UNIVERSITY OF NAIROBI

EVALUATION OF THE RECENT THUNDERSTORM-RELATED INCIDENCES OVER THE KENYAN AIRSPACE

By

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I56/7972/2017

A RESEARCH DISSERTATION SUBMITTED FOR EXAMINATION IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR AWARD OF THE DEGREE OF MASTER OF SCIENCE IN AVIATION METEOROLOGY OF THE UNIVERSITY OF NAIROBI.

2019

DECLARATION AND PLAGIARISM STATEMENT

I declare that this dissertation is my original work and has not been submitted elsewhere for examination, award of a degree or publication. Where other people's work or my own work has been used, this has properly been acknowledged and referenced in accordance with the University of Nairobi's requirements.

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ABSTRACT

Thunderstorm is one of the leading hazards to aviation operations in the tropics. It is associated with severe turbulence, aircraft icing, heavy precipitation, lightning, wind shear and hail. These hazards cause the closure of airports, reduce airport capacities for arrival and departure, and can stop ground operations. Furthermore, it may cause severe damage to communication systems, start fires, structural damage, and reduction of the aerodynamic effectiveness of the aircraft. All these impacts cause loss of revenue to the airlines and occasionally loss of lives.

This study aimed at evaluating the recent thunderstorm-related incidences over the Kenyan airspace. This was achieved through the review of thunderstorm climatology over Kenya, determination and comparison of rainfall and thunderstorm trends over Kenya and through a case study to analyze the possible causes of recent aircraft incidences over western Kenya.

The meteorological data used was obtained from the Kenya Meteorological Department (KMD) for the period January 1987 to December 2017. This included the monthly thunderstorm occurrences and rainfall amounts, a two day Meteorological aviation forecasts and synergy forecast products used for the case study. The Flight schedules for 19th February 2019 and 26th March 2019, when there was failed landing and diversion respectively in Kisumu airport, were obtained from Kenya Civil Aviation Authority.

The spatial and temporal characteristics of monthly, seasonal and annual frequencies results were presented on spatial maps and time cross-sections. Time series was used to display the pattern for annual cycle, seasonal variations and the inter-annual variability of rainfall amounts and thunderstorm occurrences. Mann Kendall (MK) non-parametric statistical method was used to determine and compare the significance of the trends. The case study applied qualitative methods of research, mostly the explanatory method and partly applied exploratory and descriptive methods.

Thunderstorms frequencies over the Eastern, Central and Coast regions of the Country showed a bi-modal pattern with high frequencies coinciding with March-April-May (MAM) and October-November-December (OND) rainy seasons. Very few thunderstorms days were reported over June-July-August (JJA) season. The areas to the western part of the Country,

near Lake Victoria, were the most thundery places in the Country. They reported the highest number of thunderstorm days over the three seasons; MAM, JJAS and OND. This showed a quasi uni-modal pattern.

The most thundery places near Lake Victoria showed significant increasing thunderstorm trends during the MAM and OND seasons. This was irrespective of whether the rainfall trends were reducing or increasing. This shows the effects of Lake Victoria over these areas, it acts as a continuous source of moisture for thunderstorm formation. However most stations across the country showed a reducing trend of thunderstorm frequency during MAM and JJA season.

From the analysis of the case study, the affected aircrafts were those which were scheduled to land in the late afternoon. This showed that most thunderstorm related cases were likely to occur in the afternoon. Using an average estimated cost adopted from previous studies of $100,000 per diversion, the resultant cost involving three flights was approximately $300,000. Improving the accuracy of the aviation forecasts and advisories could lead to reduced costs of aircraft operations, enhanced profit, safety and improved employment opportunities; leading to fast economic growth and sustainable development.

DEDICATION

This dissertation is dedicated to my cherished family; my husband John, my daughters Dorah and Faith, and my sons Felix, Aaron and Eliab Prince. You all walked with me through my academic success, your love, support and prayers kept me going. My mum, sisters, brothers and dear friends, I also dedicate this work to you. You prayed and cheered me through the journey.

ACKNOWLEGMENTS

I am mostly grateful to God the Almighty Father for His uncommon favor unto me as His child. I know this far I have come is not by might nor by power but by your spirit ooh God, Zachariah 4:6.

Special appreciation goes to my University supervisor Dr. Wilson Gitau. Thank you for your excellent guidance and support, May God bless the works of your hands. Also, to Prof. Joseph Mwalichi Ininda (6^{th} October 1957-13^{th} June 2019), your sacrifice and labor will never be in vain. You gave the best in aviation meteorology. Rest in peace Prof.

Secondly, I thank the University of Nairobi (UON), Department of Meteorology and Kenya Meteorological Department (KMD) especially, the Data Management Division, climatological, National Meteorological Centre (NMC) and Moi Airbase Meteorological Office.

I am grateful to all my friends, colleagues, classmates, staff and lecturers of Meteorology Department University of Nairobi.

Lastly, I appreciated everyone who supported me in one way or another.

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LIST OF ACRONYMS

AAID	Aircraft Accidents Investigations Department
ALAR	Approach and Landing Accident Reduction
AMSL	Above Mean Sea Level
CAPE	Convective Available Potential Energy
CAVOK	Cloud and Visibility Okay
CWT	Circulation Weather Types
DRR	Disaster Risk Reduction
ECMWF	European Centre for Medium Range Weather Forecast
ERA	European Re-Analysis Data
FAA	Federal Aviation Authority
GDP	Gross Domestic Product
HRES	High Resolution model
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ITCZ	Inter-Tropical Convergence Zone
JJA	June-July-August
JKIA	Jomo Kenyatta International Airport
KCAA	Kenya Civil Aviation Authority
KMD	Kenya Meteorological Department

MAM	March- April- May
MERRA	Modern-Era Retrospective analysis for Research and Applications
METAR	Meteorological Aviation Report
MSG	Meteosat Second Generation Satellite
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Association
OND	October- November- December
PROB	Probability
ROFOR	Route Forecast
RH	Relative Humidity
SCT	Scattered
SON	September- October- November
SST	Sea Surface Temperature
SYNOP	Surface Synoptic Observations
TAF	Terminal Aerodrome Forecast
TEMPO	Temporarily
TS	Thunderstorms
UTC	Universal Time Coordinated
WMO	World Meteorological Organization

DEFINITIONS OF TECHNICAL AVIATION TERMS

Aerodrome- A specified zone on land or water (any buildings, installations and equipment) used either as a whole or in part for the arrival, departure and surface movement of aircrafts.

Accident- Any occurrence in which a person suffers death or serious injury as a result of being in the aircraft or by direct contact with the aircraft or anything attached, between the time of flight and landing. In reference to the aircraft, it is the substantial damage of an aircraft associated with the operation.

Alternate Aerodrome- An aerodrome to which an aircraft may proceed when it becomes either impossible or inadvisable to proceed to or to land at the aerodrome of intended landing.

Approach- The phase of flight starting when an airworthy aircraft under the control of the flight crew descends below 5,000 feet above ground level with the intention to conduct an approach and ending when the aircraft crosses the approach end of the landing runway or at the commencement of a go around maneuver.

Cancellation of flight- A cancellation occurs when the airline does not operate the flight at all for a certain reason.

Cruise- Any level of flight segment after arrival at initial flight altitude until the start of descent to the destination. Cruise is a sub-phase of the en-route phase of a flight.

Diversion- A flight which is operated from the scheduled origin airport to an airport other than the planned destination point in the carrier's published schedule.

Failed landing- A decision to reject a landing which has previously been judged achievable to avoid aircraft damage through a loss of control near to or on the runway. This could be due to a sudden deterioration in forward visibility or extreme wind velocity variations.

Flight Delay- A flight delay is when an aircraft takes off and/or lands later than its scheduled time.

Incident- An occurrence, other than an accident, associated with the operation of an aircraft which affects or could affect the safety and effectiveness of flight operation.

International Airport- Any airport designated by the contracting state in whose territory it is situated as an airport of entry and departure for international air traffic.

Taxiing - Movement of an aircraft while on the surface of an aerodrome, under its own power, when it is neither taking-off nor landing.

Thunderstorm- A thunderstorm is a storm with thunder and occasionally accompanied by lightning.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background of the Study

Air transport industry remains an important sector in a country's economy due to its vast significance in the transportation of people and cargo. It is still the safest and fastest means of transport. The present day air traffic infrastructure is reaching its operational limit and any constraint, be it in the form of the hazardous weather, can cause delays and serious losses (Alam *et al.*, 2003).

Recent studies on the importance of air transport towards Kenya has revealed that air transport sector in Kenya contributes up to 5.1% of Gross Domestic Product (GDP). It provides job opportunities of approximately 620,000 (Oxford Economics, 2011).

Thunderstorms are usually associated with deep convective clouds (Okoola, 2005). Virtually, these thunderstorm clouds can occur in any month due to the large water bodies and the position of the Country on the Equator. Close to the Equator, the winds are light because of the feeble horizontal pressure gradients. Additionally, intense heating result in low pressures due to the warm surface conditions. These result in low level convergence of winds near the Equator. The raising warm air causes instability in the atmosphere, it cools, condenses and produces clouds. Deep convective clouds cause thunderstorms to develop due to the release of large quantities of latent heat into the atmosphere. During a lightning flash, the atmosphere is suddenly and intensively heated and this leads to massive expansion of air which then produces sound waves that are heard as thunder (Alusa, 1986)

The thunderstorm hazards to aviation comprise of heavy precipitation, huge hail, severe turbulence, wind shear, lightning, and severe icing. Turbulence is the most significant hazard that poses danger to the aircraft; wind shear makes it difficult for the pilot to control the aircraft and severe turbulence can cause damage to the fuselage of the airplane. Turbulence can exist in the form of micro bursts, macro bursts, gust fronts and strong low-level winds, (Kulesa, 2003).

The dissipation stage of a thunderstorm is dominated by downdrafts that push down out of the thunderstorm cloud, hit the ground and spread out as down burst. The downburst can be disastrous during braking because the aircraft can gain Lift. This stage is also manifested by heavy precipitation produced by the deep convective clouds. Heavy precipitation is hazardous to aviation, it causes reduced visibility and/or slippery runway which affects landings and takeoffs.

Hailstones of a sufficient size which is a product of thunderstorms may cause destruction to the engine blades, propeller, shatter the windscreens and can damage the surface of the aircraft thus interfering with its aerodynamic effects. Small hail might have little influence on the structure of an aircraft, however it can have substantial negative effects on visibility. This reduces the efficiency of an aircraft; will lead to increased cost of service and maintenance. Severe thunderstorm significantly impacts the safety and operational efficacy of air traffic, mainly at the terminal areas. The unavoidable outcomes of reduced efficiency are delays, diversions and cancellations of flights, (Remi, 1987)

The pilot's dilemma increases when he has low altitude; close to the ground. This can be the hardest time to handle and come across thunderstorms, that is, during landing, take-off and on final approach. This is because there is no altitude cushion in which to recover from the turbulent motions (Buck, 2013). Disaster can arise close to the ground surface due to uncontrolled altitude loss.

An accident means any occurrence in which any person suffers death or is severely injured for being inside the aircraft or by touching base with the aircraft or anything attached to it; or whereby the aircraft is substantially damaged. It is linked with the use of an aircraft between the times any individual boards the aircraft for a flight till the time the persons have landed. On the other hand, an incident is an occurrence which affects or could affect the safety of operation and effectiveness of aviation services. It mostly affects the revenue through delays, flight diversions and cancellation of flights (The Civil Aviation Act, 2007).

1.2 Statement of the Problem

While forecasting of thunderstorms and detection of convective features in their early stages is important to aviation industry, it is still difficult to achieve without meteorological tracking and detection systems. Even though modern planes are equipped with weather-detecting equipment for adverse weather like thunderstorms, the terrain may hinder the transmission of the signals for low level flights.

One of objectives of Sendai framework 2015 - 2030 is to mainstream and integrate Disaster Risk Reduction (DRR) within and across all sectors for sustainable development. Thunderstorm is the most common weather related hazard that affects aviation operations. It causes death, damage of property and loss of revenue to the airlines. Understanding of where and when thunderstorms are likely to occur is crucial in issuing early warnings, so as to avoid disaster.

An achievement of relatively higher skill and accuracy in issuing of meteorological aviation forecasts and advisories to stakeholders results in better short and long term planning. Efficiency is critical in aviation industry, it brings customer satisfaction and retention of clients. However, weather related delays interfere with organization of flight schedules and causes additional operational costs to the airlines (Wu, 2005). It also causes inconvenience to the travelers.

1.3 Objective of the Study

The core objective of this study was to evaluate the recent thunderstorm-related incidences over the Kenyan airspace. The specific objectives were:

a) To review the thunderstorm climatology over Kenya.
b) To determine and compare the trends of rainfall and thunderstorms over Kenya.
c) To analyze the possible causes of the recent aviation operation incidences over western Kenya.

1.4 Justification of the Study

Thunderstorms are the main cause of weather-related aircraft accidents and incidents and a significant ratio of flight delays (Mahapatra, 1991). Therefore, a good understanding of this subject matter is very important to aircraft operators, pilots, meteorologists and flight crew members as safety of lives and property should be ensured and the risks significantly reduced if not totally avoided.

The study of other parameters like rainfall and temperature which are related to thunderstorms showed an increasing significant/non-significant trend (Opiyo *et al*, 2014; Gitau *et al, 2018*). Based on that, there was a need to investigate the thunderstorm signal and confirm whether it has followed suit.

Previous studies (Chaggar, 1977; Koros, 2014; Maloba, 2015) had also shown that areas surrounding the Lake Victoria including Kisumu had high thunderstorm frequencies. Amongst the other International Airports in Kenya, Kisumu Airport was selected because it demonstrated the impacts of thunderstorm on aviation operations in the Country well.

Aviation industry has a high potential for growth in Kenya; the introduction of direct flights to the United States of America has already been operationalized and is anticipated to increase air traffic. Kenya is also elevating and improving domestic airstrips and airports to expand air transport linkage domestically. It is also taking advantage of economic potentials at County level. Outstanding among these airstrips include: Suneka (Kisii County), Manda (Lamu County), Mandera, Kitale (Trans- Nzoia county), and Kabunde (Homa-Bay County). These calls for timely and improved accuracy in the aviation forecasts.

Besides enhancement of the existing knowledge, the review of thunderstorm climatology in Kenya aims to give a better understanding of where, when and how thunderstorms are likely to occur and their possible impacts to aviation operations. This will possibly result in policy shift towards the improvement in the forecasting skills and exchange of information. Improved accuracy in meteorological aviation forecasts and weather advisories, therefore, leads to reduced costs of operations, enhanced profit, safety and customer satisfaction.

1.5 Area of Study

Kenya is situated along the Equator in the Eastern part of Africa and it lies between 5^o North and 4^0 South latitude and between 32^o and 42^o East longitude. The countries which border Kenya are Ethiopia and South Sudan on the northern side, Uganda on the western side, Tanzania on the southern side and Somalia on the Eastern side.

1.5.1 Physical Features of the Study Domain

Figure 1 shows the area of the current study. Kenya has a total area of 580,367 km^2, 569,140 km^2 of which is land while 11,227 km^2 is water. The water masses include Lakes Victoria, Turkana, Naivasha, Baringo and Nakuru among others. Lake Victoria is the largest fresh water lake with an area of about 68,000 km^2, it is pooled between Kenya, Uganda and Tanzania. The coastline has East African Mangroves, going further inland the terrain consists of wide plains and small hills. The central areas and the western parts of the country run north-south, parallel to the Great Rift Valley. Mount Kenya is the highest point at 5,199 meters high. Most of the country lies above 1000 meters above mean sea Level (AMSL). This elevation is highest over the Highlands and West of the Rift Valley (Kinuthia and Asnani, 1982).

The unique orographic features and intense equatorial insolation generate intense meso-scale circulations with intense diurnal cycle of temperature and rainfall over Lake Victoria and the neighborhood.

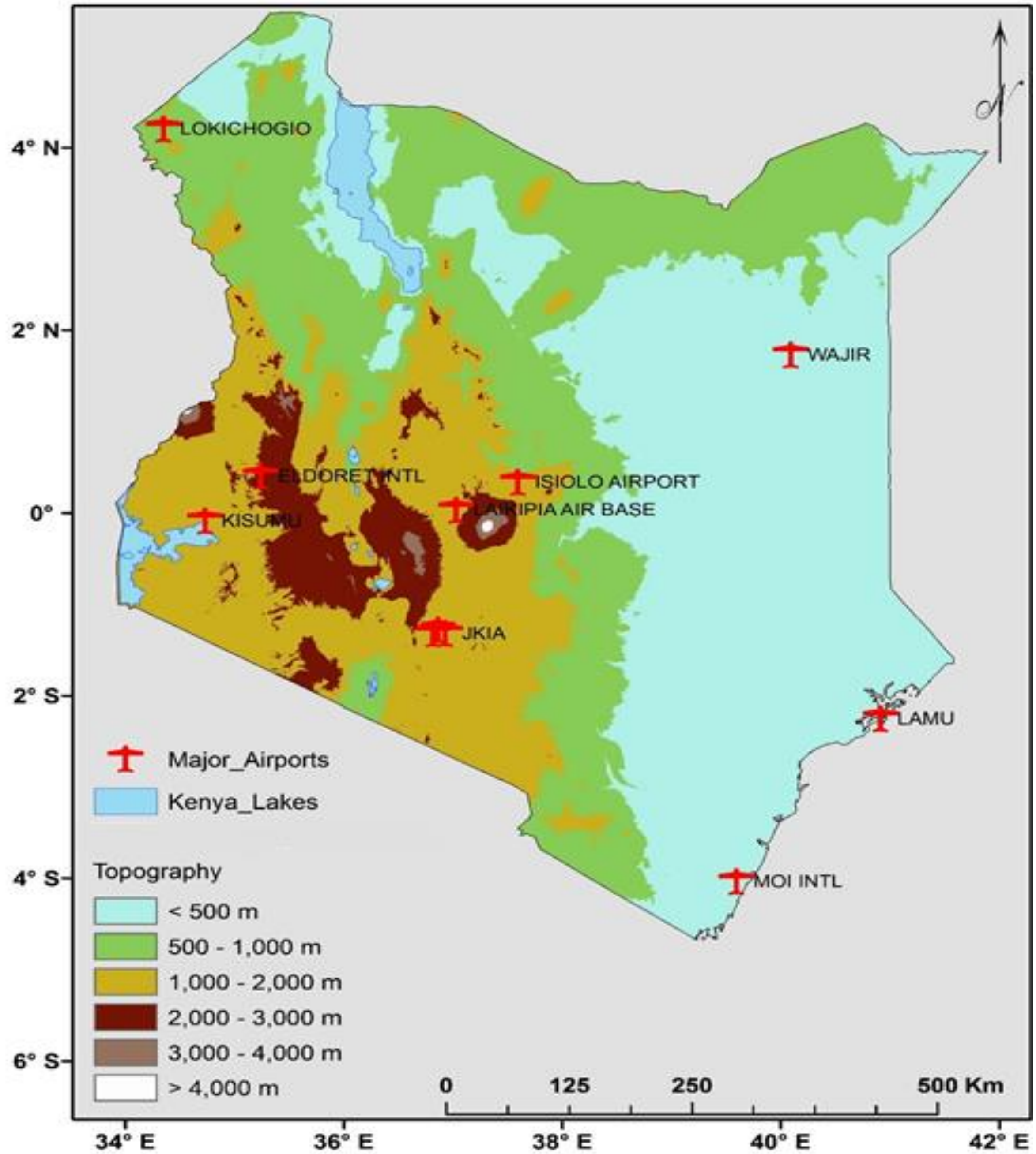

Figure 1: Map showing the area of study with topography and major airports in Kenya

1.5.2 Area of the Case Study

There are eleven Civilian aerodromes in Kenya operated by Kenya Airport Authority (KAA), they include both airports and airstrips. An airport handles more in terms of capacity and size of aircrafts than an airstrip, it has bigger airfields than an airstrip. The airports are: Jomo Kenyatta International Airport (JKIA), Eldoret International Airport, Moi International

Airport (MIA) – Mombasa, Wilson Airport – Nairobi, Kisumu International Airport, Isiolo International Airport, Malindi Airport and Wajir Airport. The Airstrips are: Lokichoggio Airport, Manda Airport – Manda Island, Ukunda Airport – Diani Beach. Other airports are the military airbases, these are Moi Airbase- Nairobi and Laikipia airbase- Nanyuki. The case study was done over Kisumu airport.

Kisumu International Airport is the Country's fourth founded International Airport, after JKIA, MIA and Eldoret. It is also ranked the third-busiest Airport in Kenya. It is located 5km away from Kisumu City and to the East of Lake Victoria. The Airport is situated along the Equator (latitude 00-05.2/E034-43.7). This leads to a hot and humid year-round climate and annual rainfall of about 1,200 mm.

Kisumu International Airport has a runway which is 3293.05 meters long and 45.11 meters wide. The ICAO code F (runway of 60 meters wide and 4.2 kilometers long) is able to handle the new generation huge bodied aircraft (Airbus A380 and the Boeing 747-8). The 06/24 orientation describes the direction where the wind is coming from; 06 denotes 60^{o} North easterly direction and 24 denotes 240^{o} south westerly wind direction.

CHAPTER TWO

2.0 LITERATURE REVIEW

This chapter discusses what has been done before in the study of thunderstorms in Kenya and their impacts on aviation operations. Specific areas covered are: recent thunderstorm climatology, rainfall occurrences in relation to thunderstorm, case study on thunderstorm-related aircraft incidents and mechanisms of thunderstorm formation. It begins by giving a theoretical background.

2.1 Theoretical Background

A thunderstorm day is defined as a day on which thunder is heard at an observing station (WMO, 1992). It is recorded as such regardless of the actual number of thunderstorms heard on that day and therefore the records do not give information on the frequency of occurrence of individual thunderstorms or their time of occurrence. It should however be noted that lightning without thunder is not recorded as a thunderstorm day, this is because light travels faster than sound at a speed of 2.998×10^8 m/s and sound at 3.43×10^2 m/s. It is possible to observe lighting outside the station radius. The condition that thunder must be heard restricts the covered area to a circle with a maximum radius of about 20km by each observing point (Chaggar, 1977). It is also possible for two neighboring stations to hear and report the same thunderstorm if they are within the 35km distance apart.

ROFORs are aviation forecasts issued daily from an Airport Meteorological Office (AMO). They contain winds at different pressure/flight level (direction and speed), prevailing weather, clouds, information on significant weather for aviation, and surface visibility. A typical ROFOR is shown in Appendices 1 and 4.

