UNIVERSITY OF NAIROBI

SPATIAL AND TEMPORAL CHARACTERISTICS OF THUNDERSTORMS OVER THE EASTERN REGION OF LAKE VICTORIA BASIN IN KENYA

BY

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DECLARATION

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DEDICATION

I dedicate this dissertation to my cherished family; my spouse Mr. **Charles Shem Maloba**, our daughter **Melva Mitsa** and our son, **Medwin Shem**.

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ABSTRACT

Weather is very important on human activities over western Kenya just like the rest of the world. It affects lives in different ways, including the food and water resources. Western Kenya is the food basket of the country. The inhabitants depend on agriculture for food and socioeconomic developments. Accurate information on thunderstorms (TS) could therefore assist in the planning and management of agricultural production, water resource management, aviation safety, communication and environmental protection among others.

Thunderstorms being one of the most significant weather parameters are of great concern to forecasters. Thunderstorms may cause large damages to infrastructures and population, therefore, possible identification of the areas with the highest occurrence of these events is especially relevant. Studies have been done on organized convection in Africa and East Africa but not much over the Eastern part of the Lake Victoria basin in Kenya.

This study investigates the spatial, temporal and propagation characteristics of thunderstorms to the east of the Lake Victoria basin in Kenya. The study focuses on March–May (MAM) and September-October (SON) seasons which recorded high thunderstorm occurrences.

The data used consisted of observed thunderstorm data (2000-2013) from Kenya meteorological services for four synoptic stations to the east of Lake Victoria. Other datasets used were cloud top temperature (2006-2008) and the wind data (2006-2008) from the European center for medium range and weather forecasting. The data were subjected to several analyses which included frequency analysis, the longitude-time analysis (Hovmoller diagrams), and wind pattern analysis.

The study showed that within the study period (MAM), the year 2006 recorded high thunderstorm occurrences while lower thunderstorm frequencies were reported in 2007 for both MAM and SON seasons. High thunderstorm frequencies were recorded during the SON season in the year 2008. The three years were chosen because the pattern of thunderstorm occurrence from the temporal graphs was more consistent (TS frequencies were increasing /decreasing in all stations). Temporal analysis of the observed thunderstorm data showed that thunderstorm frequency peaked between 1200 UTC and 1500 UTC when maximum convection is attained. The longitude-time analysis showed that organized convection evolved from the heat source, Mau Hills (~35.5^0E) and propagated westwards towards the lake. Some of the convective cells dissipated before reaching the lake.

The wind analysis at low, medium and upper levels (850mb, 700mb and 200mb) respectively, revealed the circulations associated with thunderstorm characteristics over the study area. The levels 850mb and 700mb showed the areas with calm conditions and the moisture source, hence indicating if the region of study was under deep convection or not. The 200mb level revealed the direction in which the organized convection shifted.

Results from this study provided information that can be used in water planning through water harvesting when severe storms occur in the area of study during the MAM and SON seasons. The information can also be used for disaster risk reduction by issuing early warning to residents living in lowland so that they can move to higher ground in case of floods as a result of severe storms. Dykes can also be built along the river banks well in advance to avoid overflowing waters from submerging the surrounding lands. The transportation industry, particularly Aviation, can also benefit from timely forecasts for aircrafts approaching the international airports in the region. The information on the evolution and propagation characteristics of thunderstorms can also be used by Kenya Meteorological Department (KMD) to come up with thunderstorm forecasts in support of sustainable livelihoods and development of the nation.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

AMSL	Above Mean Sea Level
CTT	Cloud Top Temperature
ECMWF	European Centre for Medium Range Weather Forecasting
EPSAT	Estimation of Precipitation by Satellites
ERA	ECMWF Re-analysis
GrADS	Grid Analysis and Display System
Hrs	Hours
ITCZ	Inter-Tropical Convergence Zone
JRA	Japan Reanalysis
KMD	Kenya Meteorological Department
LVBC	Lake Victoria Basin Commission
MAM	March- April- May
Mb	Millibars
MERRA	Modern-Era Retrospective analysis for Research and Application
MSCs	Mesoscale Convective Systems
MSG	Meteosat Second Generation
MWA	Mobile Weather Alert
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environmental Prediction
NMC	National Meteorological Center
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SON	September- October- November
TRMM	Tropical Rainfall Measuring Mission
TS	Thunderstorm

UDoM	Uganda Department of Meteorology
UKMO	UK Meteorological Office
UoN	University of Nairobi
UTC	Universal Time Coordinated
WMO	World Meteorological Organization

CHAPTER ONE

1.0 Introduction

A thunderstorm (TS) is a storm with thunder and occasionally accompanied by lightning. It is formed by a cumulonimbus cloud, usually producing gusty winds, heavy rain and sometimes hail. It may be produced by a single cumulonimbus cloud and influence only a small area, or it may be associated with clusters of cumulonimbus clouds covering a large area (Lutgens and Tarbuck, 2010). Although, by definition rainfall need not be associated with thunderstorm (in dry climates, TS often occurs without quantifiable precipitation) (Oliver and Hidore, 2003).

The cumulonimbus grows horizontally from 2000 to 4000 meters in diameter to 10,000 or 15,000 meters. The tops of cumulonimbus clouds can easily reach 12,000 meters during the cumulus stage. The cloud reaches its vertical development near the end of the dissipating stage, usually reaching about 10,000 meters and sometimes penetrating the tropopause to altitudes greater than 15,000 meters (Muthama *et al*., 2003).

It is approximated that nearly 45000 thunderstorms occur daily in the world that is, 16 million thunderstorms each year (Khan and Arsalan, 2007). Due to their occurrence at anytime and anywhere, thunderstorms are considered as a parameter having a special importance among the meteorological parameters (William, 1961). They can lead to casualties and/or loss of lives and damage of property.

Thunderstorms have led to the loss of many lives through lightning strikes or aircraft accidents associated with severe thunderstorms. As an economic factor, aircrafts are forced to divert from their routes away from thunderstorm areas and therefore use more fuel. Accidents of aircrafts can also occur in downbursts.

A study in Kericho by Sansom and Gichuiya (1971) showed that the occurrence of hail was increasing over the years. Huge hailstones have a negative effect on a society in that it can wipe out a field of crops in minutes and damage property. Food crops are also destroyed yet agriculture is the main source of livelihood for many people in tropical areas.

Convection is a very important activity in the tropics and when it occurs, there is a release of latent heat, the formation of clouds and precipitation. In understanding the timing, duration, and frequency of deep convection in equatorial Africa, satellite observations are used. Equatorial Africa is a region with some of the most intense thunderstorms. Convection starts by heating of water surfaces and elevated terrain (Laing and Carbone, 2011). Convection can also be caused by latent heat released when water vapor condenses to form liquid droplets.

Thunderstorms are driven by deep convective clouds in East Africa and other parts of the world. The atmosphere is abruptly and intensely heated during a lightening flash, with an enormous expansion of air, which produces sound waves that are heard as thunder occurs as a result. Owing to its powerful and destructive effect and complex forming mechanism, meteorologists have continued to pay attention to thunderstorm forecasting for a long time, and research on the mechanism, thunderstorm climatology, convection parameter calculation, statistical forecasting, numerical weather prediction and joint monitoring and nowcasting of satellite and radar have been undertaken (Lian *et al*., 1998, Hao *et al*., 2007, Wagner *et al*., 2008).

Lake Victoria is the largest fresh water lake in Africa covering around 68,800km^2. The lake straddles the equator and it is shared by three East African countries of Kenya, Tanzania and Uganda. The three countries have jointly established the Lake Victoria Basin Commission (LVBC) for sustainable management of the lake’s natural resources and its environment. The huge size of this inland lake has resulted in the lake, creating its own mesoscale circulation, which is associated with deep convection and strong winds. The area neighbouring lake Victoria has been known to be among the regions that experience the highest fquency of thunderstorms and hailstorms in the world (Griffiths, 1972; Chaggar, 1977; Anyah and Semazzi, 2004).

Lake Victoria Basin Commission report (2011) indicates that, the frequent recurrence of severe storms continues to threaten the safety of marine navigation since Lake Victoria is used by a large number of boats on a daily basis to sustain a fishing industry. Hundreds of people lose their lives on the lake each year, with a share of these related to storm conditions.

Due to demand of weather forecasts and warnings for safety of navigation emphasized in the LVBC report (2011), the Uganda Department of Meteorology (UDoM) with assistance from the World Meteorological Organization (WMO) and the UK Meteorological Office (UKMO) developed the Mobile Weather Alert (MWA) service in response to the need to improve safety on the lake.

The accidents involving transport and fishing boats occur frequently over the lake and the most pronounced are over the western parts of the lake (e.g. The Bukoba accident). According to Chamberlin *et al.* (2014), the accidents are attributed to in part; high winds and waves associated with storm downdrafts and in part by the poorly maintained boats, a lack of health and safety awareness/equipment, and swimming ability.

In view of the foregoing, there is a need to provide information on thunderstorm characteristics to ships and other vessels using the lake for the safety of navigation since the importance of the lake as a resource that supports community livelihood is increasing.

1.1 Statement of the problem

The region east of Lake Victoria is prone to extreme weather events such as floods, storms (Thunderstorms/Hail) and landslides that lead to severe and adverse social and economic impacts. These impacts include population displacement, property and infrastructure damage, disease outbreaks and loss of life. Such impacts impede the economic growth and development of a country.

Occurrence of thunderstorms (deep convection) also has positive impacts. Thunderstorms if not severe can be a source of water in a region (Basak *et. al*., 2012) and this can help to reduce water stresses. Hence information from the study of thunderstorm characteristics can be used for local drought and flood management and in support of local disaster risk reduction strategies.

Previous studies on thunderstorm characteristics and active convection have focused on hourly, monthly, seasonal and annual time scales mostly over the equatorial Africa and East Africa in particular (Chaggar, 1977; Okoola and Ambenje, 2003; Laing and Carbone, 2011).

This study, therefore, aims to address the thunderstorm characteristics (spatial, temporal and propagation) so as to enhance the existing knowledge on the distribution of the thunderstorms over the study area.

1.2 Objective of the Study

The main objective of this study is to investigate the spatial, temporal and propagation characteristics of the thunderstorms to the east of the Lake Victoria Basin. To achieve this main objective, the following specific objectives were pursued.

(a) To determine the spatial and temporal distribution of thunderstorms to the east of the Lake Victoria basin
(b) To analyze the evolution and propagation characteristics of organized convective systems
(c) To analyze the circulation patterns associated with thunderstorm characteristics over the study region.

1.3 Justification

Thunderstorms have claimed many lives through lightning strikes or accidents associated with severe thunderstorms. It is also an economic factor, because aircrafts are diverted away from thunderstorm areas and therefore spending more fuel.

Thunderstorms produce hailstones. According to Sansom (1965) and Sansom and Gichuiya (1971), the frequency of hail was increasing in Kericho over the years. Huge hailstones can lead to loss of lives and damage to property in minutes. Such damage causes food insecurity since crops are destroyed, and yet agriculture is the main source of livelihood to many people in the area of study.

In the absence of conventional methods of radar, storm detections and sparse, uneven distribution of station networks, satellite imagery from Meteosat Second Generation Spinning Enhanced Visible and Infrared Imager (MSG-SEVIRI) potentially identifies abrupt and short lived convective storms developing over these regions (Thies *et al*, 2008b). This study used satellite data so as to enhance our knowledge on forecasting the phenomenon.

This study seeks to add new information on the spatial, temporal and propagation characteristics to the results from Chagger, 1977 and Asnani, 2005, who found out that the area under study was one of the most thundery places on the earth. Obiero (2013) also found out that thunderstorm frequency was higher in stations adjacent to the lake. This is due to convective activities associated with the lake.

The results from the study will enhance our knowledge of the phenomenon and thus assist in issuing early warnings and alerting residents on the occurrence of thunderstorms/hailstones, hence put in place protective measures to fight the phenomenon.

Most previous studies covered the equatorial Africa (Laing *et al*., 2008; Laing and Carbone, 2011; Jackson *et al*., 2009) or East Africa as a whole (Chaggar, 1977; Mpeta and Jury, 2001). This study narrows down to the country Kenya over the eastern part of the Lake Victoria basin.

1.4 Region of Study

The area of this study is to the east of the Lake Victoria basin bounded by longitudes ranging from 34°E to 36°E and latitudes 2°N to 2°S and it is located in the western part of Kenya. The area experiences a high frequency of thunderstorms which have led to loss of lives and property over the years.

1.4.1 Physical features to east of Lake Victoria Basin

The landscape of the western part of Kenya is complex, consisting of the highlands and mountain ranges, the Great Rift Valley that runs from north to south, forests, lakes and a network of river systems. Topographical diversity and closeness of Lake Victoria determine the climate characteristics of the western part of the country. Active convections form in this area with heavy precipitation on most afternoons (Tomsett and Toum, 1994; Asnani, 2005).

1.4.2 Thunderstorm Climatology in the Area of study

Thunderstorms form year-round to the east of Lake Victoria, because of a complex lake breeze (comparable to the sea breeze in coastal areas) that forces warm moist air up the mountains of western Kenya., Lake Victoria region is relatively wet most of the months, this is due to a complex series of airflow interactions, which ensures that showers and thunderstorms that occasionally produce hail occur all year long on the Kenyan side of the lake (Walter and Arnold, 1992).

The study of Yin and Nicholson (2000) showed that different months showed different times of maximum convection. In March and April, maximum convection occurs around 02.30 UTC in the west of the lake and around 14.30 or 17.30 UTC on the eastern side. The shift in the timing occurs at roughly 33^0E. This elementary pattern also represents the drier months of February to May, although the timing of maximum changes to 05.30 UTC in February and 23.30 UTC in May.

Through the dry season from June to September, frequent convection is mostly restricted to the northwestern part of the lake and maximum generally occurs toward 05.30 UTC or 08.30 UTC.

During the secondary rainy season of October to December, there is still a contrast between the eastern and western sectors of the lake, over the center of the lake a somewhat dissimilar cycle emerges. In October the convection maximum in the east is still around 14.30 UTC, compared to 08.30 UTC in the west. In November, the western maximum is around 05.30 UTC over much of the lake, compared to 14.30 UTC in the east and 02.30 UTC or 08.30 UTC in mid-lake A pattern comparable to that of November persists into both December and January, although with less intense convective activity (Yin and Nicholson, 2000).

1.5 Systems affecting thunderstorm occurrence

1.5.1 Mesoscale Convective Systems

A mesoscale convective system (MCS) is a collection of thunderstorms that act as a system. MCS are organized on a scale (on the order of 100 kilometers) larger than the individual thunderstorms but smaller than extratropical cyclones. Forms of MCSs that develop within the tropics use either the Intertropical Convergence Zone or monsoon trough as a focus for their development.

The development of mesoscale circulations is often associated with spatial heterogeneities in surface heat fluxes (Laird *et al.*, 2003). These surface heterogeneities can result from land-water boundaries; surface vegetation and land use differences and sea surface temperature gradients. The most obvious examples of the development of mesoscale circulations in response to variations in surface heat fluxes are the afternoon and early morning thunderstorms in the tropics. Studies have shown that the highest number of recorded thunderstorms in tropical Africa (and over the globe) occurs around the Lake Victoria Basin, with nearly 300 thunderstorm active days in a year (Asnani, 1993).

The lake-induced mesoscale systems and associated thunderstorm activities coupled to their surface heat and moisture source (i.e. Lake) often results in substantial localized precipitation over the lake and its immediate surroundings compared to land areas farther away from the lake boundary (Anyah *et al.,* 2006).

Mesoscale lake-effect circulations have been shown to develop through complex interactions of a range of environmental and geographic variables such as lake-air temperature differences, wind speed, lower tropospheric stability, lake shape or bathymetry (Laird *et al.,* 2003).

There are local circulations such as Lake Victoria, mountains and strong solar insolation that causes steep temperature gradients between the water surface and the surrounding high grounds as a result of the overhead sun. These give rise to strong mesoscale circulations over the region. Deep convective systems are initiated around 0700 UTC in the morning to 1000 UTC in the afternoon and peak during the late afternoon and evening times around 1200 UTC to 1600 UTC (Koros, 2014).

The convective systems are westerlies around Lake Victoria tending to easterlies originating from Mau forests, then decays towards the morning hours. Lake Breeze dominates the afternoon/evening and land breeze dominates the late night/early morning. Mesoscale circulation systems (Indeje, 2000) control the spatial and temporal variation of thunderstorm characteristics over the study region.

1.5.2 Equatorial Westerlies

Nakamura (1968) has studied the nature of equatorial westerlies over East Africa. The study showed that frequent incursions of westerlies resulted in heavy thunderstorms over the Kenya Highlands, but the lee effect was evident in the region east of the Highlands. The equatorial westerlies are vital because they fetch moisture from the west (Antlantic Ocean/Congo basin/Lake Victoria basin) into the study region.

CHAPTER TWO

2.0 Literature Review

This section reviews some studies that have been done in the past on thunderstorm characteristics over equatorial Africa and East Africa. The chapter is divided into; past studies on the thunderstorm frequency, distribution, their effects and circulation patterns associated with TS over the study region..

2.1 Frequency of Thunderstorms

Chaggar (1977) carried out a study on the Geographical distribution of monthly and annual mean frequency of thunderstorm days over eastern Africa. The study noted that a high frequency of thunderstorms occurred over high ground and Lake Convergence Zones. The observations were mainly confined to daylight hours and most of the data was missing. This study makes sure that any incomplete data is filled.

Enhanced convection and thunderstorm activity over Kenya is likely when the easterly flow is strong and increasing (Chaggar, 1977). This study will rely on the wind flow over the study area to explain the kinematic associated with the thunderstorm characteristics during the March- April-May (MAM) and September-October-November (SON) seasons.

Zipser *et al*. (2006) used Tropical Rainfall Measuring Mission (TRMM) satellite data and showed that the equatorial Africa experiences the most intense thunderstorms in terms of microwave scattering signature and occurrence of lightning flashes worldwide.

Numerous thunderstorms have the potential of giving hailstones. Very little was known about the occurrence of hailstones in Kericho until Sansom (1965) drew the attention of the scientific world of the fact that, this hill station had a hail storm frequency of about one in 3 days, almost all through the year, Alusa (1986).

