30	-0.14	-0.09	-0.48	0.14	-0.22	0.28
NYERI	0.29	0.18	-0.08	-0.16	-0.26	0.31	0.05	-0.53	-0.50	0.24	-0.04	-0.16	0.20	-0.15	0.11	-0.45
DAG	0.33	-0.25	-0.39	0.08	-0.14	0.01	-0.17	0.29	-0.02	0.40	-0.18	0.28	0.15	0.01	-0.37	0.06
MAR	0.26	0.38	0.11	-0.06	-0.33	0.07	-0.29	0.16	-0.10	0.22	-0.04	-0.45	0.33	-0.25	-0.15	0.33
MAK	0.36	0.38	-0.29	-0.01	-0.21	-0.31	-0.07	-0.16	-0.04	0.28	-0.18	-0.20	0.20	0.46	-0.40	0.50
GAR	0.13	0.08	0.34	-0.08	0.01	0.31	0.32	-0.18	-0.07	0.13	0.01	-0.39	0.01	-0.15	0.57	0.36
LAMU	0.34	0.01	-0.05	0.01	0.01	-0.51	-0.03	0.04	-0.05	0.01	-0.19	0.01	0.01	0.12	-0.33	0.22
MOM	0.32	0.06	-0.16	-0.08	0.01	0.31	-0.17	0.23	-0.04	0.13	-0.27	-0.39	0.01	-0.14	-0.03	-0.11
VOI	0.35	0.05	-0.19	0.17	-0.24	-0.07	-0.19	0.10	-0.06	0.19	-0.18	-0.16	0.22	0.32	0.07	0.07

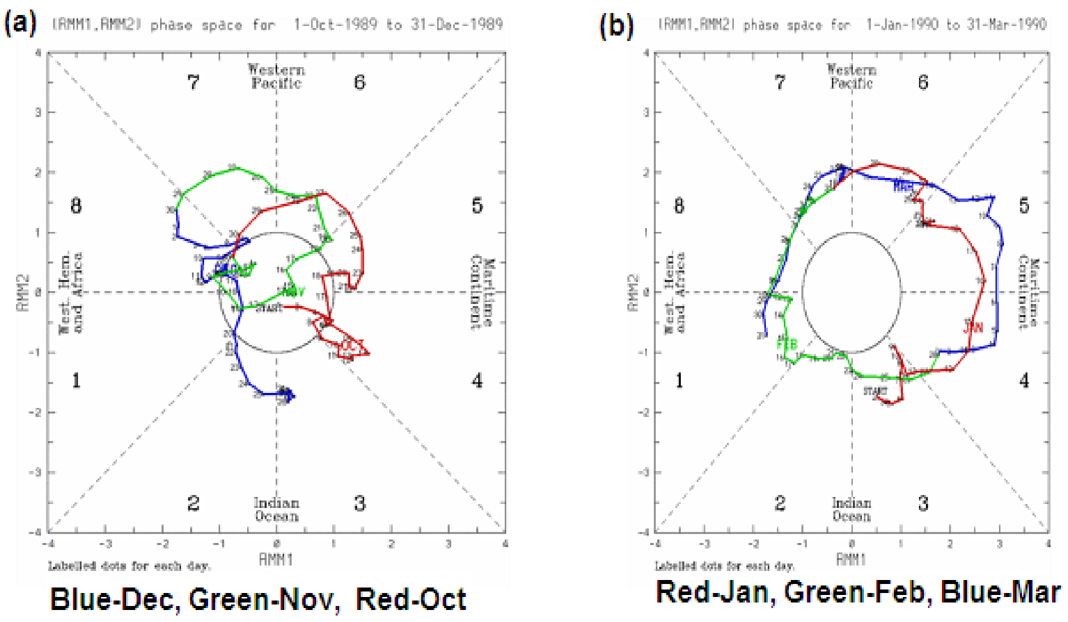


Figure 22: MJO Phase diagram for (a) OND 1989 and (b) JFM 1990 (Source: http://www.bom.gov.au/climate/mjo/ >on 18th March, 2014)