TAFs are aviation meteorological forecasts issued to aviation industry at different times of the day. The forecasted elements may change rapidly or gradually within 3 to 6 hours interval. Currently, JKIA meteorological watch office issues TAFs for JKIA, Kisumu, and Wilson and Eldoret airports. The first TAF whose validity is 24 hours is issued at 2300Z then at 0500Z, at 1100Z and at 1700Z. The validity of the TAFs ranges between 24-30 hour periods based on airport size which is categorized as ‘A’- international airport. The body of the TAF gives the expected weather condition of winds, visibility, significant weather and clouds for the validity period. It also shows the expected changes during the period of the forecast. These are used to predict changes in values or states of weather conditions. The TAF describes the weather conditions expected in the terminal aerodrome up to a radius of 8 km. A typical TAF is shown in Appendices 2 and 5.

Meteorological Aviation Reports (METARs) are hourly observations covering the 24 hours of a day; describing the winds, horizontal visibility, significant weather, clouds-amounts, heights and types, dew point and surface temperatures and the pressure. A METAR without a trend is just a meteorological observation but when a trend is added to the METAR it becomes a trend type forecast (TTF) which is valid for the next two hours from the time of the METAR. A meteogram is a visual presentation of surface weather conditions at a station for a given day.

The European Centre for Medium range Weather Forecast (ECMWF) High Resolution (HRES) model is a highly rated weather model globally, it has the highest resolution of 9 km which is currently the finest resolution global model available. The comparison of the skills of the 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 the ERA-Interim re-analyses were good estimates of the real flow fields; it represented well the worldwide circulation of winds (Lin *et al.*, 2014). The datasets were for wind, Relative Humidity (RH) and CAPE.

Measurements made during the previous thunderstorm Project showed that local surface convergence was often found to precede the onset of convective precipitation, (Byers and Braham, 1949). Upper level divergence at 300Hpa allows for the opening up of the atmosphere thus enhance convective lifting. The current study used the 1200Z data because previous studies (Sakwa, 2006) over the same region found that at 0000Z, the convergence is over Lake Victoria and at 1200Z the convergence is over the surrounding parts of the lake which includes Kisumu Airport.

Milne (2004) found a strong correlations between moisture at 700HPa level and thunderstorm development, severity of thunderstorms and the probability of precipitation. In prediction of thunderstorms, 700HPa level is preferably used because 850HPa level is often at or below the surface and therefore fails to account for the moisture necessary for thunderstorm development. Huge increase in instability was largely due to the increase in mid-level relative humidity.

CAPE is the maximum buoyancy of undiluted air parcel, it is related to the potential updraught strength of thunderstorm. The larger the CAPE the greater energy provided for thunderstorms development, (Blanchard, 1998). Maximum surface heating occur at 1200Z.

This study preferred using the Re-Analysis data from the ECMWF model because several studies over East Africa including Murakami and Sumathipala (1989), Mukabana and Pielke (1996), Okoola (1999), Gitau *et al*., (2018), and Koech (2014) have successfully used the ECMWF datasets.

Infrared (IR) images 10-13μm can be used for 24-hours, it does not depend on day time insolation. One of the application of IR is the observation of cold cloud surfaces. High and vertically well-developed clouds with low brightness temperatures can be distinguished from medium and low level clouds with higher brightness temperatures. Images taken at 1245Z and 1545Z were used in order to monitor how the clouds developed before and during the time of the incident. Koros (2014) showed that deep convective systems are at the peak during the late afternoon and evening times around 1200 UTC to 1600 UTC.

The particular incidents used in the case study were the most recent and therefore data was readily available. Previous studies (Chaggar, 1977; Maloba, 2015) had also shown that areas surrounding the Lake Victoria including Kisumu had high thunderstorm frequencies. Amongst the other International Airports in Kenya, Kisumu Airport was selected because it demonstrated well the impacts of thunderstorm on aviation operations in the Country.

2.2 Mechanisms of Thunderstorm Formation

The necessary ingredients for thunderstorm formation are atmospheric instability, low-level moisture and trigger mechanism (Murray, 2002). Instability happens when a parcel of air is warmer than the environment and rises on its own due to positive buoyancy. It lets moist air from near to the ground level to rise to high levels, cools and condenses therefore supports deep convection and thunderstorms. Daytime heating can increase instability. Stability indices are useful tools that can be used to measure convective instability (Galway, 1956). Thunderstorms are more likely when there is ample low level moisture, it enhances latent heat release which fuels instability in the atmosphere this is often deepened by advection from warm water sources.

A process that forces the air to rise provides a trigger mechanism. Lifting processes like low level convergence, fronts, low level moisture advection, mesoscale convergence such as sea breeze, orographic upslope and frictional convergence are trigger mechanisms for thunderstorm. The region that has the greatest combination of these conditions is often the location that thunderstorms first develop. A thunderstorm will first be formed and developed in the direction of the area that has the finest blend of high Planetary Boundary Layer (PBL) moisture, low convective inhibition, Convective Available Potential Energy (CAPE) and lifting mechanisms. CAPE is the driving force in the development of thunderstorms (Williams, 1995).

Ngaina (2015) showed that CAPE is a useful tool that enables identification of areas where energy for convection is available. The more moisture that is available, the more the latent heat can be released when storms grow. On a day when severe weather is expected, it is important to look out for moisture advection hour by hour. The air is extra unstable in areas of dew point maxima.

Table 1 gives a guide to dew point worth, the instability and the latent heat they can provide as shown in the weather prediction manual.

Table 1: Dew point value versus instability state

Dew point value	Instability state
More than 75	Extremely High
65-74	High
55-64	Moderate
Less than 55	Low moisture content

Source: Habby, 2000

As the temperature increases, air density reduces. The atmospheric instability is greater when there is more heating during the day. Days with sunshine are convectively more unstable than days with incessant cloud cover. On a day when severe weather has been forecasted, the breaking of clouds increases the possibility of severe weather (Habby, 2000).

A thunderstorm is made up of two or more thunderstorm cells and each cell has three stages of development, namely, the cumulus stage, the mature stage and the dissipation stage (Byers and Braham, 1949). Each of these stages of development poses a challenge to aviation operations.

During the cumulus stage, rising warm air results in a cumulus cloud growing in moist unstable air. Aviation hazards through this phase of thunderstorms are mostly produced by super cooled water (Okoola, 2005). Super cooled water causes the icing on the airframe thus changing the aerodynamics effects of an aircraft. Several cumulus clouds may combine to form a single cell. This stage takes 10-15 minutes in duration.

During the mature stage both vigorous updrafts and downdrafts currents occur within the cloud. If an aircraft penetrates the cloud, severe turbulence could be experienced due to the close distance of rising air and falling air. The clouds droplets can become charged with static electricity in the environment, which builds up until a discharge occurs in the form of a lightning flash and accompanying thunder. This mature stage lasts between 15 and 30 minutes, (Okoola, 2005).

During the dissipation stage, the cold downdrafts air spreads out below the cell, the updraft weakens and disappears, and the downdrafts extends to occupy the entire cell, but also weakens and eventually disappears. Aircrafts always land against the direction of the wind, into the headwinds, this aids the braking system of an aircraft. Downburst are disastrous during landing because wind shear can cause the aircraft drift out of the runway. An average thunderstorm has a horizontal diameter of about 24 kilometers. Depending on the conditions present, it may take about 30 minutes to complete the life cycle of a thunderstorm from development to decay (Byers and Braham, 1949).

Local forcing such as Lake Victoria, mountains and strong solar insolation, causes steep temperature gradients between the water surface and the surrounding high grounds, as a result of different thermal capacities. 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). These circulations characterize the space and time distribution of thunderstorms in the western Rift valley.

2.3 Thunderstorm Climatology

Changnon *et al.,* (1984) investigated the temporal distribution of global thunder days from 90 stations in Northern America and 131 stations across the world. The results suggested that the variations in thunder days' frequencies are due to major shift in large scale circulation oscillations. Enno *et al*., (2014) in a study of the long-term changes thunder days frequency over the Baltic countries noted that a long-term reduction in the Thunderstorm Days frequency go with an augmented frequency of northerly Circulation Weather Types (CWTs) that are negative for thunderstorm development. Meanwhile, the frequency of southerly and easterly CWTs that are positive to thunderstorm formation decreased. The influence of some large scale systems on thunderstorm frequencies over Kenya might be established on the current study.

In the central United States, the study of contrails showed that there was an upsurge in cloudiness and a reduction in sunshine from the 1930's at times and areas where thunderstorm frequencies seemingly reduced. Such variations in cloudiness and their causes may be pertinent and connected to the reduction in thunderstorms because high cloudiness should, on the average, deter convective activity and thunderstorm growth. (Changnon, 1981; Changnon, 1984). It is important for this current study to investigate the variations of thunderstorms during seasons of cloudiness and sunshine. This can be achieved through the comparison of thunderstorm frequencies during different seasons in Kenya.

The study of geographical distribution of monthly and annual frequency of thunderstorm days over east Africa was done by Chaggar (1977). The findings noted that in March-April- May there is a slight north ward movement in the patterns of the frequency of thunderstorm days but maximum frequency is in the area east and north of Lake Victoria into Western Kenya. There is a decrease in May over most of Kenya except the western areas. General reduction in most parts is in June and July. The study was done over 40 years ago using sparse data observed only during daylight. The current study seeks to update this knowledge by use of more recent data. It used 24 hourly observations and complete any missing gaps in the data.

Chaggar (1977), also showed that high frequency of thunderstorms occurred over high ground and lake convergence zones in East Africa and in spite of a plenty supply of moisture at the Coast of Kenya the average annual number of thunderstorms is remarkably low. The Lake Victoria region in East Africa lies in a valley between two mountain ranges with a difference of 1,135m elevation. The unique orographic features and intense equatorial insolation generate intense meso-scale circulations with intense diurnal cycle of temperature and rainfall over Lake Victoria and the neighborhood. Thunderstorm frequency in the region may come out to be the highest in the world (Murray, 2002; Asnani, 2005).

Maloba (2015) carried out a study on temporal and spatial characteristics of thunderstorms over the region east of Lake Victoria Basin in Kenya over the period 2000 to 2013 and established that the year 2016 March-April-May (MAM) season recorded the highest frequency of thunderstorms occurrence while the lowest occurrence was 2007 for both MAM and September-October-November (SON) seasons. It was necessary to investigate thunderstorms over the whole Country and extend the duration of the study to bring out the climatological view.

The highlands West and East of Rift Valley experienced the most clouds all year round. The frequencies of the most dangerous clouds to aviation are observed over these regions (Murray, 2002; Jagero, 2018). The current study seeks to re-evaluate the spatial distribution of thunderstorms over the whole of Kenya.

2.4 Rainfall Occurrences

In Australia, (Kuleshov *et al*., 2002) through the analysis and comparison of time series of thunder-day frequency with rainfall variations during the period 1970-1999 concluded that the frequency of thunderstorm did not, in general, seems to differ in any reliable manner with rainfall.

Liebmann *et al.,* (2014) in their study have credited the reducing trend of the rainfall seasonal totals during the OND season to an augmented zonal gradient in SST between the Central Pacific and Indonesia, though a contribution from human-induced global warming is probable (Hoell *et al.,* 2017).

Ayugi *et al*., (2016*)* analysed the monthly, seasonal and annual scales of rainfall variations over Kenya data from1971 to 2010. The findings showed that among the two seasons there was a noticeable decrease of rainfall over MAM season and a slight increase over OND season. Further results showed an overall significant decrease in rainfall over Kenya. Later studies have shown that there was some increasing trends over the short rainfall season (OND) and these were credited to Sea Surface Temperatures (SST) warming in western Indian Ocean, (Gitau *et al*., 2018).

Although, comparison of the trends in the thunderstorms and other weather elements have been done in other parts of the world, such as Australia (Kuleshov *et al.,* 2002) and Baltic countries (Enno *et al.,*2014), similar studies have not been done over Kenya. The current study therefore aims at addressing this gap by analyzing the trends of interannual variability of thunderstorm and rainfall at seasonal scale and comparing the two parameters.

2.5 Case Study on Thunderstorm Related Incidents

For a while, Approach and Landing Accident Reduction (ALAR) has been amongst the main goals in aviation industry. In a normal situation a standard approach and landing comprises the use of procedures. The necessary conditions include that engine power is available, last approach is done straight into the wind, no obstacles on the path of approach, the landing surface is firm and there is amble runway span to progressively bring the airplane to stop (Airbus, 2002).

The different phases in a flight include taxiing, taking-off, initial climbing, climbing, cruising, descending, initial approach, final approach and landing, as shown in Figure 2. Almost half of the accidents and fatalities take place during last approach and landing phases. The causes of accidents during this phase can be due to bad weather conditions, contaminated runway, weight and balance problems, and aircraft system failure or reduced pilot capabilities, (Ranter, 2006).

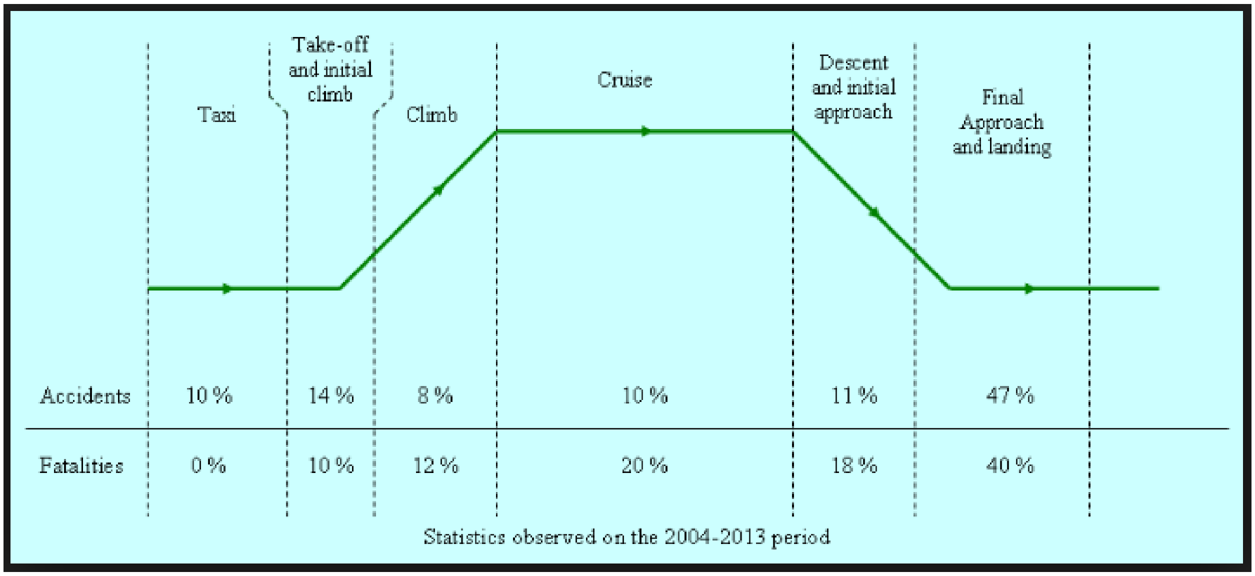

Figure 2: Statistics of Phases of accidents occurrence globally between 2004-2013

(Source: Flight safety.com)

In Australia, Leigh *et al.*, (1997) led a study on the economic worth of a TAF, with reference to Sydney Airport and Qantas Airways Limited airline. Based on the case study, improvements in TAF accuracy would yield significant positive benefits for the airlines. Economic benefit of a supposed increase in TAF accuracy of 1% is approximately AUD 1.2 million per year. The calculations were based only on the additional fuel decision, and not on other important operational decisions, and therefore the estimated figure was deemed as a minimum value (Leigh *et al.*, 1997).

Outside Africa, Sasse and Hauf (2003) examined impacts of thunderstorms at Frankfurt Airport, Germany on flight landing operations. The study did a comparison between days without thunderstorms and thunderstorm days. Five days of thunderstorm and five days of non-thunderstorm in the summer months of the years 1997 and 1998 were selected. The results showed that there was a clear rise in delay minutes which depended on instant capacity of the airport, and the intensity and duration of the thunderstorm event. It determined that of the 10 thunderstorm events designated, 100 incoming aircraft were impacted, resulting in 1000 total delay minutes, approximately 750 delay minutes more than for the days with non-thunderstorm.

Uman and Rakov (2003), in the study on the lightning- related aircraft incidences that involved commercial airplane in Los Angeles, USA established that on average, lightning strikes one airplane per year. They noted that, in 1987 six airplanes were hit by lightning within a couple of hours. Lightning is a more severe product of thunderstorm to the aviation.

In Africa, Lara (2015) investigated the impacts of weather on aviation delays in South Africa at Oliver Reginald Tambo international airport (ORTIA) from 2010 to 2013, the study established that the main significant weather phenomenon which causes most delays remain to be thunderstorm. The study highlighted that all the delays that are weather related can be minimized through better planning, effective evaluation of weather predictions and collective and timely decision making. Even though delays which are related to weather will always occur in aviation sector, improved weather forecasting will reduce its impacts and the length of delays.

In Nigeria, Remi (1987) while analyzing factors of air crash in Port-Harcourt Airport in 1987, stated that the prevalent weather at the time of the crash was thunderstorm. Severe thunderstorm significantly impacts the safety and operational effectiveness of air traffic, particularly at the terminal areas. The inevitable consequences of reduced efficiency are diversions, delays, and cancellations of flights.

Of all aviation accidents, weather accounts for about 15% of the accidents. Some of the weather-related aviation hazards include clear air turbulence, fog, rainfall, snow, sandstorm, volcanic ash and thunderstorm. Thunderstorm is one of the most significant among them because it affects both ground and airspace operations, leading to interruption of schedules which causes delays and diversions of aircrafts. The delays prompt additional expenses such as additional airport charges, upkeep and crew costs and passenger compensation Therefore, giving accurate forecasts on the same is vital. In forecasting thunderstorms, it is important to know their severity, whether they will happen; and the kind of storm that is probable to be witnessed (Wan & Wu, 2004; Pejovic *et al.*, 2009; Jagero, 2018).

Thunderstorms which are more pronounced in the Airport seem to have greater influence on flight delays and cancellations than it has on diversions. This is because ground operations are affected too. Thunderstorms which are out of the airport can be avoided by changing the route to avoid the penetration of thunderstorms due to its severe impacts. Thus, thunderstorm activity in the Airport has an increasing impact on flight operations (Enete, *et al.*, 2015).

The current study seeks to carry out a case study in Kisumu Airport. Kisumu is the third busiest airport in Kenya and it is located in an area with high frequencies of thunderstorm. The study is meant to assess the impacts of thunderstorms on aviation operations through the analysis of recent thunderstorm related incidents. Considering that a flight from Nairobi to Kisumu takes between 45 to 60 minutes, it will be advisable to delay a flight than to risk a diversion. The approximated cost of a diversion is $ 100,000. Delay time will be relatively short because the mature stage of a thunderstorm takes approximately 30 minutes (Okoola, 2005). The study will evaluate the forecasts for the specific days of the incidents to establish inaccuracy.

CHAPTER THREE

3.0 DATA AND METHODOLOGY

The chapter presents the types of data used and the methodology employed to achieve the specific objectives discussed in section 1.3. The datasets used are discussed first then the methods used to achieve the specific objectives follows.

3.1 Data Type and Source

The data used in this study comprises of observed monthly rainfall amounts, monthly frequency of thunderstorm days, flight schedules and folders, re-analysis data, and aviation meteorological forecasts. These datasets are individually discussed in the next sub-sections.

3.1.1 Meteorological Data

The thunderstorm data and observed monthly rainfall amounts used were obtained from Kenya Meteorological Department (KMD). The Thunderstorm data was extracted manually from SYNOP registers in each month of the year from January 1987 to December 2017 for the various stations within the area of study. The rainfall data obtained from KMD database was for the same period, this was important for comparison purposes between thunderstorms and rainfall occurrences in this study.

3.1.2 Aviation Data Sets

The aviation forecast data which was used in this study was obtained from Kenya Meteorological Department. They included the Route Forecasts (ROFORs) from Nairobi to Kisumu, Terminal Aerodrome Forecasts (TAFs) for the specific days when the incidents were reported and Meteorological Aviation Reports (METARs). The geostationary meteorological satellite imagery and meteograms which were used for the two days (19th February 2019 and 26th March 2019) were obtained from KMD.

The data used in the case study was acquired from Kenya Civil Aviation Authority (KCAA) database. This dataset was for two incidents reported in Kisumu International Airport on 19th February 2019 and on 26th March 2019. On the 19th February the incident was the diversion of two Flights JMA8656 and FF1409 and on 26th March 2019 the incident was failed Landing of Flight JMA8656. It comprised the hour in Universal Time Coordinated (UTC) of flight diversion incurred, date and duration of delay, the incidents conformed to the 2001 definition of the 9th edition of the convention on International Civil Aviation Annex 13. There were three different types of flights involved in the two incidents.

3.1.3 Re-Analysis Data

The European Centre for Medium range Weather Forecast (ECMWF) was used, it was data for the two days of the incidents that is 19th February 2019 and 26th march 2019. It included the following:

a. ERA dataset for wind at two levels 850HPa and 300HPa at 1200Z.
b. ERA dataset for Relative Humidity (RH) at 700HPa level at 1200Z and 1800Z, the RH for 1800Z was considered because of the time of occurrence of the first incident on the 19th February 2019.
c. ERA dataset for Convective Available Potential Energy (CAPE) at 1200Z were used since CAPE is the driving power for thunderstorm growth and wet bulb temperature closely controls (Kuleshov *et al.*, 2006).

3.2 Methodology

This section presents the various methods that were applied to the datasets outlined on section 3.1 to achieve the specific objectives highlighted in section 1.3. The data quality control procedures are presented first.

3.2.1 Estimation of Missing Data and Homogeneity Test

Data quality control ensures that high quality data are used for analysis which guarantees meaningful results Arithmetic Mean Method was used to calculate the long term mean; which was then used to fill the missing gaps Equation (1). All the stations used in this study had missing data which was less than 10 % for thunderstorm days while rainfall data had no missing data.

$$\bar{X} = \frac{1}{n}\sum x_i \quad \dots\dots\dots\dots\dots\dots\dots\dots \text{Equation (1)}$$

Where;

$\bar{X}$ = long term mean of thunderstorm days

n = number of stations surrounding station with missing data

X_i = thunderstorm days

This is a technique recommended by the World Meteorological Organization (WMO) for estimating missing monthly, seasonal or annual meteorological data provided the percentage of the missing data does not exceed 10 % of the total, (WMO, 1992).