Obiero (2013) studied thunderstorm hazards and their influence in the Lake Victoria basin of Kenya. He examined the relationship between thunderstorms frequency and other weather variables, analyzing the storms' spatial and temporal variation, establishing the frequency characteristics of rainfall related to the storms and evaluating lightening severity in the area. A monthly examination of the storm's frequency showed each recording station had its own peak.

The first peak was marked in Kisii during the month of March followed by Kericho in May. The third peak was detected in Kitale during the month of August. The lowest peak was evident in Eldoret.

2.2 Distribution of thunderstorms

Chaggar (1977) found out some fascinating features about the distribution of thunder in eastern Africa. The movement of the centre of thundery activity from the south over northern Zambia (in December and January) to the north over Uganda (in July and August) via the two tongues, one along the western rift valley and the other west of lake Victoria, revealed an interesting movement from month to month.

The latter progressively moves from the west of the Lake to the North and eventually into western Kenya, whereas the former shows a northward movement in February and March, linking the two centers in April, and finally retracting towards the north in May and June.

In September, the Tongues start moving southwards, the western tongue connecting the two centers in October and November, and finally the center returns to the south. There is still need to update the knowledge by studying the recent trends of thunderstorm occurrence in these areas because according to the foregoing study it was one of the most thundery places on the globe (Chaggar, 1977 and Asnani; 1993, 2005).

Laing and Carbone (2011) studied the spatial and the hourly distribution of deep convection over equatorial Africa. They found out that deep convection is most frequently initiated in the lee of high terrain during the mid- to late afternoon. Maximum in deep convection is also associated with the sea-land breezes and Lake Victoria breezes. They also found out that small areas of deep convection form an arc along the slopes of the East African mountain ranges from 1100- 1200 UTC. The primary thunderstorms grow, merge, and propagate to maximum intensity between 1700 and 1800 UTC.

2.3 Effects of Thunderstorms on Weather over East Africa Lake Basin

Thunderstorms occur with high frequency over the Kenyan Highlands. The eastern lowlands experience little thunderstorm activity except in March and April because wind flow pattern at low-levels in this region are generally divergent. Showers develop frequently when unstable tropical westerly flow frequently penetrates over the Kenyan Highlands, converging with the northwesterly flow (Trewartha, 1981). Convective cloudiness occurs mostly over the western slopes of the mountains. The probability of penetrating westerlies is increased if the subtropical anticyclone over northwest Southern Africa is intense or building.

A case study; severe storm in the Buvuma region on 1 March, 2012 was carried out. In this study, Chamberlain *et al* (2014) verified the Lake Victoria model performance on a case study of a storm that occurred on 1 March 2012 around 1630 UTC.

This storm incident and associated high waves in the Buvuma region led to a boat capsizing, killing 17 passengers and crew with only two people surviving. Satellite observations showed the storm developing between 1200 UTC and 1500 UTC on 1 March in the North-eastern parts of the lake (Buvuma) and dissipated by 1800 UTC although by then there were signs of new convective activity south of the original stream (Chamberlain *et al*., 2014).

2.4 Mechanism of Thunderstorm formation

A normal thunderstorm or single cell thunderstorm is distinguished by a well-defined life cycle that takes about an hour and consists of 3 stages: the cumulus stage, the mature stage and the dissipating stage (Kessler, 1986), shown in figure 1.

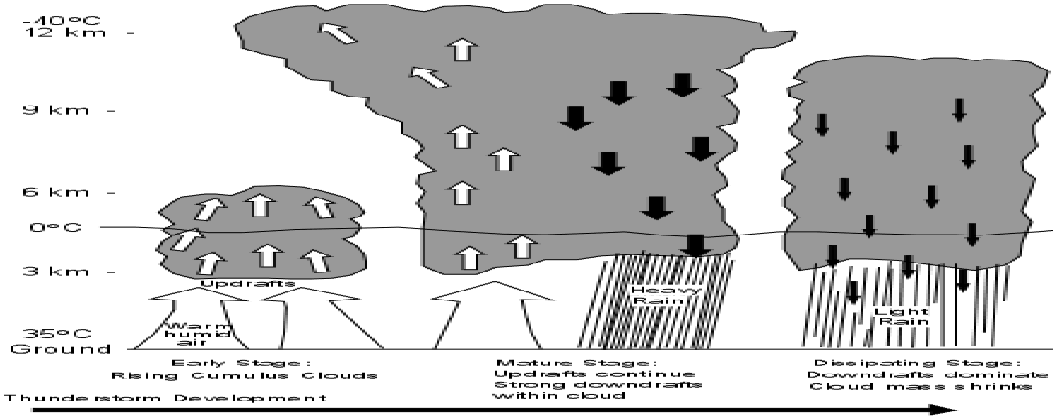


Figure 1: Illustration of 3 thunderstorm stages: the cumulus stage, the mature stage and the dissipating stage.

There are two main types of thunderstorms: ordinary and severe. Ordinary thunderstorms are the common summer storm and usually last about one hour. The precipitation associated with these storms includes rain and occasionally small hail. With ordinary thunderstorms, cumulonimbus clouds can grow up to 15,000 meters high (Muthama *et al.*, 2003).

Severe thunderstorms are very dangerous. They are capable of producing baseball-sized hail, strong winds, intense rain, flash floods, and tornadoes. Severe thunderstorms can last several hours and can grow 18 kilometers high. Several phenomena are associated with severe thunderstorms, including gust fronts, microbursts, super cell thunderstorms, and the squall lines.

2.5 Circulations associated with TS

Winds originating from the west (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 leading to thunderstorms/ precipitation if there is enough moisture and condensation nuclei (Okoola, 1999).

Sakwa (2006) carried out a study on assessment of the skill of the high resolution regional model in the simulation of airflow and rainfall over east Africa. He found out that the lake breeze dominated over the lake basin region in the afternoon (1200 UTC) and evening (1800 UTC). Strong land breeze circulation occurs late at night (0000 UTC) and early in the morning (0600 UTC) when there is convergence over the lake. His results were consistent with those of Song et al., (2004). At 0000 UTC, the convergence is over Lake Victoria and at 1200 UTC the convergence is over the surrounding parts of the lake.

During SON season, the east Africa region experiences southeasterly monsoon. There is a line of confluence that runs continuously from north to south around 35.9 degrees east as a result of the effect of the Great Valley escarpment (Sakwa, 2006).

This study adds to our knowledge of thunderstorm characteristics east of the Lake Victoria basin by; documenting the systematic propagation and evolution of thunderstorms in the study area using cloud top temperature as an indicator of the zone of convective activity (Matsumoto, 1992), assessing the seasonal, monthly and diurnal characteristics of thunderstorms. The results will provide more insight into the long-term and short-term forecasts on thunderstorm occurrence over the study area.

CHAPTER THREE

3.0 Data and Methodology

This chapter discusses the datasets and the methods which were used in order to achieve the specific objectives in section 1.2.

3.1 Data

The datasets used in this study are; thunderstorm data, cloud top temperature data (CTT), and wind field data. The detailed description of these datasets is discussed below.

3.1.1 Observed thunderstorm data

The daily observed thunderstorm (frequency of occurrence from hours 0900 UTC to 1800UTC) data from five stations in the area of study were used. The synoptic stations are; Kisii, Kericho, Kisumu, Nakuru and Narok (Table 1). The data covers a period of 14 years (2000 to 2013), and it was extracted from the meteograms from the national meteorological Centre (NMC) and the METAR books (climatological section); from the Kenya Meteorological Service (KMD).

Table 1: Details of the stations used in the study

Stations	Latitude (^{0}S)	Longitude (^{0}E)	Elevation in Meters (AMSL)
Kericho	00.22	35.21	2182
Kisii	00.40	34.47	1705
Kisumu	00.06	34.45	1157
Nakuru	00.16	36.06	1850
Narok	01.08	35.50	1827

3.1.2 Cloud Top Temperature Data

The cloud top temperature data was chosen on the based on the results from the objective one. The data was for the years; 2006, 2007 and 2008. That is, for MAM season (2006 and 2007) while SON season (2007 and 2008).

The data were extracted online from the site, htt://disc.sci.gsfc.nasa.gov/giovanni. The data were modern-era retrospective analysis for research and applications (MERRA) hourly historical data collections under the meteorological portal. The data have a resolution of 2/3 longitude by ½ latitude degrees. Cloud top temperature data is used in this study because it has been successfully used by previous researchers (e.g. Laing et al., 2008; Laing and Carbone, 2011; Koros, 2014) with realistic results.

The choosing of the cloud temperature threshold was based on previous studies of convection in the tropics. Duvel (1989) and Machado *et al*. (1993) used 253^0K as the threshold for clouds associated with deep convection over the Sahel area and western Africa respectively. Arnaud *et al*. (1992) used 233^0K to identify convective clouds that are most likely to precipitate in Africa.

Mathon *et al*. (2002) found that Sahelian organized systems identified by the 233^0K threshold accounted for 90% of the seasonal rainfall observed by the Etudes des Precipitations par Satellite (EPSAT) -Niger rain-gauge network over a nine-year period. Based on rain-gauge and IR satellite data from Estimation of Precipitation by Satellites (EPSAT), 213^0K was optimal for identifying the peak.

Inoue *et al*. (2009) used a CTT threshold of 235^0K to 208^0K to study the life cycle of deep convective systems over the eastern tropical Pacific. This threshold is often used in studies of deep convection. Vila et al. (2008) used a threshold of 235^0K over tropical South America.

Laing *et al.* (2008) and Laing and Carbone 2011) also used a threshold of 233^0K as an indicator of deep convection over equatorial Africa. The discrimination of convective cells was performed using a temperature threshold on IR data/imagery since they constitute the coldest events observed.

This study uses a threshold value of CTT$\leq$235^{0}K for identifying thunderstorm clouds. This threshold is chosen because it has been widely used for identifying deep convective systems in previous studies in the tropics.

3.1.3 Wind Data

This study utilized the once daily full resolution ECMWF Re-Analysis (ERA) - Interim wind data (0000, 0600, 1200 and 1800 UTC) 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 (850mb), Middle (700mb) and upper (200mb) levels. The data for the years 2006 and 2007 (MAM) and 2007 and 2008 (SON) were downloaded from the ECMWF data server.

Murakami and Sumathipala (1989), Mukabana and Pielke (1996), Okoola (1999), Gitau *et al*., (2014), and Koech (2014) among others have successfully used the ECMWF datasets for various studies over east Africa.

Lin *et al.* (2014) compared the skills of five re-analysis datasets (ERA-40, ERA-Interim, and NCEP-2, Modern-Era Retrospective Analysis for Research and Applications (MERRA), and Japanese 25-yr Reanalysis Project (JRA-25)). The study further showed that ERA-Interim data has the highest skill in replicating the climatology of worldwide monsoons. The study showed that the ERA-Interim re-analyses were good estimates of the real flow fields. It should however be noted that ERA-Interim has higher resolution compared to other re-analysis datasets.

3.2 Methodology

Before the thunderstorm data were subjected to any analyses, homogeneity test was undertaken to test the quality of the data. Details of these are discussed in the subsequent sections.

3.2.1 Homogeneity of the data

Before the analysis is done on the data, there is a need for the data quality checks. Single Mass curves were used to assess the quality of the data in the study. The total seasonal thunderstorm frequencies for each station were cumulated and plotted against the years. An almost straight line shows the data are homogeneous and the reverse is true. (Muthama *et al*., 2007 and Omondi, 2010).

3.2.2 Space-time Characteristics of Thunderstorms

Maps were used to assess the spatial distribution of TS (Sagero, 2012). The total observed thunderstorm frequencies for each station were generated. The frequencies were plotted against the stations and from the plots it was possible to assess the stations which were most thundery and less thundery.

Graphs were used to display the diurnal, seasonal and annual distribution of TS. These were plotted against the hours, months and years respectively. The plots were then used to show the hours, months and years, which had high and low TS frequencies (Sagero, 2012).

3.2.3 Longitude-Time analyses

Cross-sectional analyses (Hovmoller diagrams) of cloud top temperature (CTT) were used in order to study the evolution and propagation of thunderstorms over the study. In general, a Hovmöller diagram map is a scalar quantity to distance-time space. The scalar variable is averaged along the spatial dimension (or dimensions) orthogonal to the spatial dimension plotted in the Hovmöller diagram. Among other uses, these diagrams have been used in the past to diagnose patterns and isolate signals in equatorial convection (e.g. Lau and Peng 1987; Hayashi and Nakazawa 1989).

The CTT values used in this study were averaged between latitudes 2^0N and 2^0S and plotted as longitude- time cross section to reveal the zonal transition of the centers of low CTT values ($CTT \leq 235^0K$) across the area of study (Laing and Carbone, 2011; Okoola and Ambenje, 2003). Each pixel with a threshold value of $CTT \leq 235^0K$ constitutes an event at a given distance-time coordinates.

Plots of Hovmoller diagrams were generated using GrADS software which is incorporated in the Giovanni visualization and analysis tool (Leptoukh *et al*., 2005). One Hovmoller diagram was generated every fortnight. This method has previously been used by other researchers (Okoola and Ambenje, 2003; Laing, *et al*., 2008; Laing and Carbone, 2011).

3.2.4 Wind Vector Patterns

The wind patterns were used to explain kinematics associated with thunderstorm characteristics.

Mean daily wind vectors were plotted for each season (MAM and SON). The strength and orientation of winds were analyzed to identify whether there were areas of confluence or difluence hence the observed weather patterns.

During the time of occurrence of thunderstorms, the space-time patterns of the winds at 850mb, 700mb and 200mb levels were investigated.

3.3 Challenges and assumptions of the study

The main challenge encountered in this study was the poor network of stations. Another challenge was that, the thunderstorm data is not digitized and hence a lot of time used in extracting the data from the Metar books. The assumption made based on the foregoing challenges was that the station network and study period used in this study is representative of the study region based on availability of the thunderstorm data.

The results obtained and conclusions derived in the next chapter are thus based on these major assumptions, taking into account the limitations already stated.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

Results obtained from the various methods used in subsection 3.2 are discussed in this chapter starting with, data quality control results.

4.1 Data Quality Control Results

The data from all the stations was homogeneous because a single straight line could be fitted on cumulative seasonal thunderstorm frequency amounts for the stations as shown by the two chosen stations. These quality controlled data was the basis of all analyses that were carried out in this study. The results of the homogeneity test which were achieved by the use of single mass curves (Muthama *et al*., 2007) are shown in Figures 2 and 3.

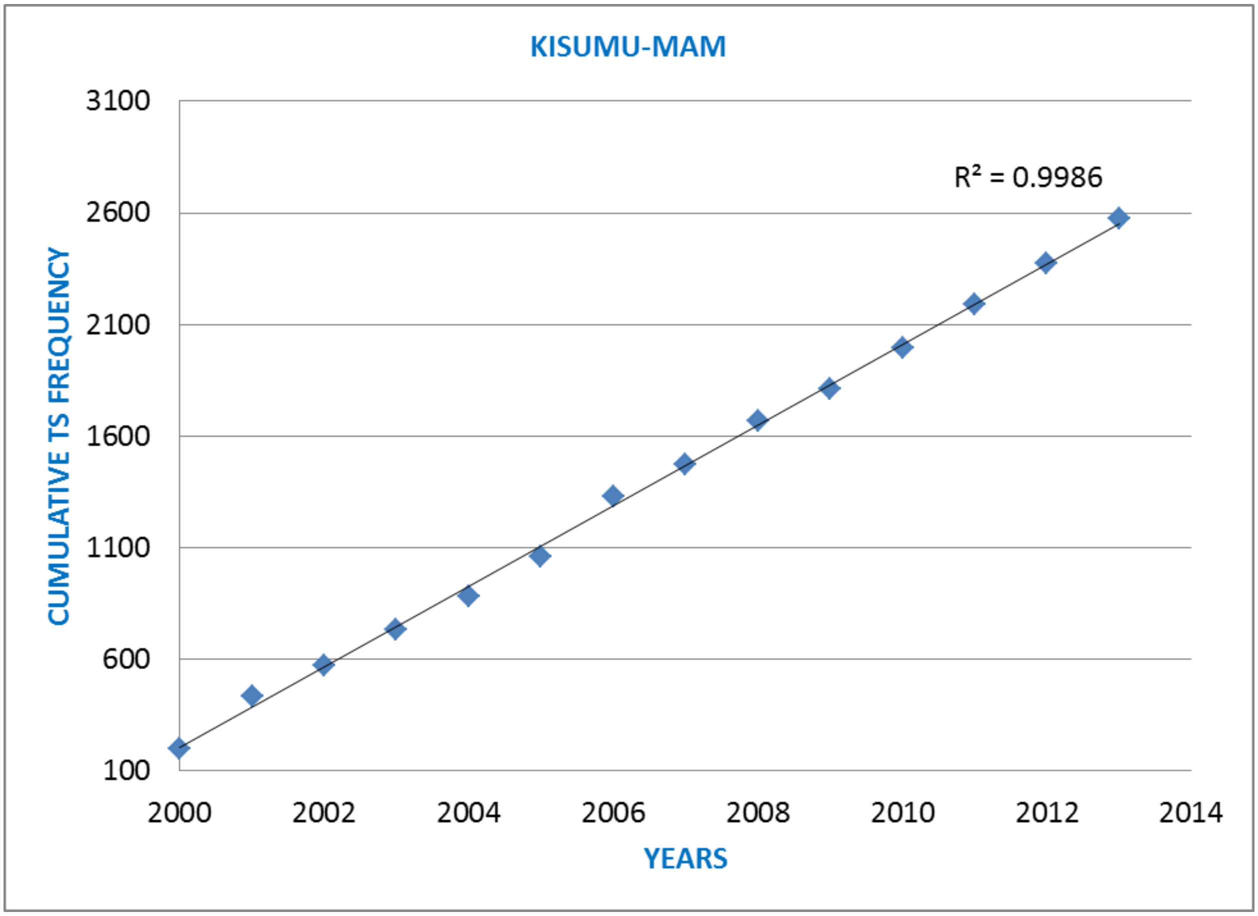


Figure 2: A plot of cumulative thunderstorm frequency for Kisumu during March to May.