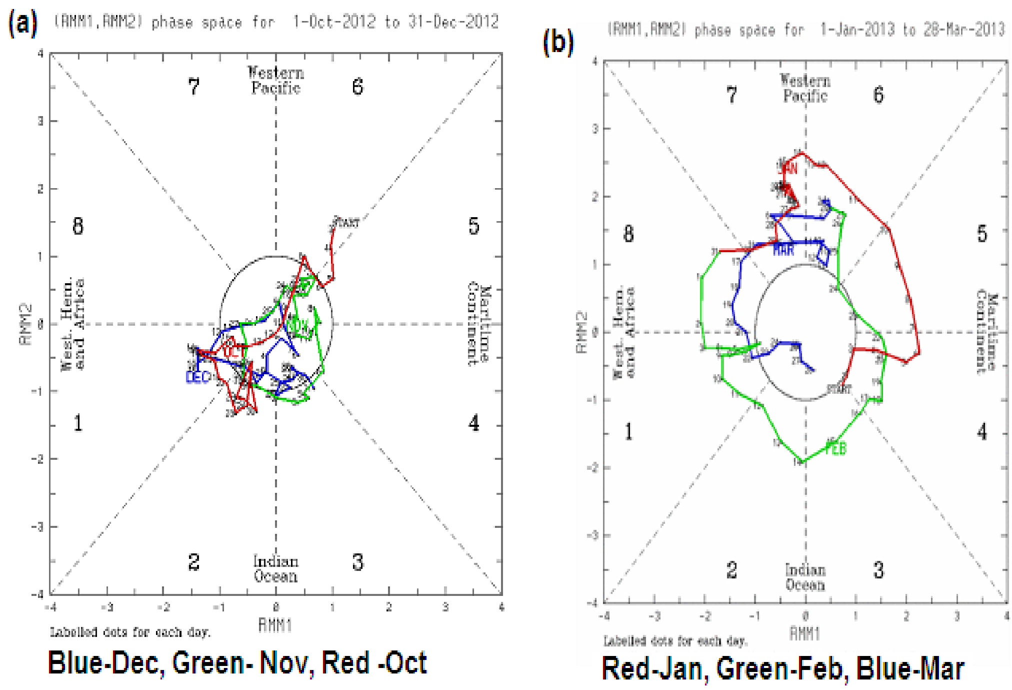


Figure 23: MJO Phase diagram for (a) OND 2012, and (b) JFM 2013 (Source: http://www.bom.gov.au/climate/mjo/ > on 18th March, 2014)

From these phase diagrams (Figure 22 (a) and (b), it is seen that during the DJF 1989/90 season, MJO amplitude was greater than 1 throughout the two seasons except for few days during December when in Phase 1. For the 2012/13 DJF season, the phase diagram shows that MJO was weak during much of December but remained active throughout the rest of the season (Figure 23 (a) and (b)). The weak MJO observed can be attributed to various factors such as a break up of equatorial convection in the Indian Ocean, cold SST bias over the eastern Indian Ocean and prevailing weak vertical easterly wind shear and easterly low-level zonal wind bias over western Pacific and Maritime continent.

From the results in Table 8, it is worth noting that the correlation coefficients between the DJF rainfall over the various stations in Kenya and the two components that define the MJO (RMM1 and RMM2), were mainly insignificant at 95% level of significance. Occasionally, significant correlation coefficients are obtained. However, stations with significant correlation coefficients do not form an organized spatial pattern. It was further noted that the correlation coefficients obtained for RMM 1 in Phase one are all positive with RMM2 values in Phase 1 being negative except in Eldoret and Narok. In Phase 3, correlation coefficients for RMM1 are all negative except in Marsabit and Garissa while RMM2 coefficients are negative except in Kisumu and Garissa.