The next test was that for data consistency or homogeneity test. It also checks the accuracy of data by identifying outliers or deviation from other related parameters or neighboring stations. This study adopted the Single Mass curves to assess the quality of the data. 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 opposite is true.

3.2.2 Annual Cycles and Seasonality of Thunderstorm Days and Rainfall

Mean monthly thunderstorm days were computed for each station to determine the annual cycle of thunderstorms, this was then plotted and presented in graphical form. Similar analyses were undertaken for the rainfall amounts.

3.2.3 Trend Analysis of the Thunderstorm Days and Rainfall

Time series plots were used to determine whether thunderstorm occurrences and rainfall amounts were increasing, decreasing or constant over the years at seasonal and monthly timescales. Using Mann Kendall's non- parametric trend test method, the assessment of whether there was a significant trend (at 95% confidence level) during MAM, JJA, and OND seasons, was determined for both rainfall and thunderstorm occurrences.

The MK test is best regarded as an investigative analysis and is at most used to recognize stations where variations are significant or of bigger scale and to quantify these findings. Secondly, this test does not require the amounts be normally spread and the trend be linear; if existing. Furthermore, the MK test can be calculated if there are missing values and values less than the one or more limits of detection (LD). However, the performance of the test is unfavorably affected by such proceedings. The assumption of the freedom requires that the time between samples be sufficiently large so that there is no correlation between measurements collected at different times, (Kendall, 1961; McLeod *et al.*, 1990). The technique involves computing a statistic that represents the Sen Slope (S), as shown in Equation (2).

$$\boldsymbol{S = \sum_{k-1}^{n-1} \sum_{j-k+1}^{n} sgn(x_j - x_k)} \text{...Equation (2)}$$

Where x_j and x_k are the annual values in years j and k, j > k, respectively.

The significance of the MK statistic can be estimated from the normal cumulative distribution function as shown in Equation (3).

$$\boldsymbol{Z = \{\frac{S-1}{\sqrt{VAR(S)}} \, if \; s > 0} \quad \text{.................................. Equation (3)}$$
$$\boldsymbol{\{0 \; if \; s=0}$$
$$\boldsymbol{\{\frac{S+1}{\sqrt{VAR(S)}} \, if \; S<0}$$

Where Z is the standard test statistic obtained from the standard normal cumulative distribution tables and VAR is the variance.

Mann-Kendall trend test interpretation was, if the computed p-value is greater than the p-value compared with test statistic at same significance level alpha=0.05, one cannot reject the null hypothesis H_o.

H_o: There is no trend in the series

H_a: There is a trend in the series.

3.2.4 Thunderstorm-Related Incidents

The choice of a definite type of case study model was guided by the general objective of the study; Yin (2003) and Stake (1995) used diverse terms to define a variety of case studies. Yin (2003) categorizes case studies as exploratory, explanatory, or descriptive, as shown in Table 2.

Table 2: Different types of case studies and their definitions

Case Study Type	**Definition**
Exploratory	Used to explore those situations in which the intervention being evaluated has no clear single set of outcomes
Descriptive	Used to describe an intervention or phenomenon and the real-life context in which it occurred
Explanatory	Used if one was seeking to answer a question that sought to explain the presumed causal links in real-life interventions that are too complex for the survey or experimental strategies. In evaluation language the explanations would link program implementation with program effects

Source: (Yin, 2003)

Qualitative methods of research were applied in this study to understand the complex interrelationship between thunderstorms and aviation operations. The current study mostly used the explanatory method and partly applied exploratory and descriptive methods.

For the purpose of evaluating the weather forecasts which were valid during the time of diversion, specific TAFs and ROFORs were carefully chosen and examined. These were TAFs issued at least six hours before the time of diversion. Six hours was considered as an adequate time for suitable flight preparation and airport capacity planning to happen. Every single incident was therefore assigned a relevant METAR, ROFOR and TAF, and hence more than one incident assumed similar METAR and TAF where the incidents were close in time.

In both cases, the observations of the day were used to evaluate the forecasts that were issued on the specific days. This was to determine the level of accuracy of the forecast. Further, an account of each case and suggestions on future action was made in order to enhance safety, reduce costs and maximize profits. As per the records, the time of the scheduled flight arrival was assumed to be the diversion time owing to bad weather.

Through a manual comparison, each METAR was compared to the selected TAF, and the prediction was determined either as a hit or a miss (correct or wrong). The following subsequent criteria was designed and applied to categorise the TAF as a hit or a miss:

1. Was the time of the harsh weather rightly forecasted?
2. Was the type of weather correctly forecasted?
3. Was the forecasted horizontal visibility correct, as per ICAO regulations annex 3?

This assessment criteria is exhibited in Figure 3. If any of the assessment criteria was not met, the TAF is regarded as a missed forecast (Lara, 2015). An over-forecast was classified as a hit while an under-forecast was classified as a miss.

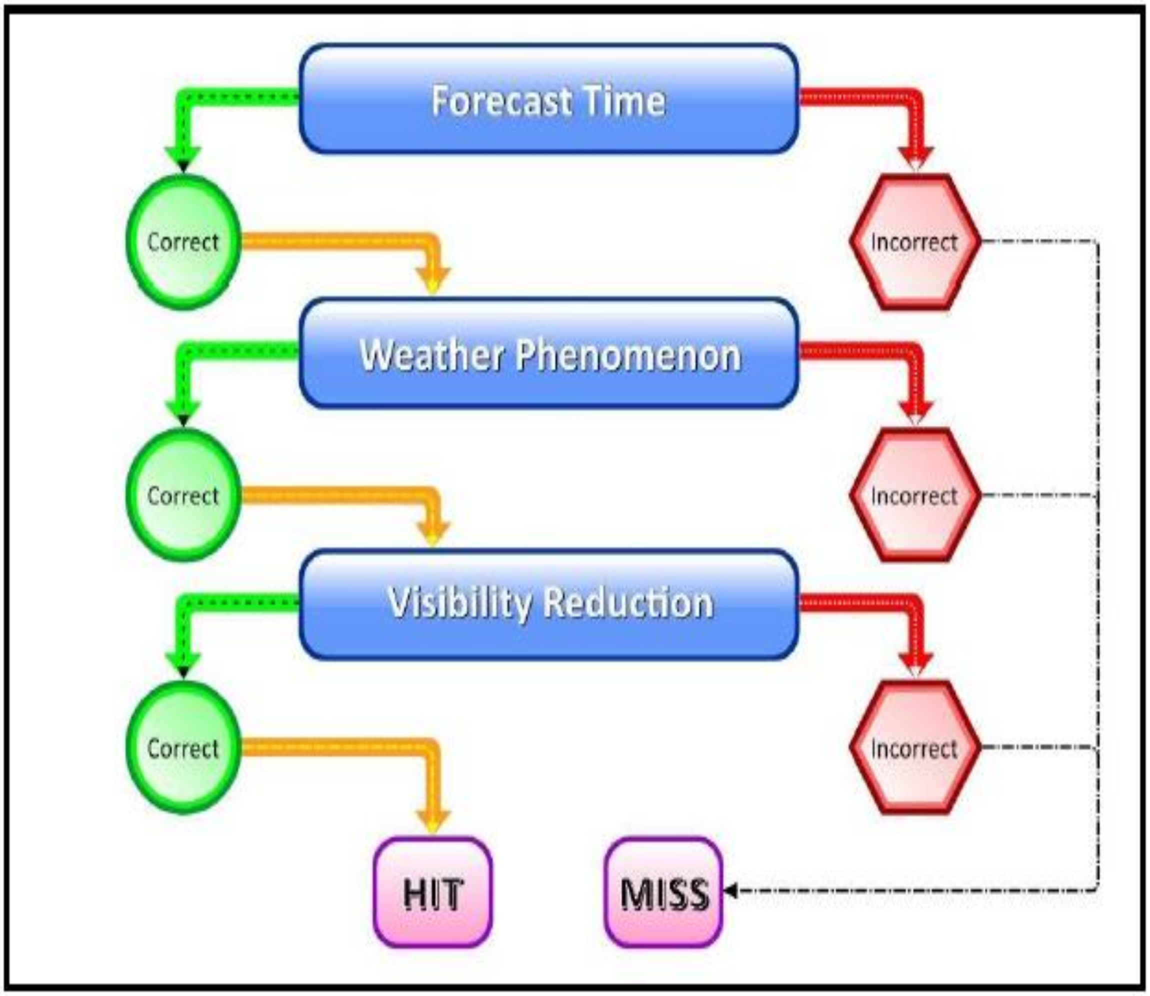

Figure 3: Terminal Aerodrome Forecast evaluation technique flow chart.

CHAPTER FOUR
4.0 RESULTS AND DISCUSSIONS

This chapter presents and discusses the results obtained from the application of the various methodologies expounded in section 3.2 on the datasets given in section 3.1 in order to achieve the specific objectives of the study outlined given in section 1.3. The data quality control results are presented first followed by other results.

4.1 Estimation of Missing Data and Homogeneity Test

Out of the 37 stations of which thunderstorm datasets was considered, 27 stations had a more complete sets and only 10 of them had more than 10 % missing data and were therefore discarded. The 10 stations were Kabete, Machakos, Msabaha, Mtwapa, Laikipia, Moi Air Base, Thika, Kabarak, Suba and Kapsoya. Figure 4 depicts the spatial distribution of the stations which were retained and subjected to further analysis. The rainfall data used for the same stations had no missing data and was good for comparison purposes.

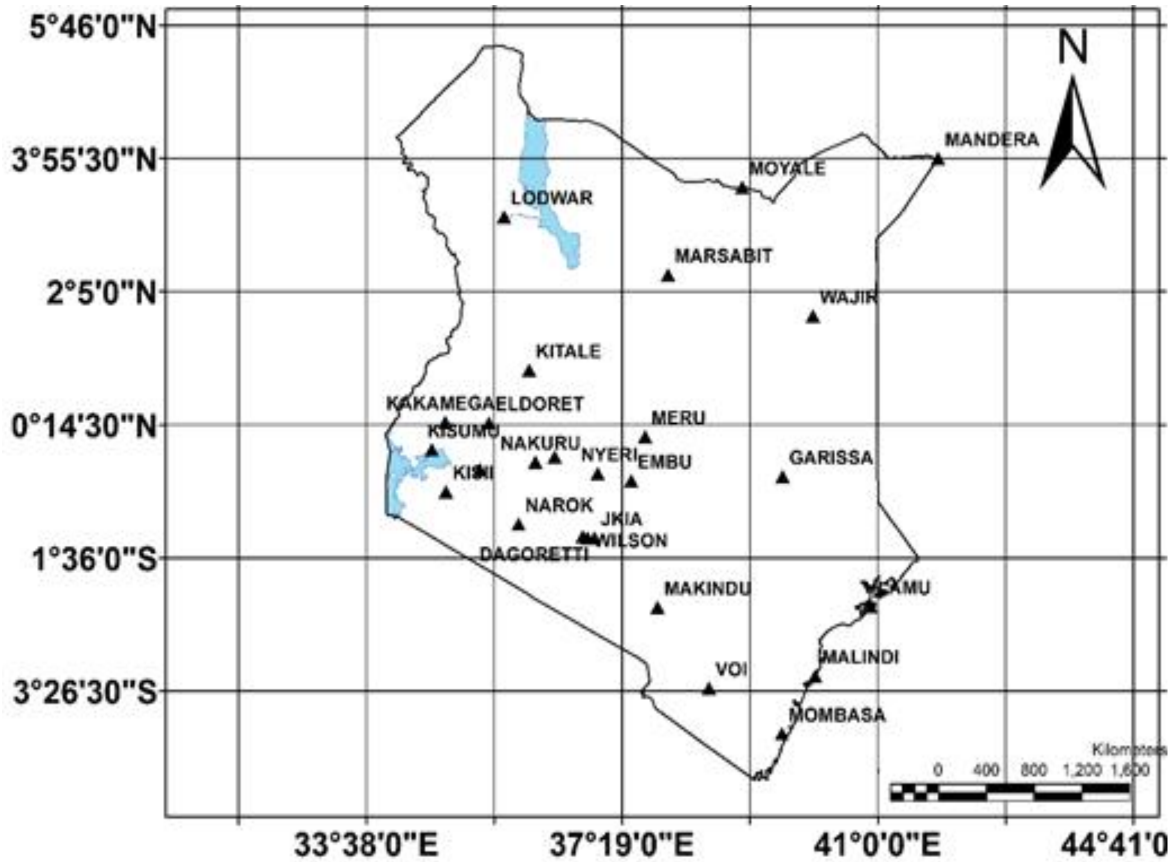

Figure 4: Kenyan map showing the distribution of 27 meteorological stations used in the study.

Figures 5 and 6 are examples of the results obtained for homogeneity tests for the thunderstorm days and rainfall amounts. Similar results were obtained for the rest of the stations. The results showed that both thunderstorm days and rainfall datasets were homogenous and good for further analyses.

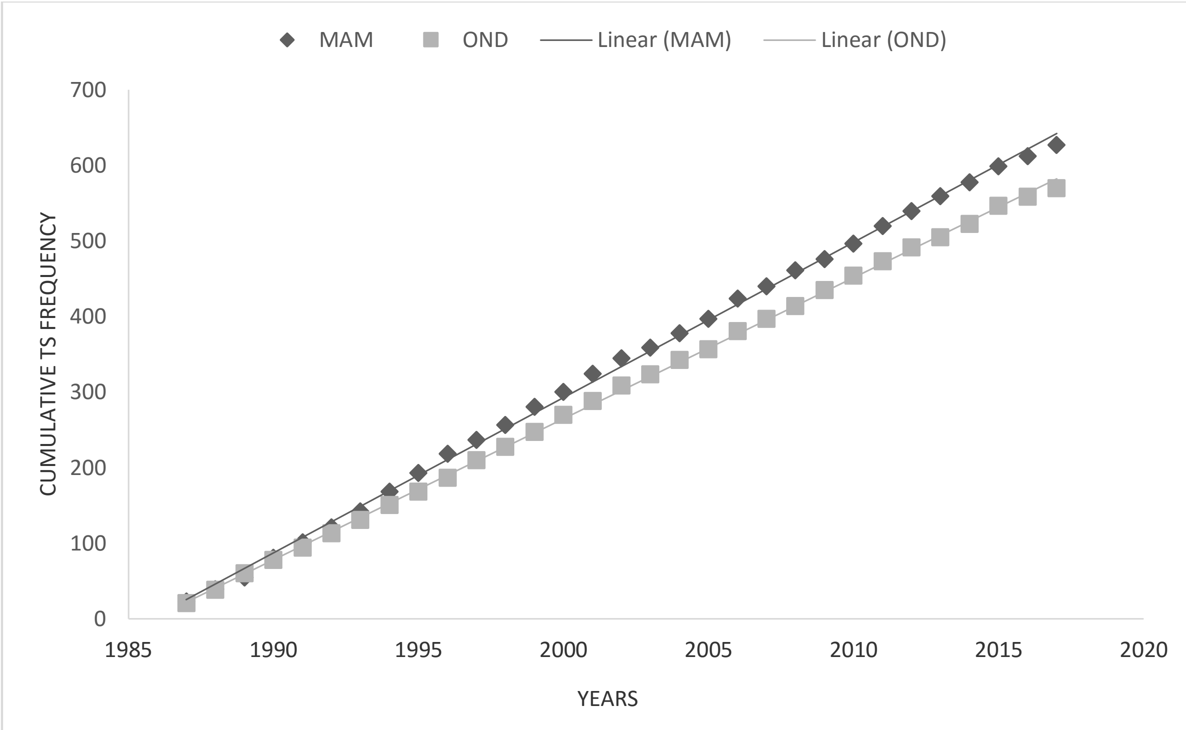

Figure 5: Single mass curve for observed thunderstorms frequencies over Kisumu from 1987-2017.

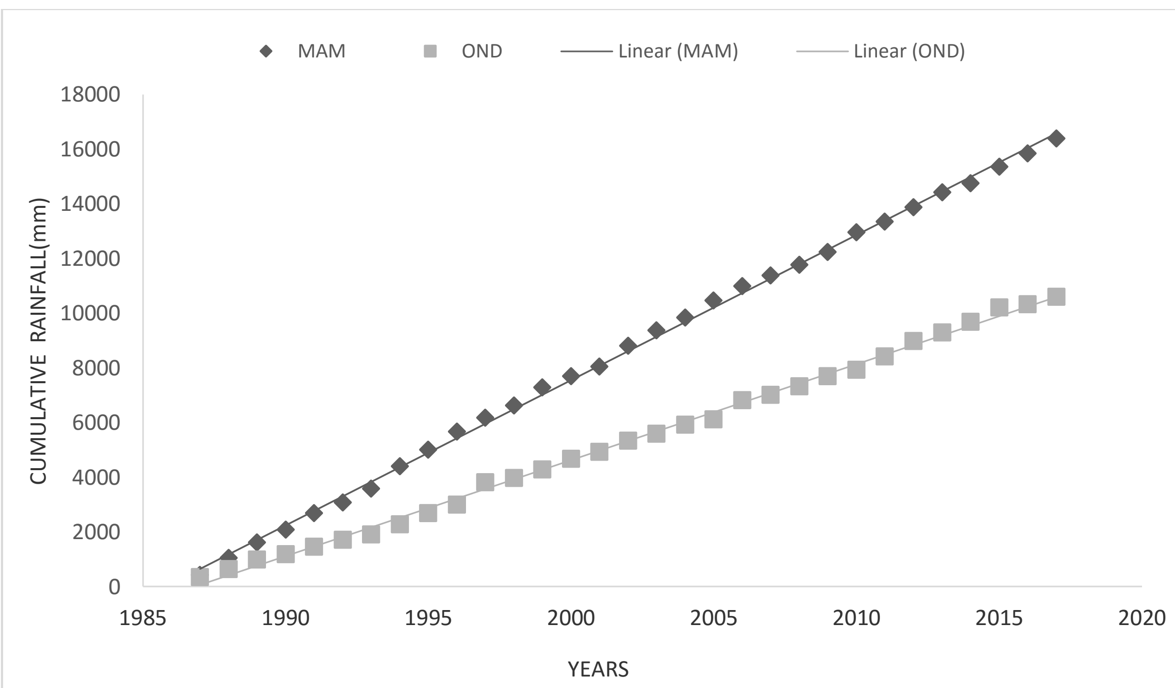

Figure 6: Single mass curve for observed rainfall amount over Kisumu from 1987-2017

4.2 Annual Cycles and Seasonality of Thunderstorm and Rainfall

The spatial distribution of thunderstorms in the Country showed that higher concentrations are to the West and over the Highlands, as shown in Figure 7. The results in the current study are consistent with those of Chaggar (1977), Asnani (2005), Obiero (2013) and Maloba (2015) which showed that Western Kenya was the most thundery place.

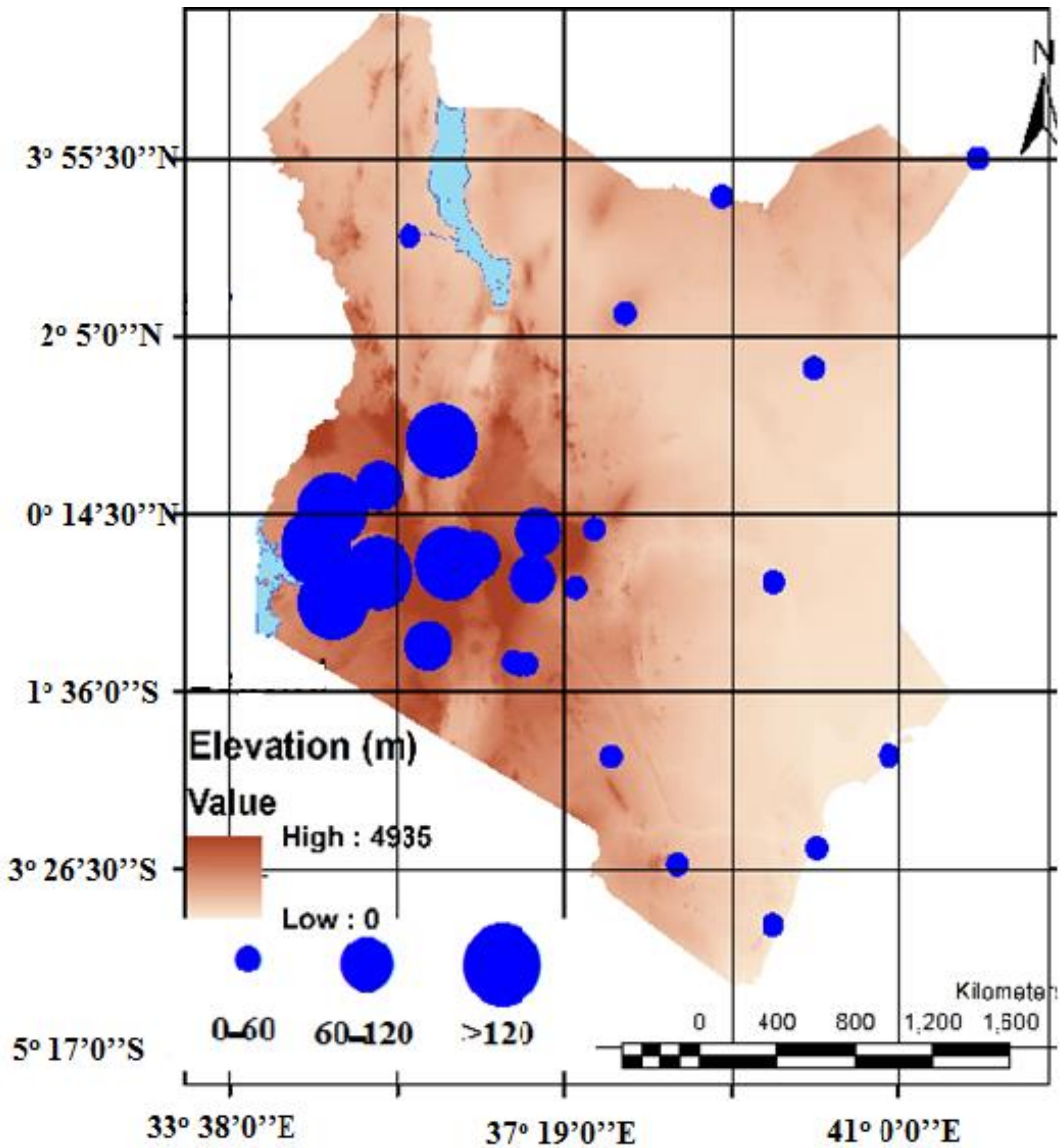

Figure 7: Spatial distribution of thunderstorm days per year over Kenya

4.2.1 Annual Cycle of Rainfall and Thunderstorm

The annual cycle of the thunderstorm days showed that they can be broadly classified as either bi-modal or quasi uni-modal. The bi-modal thunderstorm occurrence pattern was mainly observed over the North Eastern, Central and Coast regions of the country. There are two peaks; in April and November, as shown for Moyale station in Figure 8. This frequency coincides with the March-April-May (MAM) commonly referred to as the long rainfall season and October-November-December (OND) which is often referred to as the short rainfall season.