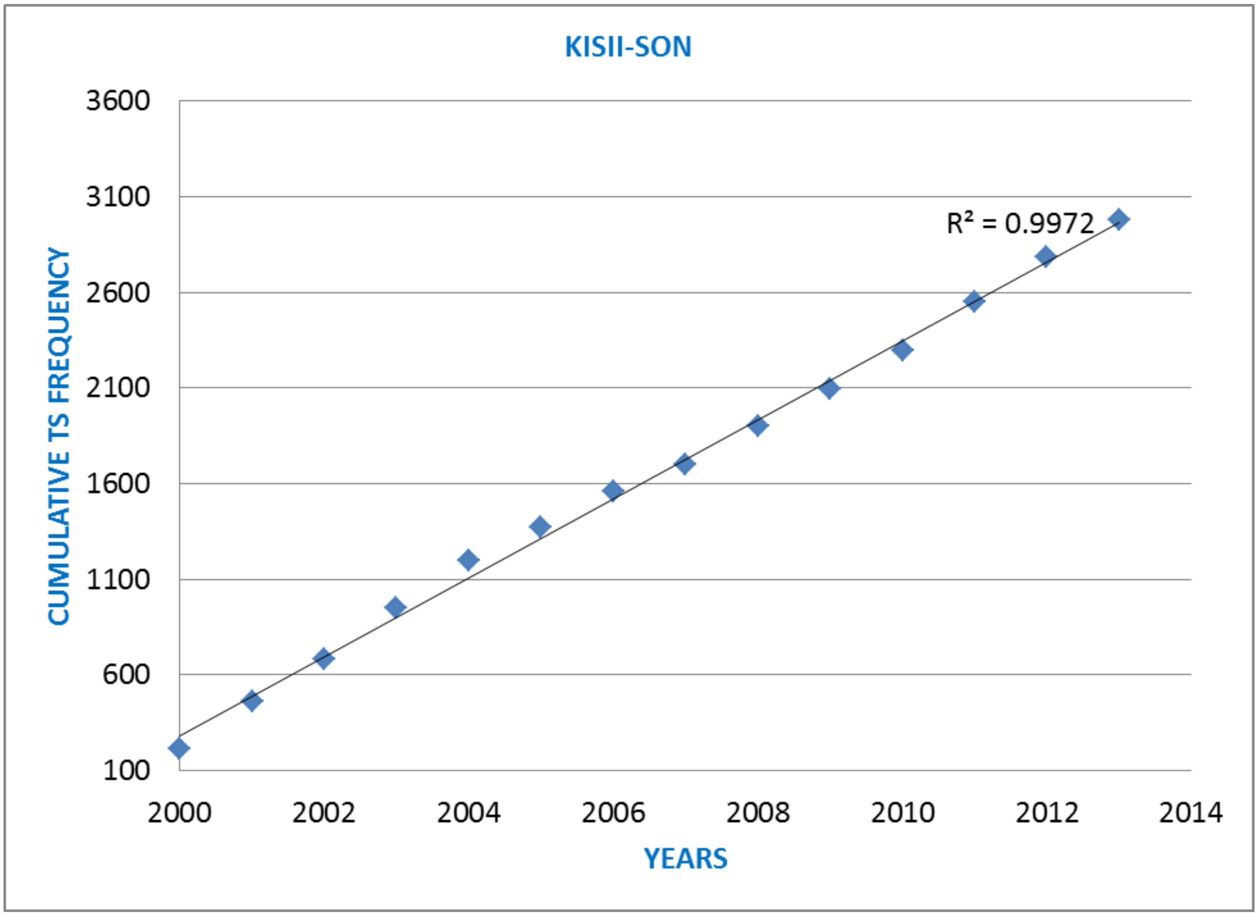


Figure 3: A plot of cumulative thunderstorm frequency for Kisii during September to October.

4.2 Analysis of observed thunderstorm frequency data

The result achieved from objective one on the hourly (Figure 4), monthly (Figure 5) and annually (Figure 6) observed thunderstorm data were the basis of choosing the satellite data used in the study. The results of temporal and spatial analysis are shown in the following subsections.

4.2.1 Temporal analysis

Diurnal thunderstorm analysis showed that TS peak is reached between 1200 UTC to 1500 UTC (Figure 4). The results of hourly analysis show that stations away from the Lake and closer to the heat source (Kericho, Nakuru and Narok) attain the peak around 1300 UTC while stations closer to the Lake (Kisii and Kisumu) attain the peak at 1400 UTC. Thus, those stations near the heat source (Mau Hills) attain their TS peak before those near the lake because they attain maximum heating much earlier than stations further away from the Mau Hills. The average TS frequencies start to decrease with time after the peak hours except for Kisumu where the frequency remains higher after the peak compared to the other stations. This trend at Kisumu is due to the higher temperatures over the lake that maintains convection for a longer period than in stations further away from the lake.

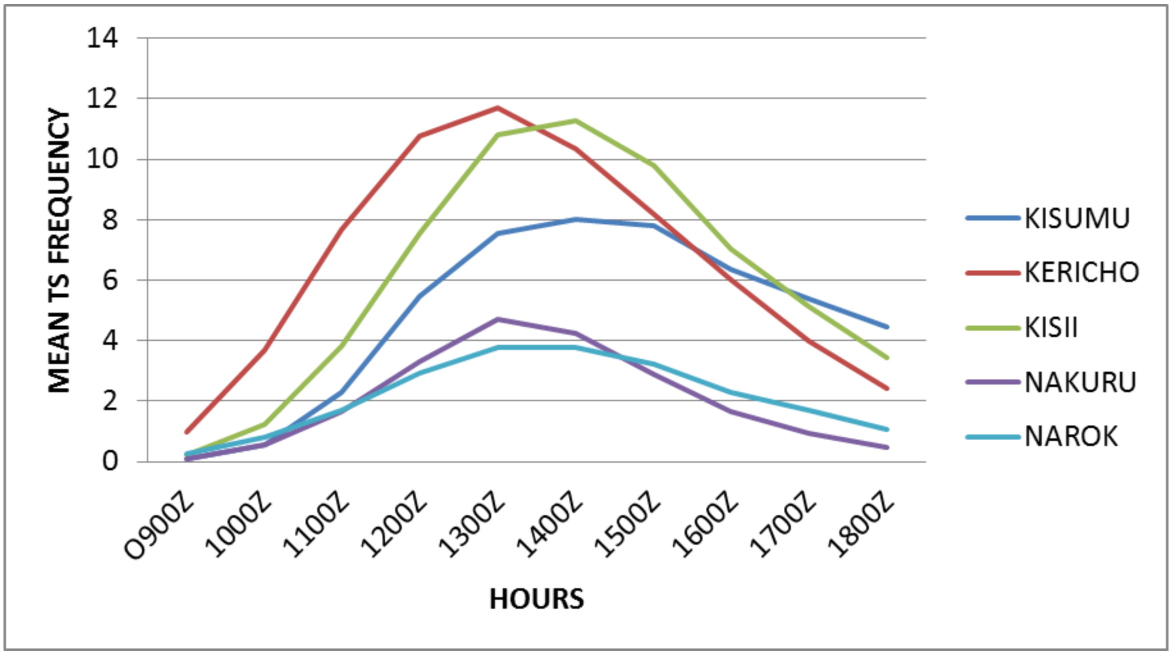


Figure 4: Diurnal cycle of Mean TS frequency from 0900Z to 1800Z for the years 2000-2013

The results from those of Koros (2014) showed that the peak of deep convection is reached during the late afternoon and evening times around 1200 UTC to 1600 UTC. Yin and Nicholson (2000) also showed that maximum convection occurs around 14.30 or 17.30 UTC on the eastern side of the lake. The results are consistent with those from this study that show the peak of maximum convection is reached around 1200 UTC to 1500 UTC.

In summary, stations near the Mau Hills are heated faster and thus attain their TS maximum much earlier than stations closer to the lake. Thunderstorm frequencies also start decreasing in stations near the Mau Hills towards the lake. This is due to the stations near the heat source loosing heat faster than those near the Lake as the day goes by.

Monthly analysis (Figure 5) revealed that high activities of thunderstorms were observed during the months of March to May, and September to November. The results from temporal analysis also show that most stations had their peaks in the same month except for Nakuru and Narok which were different. During March to May, Kericho (95.9), Kisii (85.6), Kisumu (70.8) and Nakuru (33.9) had their peaks in May while Narok (40.6) had its peak in March. During September to November, Kericho (85.6), Kisii (74.1) and Kisumu (66.3) had their peaks in September except for Nakuru, which had its peak in October (29.6) while Narok had no clear peak.

These results for Kericho are in agreement with those of Obiero (2013). The study carried out a monthly investigation of the storm's frequency and showed each recording station had its own peak. Kericho had its peak in May. Most of the stations have their Thunderstorm peaks during March – May and September – November because the activities are enhanced by the presence of the Inter-tropical Convergence Zone (ITCZ) over the study region.

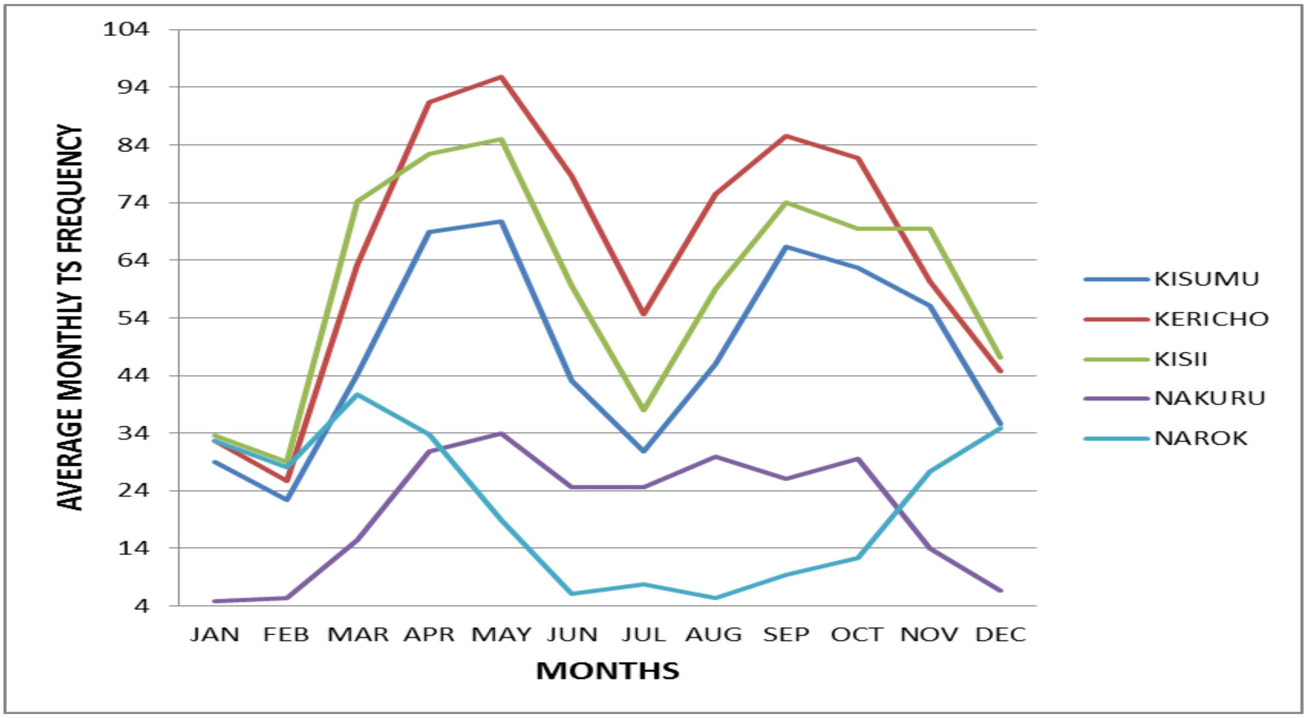


Figure 5: Annual cycle of Mean TS frequency for the years 2000-2013

The results from the analysis of the seasonal thunderstorm totals in the study area show that on average, during the MAM season, an increase in thunderstorm frequency was recorded in 2006 from the previous year while it decreased in 2007 (Figure 6 (a)). During SON, TS frequencies decreased in 2007 from the year 2006 while an increase in TS frequencies was recorded during 2008 (Figure 6 (b)). The Increase/decrease of thunderstorm frequencies in these years was more consistent.

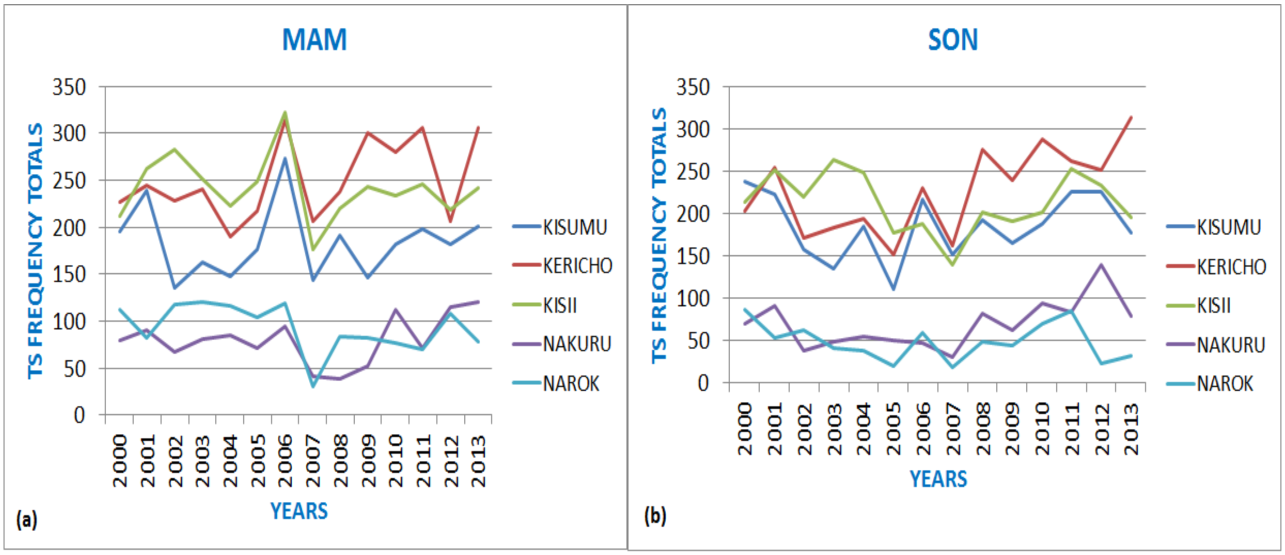


Figure 6: Interannual variability for (a) MAM and (b) SON total thunderstorm occurrences distribution.

4.2.2 Spatial analysis

The spatial analysis for the MAM, SON and annual (Figure 7) Mean TS totals show that Kericho recorded the highest thunderstorm frequency followed by Kisii, Kisumu, Narok and Nakuru respectively. The pattern portrayed is due to stations near the heat source attaining their maximum heating faster than those towards the lake.

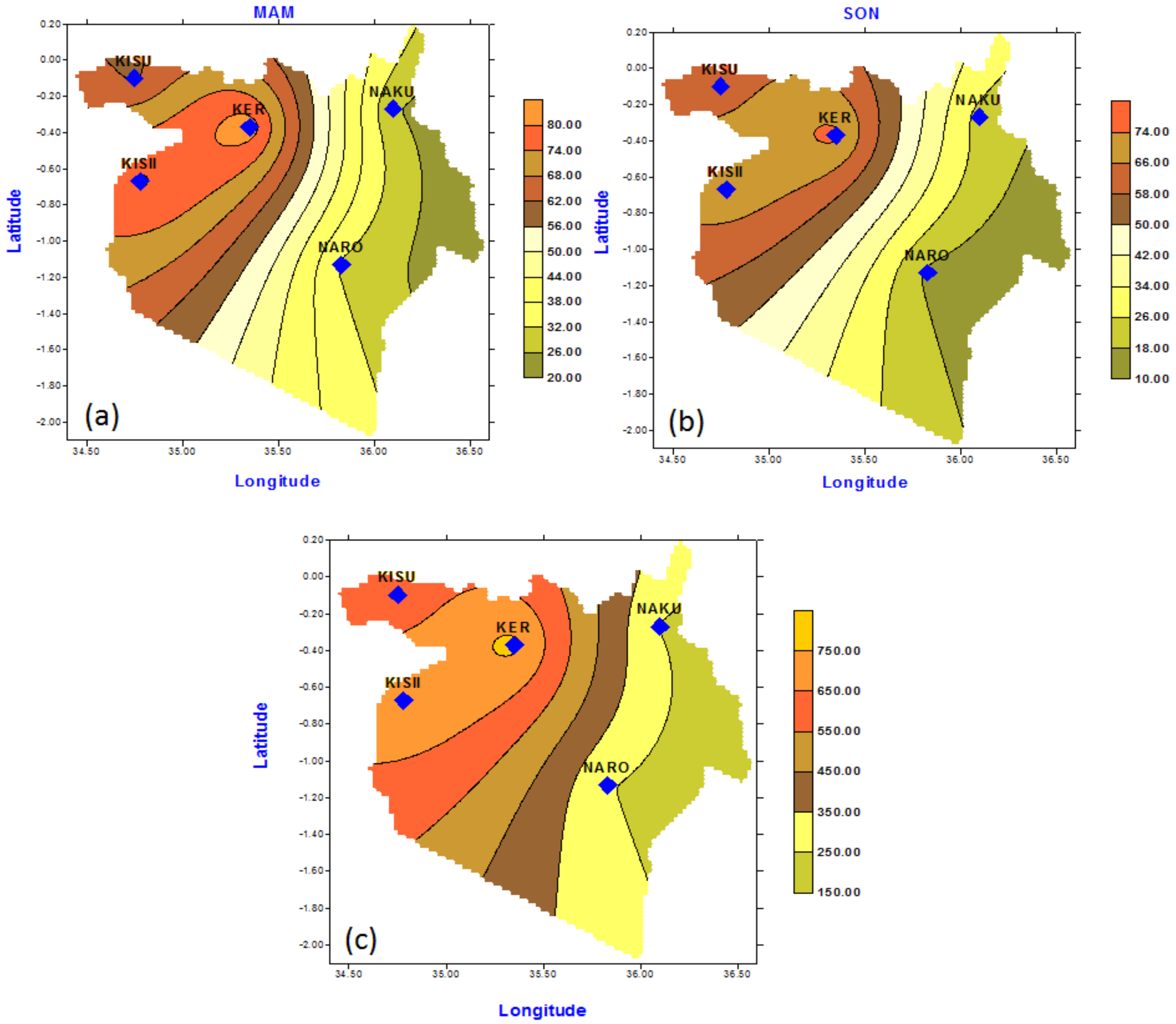


Figure 7: Spatial maps showing; (a) Mean TS frequency distribution for MAM, (b) Mean TS frequency distribution for SON and (c) Annual distribution of Mean TS Frequency.