In conclusion there is no significant association between the two components of MJO and the DJF rainfall over Kenya since no consistent pattern of the correlation coefficients can be observed.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

This chapter provides the major conclusions drawn from the results of this study. It also provides some recommendations and suggestions for future studies.

5.1 Conclusions

The overall objective of the study was to investigate the climate systems that can be associated with wet spells occasionally observed during the dry December-February season over Kenya. This was achieved through three specific objectives, which were to; Identify anomalous wet DJF seasons; determine the intra-seasonal rainfall characteristics during the selected wet seasons, and finally investigate the systems that may be attributed to the observed characteristics. From the first specific objective, results obtained showed that wet conditions are observed during warm ENSO seasons regardless of IOD phase though positive phase enhances the intensity of rainfall received. This enhanced rainfall was also observed for neutral ENSO when IOD is positive though wet conditions are observed frequently when IOD phase is neutral.

The wet spells observed were found to be concentrated on specific dekads that seemed to have been linked to occurrence of tropical cyclones over South Western Indian Ocean during neutral ENSO seasons. During 1989/90 and 2012/13 DJF seasons for example, three wet spells were observed in each season and during the third dekad of December, the rainfall received contributed the highest average percentage of the long term mean of 61% and 70% respectively.

No significant association was observed between the majority of the occasional DJF wet spells and MJO phases. Wet spells occasionally observed during the otherwise dry DJF season are therefore not purely associated with systems that cause rainfall during OND. The information obtained from this study can be used in different rain-dependent sectors over the country for water use planning through water harvesting for irrigation and domestic use before the March-May rainfall season begins, disaster risk reduction, among others in support of sustainable livelihoods and national development.

The next section provides some specific recommendations to various areas and future studies.

5.2 Recommendations

The results obtained in this study provide useful information that can be incorporated in many sectors that directly or indirectly rely on rainfall. The recommendations are made for international and regional climate institutions, universities and research institutions, Kenya Meteorological Services, sector specific users and NGOs/CBOs.

5.2.1 Recommendations to Universities and Research Institutions

Since this study focused on Kenya alone, there is need to expand this research to other regions so as to quantify the amount of rainfall that can be associated with tropical cyclones occurring over the Indian Ocean during the dry seasons. This will provide essential information that can help these countries in disaster risk reduction and promote national development.

5.2.2 Recommendations to ICPAC and Kenya Meteorological Services

ICPAC being a focal point for seasonal forecasting over GHA, it is recommended that there should be continuous monitoring of tropical cyclones over the Indian Ocean and information on the expected impacts over the region provided regularly. Through this continuous monitoring, verification of forecasts issued can be easily carried out and improve the skill of future predictions. The Kenya meteorological services on the other hand being the sole national centre responsible for issuing national weather forecasts can use this information to incorporate tropical cyclones as a major system causing rainfall during DJF; this will improve the skill of seasonal forecasting over the country. They should also issue the forecast early enough to different rain dependent sectors. By using the information obtained from this study, they can also organize capacity building workshops to understand the influence of tropical cyclones over the South Western Indian Ocean during different ENSO phase seasons.

5.2.3 Recommendations to Socio-economic Sectors

Information from this study will play an important role in the water resources, agriculture, and health sectors. It is recommended that these sectors work closely with local communities relevant to their sectors. For example, when the dry DJF season is expected to be wet, agricultural experts can advise farmers to plant crops that have short maturity periods and require little water to grow hence improve food security. They can also advice farmers on proper storage facilities to avoid spoilage of harvested agricultural products. Water and health sectors should also ensure that they have enough resources to handle problems associated with extreme rainfall like floods and disease outbreaks, respectively.

5.2.4 Recommendations to Non-Governmental Organizations and Community Based Organizations

Non-Governmental Organizations (NGOs) and Community Based Organizations (CBOs) play an important role in disaster risk reduction and emergency response. From the information obtained from this study, NGOs and CBOs are advised to work with local communities to ensure that they remain safe in case of disasters due to heavy rainfall and also help them build structures that can be used to harvest water when such wet spells occur.

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