Other stations which observed the bi-modal pattern are in the Central Kenya (Nyeri, Meru, Embu, Wilson Airport, Jomo Kenyatta International Airport, and Dagoretti Corner), Northern Eastern (Garissa, Wajir, Mandera, Lodwar and Marsabit) and Coastal parts of Kenya (Makindu, Voi, Malindi, Mombasa and Lamu).

During the monsoon transition periods, the North-East in November to March and the South-East in April to October much of equatorial eastern Africa receives rainfall. This corresponds with the passage of the Inter-Tropical Convergence Zone (ITCZ) over the region resulting in the two rainfall seasons (Gitau *et al.*, 2018).

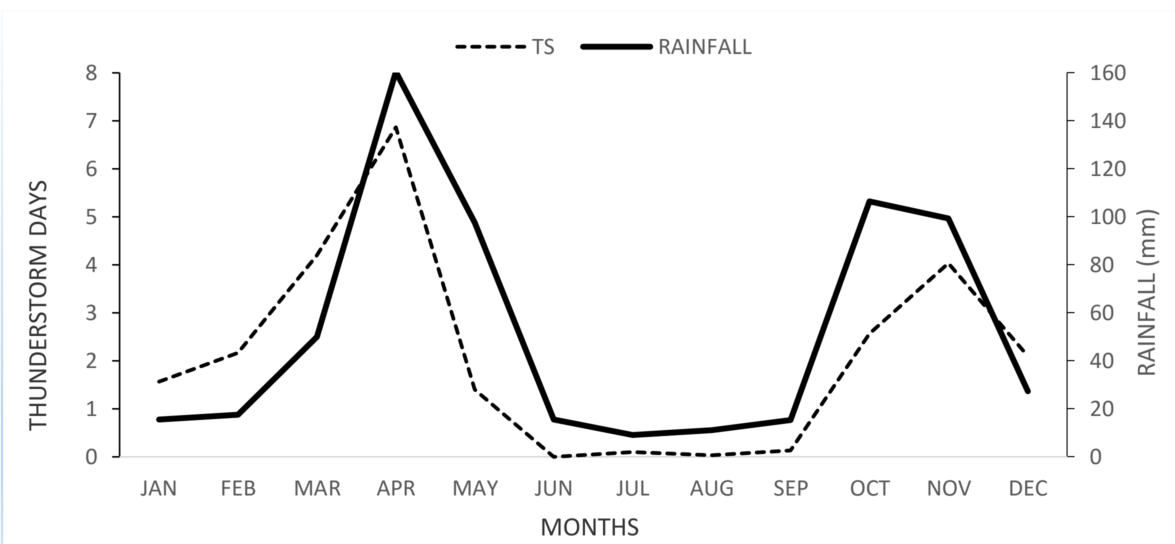

Figure 8: Annual cycle of thunderstorm days and rainfall amounts over Moyale from 1987-2017

The quasi uni-modal thunderstorm occurrence pattern has only one peak month but the timing of this peak varies from one location to another. This pattern was observed over the highland

West of Rift valley and Lake Victoria region as shown in Figure 9. These areas to the western part of the Country near Lake Victoria reported almost equal number of thunderstorm days over the three seasons; MAM, JJA and OND.

Lake Victoria acts as a continuous source of moisture which is an essential ingredient for thunderstorm formation. Chaggar (1977), Asnani (2005) and Obiero (2013) found out that thunderstorm frequencies were higher in stations adjacent to the lake and those on high ground areas. These stations were Kisumu, Kisii, Kakamega, Kericho and Nakuru and includes Nyahururu.

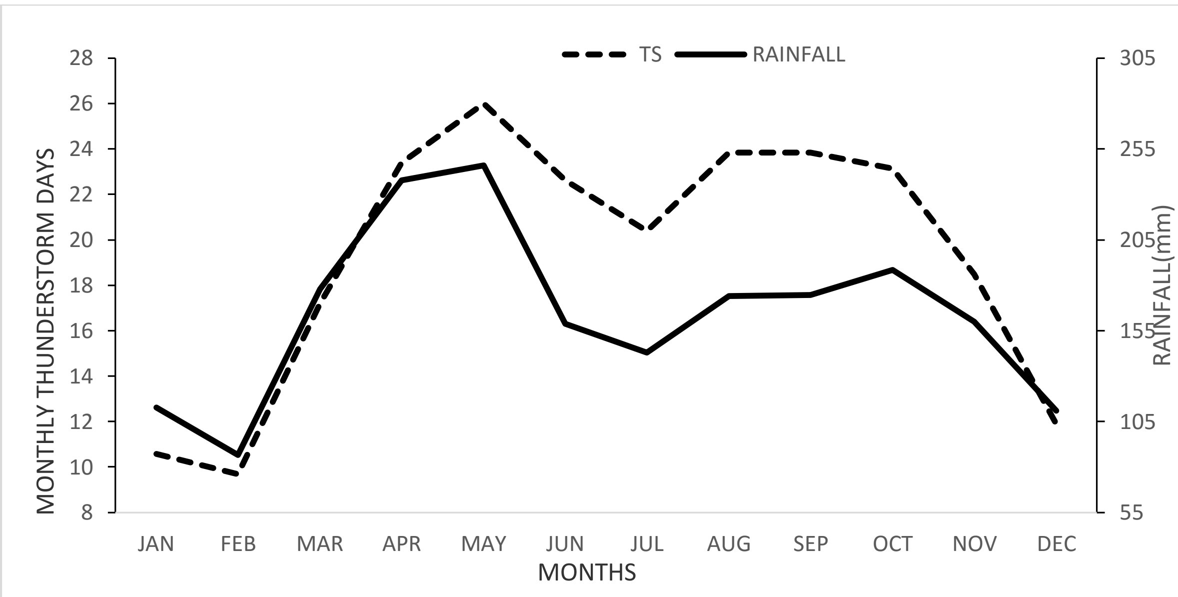

Figure 9: Annual cycle of thunderstorm days and rainfall amounts over Kericho from 1987-2017

Narok in the southern part of Rift Valley, had a similar pattern but with a different peak month (April) and lowest in July, as shown in Figure 10. Location in the northern or southern hemisphere seems to influence the seasonal maxima/minima of thunderstorm days. Previous studies like (Chaggar, 1977) on the distribution of thunderstorms showed that the movement of the center 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.

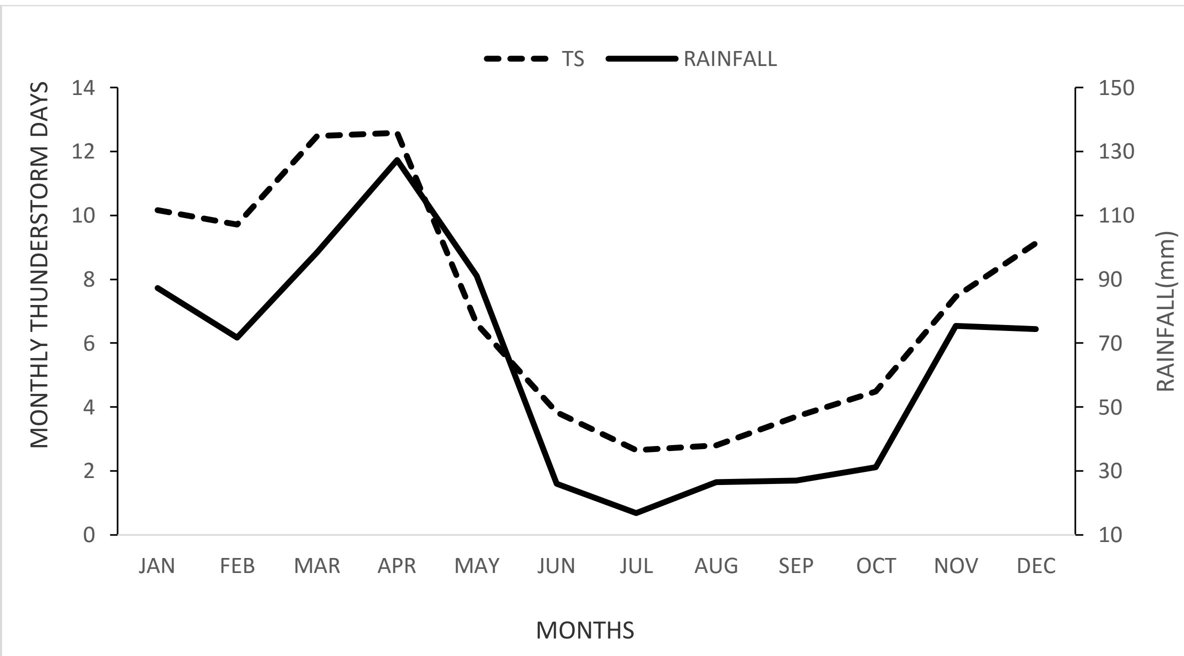

Figure 10: Annual cycle of thunderstorm days and rainfall over Narok from 1987-2017

Over most stations, the seasonal variation of thunderstorm was similar to the rainfall pattern. It showed that rainfall had a positive relationship with thunderstorm over the country.

4.2.2 Seasonal Variability of Rainfall and Thunderstorm

During MAM season rainfall activities were reported throughout the country in varying amounts. The rainfall amounts increased towards the western parts of the country, as shown in Figure 11. With the availability of moisture from the long rain season, the high ground areas over the western parts of the country recorded high frequencies of thunderstorms.

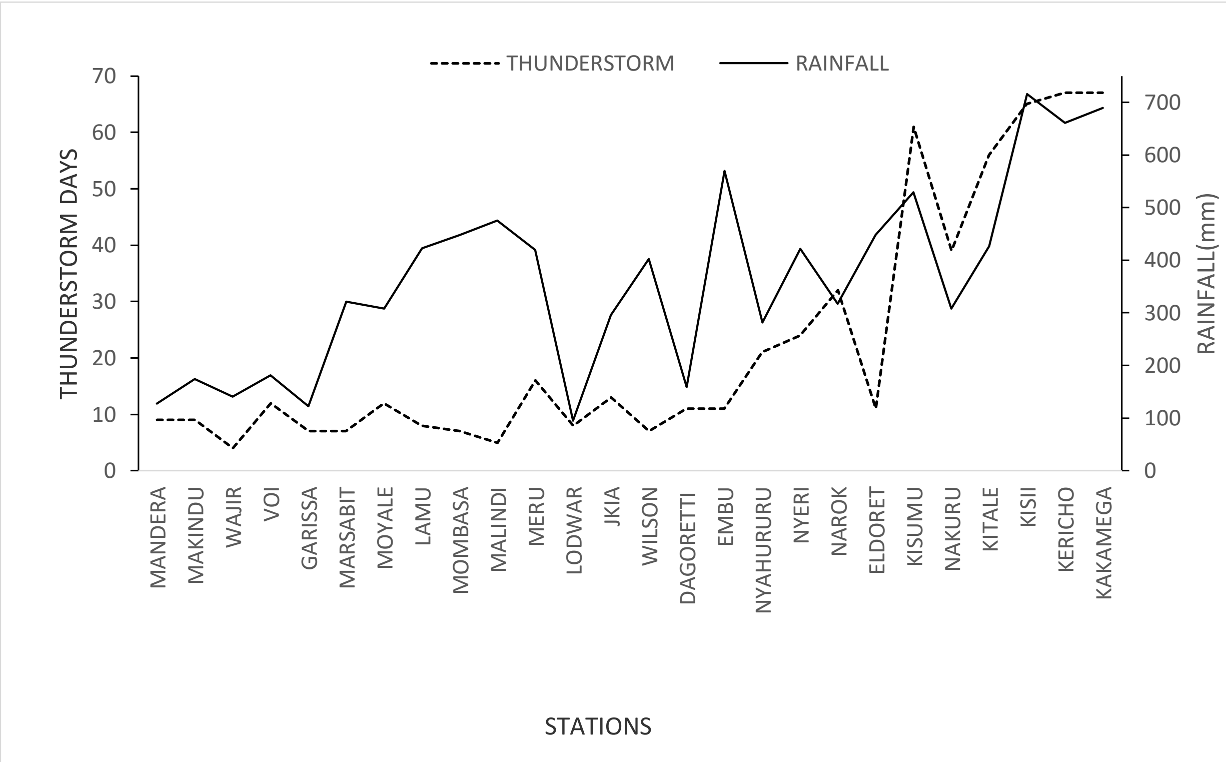

Figure 11: Mean Seasonal variation of rainfall and thunderstorms during MAM over Kenya

Over June-July-August (JJA) season, least number of thunderstorms days were reported over the Highland East of Rift Valley, North Eastern and the Coast of Kenya, as shown in Figure 12. Higher frequencies were observed over the highland west of Rift Valley, Nakamara (1968) in the study of equatorial westerlies over East Africa showed that frequent incursions of these winds resulted in heavy thunderstorms over the Highlands of Kenya but a lee effect was evident in the regions east of the highlands.

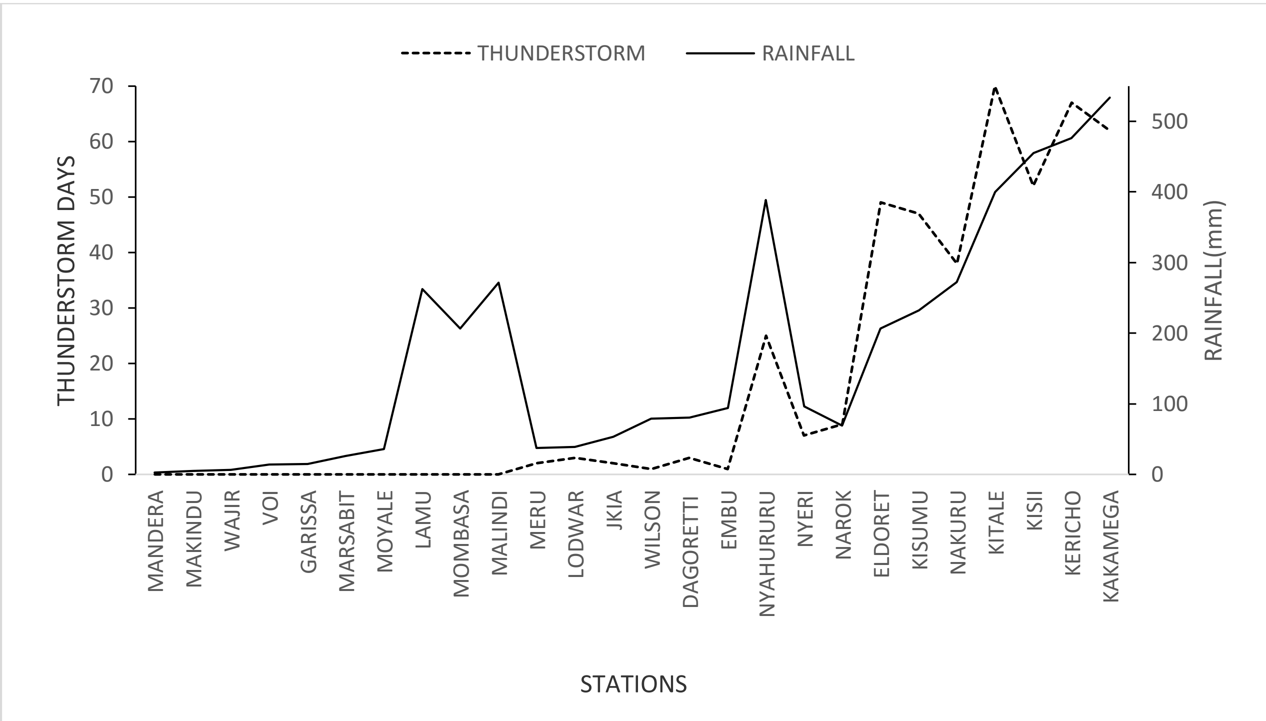

Figure 12: Mean Seasonal variation of rainfall and thunderstorms during JJA over Kenya

During the short rainy season (OND) the eastern half of the country reported low frequencies of thunderstorms whereas there was a notable peak over the western part of the country. Even though there were peaks of rainfall frequencies over Central Kenya that is (Meru, Embu, Nyeri) thunderstorm frequencies were minimal, as shown in Figure 13.

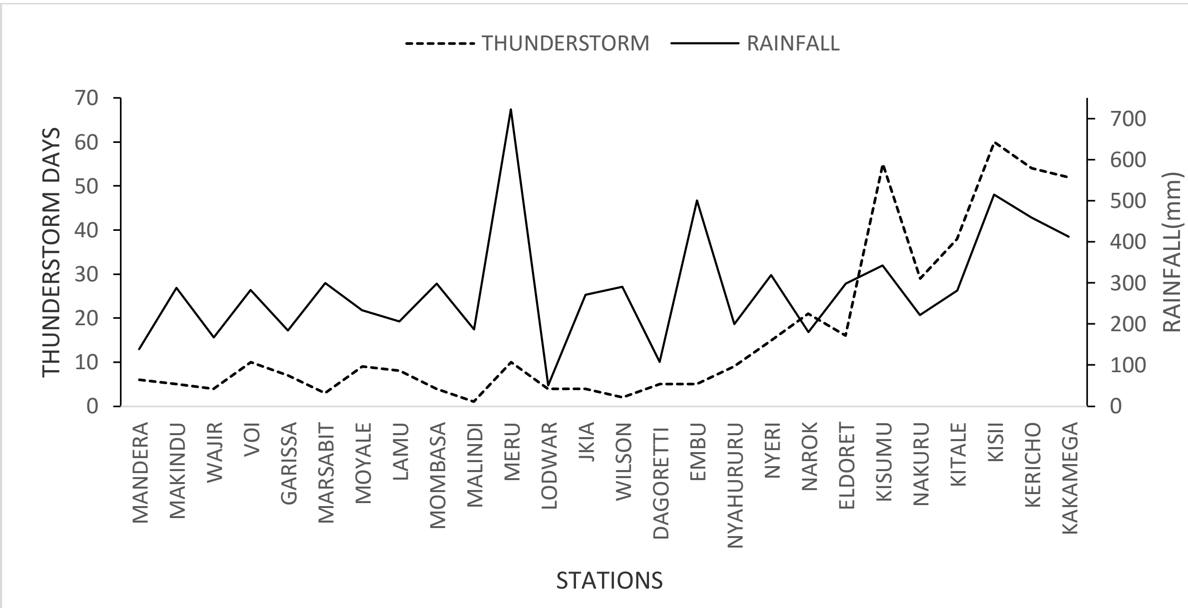

Figure 13: Mean Seasonal variation of rainfall and thunderstorms during OND over Kenya

Variations and magnitudes in sensible and latent heat fluxes influence local and regional climate and thus conceivably the formation of thunderstorms (Lafleur and Rouse 1995; Pielke and Vidale 1995; Chapin *et al.*, 1998; Eugster *et al*., 1998). The western part of the country have high influence from Lake Victoria basin as its source of moisture and therefore, the latent heat over these areas is higher than the highlands in Central Kenya. The triggering mechanisms also include the orographic upslope. Even though we have adequate moisture from the Indian Ocean over the coastal region, low elevation over this region limits the formation of thunderstorms.

In general, the preconditions for thunderstorm formation that must be satisfied are adequate amounts of moisture in the lower (< 3km) atmosphere and an unstable air mass with a triggering mechanism to set off the convective activity. The moisture provides the thunderstorm with energy by the release of latent heat through condensation (Grice and Comisky, 1976). The triggering mechanism, which was the heating from below and low-level convergence (sea/land breeze) caused the instability of the atmosphere (Schroeder and Buch, 1970).

4.2.3 Inter-Annual Variability of Rainfall and Thunderstorm

Over the North Eastern parts of the Country the thunderstorm days were mainly observed during MAM and OND seasons with slightly higher frequencies during OND season. It also appeared to be consistent tendency for peaks and troughs in thunderstorm frequency to coincide with the El Nino events (1987, 1991, 1992,1994,1997,2002,2004,2006,2009 and 2015) or La Nina events (1988, 1995, 1998, 1999,2000,2005,2007,2010,2011,2016 and 2017). During OND season in the northeastern parts of the Country, as shown in Figure 14.

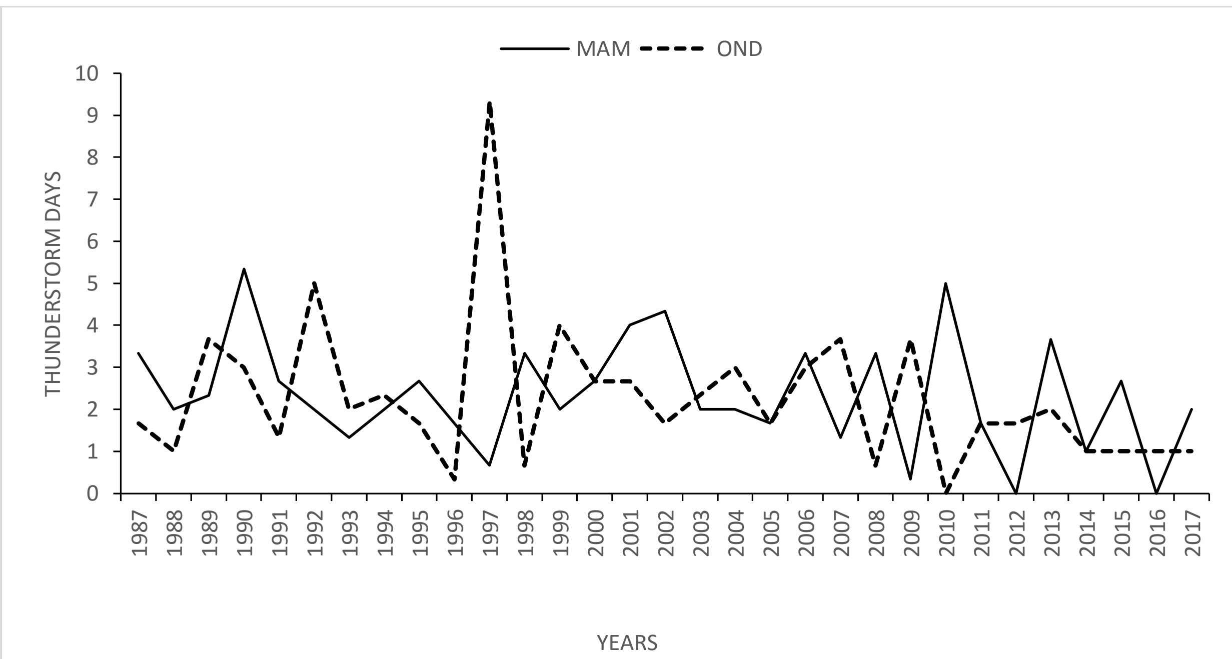

Figure 14: Inter-annual variability of thunderstorms over Garissa during the MAM and OND seasons

The coastal areas had similar pattern as that of northeastern parts but the MAM season had higher frequencies of thunderstorms than OND, as shown in figure 15. Higher frequencies of thunderstorms over MAM season, may be associated with the seasonal migration of the zonal arm of the Inter-Tropical-Convergence-Zone (ITCZ) from South to North, more moisture implied.