4.3 Propagation of organized convection

The analysis was carried out for MAM and SON (Figure 5) seasons, which had high thunderstorm activities over the study area. Most of the longitude-time (Hovmoller diagrams) analysis showed that the organized convection evolved from the Mau hills and propagated westwards towards the lake.

4.3.1 Hovmoller diagrams showing propagation of organized convection during MAM

Results on the interannual variability of total TS occurrences revealed that, during MAM season (Figure 6 (a)), the year 2006 was more active in terms of TS activities compared to the year 2007. Hence, for the MAM season, analysis of the propagation characteristics of thunderstorms over the study area is based on the two years.

4.3.1.1 Hovmoller diagrams showing propagation of organized convection in March 2006 and 2007

In the month of March 2006 (Figure 8 (a)), thunderstorm activities started as early as 1st March then relaxed towards the end of the 2nd. On 3rd, a convective system propagates westwards towards the lake. Intense activities were recorded from 6th to 9th followed by isolated thunderstorm activities between 10th and 13th and then intensifying as from 14th to 30th March 2006 with intervals of warm temperatures (CTT>235^{0}K) in between as shown by the red color.

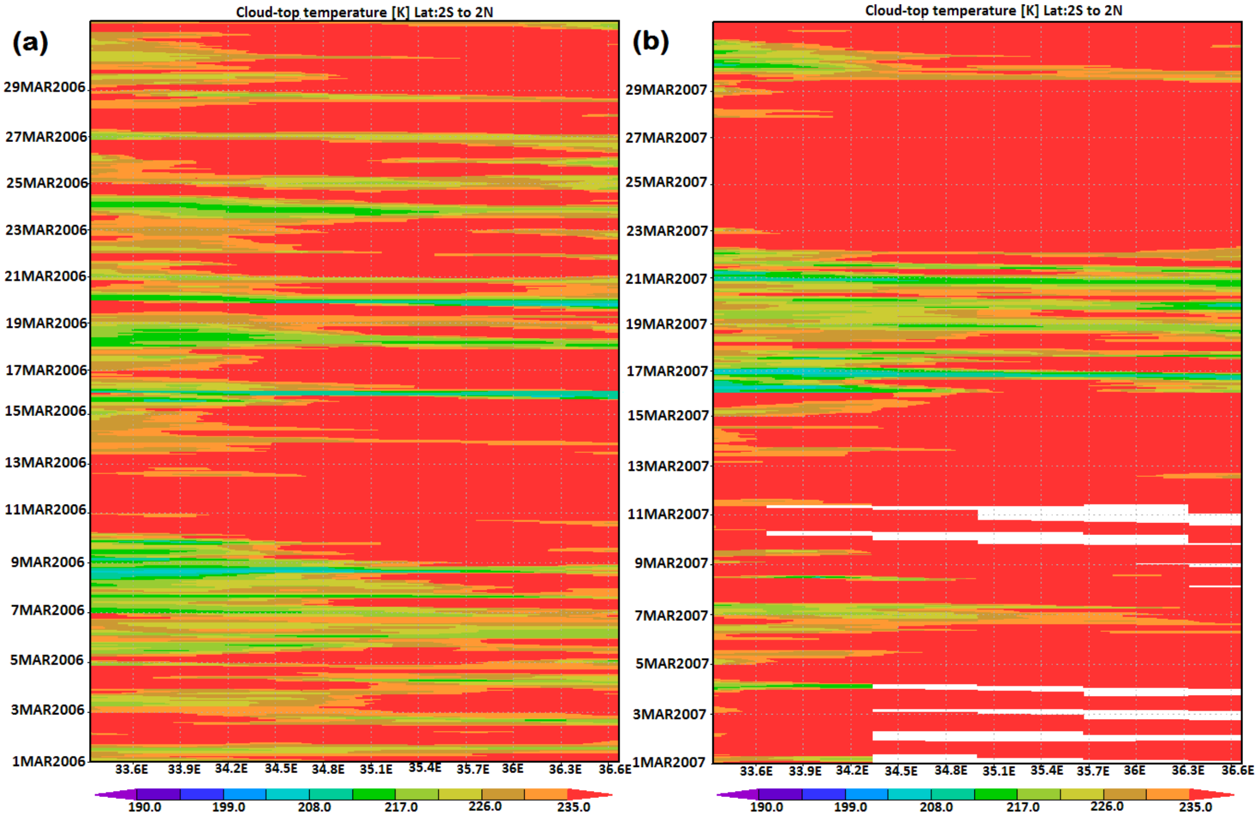


Figure 8: Hovmoller diagrams showing propagation characteristics of organized convection for (a) March 2006 and (b) March 2007

The results in Figure 8 (b) show that the month of March 2007 was less active (red color) than March 2006. The white lines on the diagram indicate missing data. Most of the days between 1st and 15th March 2007 were not active except over the lake (33^{0}E-34^{0}E) and adjacent areas (yellowish to green color). On 7th March 2007, intense TS activities (deep convection) were experienced over the whole study area.

Most of the convective systems were observed to be evolving and propagating towards the lake (7th March 2007) from the Mau Hills. The onset of thunderstorms was much later (16th March 2007) compared to 1st March 2006 which came much earlier. It was active from 16th to 22nd which was then followed by no TS activities (red color) up to 29th March 2007 then some TS activities were recorded on 30th March concentrating more towards the lake.

Generally, March 2006 was more active (less red color) than March 2007 (shown by more red color) and the convective (TS) systems propagated westwards from the high ground towards the lake.

4.3.1.2 Hovmoller diagrams showing propagation of organized convection in April 2006 and 2007

In Figure 8 (a), thunderstorm TS) activities were present from March 2006 continuing up to 5th April 2006 with 3rd April 2006 (Figure 9 (a)) recording reduced TS activities. Most TS were concentrated towards the lake. After 5th April 2006, most of the days recorded few TS activities, especially towards the lake region. Activities (yellowish to green color) started increasing from 17th to 26th April 2006. The activities relaxed (reduced in intensity) on 27th and 28th then the activities intensified on the 29th while 30th April 2006 registered no activities as shown by the red color.

In April 2007 (Figure 9 (b)), there were no TS activities (shown by red color) over the study region from 1st up to 9th April 2007. Thunderstorm systems between 9th and 11th, April 2007, were observed originating from 35.5^{0}E and propagating towards the lake. Reduced TS activities were observed on 12th and 13th April 2007 and then started increasing from 14th April 2007 to 22nd April 2007. Few activities were recorded on 23rd, 27th and 28th. It was active on 24th, 25th, 26th, 29th and 30th.

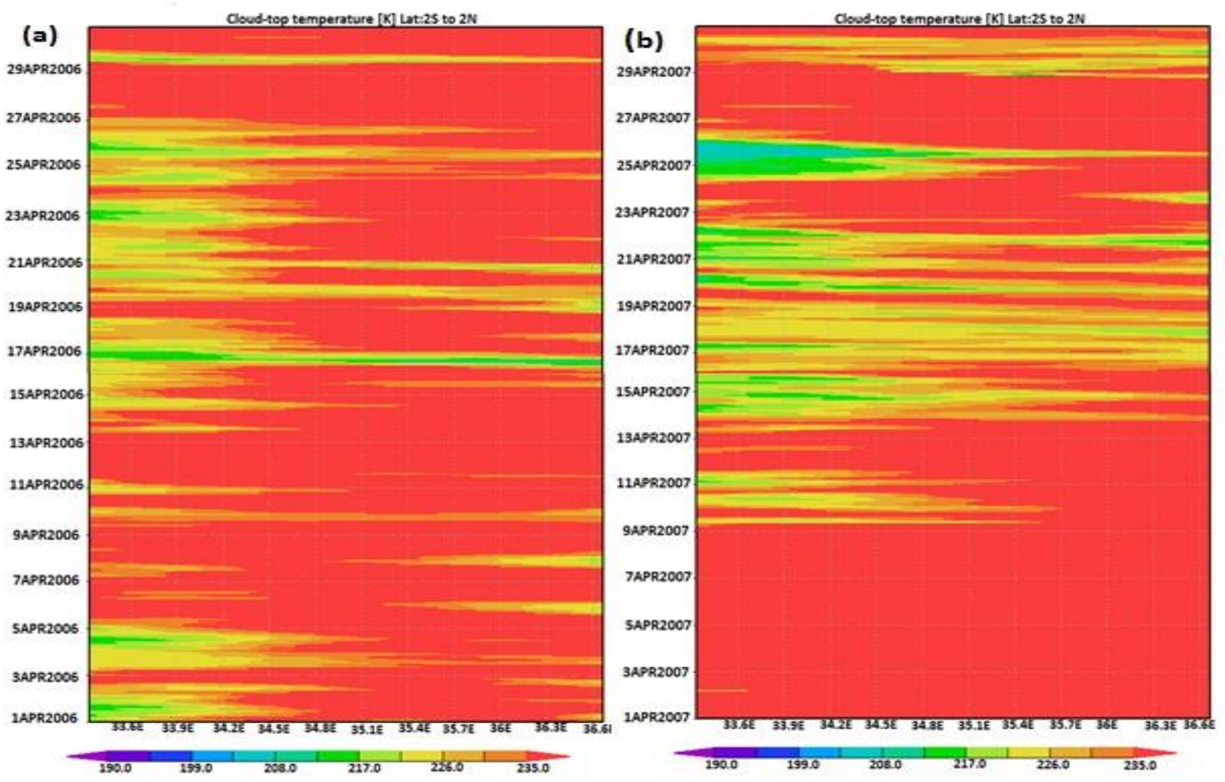


Figure 9: Hovmoller diagrams showing propagation characteristics of organized convection for (a) April 2006 and (b) April 2007

4.3.1.3 Hovmoller diagrams showing propagation of organized convection in May 2006 and 2007

Isolated activities were observed from 1st to 11th May 2006 with activities, increasing from 12th to 22nd alternating with patterns of warm (≥235 ^{0}K) temperatures as shown by the red color. Thunderstorm clouds were more concentrated towards the lake (Figure 10 (a)). Isolated activities were observed between 23rd and 26th May 2006 then TS activities were increased again from 27th to 30th. 1st to 20th May 2006 on average, clearly showed organized convection propagating from the Mau Hills at latitude ~35.5^{0}E

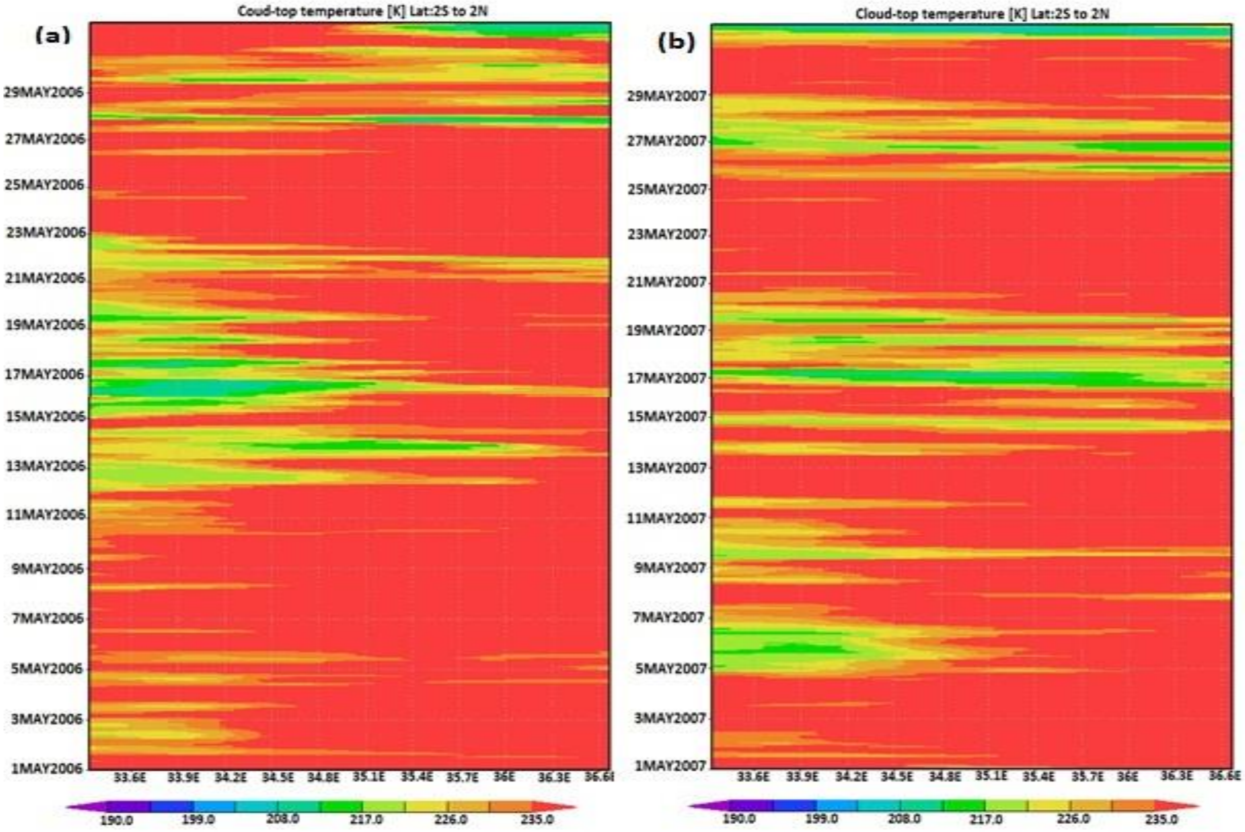


Figure 10: Hovmoller diagrams showing propagation characteristics of organized convection for (a) May 2006 and (b) May 2007

Isolated thunderstorm (TS) activities were recorded between 1st and 4th May 2007 (Figure 10 (b)). Thunderstorm activities were observed evolving from Mau Hills and propagated towards the lake. Some days were active throughout over the study area (10th, 15th, 17th, 18th, 20th, 26th, 27th, 28th, and 31st May 2007). No activities were recorded on 12th and 23rd.

4.3.2 Hovmoller diagrams showing propagation of organized convection during SON

Results on the inter-annual variability showed that, during SON season (Figure 6 (b)); the year 2008 was more active in terms of thunderstorm activities compared to the year 2007 which had lower (less active) thunderstorm activities. Therefore, SON season analysis of the propagation characteristics over the study area is based on the two years.

4.3.2.1 Hovmoller diagrams showing propagation of organized convection in September 2007 and 2008

Few TS activities (red color) were experienced between 1st and 16th September 2008 (Figure 11 (a)). Due to the short life span of convective systems, some dissipated before reaching the lake (e.g. 10th, and18th September 2008). Organized TS clouds were seen evolving from the heat source (35.5^{0}E) and propagating towards the lake.

The month of September 2007 (Figure 11 (b)) experienced high TS activities on 7th, 8th, 10th, 11th, and 12th, while lower (more red color) activities were recorded on 16th, 17th, 24th, and 25th with the rest of the days registering isolated (yellowish color) or no TS activities (red color).

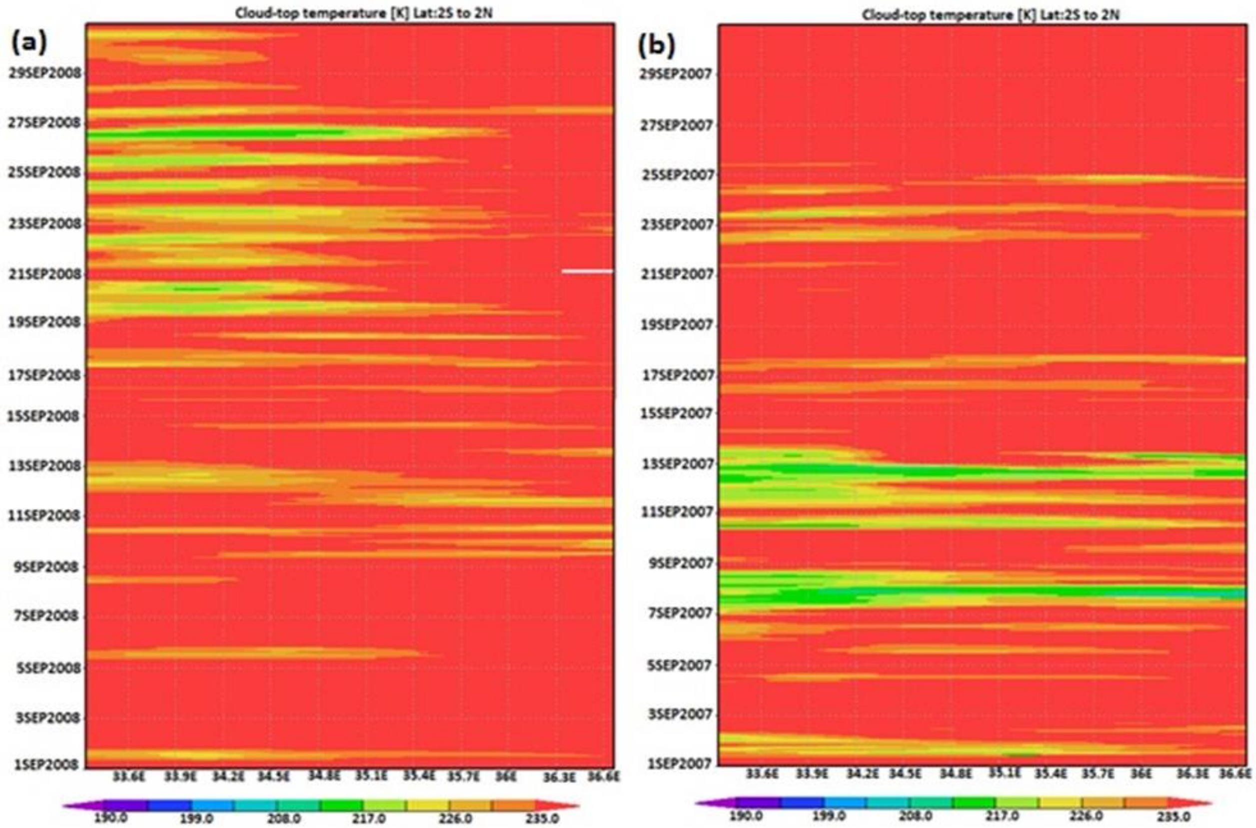


Figure 11: Hovmoller diagrams showing propagation characteristics of organized convection for (a) September 2008 and (b) September 2007

4.3.2.2 Hovmoller diagrams showing propagation of organized convection in October 2007 and 2008

In October 2008 (Figure 12 (a)), intense thunderstorm activities (yellowish to green color) were observed on 9th -13th, 22nd -27th, 29th - 31st. The rest of the days reported lower TS or no TS activities.