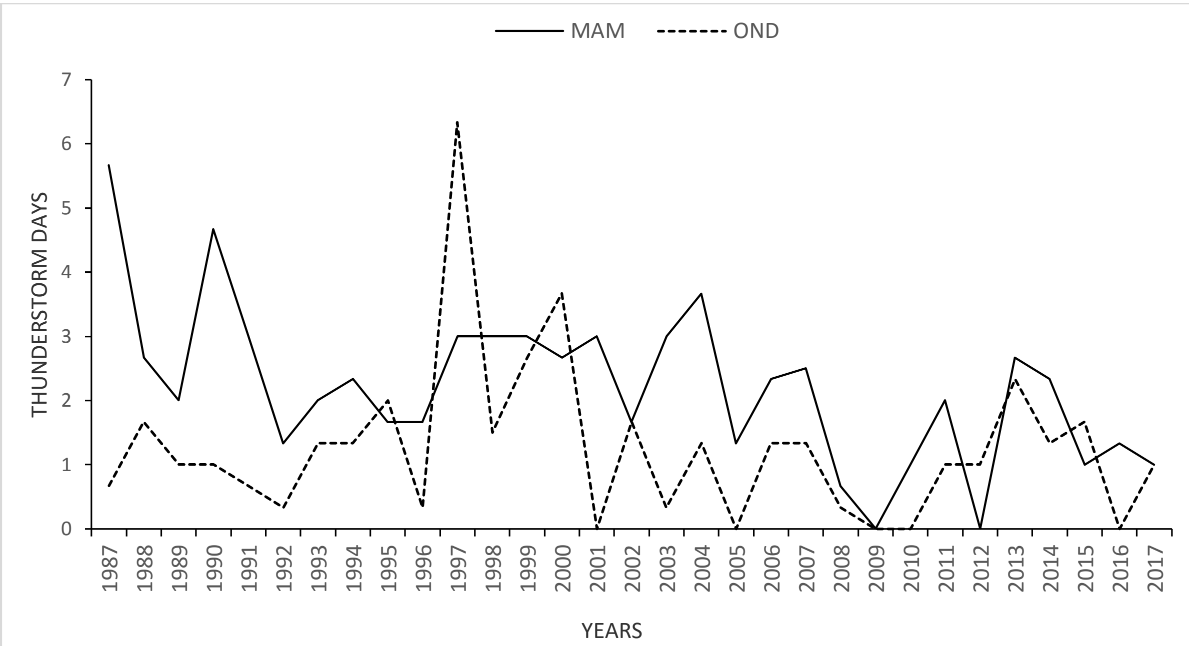

Figure 15: Inter-annual variability of thunderstorms over Mombasa during the MAM and OND seasons

The analysis of thunderstorm data in areas around Lake Victoria showed that thunderstorm frequency did not vary significantly over MAM, JJA and OND seasons as shown in Figure 16. There were almost equal frequencies. These stations Kericho, Kakamega, Kisumu and Kisii are the same stations with quasi-unimodal pattern of thunderstorm occurrence, highly influenced by Lake Victoria which acts as a constant source moisture.

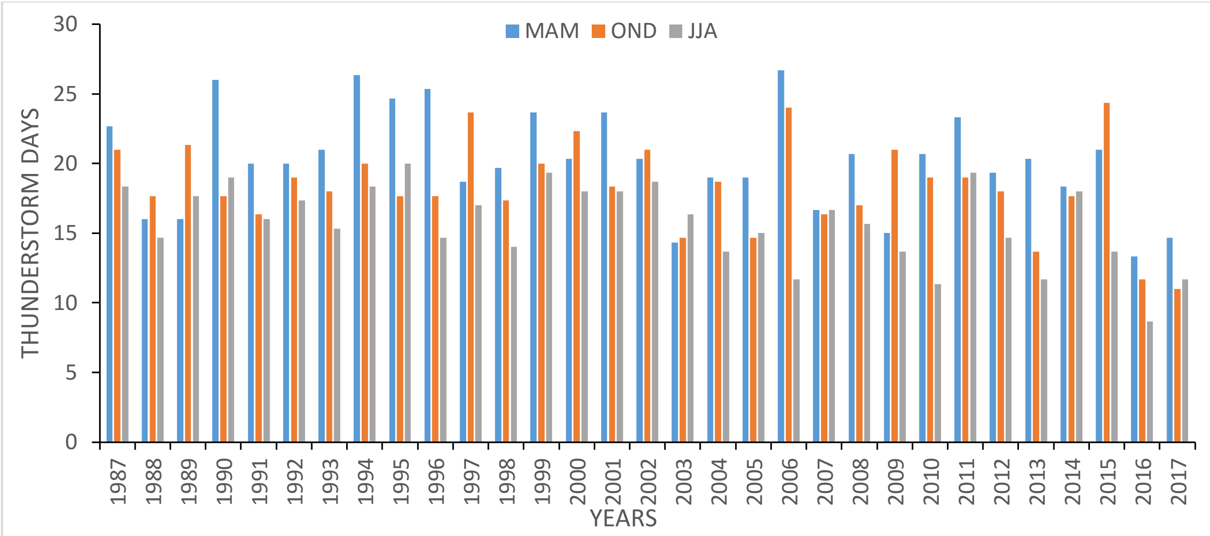

Figure 16: Inter-annual variability of thunderstorms over Kisumu during MAM, JJA and OND

4.3 Trend Analysis of Thunderstorms and Rainfall

The sub-section presents the results of seasonal rainfall and thunderstorm trends observed, also the comparison of rainfall and thunderstorm trends over the country.

4.3.1 Trend Analysis of Thunderstorms

The trend of annual thunderstorm days in Kericho was increasing, as shown in Figure 17. Other stations which had a similar increasing trend were in Western Kenya: Kitale, Kakamega and Eldoret.

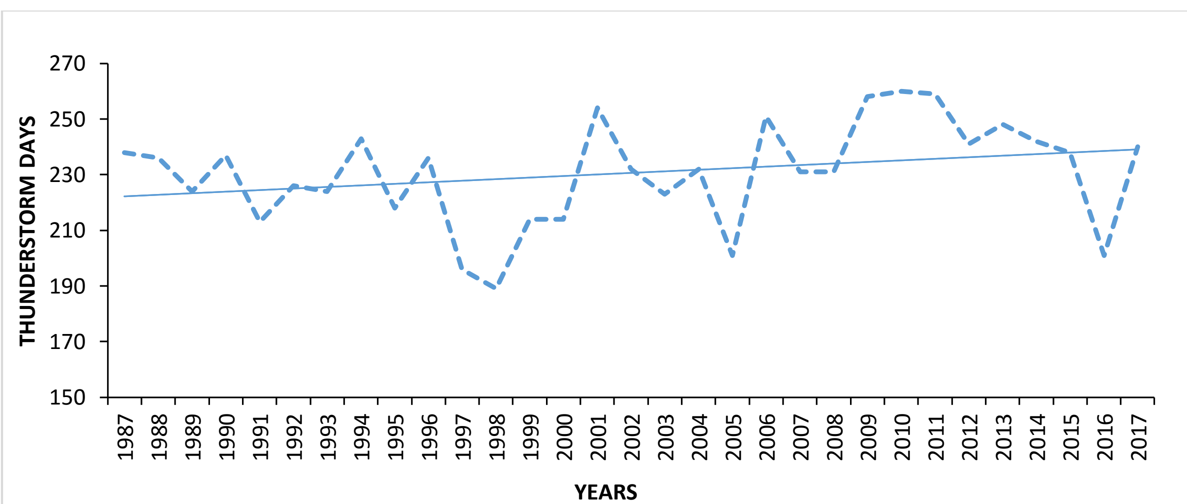

Figure 17: Thunderstorm days' time series over Kericho from 1987-2017

Despite other stations like Nyeri, Dagoretti Corner, Wajir and Kakamega having an increasing trend, the gradient less steep, as shown in figure 18.

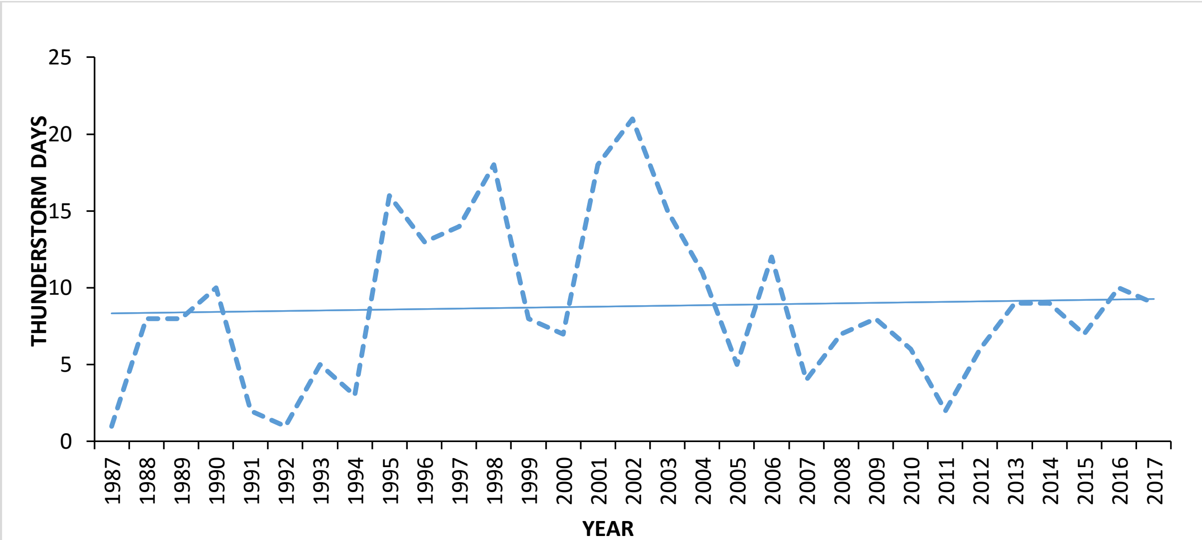

Figure 18: Thunderstorm days' time series over Wajir from 1987-2017

Makindu had a decreasing trend, as shown in Figure 19. Other Stations with a decreasing trend were Moyale, Marsabit, Mandera, Garissa, Embu, Jomo Kenyatta Airport, Lamu, Nakuru, and Mombasa.

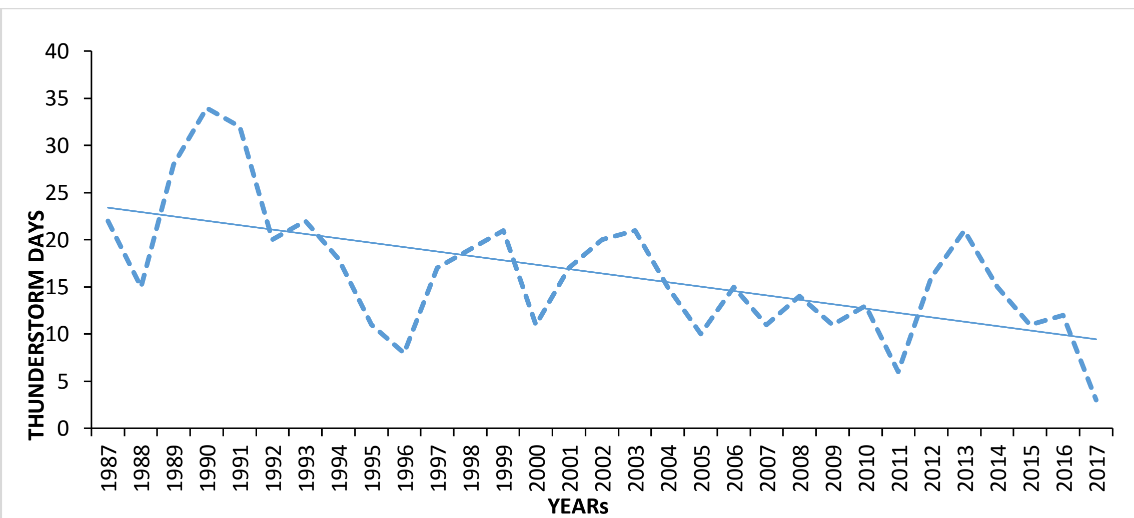

Figure 19: Thunderstorm days' time series over Makindu

Generally, across the Country, a reducing trend of thunderstorm days was observed during the MAM and JJA seasons while most stations had an increasing trend during the OND season.

In contrast, the stations around the Lake Victoria region mainly had an increasing trend during MAM and OND seasons.

4.3.2 Comparison of Inter-Annual Thunderstorm Trends With Inter-Annual Rainfall Trends

During the study period, thunderstorms and rainfall trends varied over different Regions of the country in each season.

During MAM season, stations near the Lake Victoria Basin, Central and the Highland East of the Rift Valley had a non-significant reducing trend of rainfall but increasing significant and non-significant trend of thunderstorm, as shown in Figure 20 for Nyeri station. Other stations with similar comparison with Nyeri were Dagoretti Corner, Meru, Eldoret, Kakamega, Kericho and Narok. This is in agreement with previous studies over Eastern Africa (Kansiime *et al.,* 2013; Viste *et al.,* 2013; Rowell *et al.,* 2015). They recorded a recent decrease in the seasonal rainfall totals during the long rainfall season. This has generally been attributed to concurrent increases in the SST of the tropical western Pacific (Williams and Funk, 2011; Lyon and DeWitt, 2012).

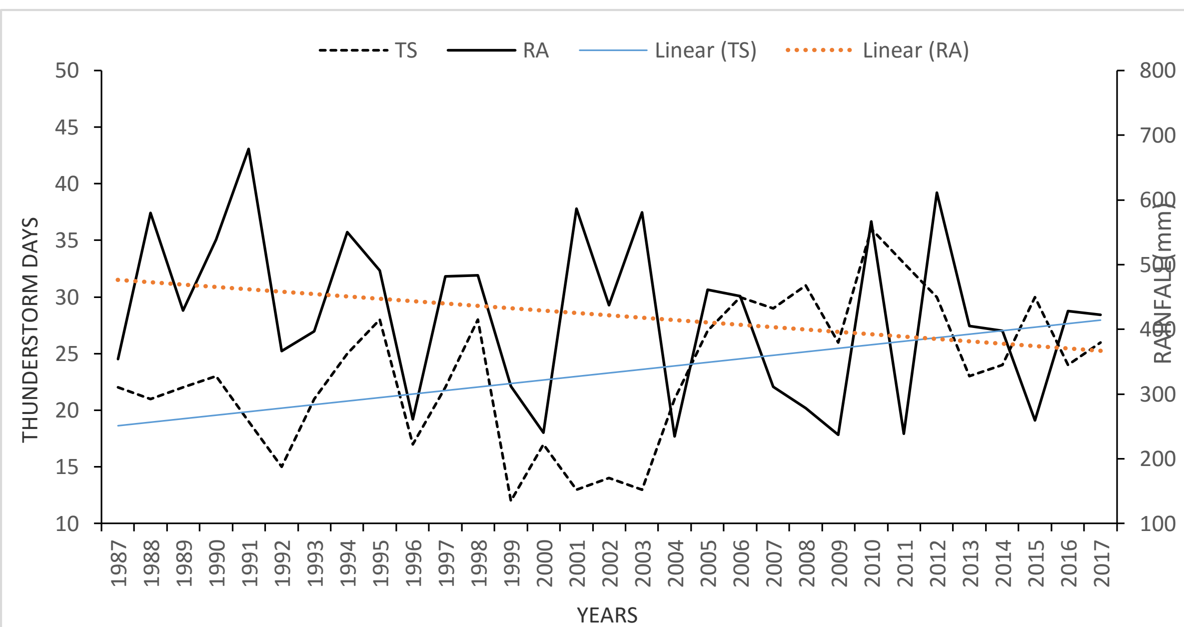

Figure 20: Comparison of rainfall and thunderstorm trends during MAM season over Nyeri.

Rainfall trends were increasing while thunderstorms trends were reducing significantly over Lodwar station, as shown in Figure 21. The station has a lower elevation of 506m AMSL as compared to those over the Highlands, this limits the development of deep convective clouds despite the availability of moisture during the rainy season.

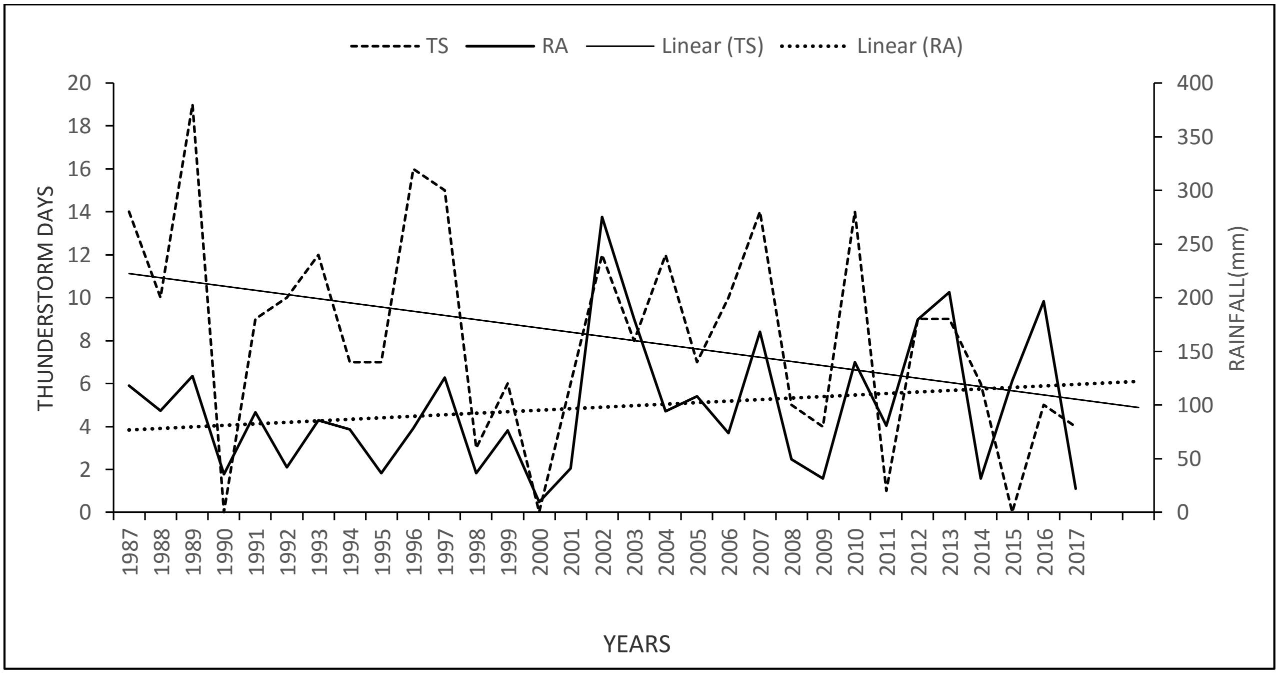

Figure 21: Comparison of rainfall and thunderstorm trends during MAM season over Lodwar

Over Northeastern and the Coastal regions, the significantly reducing trends of thunderstorms agreed with the non-significantly reducing trends of rainfall as shown in Figure 22 of Mandera station. Other stations in this category were Makindu, Voi, Lamu, Malindi, Marsabit and Garissa.

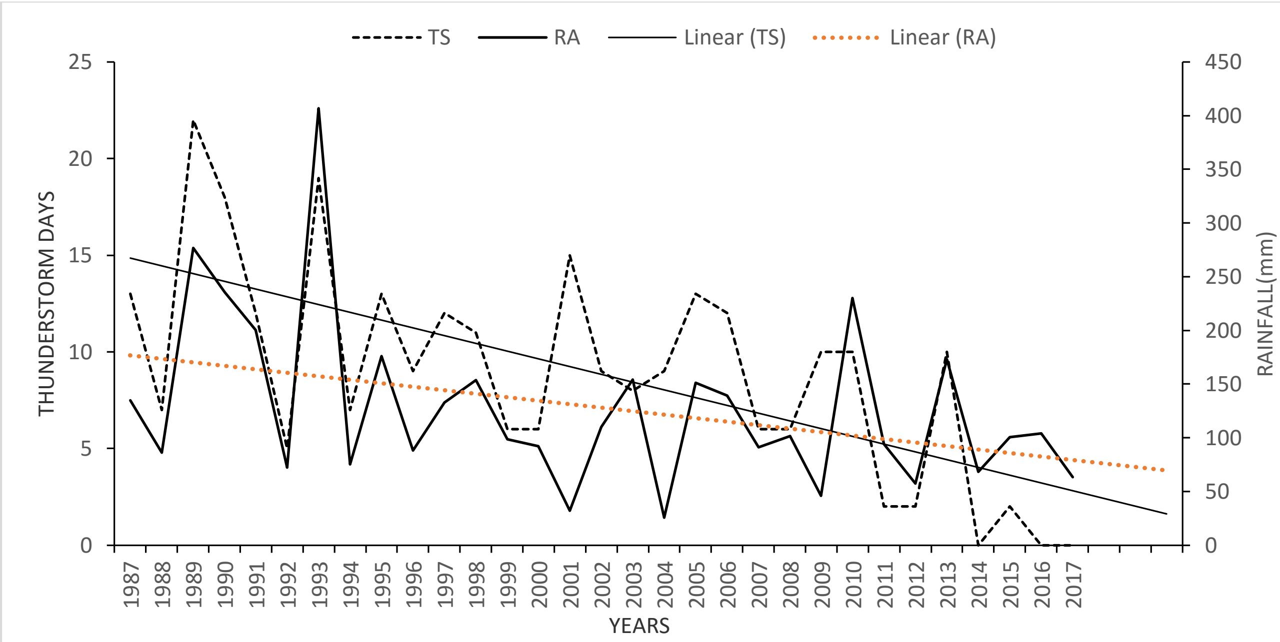

Figure 22: Comparison of rainfall and thunderstorm trends during MAM season over Mandera

During JJA season, areas which had a non-significantly increasing trend were near the Lake Victoria. The coast and the North Eastern region had a significant decreasing trend of rainfall and a non-significant trend for thunderstorms. However, both thunderstorm and rainfall trends were reducing significantly in Narok, as shown in Figure 23. Areas near Lake Victoria benefit from Westerlies incursions during JJA season, the advection of moist Congo air mass results in active weather over the Highlands west of Rift valley regions. However this advection seemingly does not extend to Narok County. Rainfall in Narok, begins from November to April, the peak month is April.