In Figure 12 (b), most of the days recorded isolated or no TS activities except for 2nd – 4th, 6th, 9th, 10th, 15th, 16th, 19th and 22nd. The thunderstorm activities were seen evolving from the heat source and propagating westwards towards the lake.

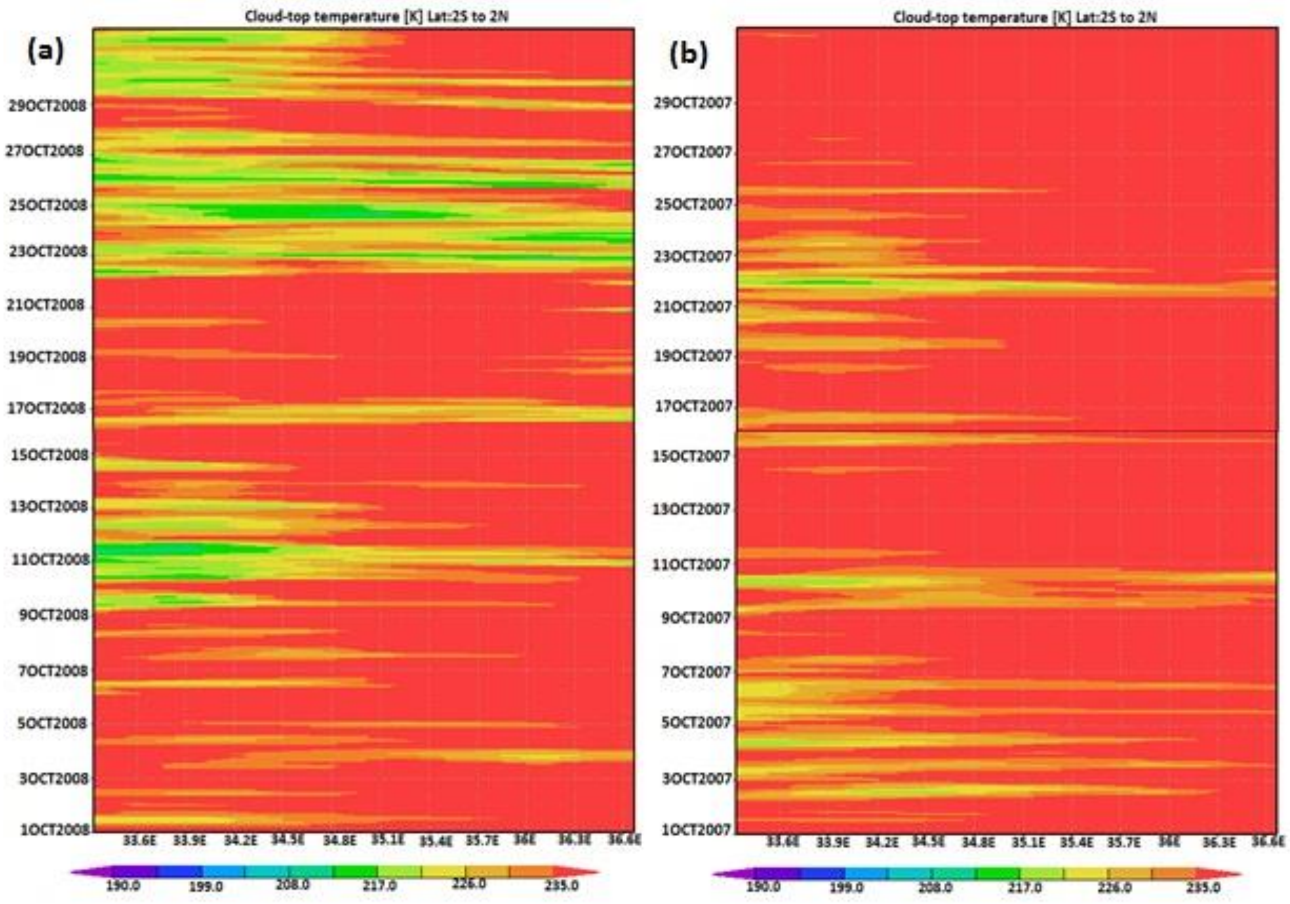


Figure 12: Hovmoller diagrams showing propagation characteristics of organized convection for (a) October 2008 and (b) October 2007

4.3.2.3 Hovmoller diagrams showing propagation of organized convection in November 2007 and 2008

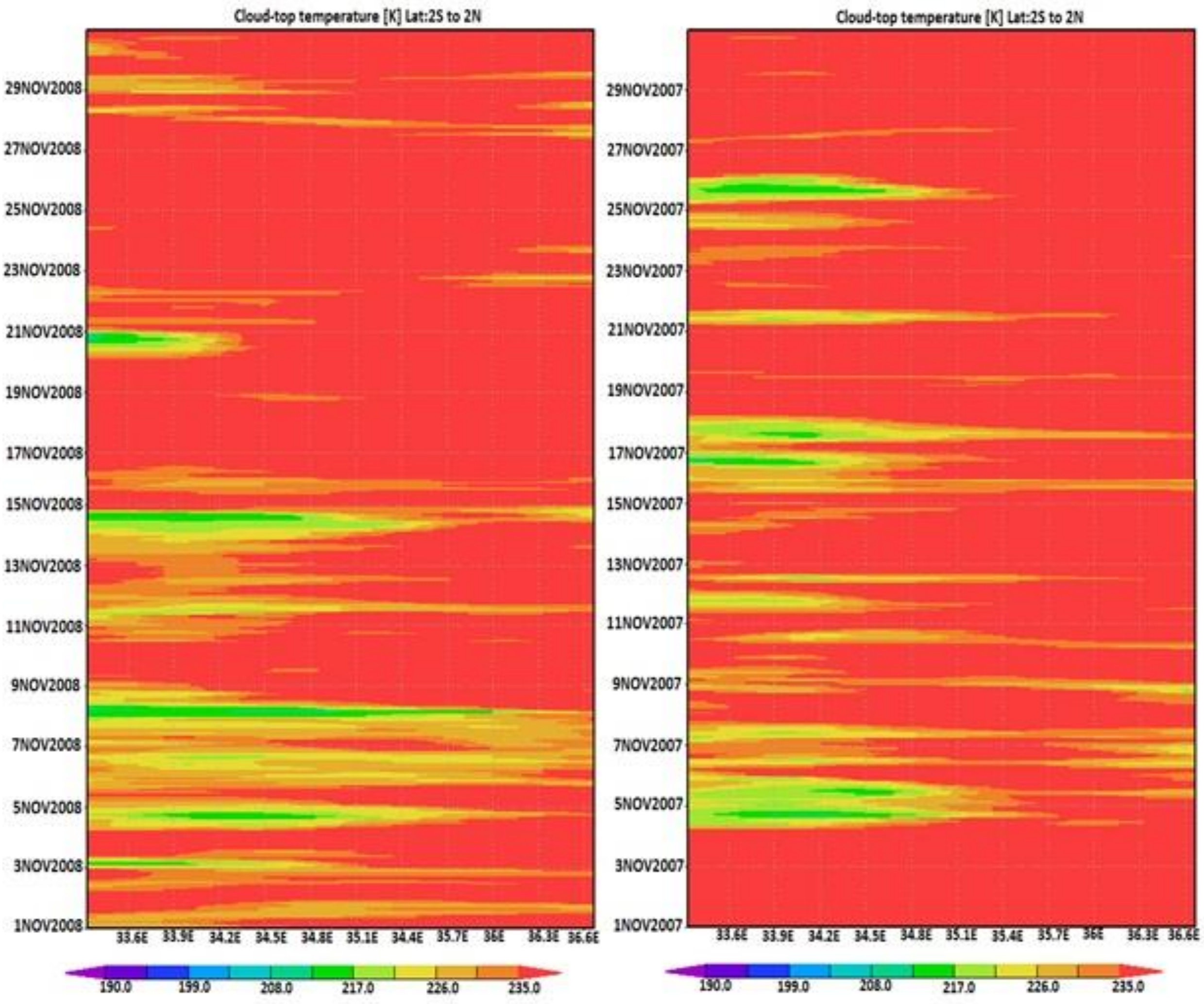


Figure 13: Hovmoller diagrams showing propagation characteristics of organized convection for (a) November 2008 and (a) November 2007.

Figure 13 (a) shows high TS activities between 1st and 15th November 2008 with an alternating pattern of cold (CTT<235^{0}K) and warm (red color) temperatures (CTT>235^{0}K). The study region experienced isolated or no TS activities on 16th to 30th November 2008.

In November 2007 (Figure 13 (b)), TS activities (CTT<235^0K) were experienced on 4th – 7th, 9th, 12th, 16th – 18th, 21st and 25th while the rest of the days recorded isolated or no TS activities. The systems were observed to originate from the Mau Hills at ~35.5^0E and moved westwards towards the lake.

The Hovmoller diagrams in general showed that during the MAM and SON seasons, organized convection evolved from the heat source (Mau Hills) and propagated westwards (as indicated by the decreasing CTT values westwards on the scale) towards the lake through an easterly flow. This characteristic is due to moist westerly air flow that had a trajectory over the Atlantic Ocean/ Congo basin/lake Victoria bringing moisture into the study region. The Mau Hills heats faster than adjacent areas and as the air becomes less dense, it rises lifting up the moist air from the west. Convective clouds start forming once the moisture is lifted to the level of cloud formation. The thunderstorm clouds then start propagating westwards towards the lake through an easterly flow.

Some thunderstorm (TS) systems dissipate before reaching the lake due to the strong winds which deplete the moisture from the study area. Organized convection systems on the lee ward side are observed on some days merging with those from the east (Indian Ocean), then propagate towards the lake.

4.4 Wind vector analysis

The wind patterns were generated using GrADS software. Contrasting events for both MAM and SON were chosen. The wind flow patterns were then used to explain the observed contrasts.

4.4.1 Wind patterns for March, April and May (MAM)

A contrasting event was chosen for the months of March and May for both the active (2006) and less active (2007) year. The wind flow patterns at the levels 850mb, 700mb and 200mb were used to explain the observed differences and thus the propagation characteristics of thunderstorm clouds over the study area.

4.4.1.1 Wind patterns on 24th March 2006 (active) / 2007 (not active) at 850mb level

24th March 2006 at 0000 UTC, calm (whitish color) conditions are observed over the study area for the two contrasting years (Figures 14 (a) and (c)). However, for the year 2006, there is convergence of easterlies and south-westerlies (decelerating winds) over the study area. The south-westerlies are moist since they have a trajectory over the Lake (Figure 14 (a)). In contrast, for the year 2007, there is no convergence (accelerating winds) over the study area, but instead dry easterlies are observed (Figure 14 (c)). The convergence (decelerating winds) is instead observed over the lake. At 0600 UTC, more calm (area under whitish color increases) conditions are observed in 2006 than in 2007 (whitish color decreases) at the same time (Figures 14 (b) and (d)).

AT 1200 UTC and 1800 UTC (Figure 15 (a) and (b)), convergence (weak winds) are observed while at the same time in 2007 (Figure 15 (c) and (d)), convection is observed to the northwest of the study area and hence no TS activities experienced on 24th March 2007.

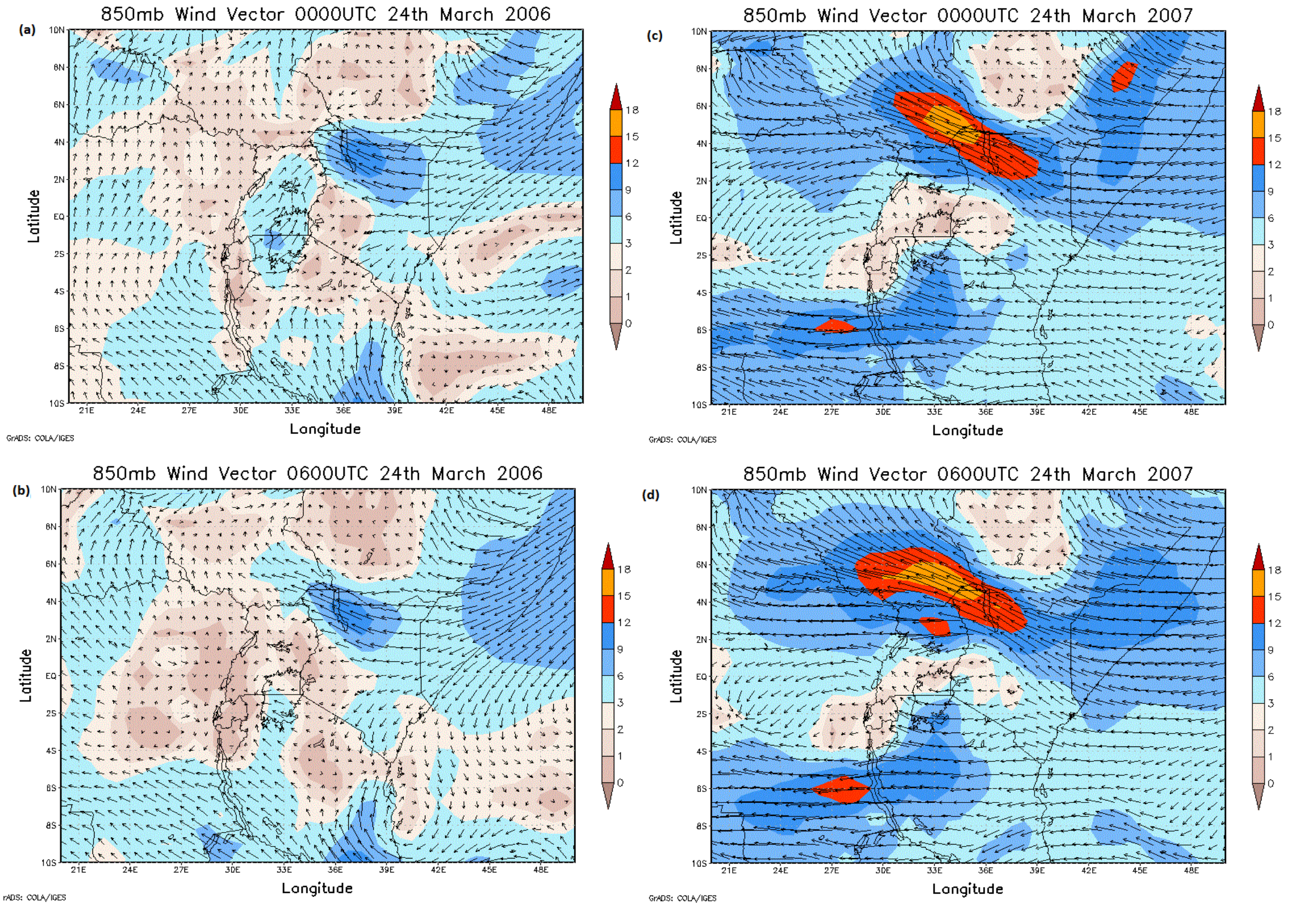


Figure 14: Wind flow patterns at 850mb level on 24th March, (a) 0000 UTC, 2006 (b) 0600 UTC, 2006 (C) 0000 UTC, 2007 and (d) 0600 UTC, 2007

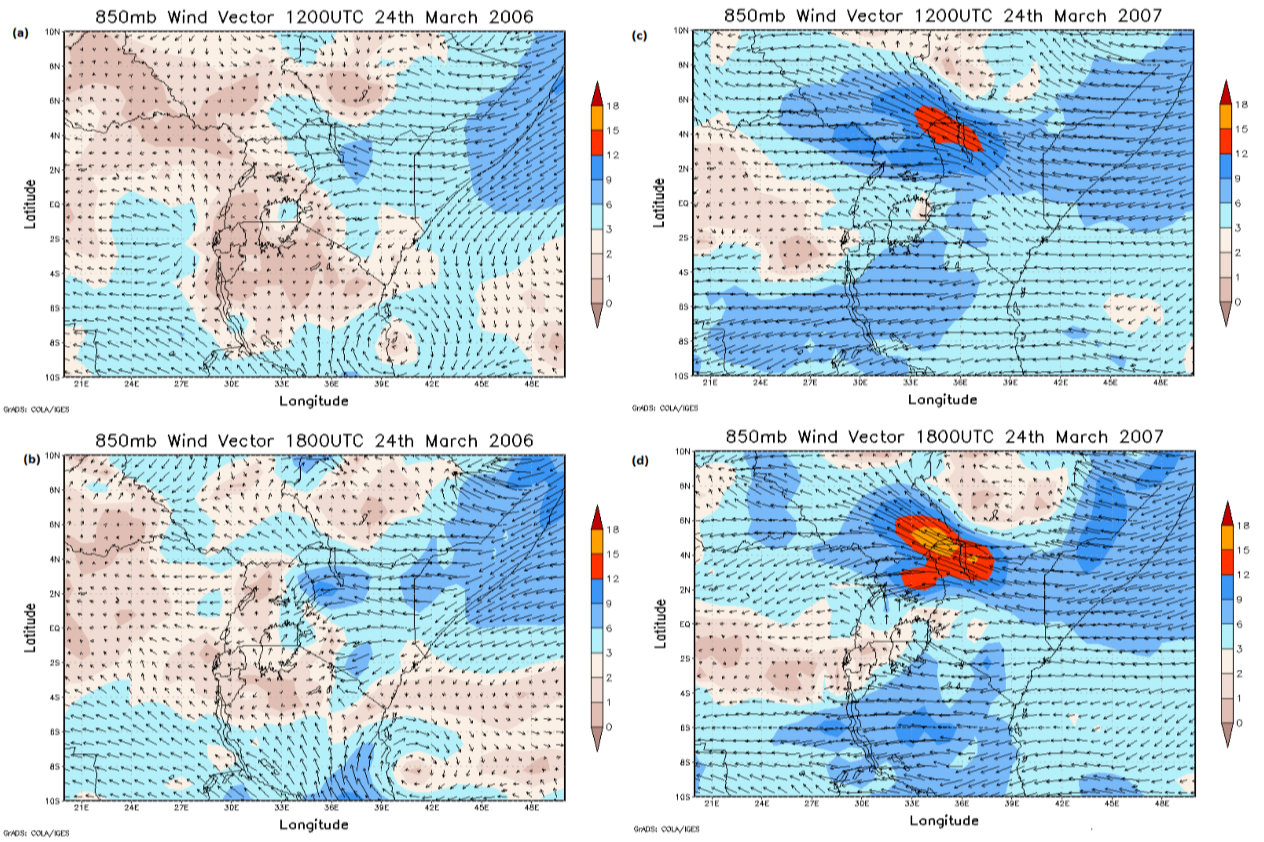


Figure 15: Wind flow patterns at 850mb level on 24th March; (a) 1200 UTC, 2006 (b) 1800 UTC, 2006 (C) 1200 UTC, 2007 and (d) 1800 UTC, 2007

4.4.1.2 Wind patterns on 24th March 2006 (active) / 2007 (not active) at 700mb level

At 700mb level on 24th March 2006, a weaker easterly wind component compared to a stronger easterly flow in 2007 at the same time of the day was observed (Figures 16 (a), 16 (b), 17 (a) and 17 (b)). The active weather in 2006 (Figure 8) was due to the weak easterlies which were an indication of convergence (decelerating winds) over the study area. From 0600 UTC to 1800 UTC, the winds were north-easterlies. The calm conditions favored the formation of convective clouds and hence the TS activities experienced over the region.

24th March 2007 was not active because on average the easterlies were rather stronger (accelerating) not favoring formation of convective clouds by depleting any available moisture over the study region (Figures 16 (C), 16 (d), 17 (c) and 17 (d)). This inhibited TS activities over the area of study.

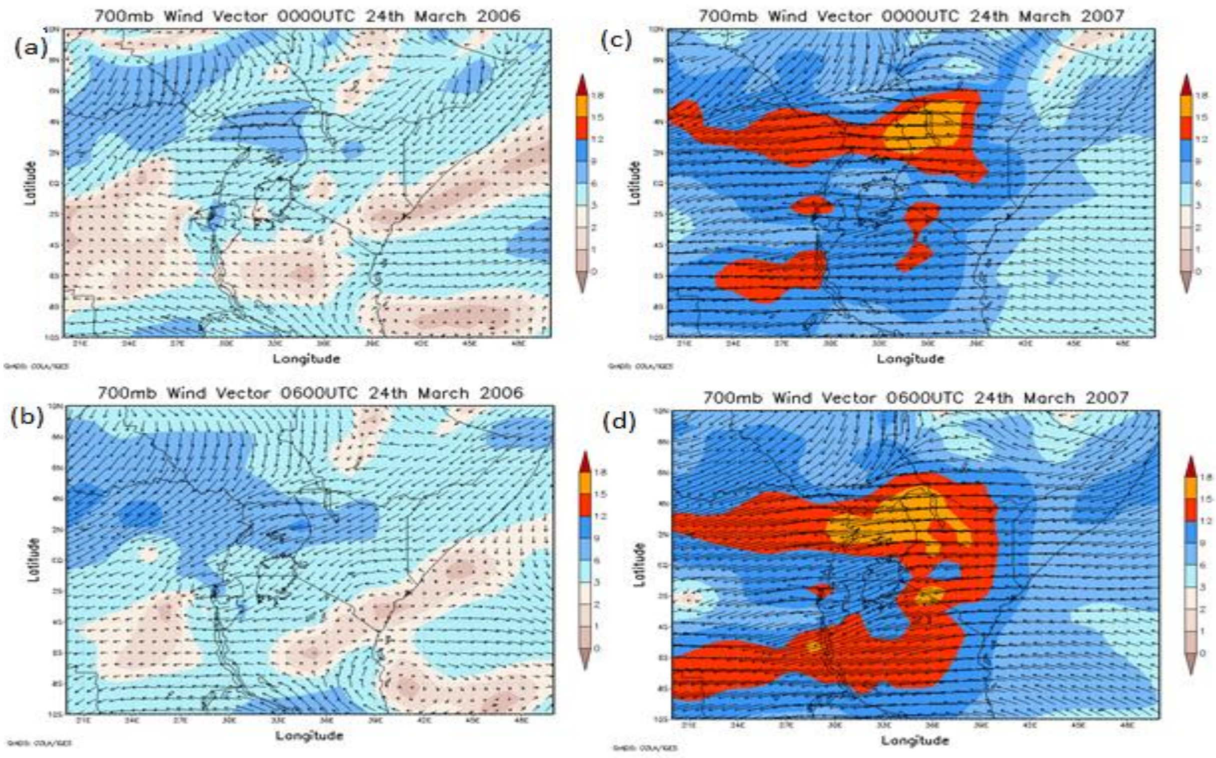


Figure 16: Wind flow patterns at 700mb level on 24th March at (a) 0000 UTC, 2006 (b) 0600 UTC, 2006 (C) 0000 UTC, 2007 and (d) 0600 UTC, 2007

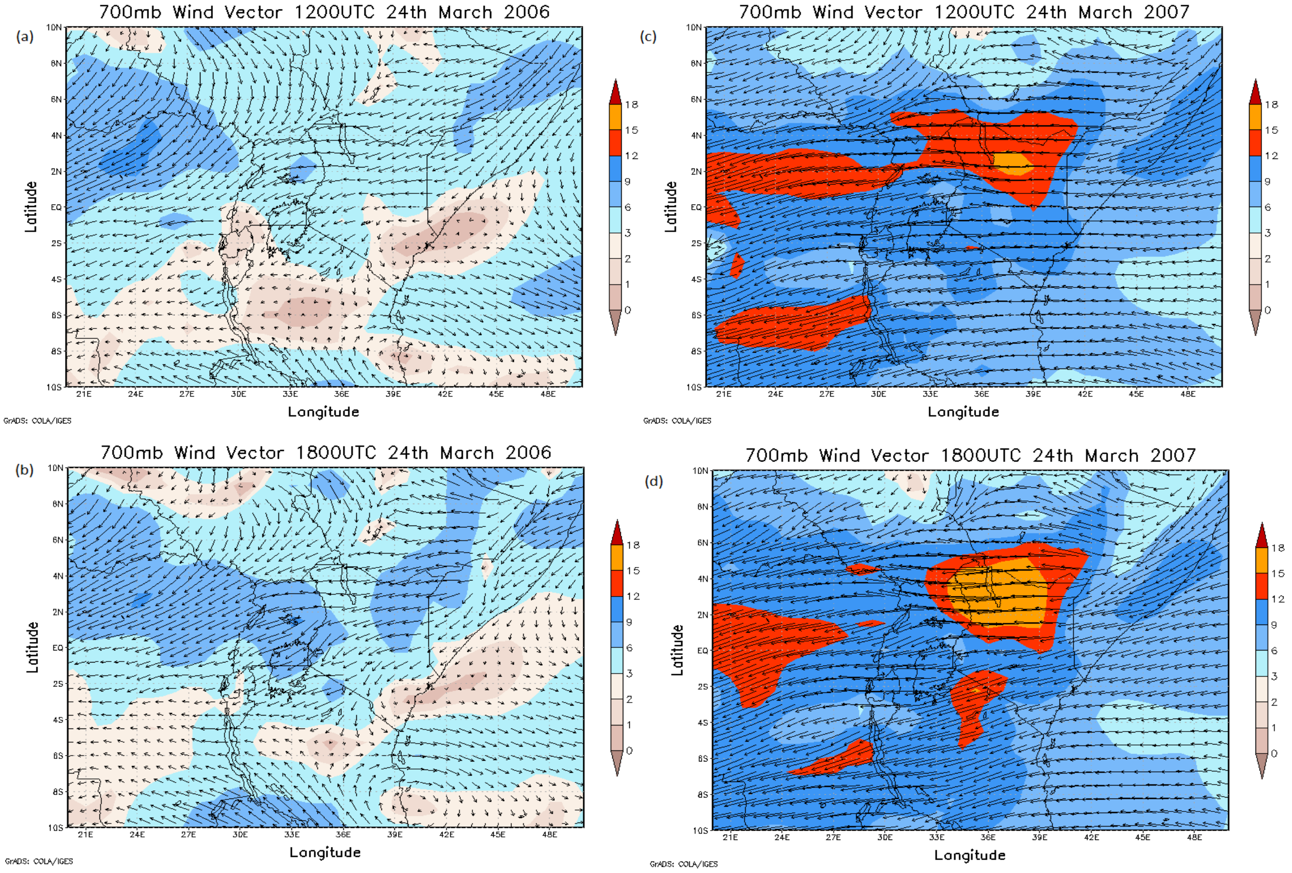


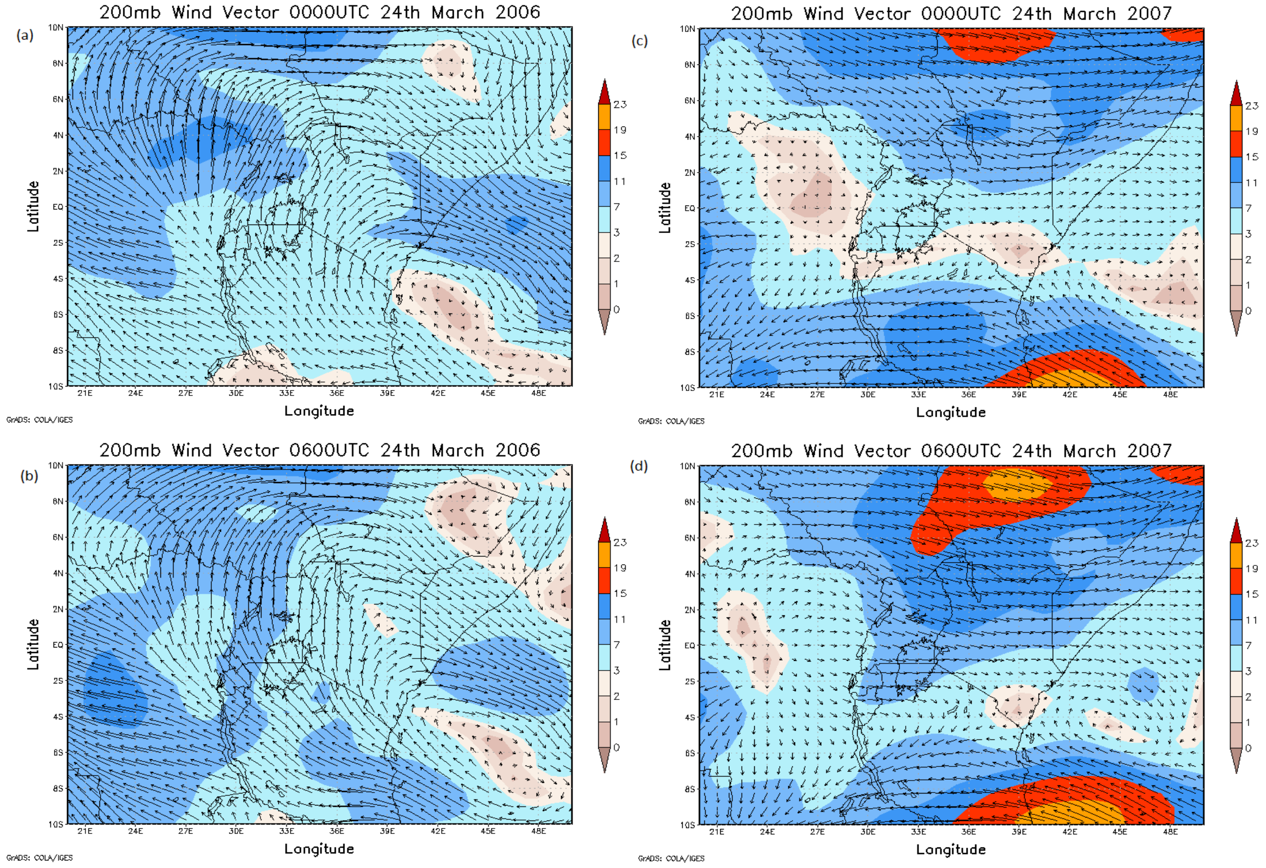
Figure 17: Wind flow patterns at 700mb level on 24th March; (a) 1200 UTC, 2006 (b) 1800 UTC, 2006 (C) 1200 UTC, 2007 and (d) 1800 UTC, 2007

4.4.1.3 Wind patterns on 24th March 2006 (active) / 2007 (not active) at 200mb level

The upper level winds (200mb) for 24th March 2006 show a southeasterly to southerly flow over the study area from 0000 UTC to 1800 UTC (Figures 18 (a), 18(b), 19(a) and 19(b)). The flow was opposite to the northeasterly to easterly flow at 850mb and 700mb levels. This was supportive of active convection over the study area through enhanced overturning (Indeje, 2000) and thus the thunderstorm activities experienced over the study area in the year 2006.

On the contrary, in the year 2007 at the same time, 200mb level generally depicted a northwesterly air flow from 0000 UTC up to 1800 UTC (Figures 18(C), 18(d), 19(c) and 19(d)).

The westerly flow cleared away convective clouds if any, over the study area further to the east, hence the dry conditions experienced on 24th March 2007.


200mb Wind Vector 0000UTC 24th March 2006

200mb Wind Vector 0000UTC 24th March 2007

200mb Wind Vector 0600UTC 24th March 2006

200mb Wind Vector 0600UTC 24th March 2007

Figure 18: Wind flow patterns at 200mb level on 24th March; (a) 0000 UTC, 2006 (b) 0600 UTC, 2006 (C) 0000 UTC, 2007 and (d) 0600 UTC, 2007

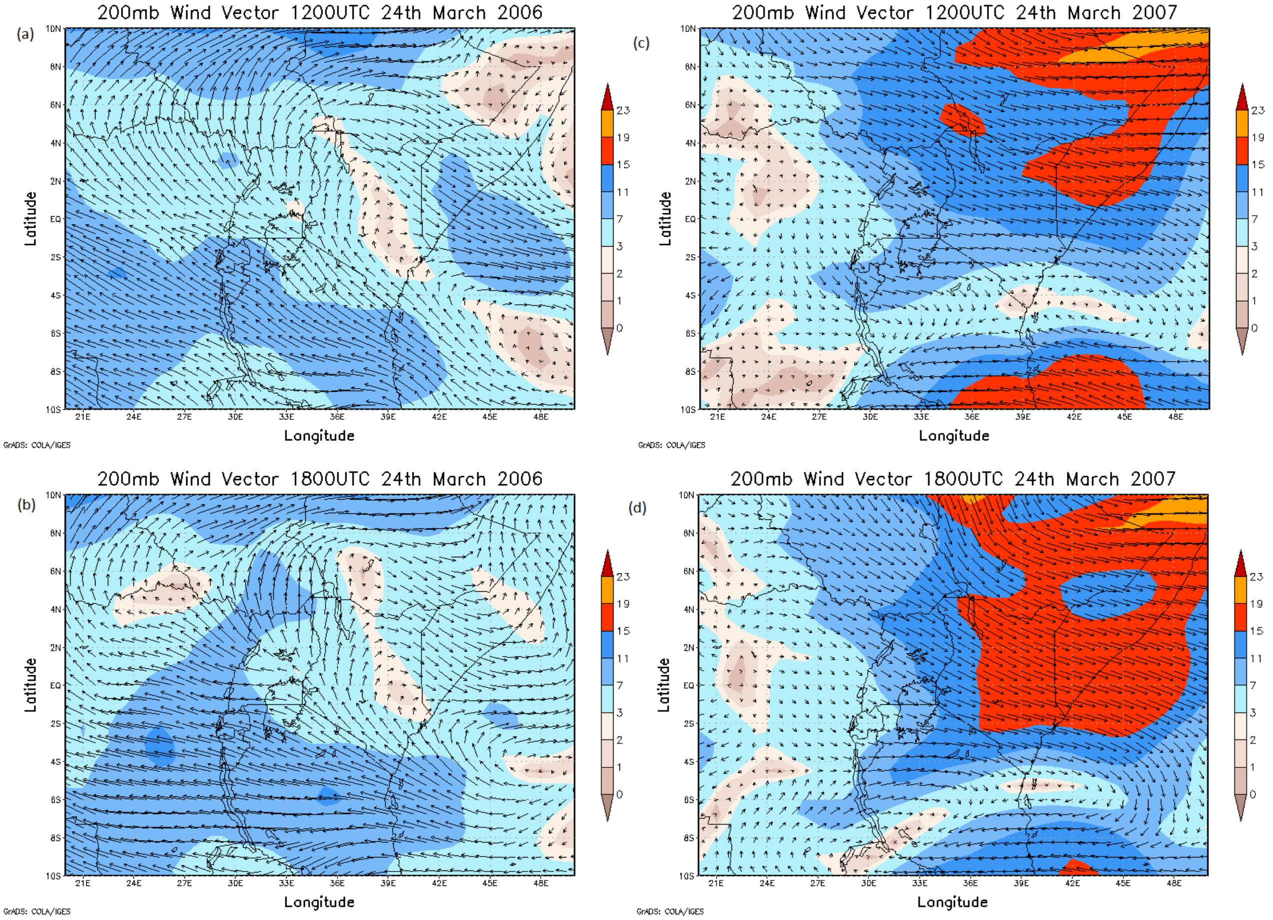


Figure 19: Wind flow patterns at 200mb level on 24th March; (a) 1200 UTC, 2006 (b) 1800 UTC, 2006 (C) 1200 UTC, 2007 and (d) 1800 UTC, 2007

4.4.1.4 Wind patterns on 14th May 2006 (active) / 23rd May 2007 (not active) at 850mb level

Contrasting events were also chosen in the month of May during the MAM season to study further the circulation patterns behind the TS propagation characteristics. 14th May 2006 was an active day while 23rd May 2007 was not (Figure not shown), on 14th May 2006 there was convergence between the westerly and easterly flow with moisture coming from the Congo basin. Calm (weak winds) conditions covered a larger area at 0600 UTC and at 1200 UTC. Convergence was well defined over the study area by 1800 UTC. This led to enhanced thunderstorm activities on 14th May 2006.