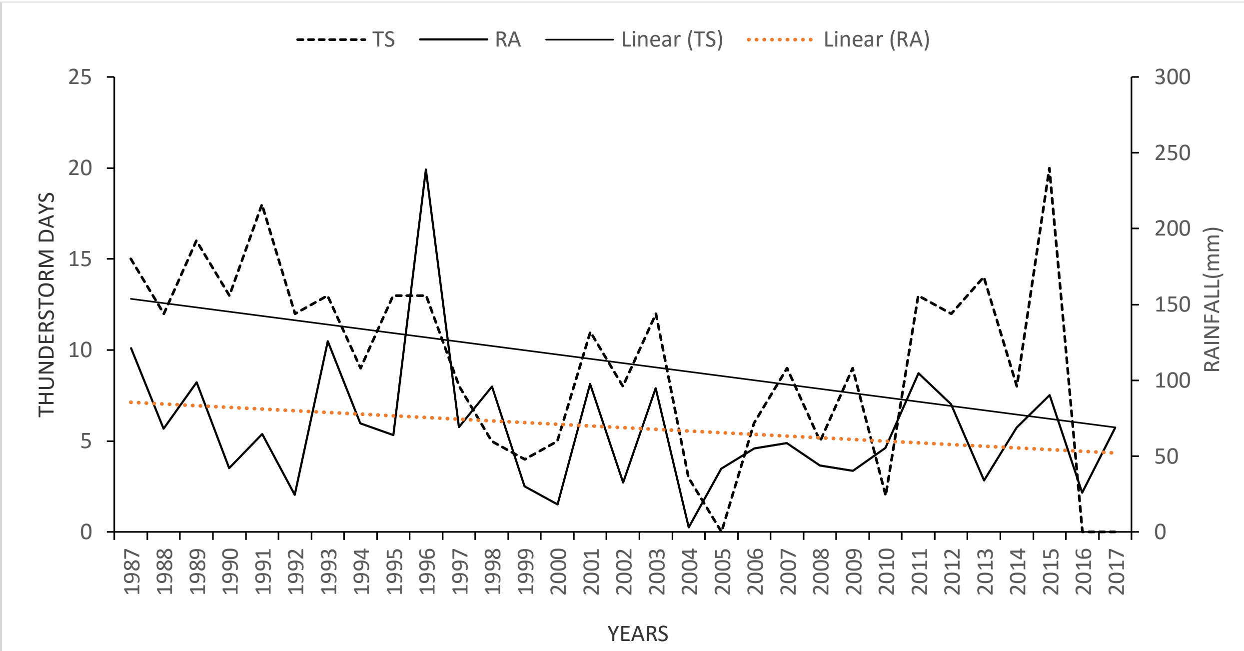

Figure 23: Comparison of rainfall and thunderstorm trends during JJA over Narok

Some stations had insignificant trends for both rainfall and thunderstorms. This was mainly observed during JJA season over North Eastern parts of the country and the Coastal Region as shown in Figure 24 of Mombasa station.

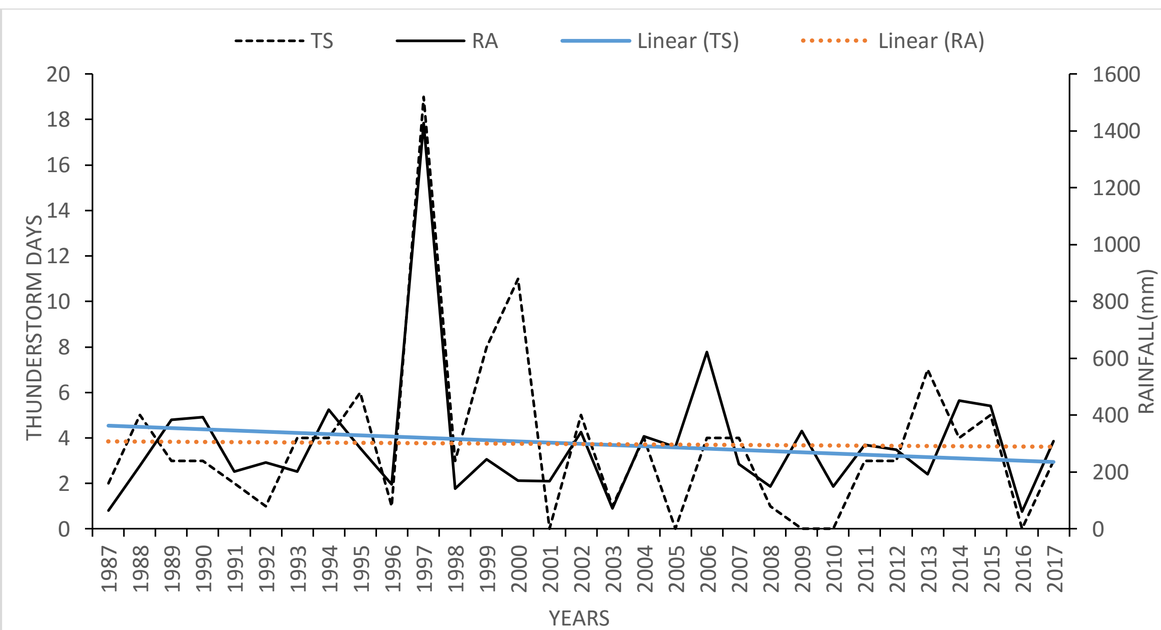

Figure 24: Comparison of rainfall and thunderstorm trends during JJA season over Mombasa

During OND season, western Kenya had a significant increasing trend of thunderstorm while rainfall was increasing insignificantly, as shown in Figure 25. Areas where convergence occurs experience upward motion of air resulting to cloud formation. This leads to formation of thunderstorm/ precipitation if there is enough moisture and condensation nuclei, (Okoola, 1999).

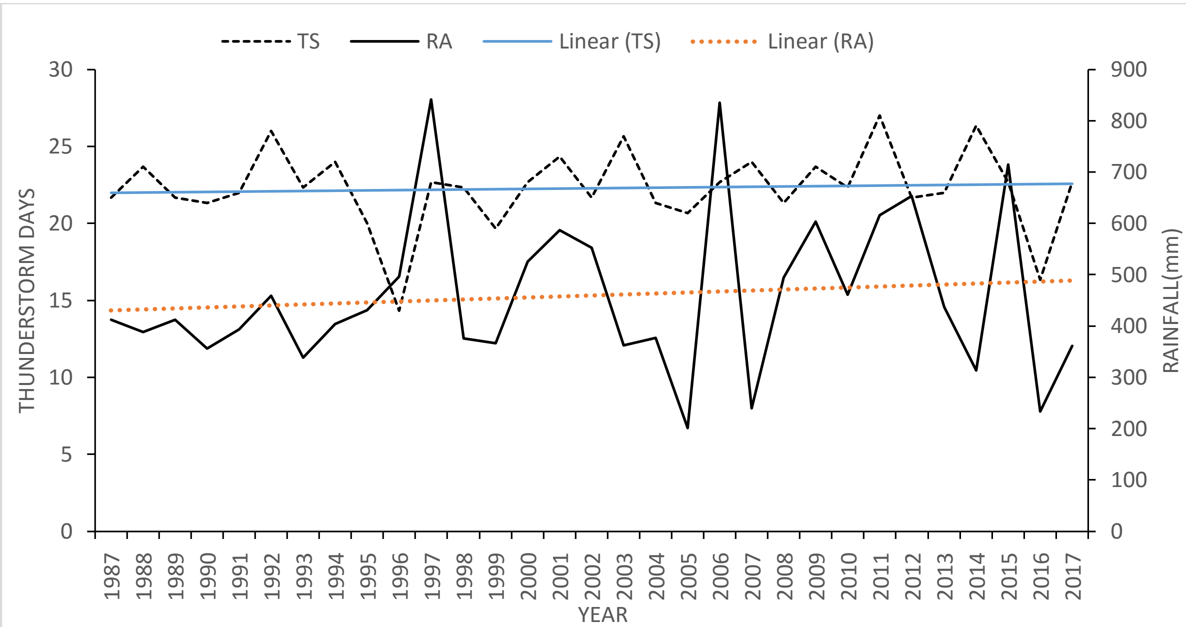

Figure 25: Comparison of rainfall and thunderstorm trends during OND season over Kericho

Rather than the availability of moisture, the physical features (elevation) of a location contributed to thunderstorms occurrences. During OND season, the same observation was made in Eldoret as shown in Figure 26.

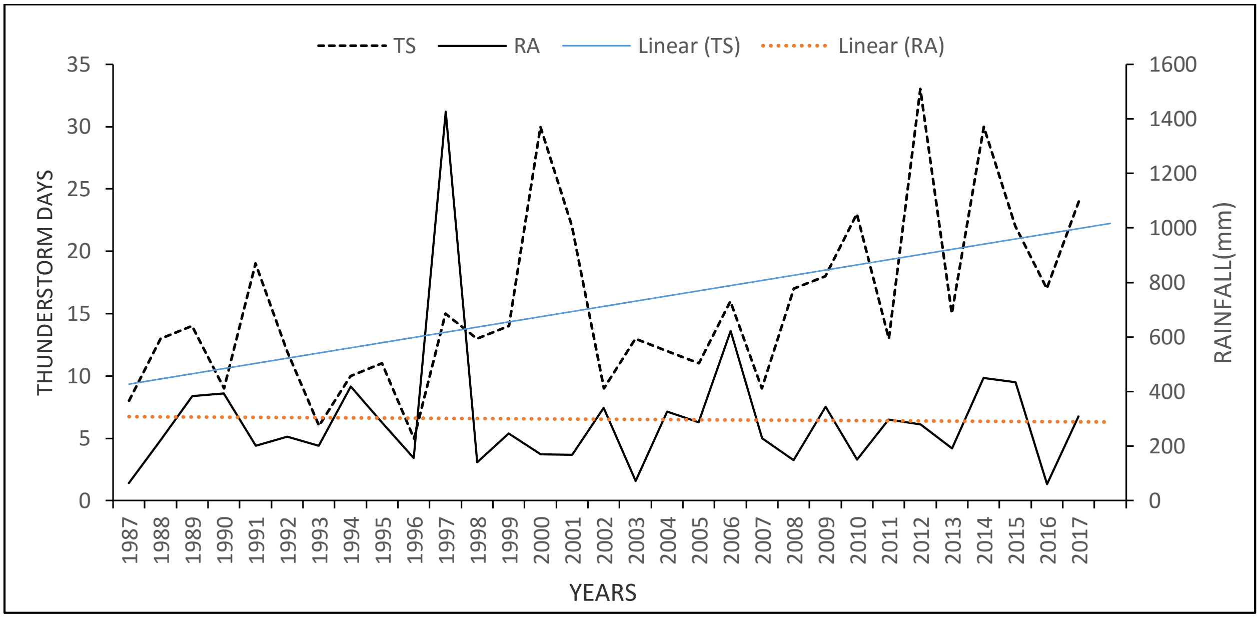

Figure 26: Comparison of rainfall and thunderstorm trends during OND season over Eldoret

In summary, both the statistically significant and non-significant thunderstorm and rainfall trends were observed during all the three seasons.

A non-significant decreasing trend of rainfall was observed over most stations during MAM season, while OND season displayed an increasing non-significant rainfall trend over most stations except over the south east lowlands of Kenya where the trends of rainfall were reducing over OND. The increasing trend during the short rainfall season has been attributed to the warming of SST in western Indian Ocean. (Gitau *et al*., 2018). Further, Liebmann *et al.* (2014) attributed the decreasing trend of the seasonal rainfall totals during the long rainfall season to an increased zonal gradient in SST between Indonesia and the central Pacific, although a contribution from human-induced global warming is likely (Hoell *et al.*, 2017). Though the finding of the current study on the rainfall trends over MAM and OND were agreeing with the previous studies (Liebmann *et al.* 2014; Gitau *et al*., 2018) the significance level differed, there were non-significant trends for the reducing MAM and the increasing OND rainfall trends.

For thunderstorms, a reducing significant trend was observed over most stations during MAM season. In JJA season, most stations over the eastern half of the country observed nil thunderstorms while the western half had reducing significant trends. During the OND season, most stations had increasing significant trends. In contrast, the stations around the Lake Victoria region mainly had an increasing trend during MAM and OND seasons.

During JJA season, in most parts of the Country, thunderstorms and rainfall trends were both reducing significantly. In contrast, over OND, there were increasing trends which were significant for thunderstorms and insignificant for rainfall in the Highland West of Rift Valley, the Lake Victoria and Central Regions. The number of stations with significant trends of both rainfall and thunderstorms, were generally fewer than those with non-significant trends. Certain locations, mostly to the east of the Lake Victoria and on the highlands, showed a consistent trend signal during all seasons for both rainfall and thunderstorms. These are shown on the various maps (Figure 27).
A unique characteristic of reducing trend of both rainfall and thunderstorm through all the seasons was observed in some stations (Embu, Garissa, Makindu, Lamu and Mombasa). The conditions favorable for thunderstorm formation were limited in these areas. The Coastal region being a low land limits the development of deep convective clouds. Lack of moisture over the North eastern parts of the Country contributed to the low number of thunderstorm days.

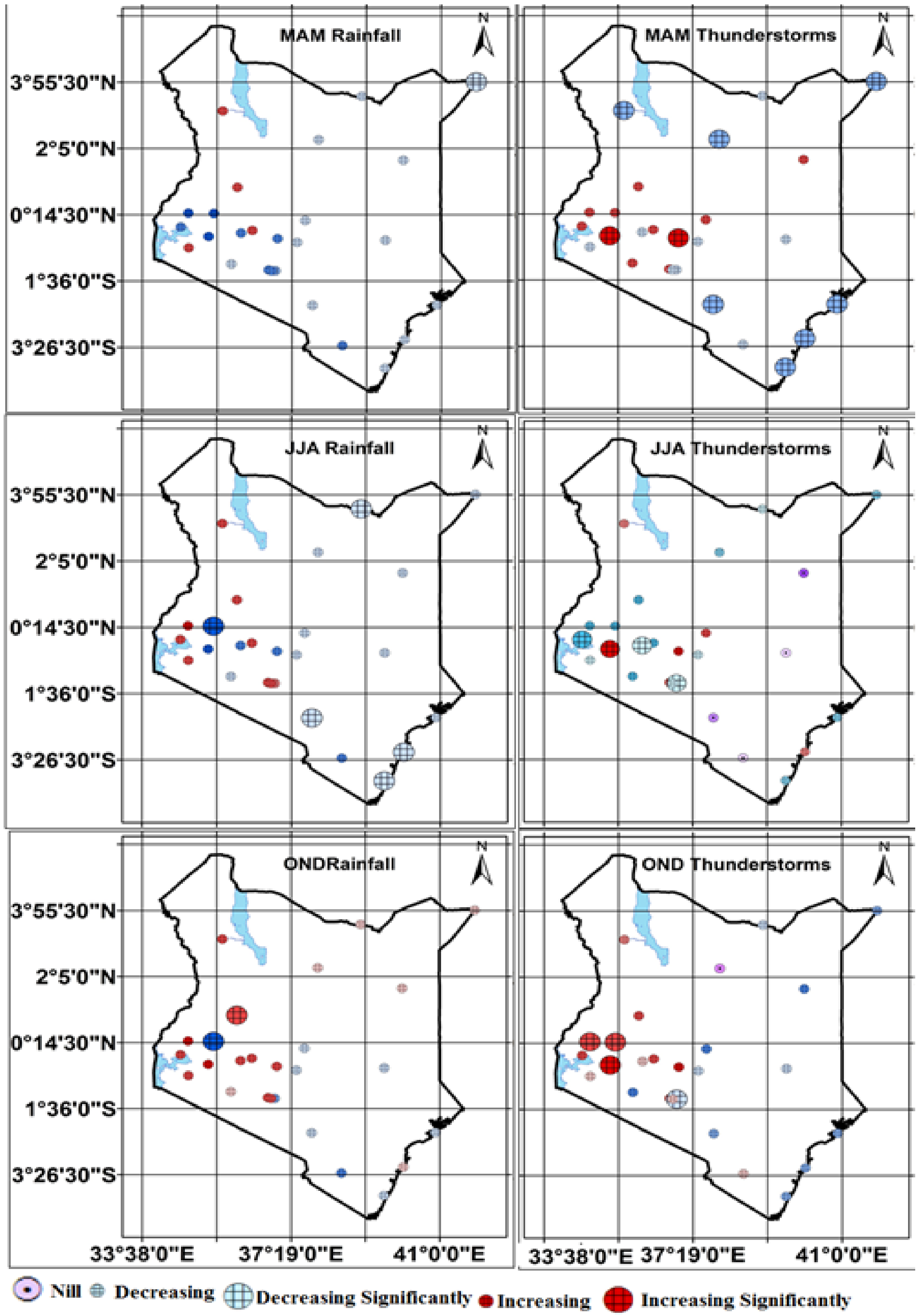

Figure **27**: Results for comparison of rainfall and Thunderstorms trends over various stations in Kenya during MAM, JJA and OND.

4.4 Thunderstorm Related Aircraft Incidents

Two aircraft incidents occurred in Kisumu International Airport, one on 19th February 2019 and the other on 26th March, 2019. These two incidences were used as case studies to illustrate the impacts of thunderstorms on aviation operations.

4.4.1 Flight Diversion on 19th February 2019

On this day, two flights 5H1409 and JMA8656, as described in Appendix 3, failed to land in Kisumu International Airport at 1630Z and 1700Z respectively. The flights were diverted back to Nairobi and returned later to Kisumu and landed safely at around 1915Z. A normal routine flight from Nairobi to Kisumu takes between 45-60 minutes depending on the aircraft.

4.4.1.1 Forecasted Conditions on 19th February, 2019

The general weather conditions which were expected on this day for flights taking off from Jomo Kenyatta International Airport to Kisumu International Airport were issued in the ROute FORecast (ROFOR) and the Terminal Aerodrome Forecast (TAF) for Kisumu.

From the ROFOR, the expected weather conditions were sunny intervals in the morning and showers with thunderstorms expected over few places in the afternoon, especially over the South Western part. The expected visibility in the morning was over 10 Kilometers with a few low clouds, as shown in appendix 1.

From the Kisumu TAF for that day, fine weather was expected in the morning. Development of cumulonimbus (CB) clouds was expected from 1500Z, the expected visibility was over 10 km throughout the forecast period (24 hours) with no significant weather expected for aviation operations, as is evidence in appendix 2.

4.4.1.2 Observed Weather Conditions on 19th February 2019

There were hourly meteorological observations recorded on the METAR book and plotted on Meteogram table for 19th February 2019. The day begun with calm conditions with cloud and visibility okay (CAVOK), as shown on Table 3. Cumulonimbus clouds were first reported at 0900Z and thunder was heard at around 1500Z.

The deep convective clouds continued building up, at 1700Z heavy showers accompanied by thunderstorms were reported and it caused reduced horizontal visibility of below 10km at around 1800Z. The different colours on the table signifies different parameters on a meteogram, a red line is used when cumulonimbus clouds are reported, green shading for rainfall and red shading for thunderstorms and rain.

Table 3: Observed weather conditions on 19th February 2019

TIME	**00-0400Z**	**0500-0700Z**	**0800Z**	**0900-1000Z**	**1100Z-1200Z**	**1300Z-1400Z**	**1500Z**
Observed Weather	9999 07006KT CAVOK	9999 CALM CAVOK	9999 19006KT FEW025 BKN280	9999 20011KT FEW027CB	9999 21018KT FEW028CB SCT029	9999 23018KT FEW027CB SCT028	9999 23015KT,-TS FEW025CB, SCT026, SCT100
1600Z	**1700Z**	**1800Z**	**1900Z**	**2000Z**	**2100Z**	**2200Z**	**2300Z**
9999 24011KT FEW025CB SCT026, SCT100	9999 TSRA 09009KT FEW018CB SCT019,BKN080	**9000 TSRA 31009KT FEW018CB SCT019**	9999 -RA 02004KT FEW018 BKN080	9999 -RA 06005KT SCT015 BKN080	9999 06007KT SCT018 BKN080	9999 07006KT FEW018 BKN080	9999 FEW018 BKN080 07005KT

The satellite image from infra-red channel (10.8µ) at 1245Z showed patches of deep convective clouds developing over the Lake Victoria Region which begun intensifying at 1545Z, as shown in Figure 28.

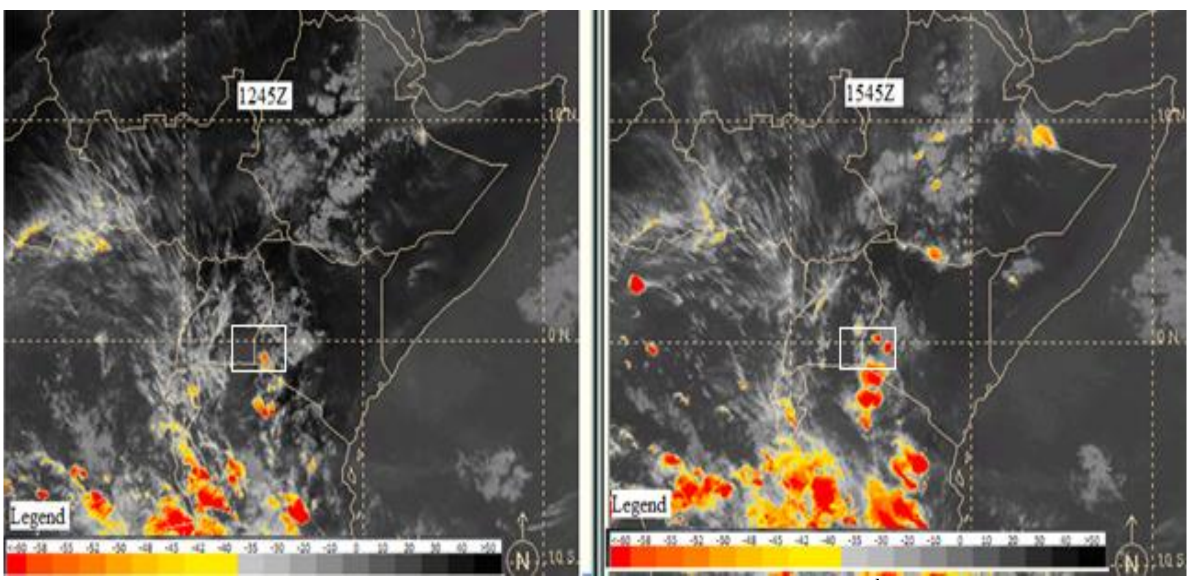

Figure 28: Satellite Pictures at 1245Z (left) and 1545Z (right) on 19th February 2019

At 1200Z, the observed relative humidity at the station was above 60%. Around 1800Z it had increased to over 90% in areas around the Lake Region, as shown in Figure 29. This was an indication that there was adequate availability of moisture for the formation of deep convective cloud.

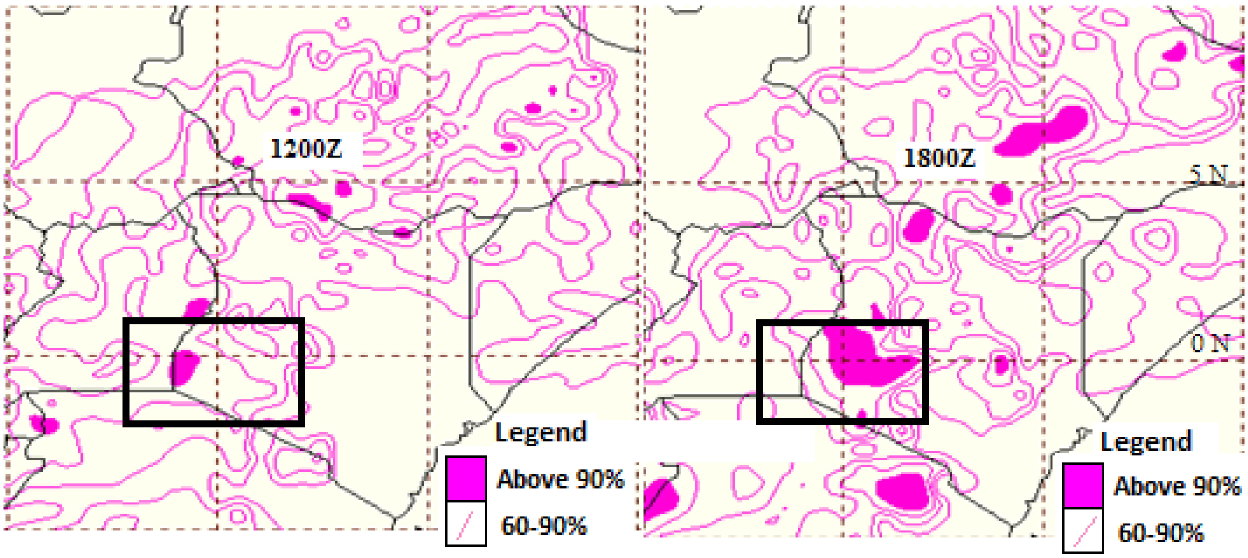

Figure 29: 700HPa Relative Humidity at 1200Z (left) and 1800Z (right) on 19th February 2019

The surface winds (850Hpa) observed were varying in direction and the speeds were reducing around the Highland West of Rift Valley and Lake Region, this implies that there were low-level convergence. At the upper levels (300HPa) the winds were mainly Easterlies with speeds above 4 m/s implying upper level divergence, as shown in Figure 30. Convergence is the heaping up of air above an area while divergence is the dispersal of air above some area. Convergence and divergence of air may result from changes in wind speed or wind direction (Ahrens, 2011).

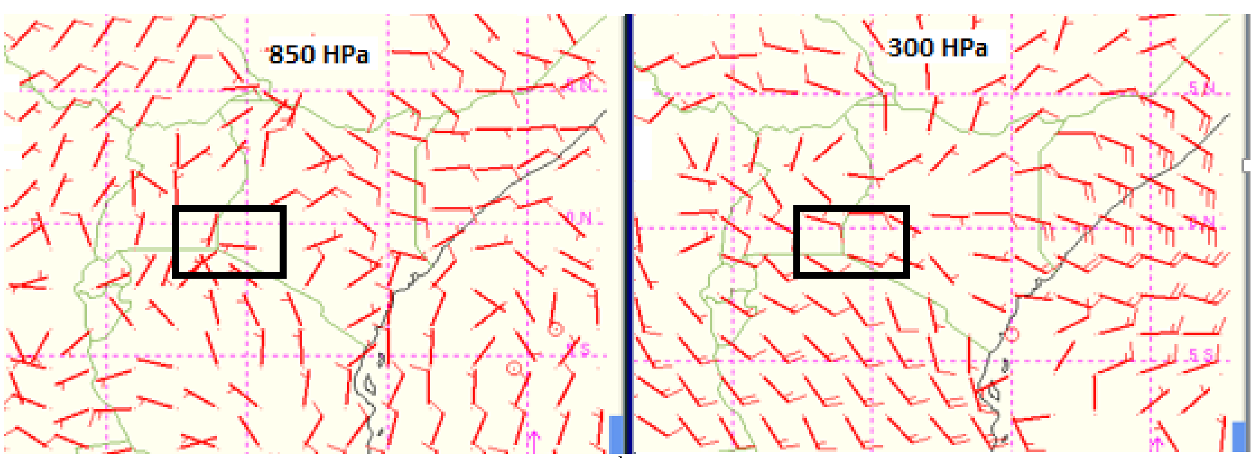

Figure 30: Surface and upper level winds on 19th February 2019 at 1200Z

The dry bulb temperature was 29.0 ^{o}C at 1200Z while the maximum temperature recorded was 30.9 ^{o}C. This showed that there was substantial insolation in Kisumu on that day. The convective available energy (CAPE) at 1200Z exceeded the threshold of 1700 joules/kg, this was likely to act as trigger for atmospheric instability hence a favourable condition for thunderstorm formation.

There were adequate amounts of moisture in the lower (< 3km) atmosphere, unstable air mass and a triggering mechanism to set off the convective activity, as shown in Table 4. The heating from below over the tropics and low level convergence boosted by sea breeze near the Lake Victoria basin caused convective instability in the atmosphere.

Table 4: Summary of the different weather conditions with their thresholds for thunderstorm formation on 19th February 2019

Weather Element	**Threshold**	**Observed**	**Remarks**
Moisture	Relative Humidity (700Hpa) above 80%	Over 90%	Adequate moisture achieved
Instability	CAPE (J/KG) 1-1500=positive, 1500-2500= Large, > 2500= Extreme	Over 1700 J/KG; positive	Adequate instability achieved
Convergence (850HPa)	Streamlines or changes in wind speed or wind direction (Ahrens, 2011).	Converging winds : indicated by reducing wind speed	Low level convergence and convection realized
Divergence (300Hpa)	Streamlines or changes in wind speed or wind direction (Ahrens, 2011).	Diverging: Easterly winds with a speed of over 4 m/s	Opening up of the atmosphere aloft was achieved
Trigger Mechanism	Surface temperature (<15.5=positive, 15.5-20.5=marginal, 21.1-26.1=fairly unstable, 26.6-31.6=very buoyant, 32.3-37.2=extremely buoyant, >37.7=incredibly buoyant) (Habby, 2000).	Maximum Temperature 30.9ºC; very buoyant atmosphere.	Greater instability of the atmosphere achieved resulting in lift of moisture

4.4.1.3 Comparison between Forecasted and Observed Weather Conditions on 19th February 2019

Table 5 presents the detailed analysis of the ROFOR. It showed that the forecast issued was generally timely and was able to capture the prevailing significant weather for that day.

Table 5: ROFOR versus observed weather conditions for Kisumu on 19th February 2019

ROFOR	TIME	FORECASTED	OBSERVED	REMARKS
SIGNIFICANT WEATHER	Morning	Sunny	NOSIG	The timing and forecast of significant weather was correct
	Afternoon	Showers/thunderstorms	Heavy showers/ thunderstorms	
SURFACE VISIBILITY	Morning	Over 10 km	Over 10 km	Correct in timing and range
	Afternoon	Less than 10 km	Less than 10 km	
LOWEST CLOUD LAYER AMOUNT AND TYPE	Validity period	FEW/SCT/BKN:CB/CU/SC	FEW/SCT: CB/CU/SC	Cloud type, amount and type was accurate
HIGHEST CLOUD LAYER AMOUNT AND TYPE	Validity period	SCT/BKN: AC	BKN: Ci	Medium cloud was not observed but high cloud was observed
LOWEST CLOUD HEIGHT (BASE TO TOP)	Validity period	1000 to 3000 ft.	1000 to 2800 ft.	The base of the cloud and extend was within the forecasted range.
HIGHEST CLOUD HEIGHT (BASE TO TOP)	Validity period	6000 to 14000 ft.	8000 TO 28000 ft.	The height was over forecasted

The results of the analysis of the TAF showed inaccuracy in predicting significant weather and timing; there was under forecasting and inaccurate timing of development of CB clouds as shown on Table 6.

Table 6: TAF versus observed weather conditions for Kisumu on 19th February 2019

TAF	TIME	FORECASTED	OBSERVED	HIT/MISS	REMARKS
SIGNIFICANT WEATHER	0300-0600 0600-0900 0900-1200 1200-1500 1500-1800	NOSIG NOSIG NOSIG CB CB	NOSIG CB CB TS +TSSHRA	HIT MISS MISS MISS MISS	The significant weather was under forecasted
SURFACE VISIBILITY	0300-0600 0600-0900 0900-1200 1200-1500 1500-1800	9999 9999 9999 9999 9999	9999 9999 9999 9999 Less than 10km	HIT HIT HIT HIT HIT	Accurate in time
LOWEST CLOUD LAYER/ AMOUNT AND TYPE	0300-0600 0600-0900 0900-1200 1200-1500 1500-1800	CAVOK CAVOK CAVOK CAVOK FEW022CB, BKNO23	CAVOK FEW027CB FEW028CB,SCT029 FEW025CB SCT026 FEW025CB,SCT019	HIT MISS MISS MISS HIT	The CB clouds developed earlier than expected
HIGHEST CLOUD LAYER/ AMOUNT AND TYPE	0300-0600 0600-0900 0900-1200 1200-1500 1500-1800	NIL NIL NIL NIL NIL	NIL BKN280 NIL NIL NIL	HIT MISS HIT HIT HIT	High clouds were observed
LOWEST CLOUD HEIGHT (BASE TO TOP)	0300-0600 0600-0900 0900-1200 1200-1500 1500-1800	Over 8000 ft. Over 8000 ft. 2800 ft. 2900 ft. 2200 ft.	Over 8000 ft. 2500 ft. 2700 ft. 2500 ft. 1800 ft.	HIT MISS HIT MISS MISS	The expected heights of low cloud was higher than the observed.
HIGHEST CLOUD HEIGHT (BASE TO TOP)	0300-0600 0600-0900 0900-1200 1200-1500 1500-1800	Nil Nil Nil Nil Nil	Nil 28000 ft. Nil Nil Nil	HIT MISS HIT HIT HIT	High clouds observed between 0600 and 0900
WIND DIRECTION (degrees)	0300-0600 0600-0900 0900-1200 1200-1500 1500-1800	000 VRB 200 200 090	010,320,000 000,180,190 200,200,210 220,230,240 230,240,090	HIT MISS HIT HIT	Between 0600 and 0900 the winds were southerlies
WIND SPEED (Knots)	0300-0600 0600-0900 0900-1200 1200-1500 1500-1800	00 05 10 10 05	03,04,00, 00,06,06 12,11,18 17,18,19 15,11,09	HIT HIT MISS MISS MISS	The speed of the wind was under forecasted. Between 1200Z and 1800Z

4.4.2 Failed Landing on 26th March 2019

On this day, JM8656 Jambo jet flight to Kisumu returns to JKIA after several attempts to land, between 1458Z and 1510Z. Jambo jet was the last flight expected to land and there after take-off from the airport at around 1545Z, as per the flight schedule. However, earlier flights had their normal landings as shown in Appendix 5.

4.4.2.1 Forecasted Conditions on 26th March 2019

Like is the routine, on the day of the incident both ROFOR and TAF for Kisumu Airport was issued. According to the ROFOR, the expected weather conditions in the morning were favorable for aviation operations; there was no significant weather, the horizontal surface visibility was over 10 kilometers and the winds were calm to moderate in speed. The afternoon weather was expected to be with showers and thunderstorms over few places, as per the tabular forecast shown in Appendix 4.

As per the TAF shown in appendix 5. The clouds and horizontal visibility were predicted to be okay in the morning; there were no low clouds that was <8000ft and the horizontal visibility was over 10 kilometres. At the time of the incident, the expected weather conditions included light thunderstorms and rain. Cumulonimbus clouds were predicted to develop between 0800Z and 1100Z.

4.4.2.2 Observed Weather Conditions on 26th March 2019

From the Meteorological Aviation Report (METAR) for that day, as shown in Table 7, heavy showers of rain which were accompanied by thunderstorms was reported between 1500Z and 1600Z in the station. Cumulonimbus clouds were observed from as early as 0400Z and the clouds had matured by 1200Z. Heavy showers of rain affects the aerodynamic effects of an aircraft. Reduced visibility were reported at 1600Z after thunder was heard and reported in the station.

Table 7: Meteorological Aviation Report for Kisumu on 26th March 2019

Time	**0000,0100Z**	**0200,0300Z**	**0400,0500Z**	**0600Z**	**0700Z**	**0800Z,0900 Z**	**1000-1100Z**	**1200Z**
Observed Weather	9999 CAVOK 04005KT	9999 00000KT CAVOK	9999 05004KT FEW019CB SCT260	9999 04003KT FEW023CB SCT260	9999 00000KT FEW025C B SCT260	9999 33005KT FEW027CB SCT090	9999 26010KT FEW028CB BKN090	-TS 24017KT FEW027CB BKN090
1300Z	**1400Z**	**1500-1600Z**	**1700-1800Z**	**1900Z**	**2000Z**	**2100Z**	**2200Z**	**2300Z**
9999 29009KT FEW026C B BKN090	9999 27011KT FEW022CB BKN090	TSRA FEW018CB BKN080 28011KT	9999 FEW018CB BKN080 06009KT	9999 FEW018CB 08006KT BKN080	9999 00000KT FEW018C B SCT080	9999 03004KT FEW18CB SCT080	9999 00000KT FEW018CB	9999 04005KT FEW018CB

The satellite image as at 1245Z showed red patches over the Lake Region, as shown in Figure 31. It indicates deep penetrating convection that causes severe weather, (Lensky and Rosenfeld, 2008).

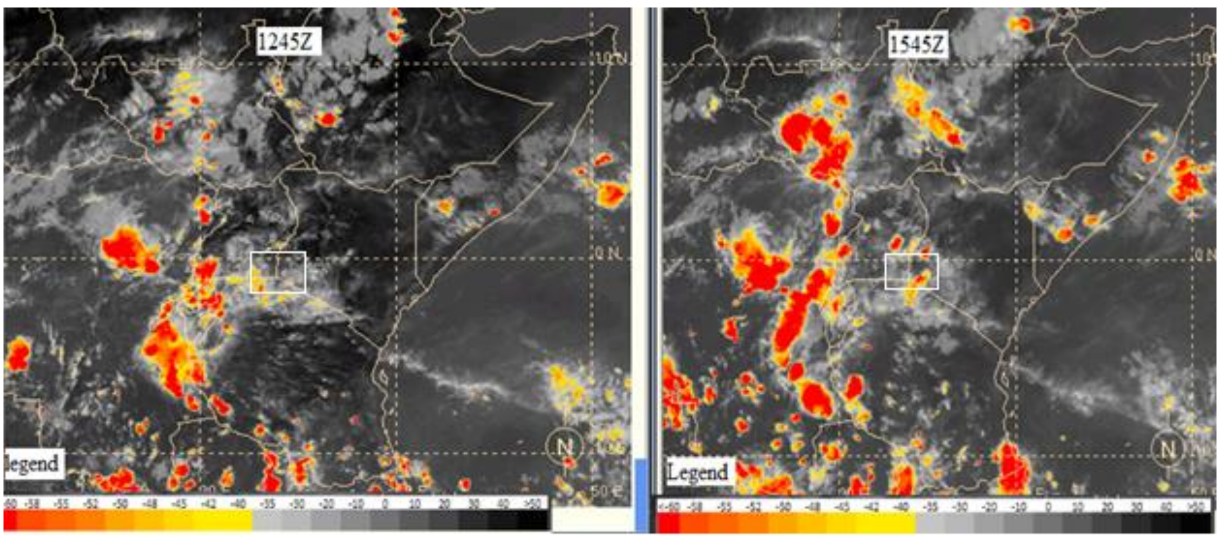

Figure 31: Satellite image on 26/03/2019 at 1245Z (left) and 1545Z (right) from RGB 10.8 µm infrared channel

The available amount of moisture was adequate for development of deep convective clouds when other factors were held constant. By 1200Z, RH of greater than 60% was achieved, as shown in Figure 32.

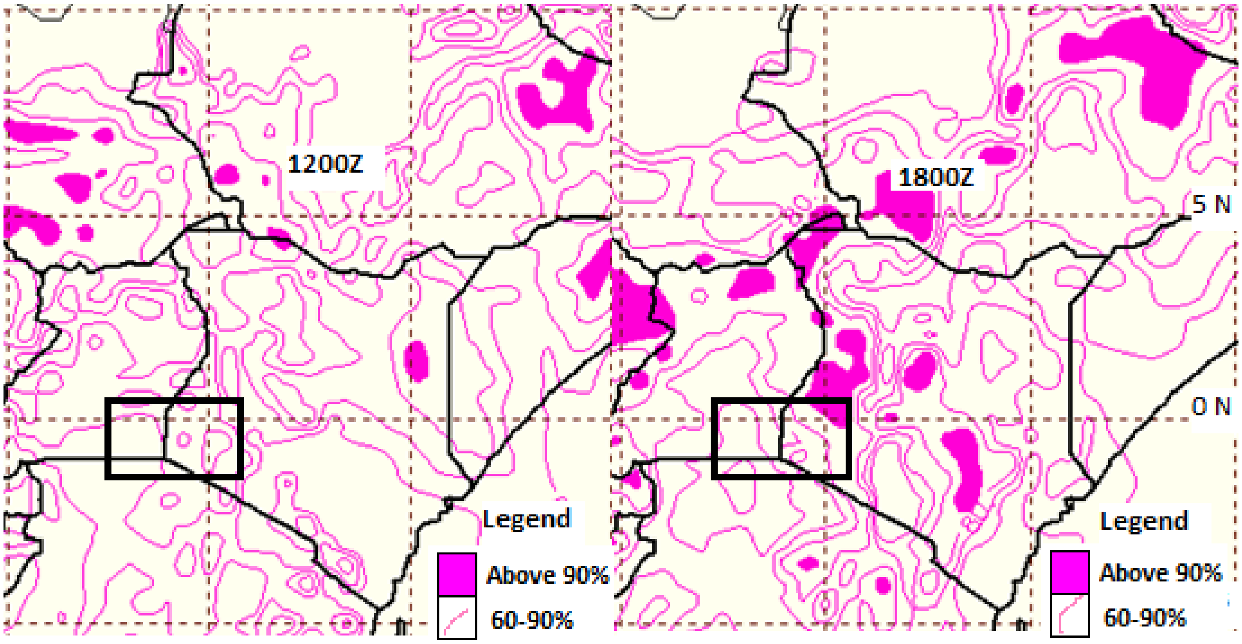

Figure 32: 700hpa Relative humidity at 1200Z and 1800Z on 26th March 2019

Convergence at the surface was observed over the Lake Victoria region as indicated by the converging and low wind speeds (left 850hpa map) while there was divergence aloft (right 300hpa), as shown in Figure 33. This caused enhanced convection and thus the formation of deep convective clouds which sire thunderstorms.

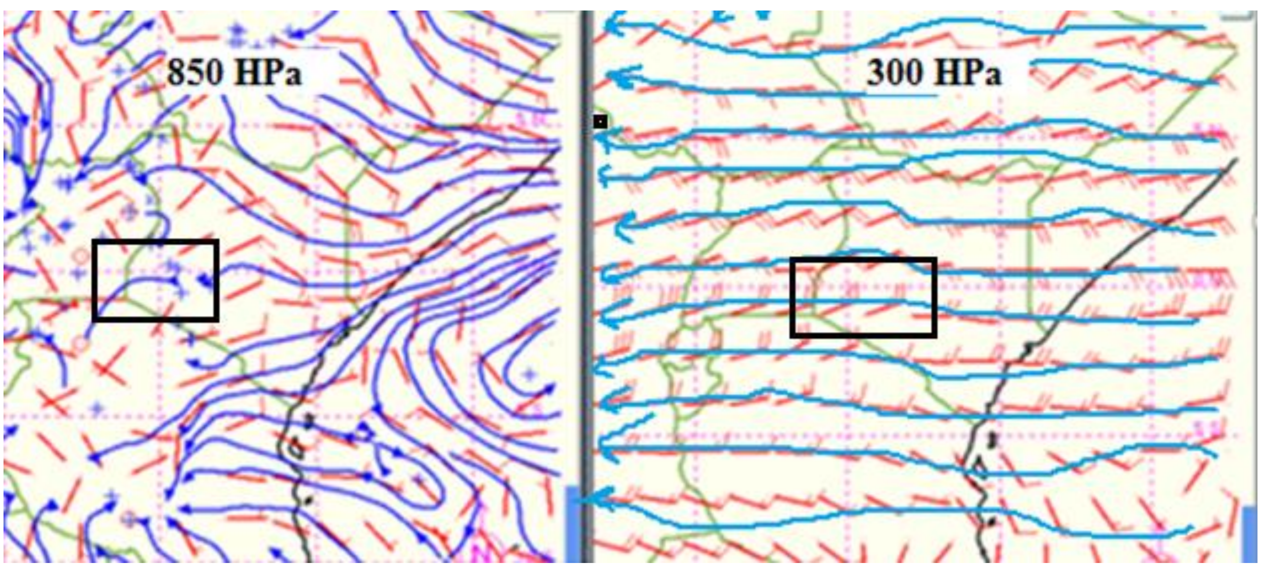

Figure 33: Winds at 850Hpa (left) and 300Hpa (right) on 26th March 2019

The dry bulb temperature was 24.8 and 29.8^{0} C at 0600Z and 1200Z respectively while the maximum was 30.9 ^{0} C. The convective available energy (CAPE) at 1200Z had exceeded the threshold 0f 1400 joules/kg. This was likely to cause the instability of the atmosphere hence, a favourable condition for thunderstorm formation.