On 23rd May 2007 at 0000 UTC (Figure not shown), there was a dry southeasterly flow, which weakened over the area of study as they turned to weak easterlies. The area under calm conditions at 0000 UTC was smaller compared to that at 0000 UTC in the year 2006. At 0000 UTC, the stronger winds depleted any moisture available and at 0600 UTC and the area under calm conditions reduced in size. At 1200 UTC and 1800 UTC, the calm conditions shifted further westwards indicating the direction (westwards) of propagation of the systems from the Mau Hills.

4.4.1.5 Wind patterns on 14th May 2006 (active) / 23rd May 2007 (not active) at 700mb level

On 14th May 2006 at 0000 UTC (Figure not shown) at 700mb level, the winds were northeasterly and calm (decelerating winds) conditions were observed over the study area. At 0600 UTC, calm conditions could still be observed while at 1200 UTC, the area under calm conditions increased in size. The calm conditions (whitish color) favored the formation of convective clouds, thus explaining why 14th May 2006 was active.

23rd May 2007 was not an active day. At 0000 UTC, a small area under calm winds was observed with strong, dry south-easterlies which decelerated to weak easterlies. At 0600 UTC the calm conditions moved further to the west by the easterly flow while at 1200 UTC and 1800 UTC there were no calm conditions over the study area (Figure not shown), inhibiting cloud formation and hence, no TS activities were observed on 23rd May 2007.

4.4.1.6 Wind patterns on 14th May 2006 (active) / 23rd May 2007 (not active) at 200mb level

At 200mb level on 14th May 2006 the flow was northerly sustaining convective activities at the surface. On 23rd May 2007 strong southwesterly flow was observed compared to the year 2006 and the flow pushed away any available moisture eastwards from the study area (Figure not shown).

4.4.2 Wind patterns for SON

In SON season, at least one contrasting event was chosen in the months of September and October for active (2008) and less active (2007) year. The wind flow patterns in the levels 850mb, 700mb and 200mb were used to explain the observed differences and thus the propagation characteristics of thunderstorms over the study area.

4.4.2.1 Wind patterns on 8th September 2007 (active) / 3rd September 2008 (not active) at 850mb level

On 8th September 2007, calm conditions were observed over the area of study which as an indication of convection. The calm conditions (decelerating) were sustained up to 1200 UTC but at 1800 UTC winds started to strengthen (Figures 20 (a), 20 (b), 21 (a) and 21 (b)). The westerly flow brought in moisture from the Congo/Atlantic Ocean and Lake Victoria enhancing the formation of convective clouds thus leading to TS activities.

On 3rd September 2008, at 0000 UTC, the area under calm (whitish color) conditions was smaller in size compared to that at 0000 UTC in 2007 (Figure 20 (c)). At 0600 UTC and 1200 UTC, the strong winds depleted the moisture from the study area. At 1800 UTC, convergence was observed to the northwest of the study area (Figure 21 (d)) hence no thunderstorm activities were reported over the study area.

4.4.2.2 Wind patterns on 8th September 2007 (active) /3rd September 2008 (not active) at 700mb level

On 8th September 2007, the winds were southerlies at 0000 UTC decelerating into south-westerlies which were converging with north-westerlies (Figure 22 (a)). The westerly component fetched moisture into the study area from the Congo/lake. At 1200 UTC, the winds were weak southerlies and the area under convergence (whitish color) expanded (Figure 23 (a)). At 1800 UTC (Figure 23 (b)), convergence was observed thus explaining why 8th September 2007 was active in terms of thunderstorms.

On 3rd September 2008, calm conditions were to the north of the study area, with a southeasterly flow. The relatively strong south-easterlies depleted the moisture from the study area at 0600 UTC and at 1200 UTC (Figures 22 (d) and 23 (c)). The strong, dry southeasterly flow prevailed at 1800 UTC (Figure 23 (d)) inhibiting formation of convective clouds over the area of study.

4.4.2.3 Wind patterns on 8th September 2007 (active) / 3rd September 2008 (not active) at 200mb level

On 8th September 2007, the flow was northeasterly at 0000 UTC and 0600 UTC. (Figures 24 (a) and (b)) and a southeasterly to easterly wind component was observed at 1200 UTC and 1800 UTC, thus sustaining the convective activities over the area of study.

On 3rd September 2008 the flow was southeasterly at 0000 and 0600 UTC (Figures 24 (C) and (d)) similar to that at 700mb (Figures 22 (c) and (d)). This kind of flow pushed the moisture north westwards (0000 UTC to 1200 UTC). Calm (whitish color) conditions were observed at 1800 UTC indicating convergence at the upper level and thus inhibited convective activities (Figure 25 (d)).

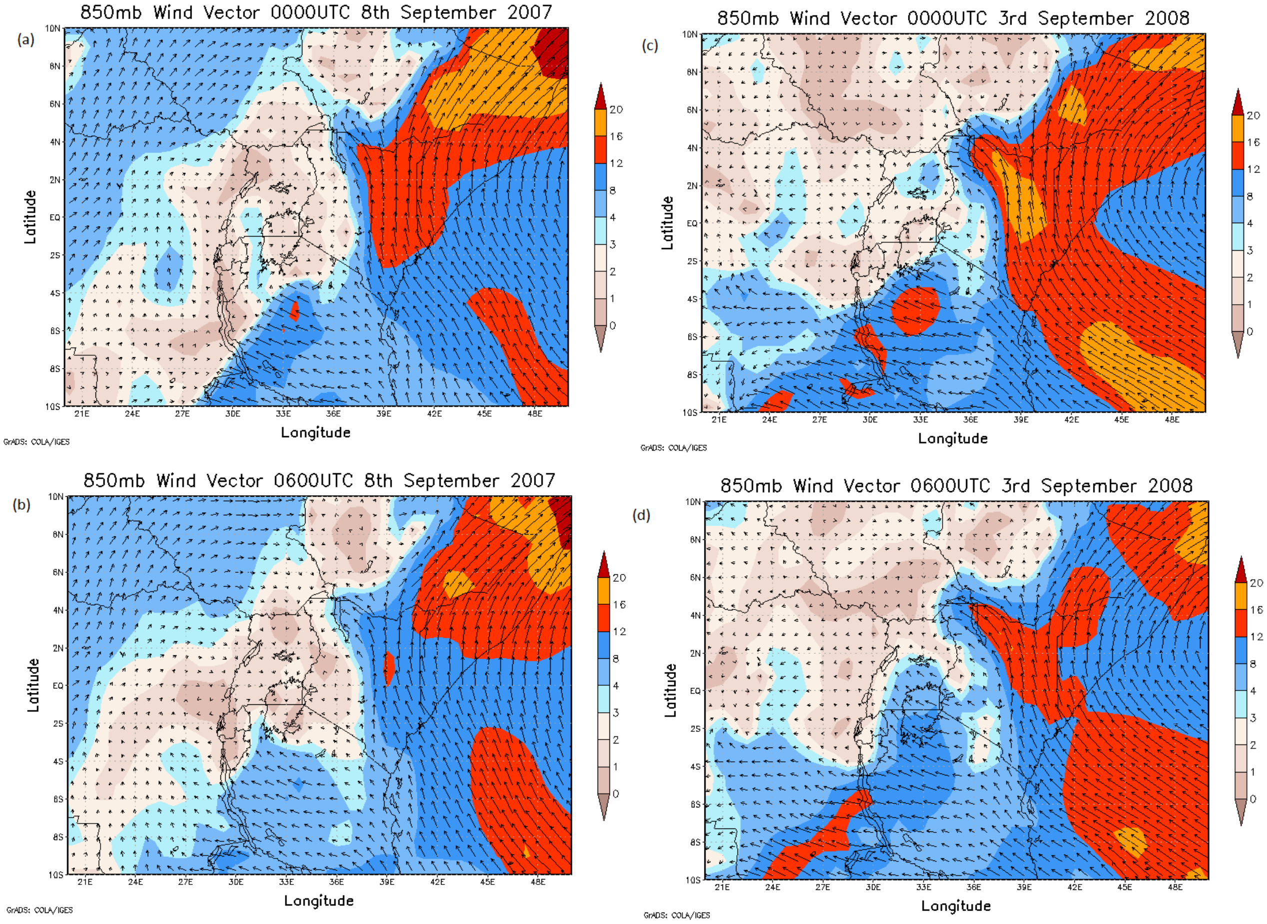


Figure 20: Wind flow patterns at 850mb level on 8th September 2007 at (a) 0000 UTC, (b) 0600, and on 3rd September 2008 at (c) 0000 UTC and (d) 0600 UTC

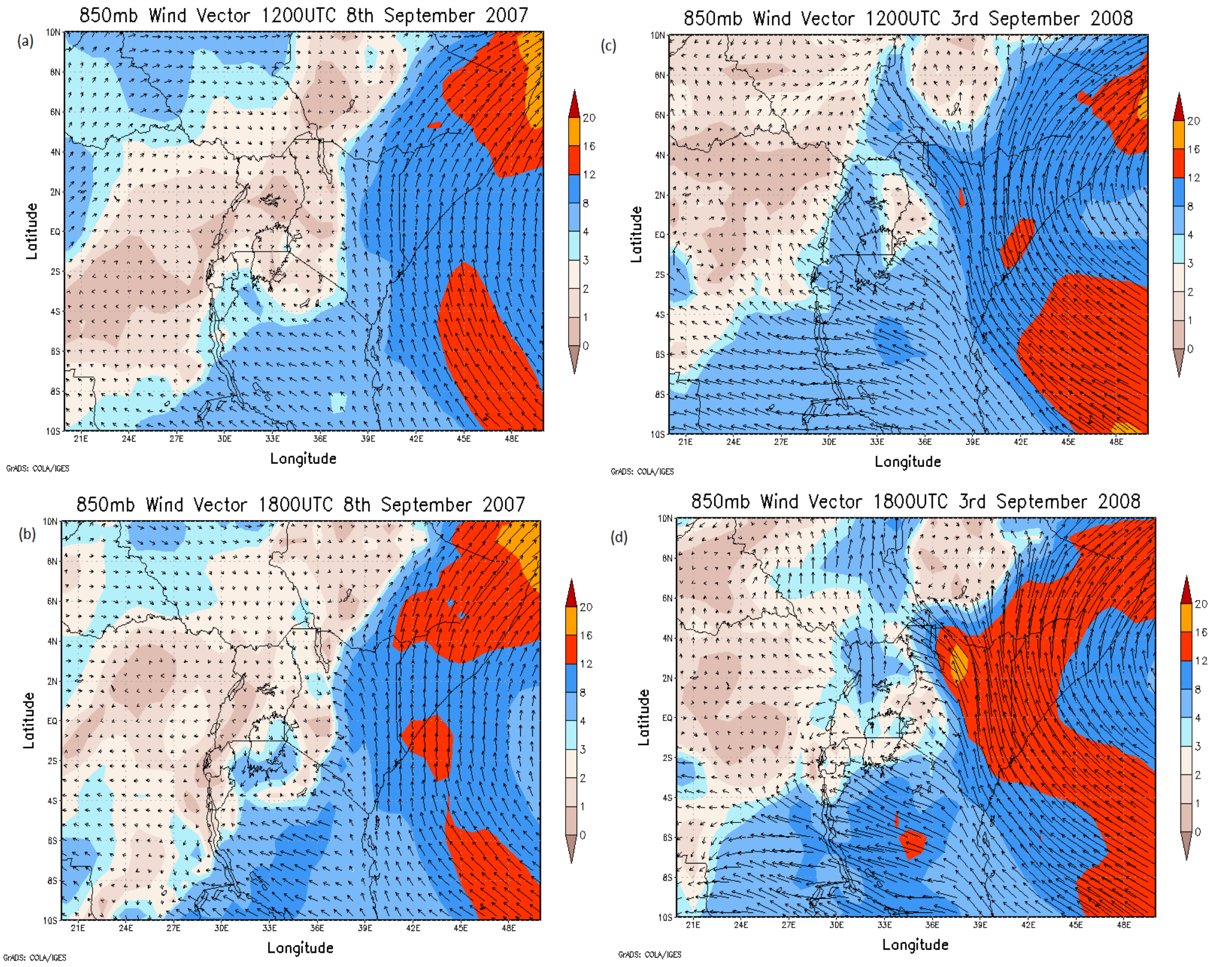
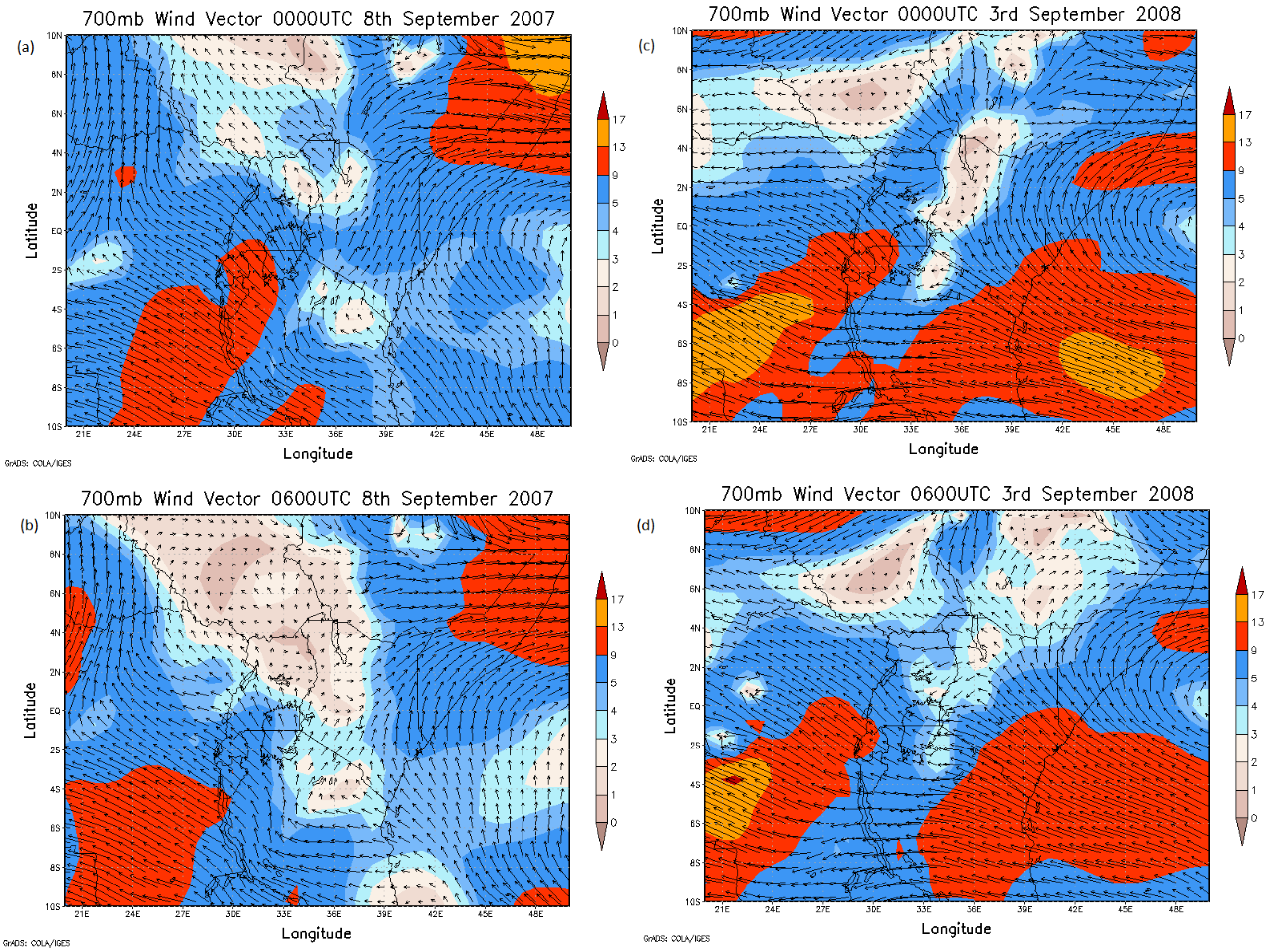


Figure 21: Wind flow patterns at 850mb level on 8th September 2007 at (a) 1200 UTC, (b) 1800, and on 3rd September 2008 at (c) 1200 UTC and (d) 1800 UTC


700mb Wind Vector 0000UTC 8th September 2007

700mb Wind Vector 0000UTC 3rd September 2008

700mb Wind Vector 0600UTC 8th September 2007

700mb Wind Vector 0600UTC 3rd September 2008

Figure 22: Wind flow patterns at 700mb level on 8th September 2007 at (a) 0000 UTC, (b) 0600, and on 3rd September 2008 at (c) 0000 UTC and (d) 0600 UTC

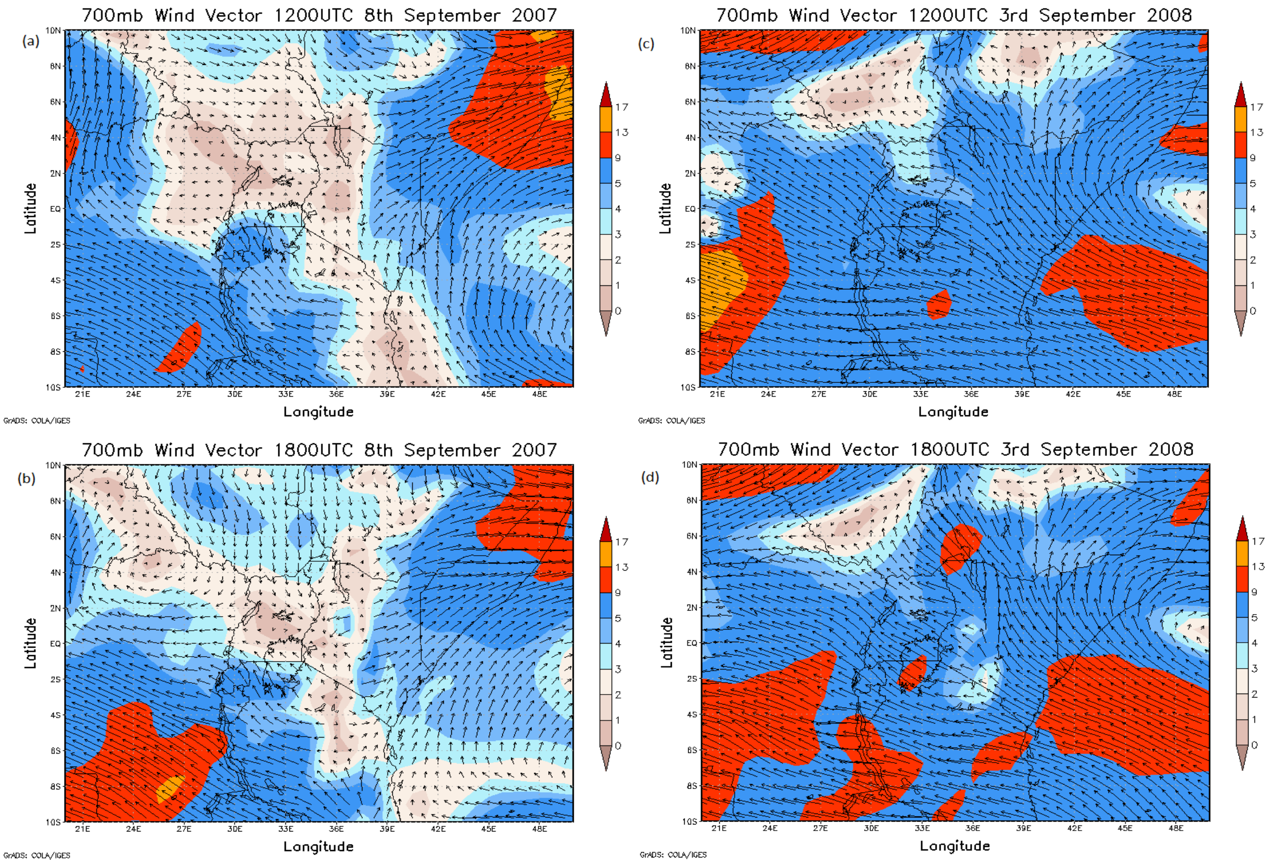


Figure 23: Wind flow patterns at 700mb level on 8th September 2007 at (a) 1200 UTC, (b) 1800, and on 3rd September 2008 at (c) 1200 UTC and (d) 1800 UTC

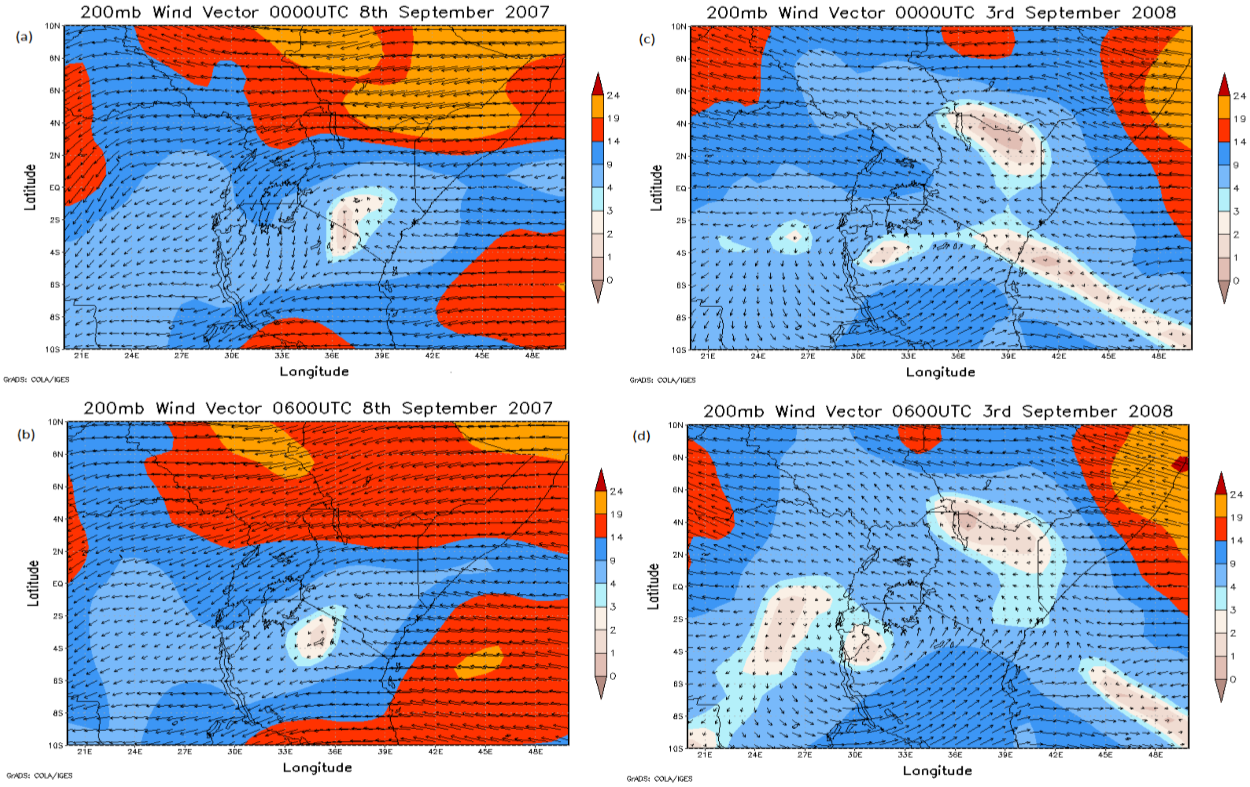


Figure 24: Wind flow patterns at 200mb level on 8th September 2007 at (a) 0000 UTC, (b) 0600, and on 3rd September 2008 at (c) 0000 UTC and (d) 0600 UTC

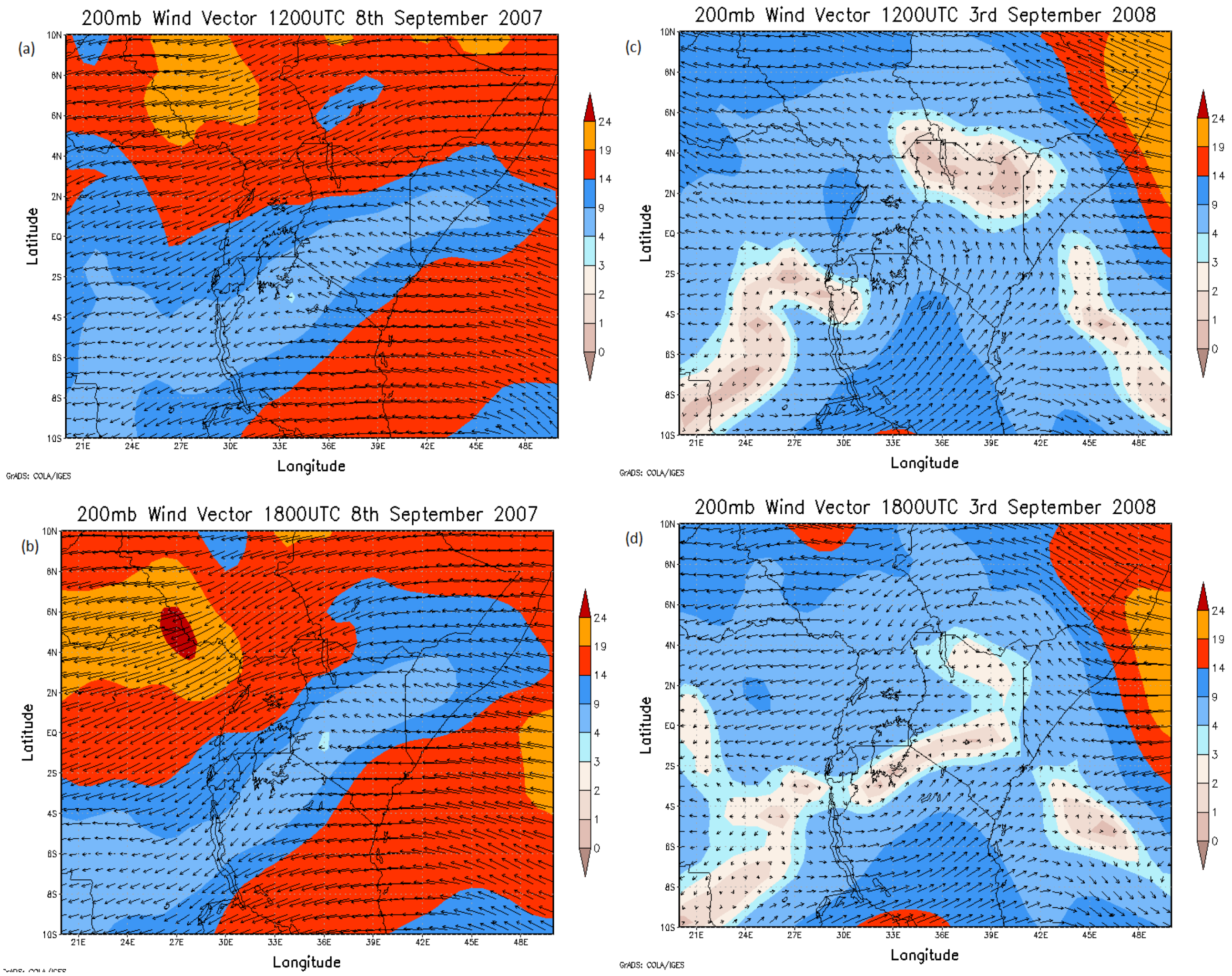


Figure 25: Wind flow patterns at 200mb level on 8th September 2007 at (a) 1200 UTC, (b) 1800, and on 3rd September 2008 at (c) 1200 UTC and (d) 1800 UTC

4.4.2.4 Wind patterns on 29th October 2007 (not active) / 24th October 2008 (active) at 850mb level

On 29th October 2007, southeasterly to easterly flow and slight convergence was observed over the lake at 0000 UTC. Calm conditions over a small area were observed at 0000 UTC and 0600 UTC (Figure not shown). At 0600 UTC the flow was easterly strengthening at 1200 UTC depleting the moisture away from the study area further to the west. At 1800 UTC, the westerly and easterly wind flows converged at the eastern border (Figure not shown) of the lake denying the study area from realizing thunderstorm activities.

On 24th October 2008 (Figure not shown) the winds were generally weaker than in 2007. The calm conditions covered a larger area at 0000 UTC. The winds were calm, indicating convective activities over the area of study. At 0600 UTC a westerly flow brought in moisture from the west (Atlantic/Congo basin/Lake Victoria basin). The cell expanded further at 1200 UTC and Convergence between the lake and land breeze was more enhanced. At 1800 UTC the flow changed to a northerly component. This flow coupled with orographic effects enhanced thunderstorm activities over the area of study

4.4.2.5 Wind patterns on 29th October 2007 (not active) / 24th October 2008 (active) at 700mb level

On 29th October 2007 (Figure not shown), the winds were stronger than those in the year 2008. At 0000 UTC, the flow was easterly strengthening at 0600 UTC. The strong winds inhibited the formation of clouds. It then decelerated at 1200 UTC and 1800 UTC.

On 24th October 2008 at 700mb level, the westerlies converged with the south-easterlies over the study area, enhancing convective activities 2007 (Figure not shown). Calm (whitish color) conditions could be seen as early as 0000 UTC. At 0600 UTC, area under calm conditions continued to expand up to 1200 UTC. This explains why 24th October 2008 was active compared to 29th October 2007. At 1800 UTC the calm conditions were still sustained over the area.

4.4.2.6 Wind patterns on 29th October 2007 (not active) / 24th October 2008 (active) at 200mb level

On 29th October, 2007 the flow was southwesterly (0000 UTC to 1800 UTC) opposite to that at 850mb and 700mb (Figure not shown) which moved the moisture further north eastwards inhibiting any possible convective activities over the area. At 1200 UTC the calm conditions were over the eastern boarder of the lake. The calm conditions aloft inhibited the formation of thunderstorm clouds.

On 24th October 2008 at 200mb level, the flow was southeasterly decelerating to southerlies at 1200 UTC and then to calm winds at 1800 UTC were observed.

In general, the wind pattern analysis revealed the circulation patterns associated with the TS characteristics observed on the Hovmoller diagrams under section 4.3. The westerly flow over the study region at 700mb and 850mb levels revealed the moisture source to be from the Atlantic Ocean/ Congo basin/Lake Victoria basin. The moisture from the west enhanced the formation of convective clouds on reaching the heat source. The easterly flow aided in shifting the convective systems from the heat source through an easterly flow.

Calm conditions at 850mb level indicated the area of mass convergence while at 700mb level calm conditions favored the formation of convective clouds. Convergence at 200mb on the other hand, did not favor cloud formation because this is an indication of divergence of the winds at the surface.

The wind flow pattern at 200mb which was opposite to that at the low and medium levels (850mb and 700mb) respectively, enhanced overturning of the airmass between the low/medium and upper levels. Lack of moisture was due to the strong winds which depleted moisture from the area by shifting it further away from the study area.

CHAPTER FIVE

5.0 Summary, Conclusions and Recommendations

This section provides the main deductions drawn from the results of this study. It also provides some recommendations for various sectors.

5.1 Summary

The overall objective of the study was to investigate spatial, temporal and propagation characteristics of TS to the east of the Lake Victoria basin in Kenya. This was achieved through three specific objectives, which were to; to determine the spatial and temporal distribution of thunderstorms to the east of the Lake Victoria basin, to analyze the evolution and propagation of organized convection systems and to analyze the circulation patterns associated with thunderstorm characteristics over the study region. From the first specific objective, results obtained showed that thunderstorm frequencies were high in stations (Kericho) near the Mau Hills and decreased to the west towards the lake (Kisumu). The higher TS frequencies in Kericho is due to Kericho being situated on a higher ground and has the TS clouds propagate towards the lake, they become less intense. This explains why stations have higher TS distribution than those closer to the lake.

The stations recorded thunderstorm peaks between 1200 UTC and 1500 UTC and started decreasing after 1500 UTC. Kisumu recorded higher thunderstorm frequencies after 1700 UTC compared to stations further from the Lake. The peaks are attained between 1200 UTC and 1500 UTC because this is when maximum heating is reached over the study region. This scenario at Kisumu station is due to the heat retained for a longer time in the lake waters which supports convective activities in stations near the lake for a long time before they dissipate completely.

Results from objective two showed that organized convection evolved from the Mau Hills and propagated westwards through an easterly flow over the study area. The results also showed that not all convective cells propagated from the heat source up to the lake. Some dissipated before reaching the lake. This characteristic of the organized convection was as a result of the convergence between the westerly and easterly winds. The convergence enhanced the formation of convective clouds which then propagated from the heat source toward the lake through an easterly wind flow.

Analytical results from objective three showed the wind patterns that were associated with the propagation characteristic of the organized convection (TS activities) over the study area. The wind patterns at 850mb and 700mb levels showed the location of calm conditions and hence convection. The source of moisture could also be deduced from the 850mb and 700mb levels. The westerly flow showed that the moisture fetch into the area of study was from Atlantic Ocean/Congo basin or from the Lake Victoria basin. An easterly flow on the other hand moved the convective clouds from the heat source towards the lake.

The wind pattern at 200mb level showed the direction in which the convective cell on the surface shifted. A westerly flow over the study area moved the cell further to the east away from the study area while an easterly flow moved it towards the lake from the heat source. The calm conditions at this level were an indication of a divergent flow at the surface.

5.2 Conclusions

The study has shown that thunderstorm (TS) peaks over the study region are attained in the afternoon hours (1200 – 1500Z) during the time when the area of study experiences maximum heating. Stations near the Mau Hills have higher TS distribution than those closer to the lake because Mau Hills are a high ground area compared to the land near the lake. Organized convection (TS activities) therefore starts from the Mau Hills and as they propagate towards the lake, they reduce in intensity hence the higher TS activities in stations near the Mau Hills (Heat source).

The study has also shown that, TS activities are high during the MAM and SON season and the activities are enhanced due to the presence of the ITCZ over the region during the two seasons. The inter-annual variability results revealed that not all years had high TS frequencies, others recorded lower TS activities.

The wind patterns have also shown that the 850mb and 700mb levels can be used to locate areas of convergence as well as the source of moisture. This can be seen from the speed and the direction of the wind vectors. The wind direction at 200mb level assists in showing the direction in which the organized convection at the lower and medium levels would drift. An easterly flow would move the convective clouds westwards while a westerly flow would move the convective clouds eastwards (at 850mb and 700mb levels).

The speed at the 200mb level was an indication of convergence /divergence at the lower or medium levels (850mb and 700mb) respectively. Accelerating/decelerating winds at 200mb level is an indication of a convergence/divergent flow at the surface or medium levels.

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

5.3 Recommendations

The results achieved in this study provide useful information that can be utilized in the following sectors.

5.3.1 Researchers

This study focused on the region east of the lake basin, there is a need, therefore, to replicate this research to the other regions of the country. This will provide essential information that can help this country in disaster risk reduction and promote national development as a whole.

The Giovanni analysis and visualization tool was used to generate Hovmoller diagrams at a two weeks interval. The patterns of the evolution and propagation characteristics could not be clearly perceived at a shorter interval. This study, therefore, recommends for the improving of the tool so that it can clearly capture the patterns at shorter intervals (weekly, hourly and daily). This will assist in establishing the duration of organized convection from the Mau Hills to the eastern border of the Lake Victoria.

5.3.2 Kenya Meteorological Department

The Kenya Meteorological Department (KMD) being the sole national center responsible for issuing national weather forecasts can use this information to issue TS forecasts (products) over the region of study. The KMD should also ensure that the TS data is digitized to save time spent on extracting data from the hard copies. It should also endeavor to improve the stations network over the region of study.

5.3.3 The Aviation sector

The aviation sector should rely on the information in order to avoid areas with deep cumulonimbus clouds, especially in the afternoon (1200 UTC-1500 UTC) when TS peaks are reached. Such clouds are associated with severe turbulence (updrafts and downdrafts, and cross winds occasioned by strong convection) and lightening.

5.3.4 Disaster Management sector

Floods, lightning strikes and cases of landslides/mudslides are usually experienced in the study region during the MAM and SON seasons due to severe thunderstorms. The National Disaster Operations Center should, therefore, be advised to take necessary measures that would ensure mitigation of any negative impacts that may arise from such situations.

5.3.5 Health Sector

The health sector should ensure and allocate enough resources to handle problems like disease outbreaks that are associated with extreme rainfall due to severe thunderstorms during these seasons.

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