Over the Lake Region, the conditions for thunderstorm formation were favorable throughout the day. There were adequate amount of moisture, convergence at the surface and low level heating which triggered the development of deep convective clouds. For each weather element essential for thunderstorm formation, the thresholds were achieved, as shown on Table 8. Temperature and air density are inversely proportional. The greater the heating is during the day, the greater the instability of the atmosphere. Days with sunshine will be more convectively unstable than days with continuous cloud cover.

Table 8: Summary of the different weather conditions with their thresholds for thunderstorm formation for 26th March 2019 over Kisumu airport station

Weather Element	Threshold	Observed	Remarks
Moisture	Relative Humidity (700Hpa) above 80%	Over 80%	Adequate moisture achieved
Instability	CAPE (J/KG) 1-1500=positive, 1500-2500= Large, > 2500= Extreme	Over 1400 J/KG; positive	Achieved
Convergence (850HPa)	Streamlines or changes in wind speed or wind direction (Ahrens, 2011).	Converging : indicated by reducing wind speed below 1 m/s and varying direction	Low level convergence and convection realized
Divergence (300Hpa)	Streamlines or changes in wind speed or wind direction (Ahrens, 2011).	Diverging: Easterly winds with a speed above 12.5 m/s	Opening up of the atmosphere aloft was achieved
Trigger Mechanism	Surface temperature (^{o} C) (<15.5=positive, 15.5-20.5=marginal, 21.1-26.1=fairly unstable, 26.6-31.6=very buoyant, 32.3-37.2=extremely buoyant, >37.7=incredibly buoyant) from weather prediction manual, 2000.	Maximum Temperature 30.9^{o}C; very buoyant	Greater instability of the atmosphere achieved resulting in lift of moisture

4.4.2.3 Comparison between the Forecasted and Observed Weather Conditions on 26th March 2019

The analysis of forecast accuracy was determined by comparing the forecasted weather with the observed conditions; checking the accuracy in time, type of weather and the horizontal visibility. Higher levels of accuracy level was observed in the ROFOR than in the TAF, as shown on Table 9.

Table 9: ROFOR versus the observed weather conditions for Kisumu Airport on 26th March 2019

ROFOR	TIME	FORECASTED	OBSERVED	REMARKS
SIGNIFICANT WEATHER	morning	Rains	NOSIG	Correct timing and significant weather.
	Afternoon	Showers/ thunderstorms	Showers/thunderstorms	
SURFACE VISIBILITY	Morning	9999	9999	The Range was within the forecasted
	Afternoon	Less than 10 km	Less than 10 km	
LOW CLOUD LAYER AMOUNT AND TYPE	Validity period	FEW/SCT/BKN:CB/CU/SC	FEW019CB	Type of cloud forecasted was correct
HIGH CLOUD LAYER AMOUNT AND TYPE	Validity period	SCT/BKN:AC	BKN080,AC	Type of cloud forecasted was observed
LOWEST CLOUD HEIGHT (BASE TO TOP)	Validity period	1000-3000 ft.	1800 FT.	The height observed was within the forecasted range
HIGH CLOUD HEIGHT (BASE TO TOP)	Validity period	6000-14000 ft.	8000 FT.	The height observed was within the forecasted range

The TAF forecast for this day failed to capture most of the conditions which were observed. There was both under forecasting and poor estimation of the time of the event, as shown in Table 10.

Table 10: TAF versus observed weather conditions for Kisumu on 26th March 2019

TAF	TIME	FORECASTED	OBSERVED	HIT/ MISS	REMARKS
SIGNIFICANT WEATHER	0300-0600 0600-0900 0900-1200 1200-1500 1500-1800	NOSIG CB CB -TSRA -TSRA	CB CB TS CB +TSRASH	MISS HIT MISS HIT MISS	The CB clouds developed earlier than expected
SURFACE VISIBILITY	0300-0600 0600-0900 0900-1200 1200-1500 1500-1800	9999 9999 9999 9999 9999	9999 9999 9999 9999 LESS THAN 10 KM	HIT HIT HIT HIT MISS	Visibility reduces during mature stage of Thunderstorms
LOW CLOUD LAYER/ AMOUNT AND TYPE	0300-0600 0600-0900 0900-1200 1200-1500 1500-1800	CAVOK CAVOK FEW026CB FEW023CB,BKN024 FEW023CB,BKN024	CAVOK FEW023CB FEW027CB FEW026CB, FEW018CB	HIT MISS HIT HIT MISS	Under forecasting of significant weather
HIGH CLOUD LAYER/ AMOUNT AND TYPE	0300-0600 0600-0900 0900-1200 1200-1500 1500-1800	NIL NIL NIL BKN080 AC BKN080 AC	NIL NIL NIL BKN090,AC BKN090,AC	HIT HIT HIT HIT HIT	Correct in timing and type of weather
LOW CLOUD HEIGHT (BASE TO TOP)	0300-0600 0600-0900 0900-1200 1200-1500 1500-1800	OVER 8000 FT. OVER 8000 FT. 2600 FT 2300 FT. 2300 FT.	1900 FT. 2300 FT. 2700 FT. 2600 FT. 1800 FT.	MISS MISS HIT HIT MISS	Under forecasting of cloud heights
HIGH CLOUD HEIGHT (BASE TO TOP)	0300-0600 0600-0900 0900-1200 1200-1500 1500-1800	NIL NIL NIL NIL 8000 FT.	NIL NIL NIL NIL 8000 FT	HIT HIT HIT HIT HIT	The clouds observed were within the forecasted range
WIND DIRECTION (degrees)	0300-0600 0600-0900 0900-1200 1200-1500 1500-1800	VRB VRB 230 VRB VRB	360 040 330 280 060	MISS MISS MISS MISS MISS	The direction was not variable at the time of observation
WIND SPEED (Knots)	0300-0600 0600-0900 0900-1200 1200-1500 1500-1800	05 05 10 10 10	04 05 05 09 11	HIT HIT MISS HIT HIT	Between 0900-1200 the speed observed was lesser than the predicted

4.4.3 Summary of the two incidents on 19th February 2019 and 26th March 2019

The observed weather in Kisumu International Airport, during the time of the incidents affected flights which were scheduled to land after 1400Z. Flights which were scheduled to land before that time had their normal landings and take-offs, see Appendix 3 and 6.

On both occasions, the development of cumulonimbus clouds that lead to the bad weather which was observed during the time of landing were recorded early in the day at about 0500Z. However, the forecast missed the anticipated time of development of the same clouds. According to Kisumu METAR report on 19th February 2019, heavy showers and thunderstorms were observed during the time of scheduled landing while in the Kisumu TAF the forecast covering the same time expected cumulonimbus clouds. In this case, it under forecasted the significant weather which was observed at the time of the incident. In addition, TAF amendment was not issued, is a requirement when there is a possibility of thunderstorms occurrence.

Some of the factors which leads to inaccuracy in TAFs preparation are, poor understanding of the climatology of the forecast area, inadequate forecasting tools (like meteograms, weather prediction models, Tephigram, satellite imagery, weather radar) and limited capacity of forecasting individual.

Using an average estimated cost adopted from previous studies (Muiruri, 2011) of $ 100,000 per diversion, the resultant cost of the three diversions was approximately $ 300,000. Based on the case study, the cost was potentially avoidable. Similar studies by Klein *et al.* (2009) concluded that up to 60% of weather-related delays are potentially avoidable, and the avoidable portion is typically related to the accuracy of a weather forecast.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

In this chapter, major conclusions drawn from the study based on the set objectives are provided. Some recommendations and suggestions for future studies are also provided.

5.1 Conclusions

The main objective of the study was to evaluate the forecast of the recent thunderstorm- related aviation incidences over the Kenyan airspace. This was achieved through three specific objectives which included the review of thunderstorm climatology over Kenya, determination and comparison of thunderstorm days with rainfall occurrence in Kenya and the analysis of the possible causes of recent aviation operation incidences over western Kenya.

The results obtained confirms that higher concentrations of thunderstorms are to the West and over the Highland parts of the Country; areas around the Lake Victoria which acts as a source of moisture for thunderstorm formation. The Coastal and North Eastern regions reported the lowest frequencies of thunderstorms, this is because of lack of moisture over the North Eastern region and the low elevation for formation of deep convective clouds over the Coast region.

Thunderstorm days' occurrence can be broadly classified as either bi-modal or quasi uni-modal in Kenya. The bi-modal thunderstorm occurrence pattern was mainly observed over the Eastern, Central and Coast regions and mostly coincides with the March-April-May (MAM) and October-November-December (OND) rainfall season. The quasi unimodal thunderstorm occurrence pattern was observed over the Highland West of Rift valley and the Lake Victoria region. These areas reported almost equal number of thunderstorm days from the month of March to December.

Both significant and non-significant thunderstorm and rainfall trends were observed during all the three seasons. For rainfall, both MAM and JJA season had decreasing trends over most stations. However, the decrease for MAM season was not statistically significant. OND season showed increasing trend over most stations, though it was not significant. For thunderstorms, a reducing significant trend was observed over most stations during MAM season. In JJA season, most stations over the eastern half of the country observed nil thunderstorms while the western half had reducing significant trends for thunderstorms. During the OND season, most stations had increasing significant trends. In contrast, the stations around the Lake Victoria region mainly had an increasing trend during MAM and OND seasons. Kericho was one of the station whose trends of thunderstorms were increasing significantly throughout all the seasons. The mesocale effects of Lake Victoria, the orographic effects of the Mau hills combined with enhanced thermal heating along the tropical areas is a source of instability. Deep convective clouds develop and form thunderstorms.

The case study has shown that thunderstorm is a phenomena which affects flight operations at Kisumu International Airport. The affected aircrafts were those which were scheduled to land in the late afternoon. This showed that most thunderstorm related cases were likely to occur in the afternoon.

The results of the analysis of the TAF showed inaccuracy in predicting significant weather type and the timing. There was under forecasting and inaccurate timing of development of CB clouds. This is despite the provision for updating the forecast through TAF amendment in its course of validity.

Improved TAF accuracy results from capacity development, improved model outputs, availability of forecasting tools, further research and development, installation of weather radars and forecast monitoring and verification. It will contribute to significant financial savings given the relative cost of a diversion or failed landing.

5.2 Recommendations

From the results obtained and conclusion drawn from this study, the following recommendations are made to different sectors.

5.2.1 To the Researchers

This study focused on re-evaluating the recent thunderstorms climatology in Kenya, a comparison with rainfall occurrence was done. The results were interesting, thus there is a need, to replicate this research to other thunderstorm-related parameters like temperature. A study can also be done to determine the trends of thunderstorm intensities for a given area.

The hourly reports from the METAR books can be used to obtain the diurnal frequency of thunderstorm in a station.

The effects of thunderstorms to aviation operations was done through a case study in western Kenya, since two case studies consisting of three aircrafts were considered. There is need to investigate more incidents and replicate this study in different airports. This will be a good contribution towards aviation disaster risk reduction.

5.2.2 To the Kenya Meteorological Department

The Department is commented for keeping the hard copies of the data securely for many years. Though it was tedious extracting the monthly thunderstorm data from the SYNOP books, it provided substantial data for this research. The KMD should then ensure that the data is digitized to save time spent on extraction from the books, this will also encourage other researchers to carry out research on this phenomena.

For verification purposes, KMD should improvise ways of archiving all forecasts. The model from which forecasts were accessible could only permit retrieval of data up to a maximum of two weeks. This is unlike observations data which were archived for many years. This study found out that it was crucial to evaluate forecasts, especially the TAFs in order to improve their accuracy in time.

There is also a need for continuous capacity building, staff competency and quality standards in all the aeronautical stations should be priority. Currently, JKIA watch office generate TAFs for Kisumu, Wilson and Eldoret airports. This is due to shortage of staff and limited availability of forecasting tools in these airports. Therefore, KMD should provide forecasting tools in all airports to enable each station generate their own TAFs, recruit more meteorologists and deploy additional forecasters to the other airports. The understanding of climatology and continuous monitoring of weather developments through observations also builds the skills of a forecaster.

5.2.3 To the Aviation Sector

The users of aviation forecasts should at all times give feedback to the producers of the forecasts. This can be through the Pilot Reports (PIREP) or the Air Reports (AIREPs).

Feedback is important for forecast evaluation. Set points should be clearly indicated for collecting feedback at all airports for pilots to drop their reports. Occasionally, seminars and workshops should be organized for the forecasters and their clients. This is another way of exchanging information and getting feedback.

REFERENCES

Airbus, 2002: Flight operations support and Line Assistance.*Getting to grips with aircraft performance,* SCM-A226.

Ahrens, C.D.2011: Essentials of Meteorology: An invitation to the Atmosphere, 6th edition.

Alusa A.L., 1986: Some Characteristics of hail-storms in Kericho, Kenya. Res.rep.no.2/86 Kenya Meteor. Dept. Nairobi, Kenya, 47 pp.

Alam J.B., Shikder H.S., Goulias G., 2003: The role of Transportation in Regional Economic Efficiency in Bangladesh. A Data Envelopment Analysis, *A MAUTC Technical Communication, TEC -01, University Park,* PA 16802.

Asnani G. C., 2005: Tropical Meteorology. Published by Prof. G. C. Asnani. Pune India. vol.**2**, 10-168.

Ayugi B., Wang W., Daisy C., 2016: Analysis for Spatial and Temporal Patterns of Rainfall Variations over Kenya. *Environmental Earth Sci. Journ*. Vol **6**, 69-83.

Buck, R.N and Buck R.O., 2013: Weather Flying, 5th ed. *MCGRAW HILL, and U.S.A*

Blanchard, D.O., 1998: Assessing the vertical distribution of convective available potential energy. *Weather, Forecasting*, **13,** 870-877.

Braham R.R., and Byers H.R., US Thunderstorm Project, 1949: The Thunderstorm project pp.17-77,115-119, 133-141, U.S *Government printing Office.*

Chaggar, T.S., 1977: Geographical Distribution of Monthly and Annual mean frequency of Thunderstorm days over Eastern Africa. EAMD Tech. Memo. No.26.

Changnon, S. A., 1981: Possible effects of contrail generated cirrus on mid-western cloud and sunshine. *J. Appl. Meteor.,* **20**, pp. 8.

Changnon S.A., Chin F.H., 1984: Temporal Distributions of Global Thunder Days, *Final Report NSF ATM-81-14724.*

Changnon S.A. & Changnon D. 2001. Long-term fluctuations in the thunderstorm activity in the United States. *Climatic Change* **50**: 489–503.

Chapin, F.S.; Eugster, W.; McFadden, J.P.; Lynch, A.H.; and Walker, D.A., 1998 summer differences among arctic ecosystems in regional climate forcing. *J. Climate*, **13**, 2002-2010.

Civil Aviation Act, 2007: The Civil Aviation (Airworthiness) Regulations. *Kenya Subsidiary Legislation*, Civil Aviation Act (Cap. 394).

Enete I.C., Ajator U., and Nwoko K.C., 2015: Impacts of Thunderstorm on Light Operations in Port-Harcourt International Airport Omagwa, River state, Nigeria. *International Journal of Weather, Climate Change and Conservation Research* **Vol.1**, No.1, 1-10.

Eugster, W.; Rouse, W.R.; Pielke, R.A.; McFadden, J.P.; Baldocchi, D.D.; Kittel, T.G.F.; Chapin, F.S.; Liston, G.L.; Vidale, P.L.; Vaganov, E.; and Chambers, S., 1998: Northern ecosystems and land-atmosphere energy exchange in arctic tundra and boreal forest: available data and feedbacks to climate. *Global Change Biology*, **6,** 84-115.

Enno S.E., Piia P., Agrita B., Inga S., 2014: Long-term changes in the frequency of thunder days in the Baltic countries. *Boreal Environmental Research.* **19** (5-6), 452-466.

Galway, 1956: The Lifted Index as a predictor of Latent Instability. *Bulletin of the American Meteorological Society,* **37**:528-529.

Gitau W., Camberlin P., Ogallo L., Bosire E., 2018: Trends of intraseasonal descriptors of wet and dry spells over Equatorial eastern Africa. *int. j. climatol.* **38***:* 1189–1200.

Grice, G.K. and Comisky, A.L., 1976. Thunderstorm climatology of Alaska. NOAA technical memorandum NWS AR-14, *Weather Service Regional Headquarters Anchorage* (dostep: http:// docs.lib.noaa.gov/noaa_documents/NWS/TM_NWS_AR_14.PDF).

Hoell A, Hoerling M, Eischeid J, Quan XW, Liebmann B. 2017: Reconciling theories for human and natural attribution of recent East Africa drying. *J. Clim.* **30**: 1939–1957.

ICAO (International Civil Aviation Organization), 2001: *International Standards and Recommended Practices. Annex 13 to the Convection on International Civil Aviation Aircraft Accident and Incident Investigation.*

Jagero, F., 2018: Numerical Model and Forecasting Potential of Aircraft Weather Hazards over Kenya. *International Journal of Civil Aviation*, Vol. **2**, no.1 1237-1356.

Habby, J., 2000: Weather Prediction Manual; www. *theweatherprediction.com, Denvor, Colarado.*

Kansiime MK, Wambugu SK, Shisanya CA. 2013: Perceived and actual rainfall trends and variability in eastern Uganda: implications for community preparedness and response. *J. Nat. Sci. Res.* **3**(8): 179–194.

Kendall, M.A., (1961): The advance theory of statistics. *Design and analysis time series London*. Charles Griff and Co. Ltd.

Kinuthia, J. H. and Asnani, G.C., 1982: A newly found jet in North Kenya (Turkana channel). *Mon. Wea. Rev*.**110**, 1722-1728.

Klein, A., Kavoussi, and Lee, R.S., 2009: *Weather forecast accuracy: study of impact on airport capacity and estimation of avoidable costs*, Paper presented to the eighth USA/Europe Air Traffic Management Research and Development.

Koech, E., 2014: Systems associated with wet spells over Kenya during the usually dry December-February season. *MSc dissertation, Department of Meteorology University of Nairobi.*

Koros, D., 2014: Determining convective precipitation using cold cloud top temperatures and its impact on aviation industry over western Kenya. *MSc. Dissertation, Department of Meteorology, University of Nairobi, 57pp.*

Kulesa, G., 2003: Weather and Aviation: How does Weather affect the Safety and Operations of Airports and Aviation? The impacts of climate change on transportation, Washington, D.C., U.S.A, **Accession Number:** 00962776. http://climate.dot.gov/documents/workshop1002/kulesa.pdf

Kuleshov, Y., G. de Hoedt, W. Wright, and A. Brewster 2002: Thunderstorm distribution and frequency in Australia, *Austral. Meteorol. Mag.* **51**, 145-154.

Kuleshov, Y., D. Mackerras, and M. Darveniza 2006: Spatial distribution and frequency of lightning activity and lightning flash density maps for Australia. *J. Geophys. Res.*, **111**, D19105, doi: 10.1029/2005JD006982.

Lafleur, P.M. and Rouse, W.R, 1995: Energy partitioning at tree line forest and tundra sites and its sensitivity to climate change. *Atmosphere-Ocean*, Vol.**33,** 121-133.

Lara, P., 2015: The impacts of Weather on Aviation Delays at O.R. Tambo International Airport, South Africa. *Department of Geography, University of South Africa*, MSC Project Report. 110pp.

Leigh, R.J., Drake, L. and Thampapillai, D.J., 1997: An economic analysis of terminal aerodrome forecasts with special reference to Sydney Airport, *Journal of Transport Economics and Policy*, **32**: 377-392.

Lensky, I., and Rosenfeld D., 2008: Clouds-Aerosols-Precipitation Satellite Analysis Tool (CAPSAT). *Atmospheric Chemistry and Physics*. **8**, 6739-6753.

Liebmann, B., Hoerling, M.P., Funk, C., Bladé, I., Dole, R.M., Allured, D., Quan, X., Pegion P., Eischeid, J.K., 2014: Understanding recent eastern horn of Africa rainfall variability and change. *J. Clim.* **27**: 8630–8645.

Lin, R., Zhou, T., and Qian, Y., 2014: Evaluation of Global Monsoon Precipitation Changes based on Five Reanalysis Datasets. *American Meteorological Society*. **27**, 1271-1289.

Lyon B, DeWitt DG. 2012: A recent and abrupt decline in the East African long rains. *Geophys. Res. Lett.* **39**: L02702. https://doi.org/10.1029/ 2011GL050337.

Mahapatra P.R., 1991: Sensors and Systems to enhance Aviation Safety against Weather Hazards. *Proceedings of the Institute of Electrical and Electronics Engineers (IEEE)*, **79** (9): 1234-1267.

Maloba S., 2015: Spatial and Temporal Characteristics of Thunderstorms over the Eastern Region of Lake Victoria Basin in Kenya. *MSC Dissertation, Department of Meteorology, University of Nairobi*, 77pp.

McLeod, A.I., Hipel, K. W. and Bodo, B.A. (1990): Trend analysis methodology for water quality time series. *Envirometrics*, **2**, 169-200.

Muiruri S., 2011: Assessment of Adverse Weather on the operation of Air Transport at JKIA and Wilson Airport. *MSc. Dissertation, Department of Meteorology, University of Nairobi*, 44pp.

Mukabana, J. R. and Pielke, R. A. 1996: Investigating the influence of synoptic scale monsoonal winds and meso-scale circulations on diurnal weather patterns over Kenya using meso-scale numerical model. *Monthly Weather Review*, **124**,222-243

Murakami, T., and Sumathipala, W.L. 1989: Westerly bursts during the 1982/83 ENSO, *J. Climate*, **2**, 71-85.

Murray J.J., 2002: Aviation Weather applications of Earth Science Enterprise data. *Earth Observing Magazine*. Vol. **11**, No. 8, 26-30.

Nakamara, K., 1968: Equatorial Westerlies over East Africa and their climatological significance. *Tokyo Metropolitan Univ.*, **3**, 43-61.

Ngaina, J.N., 2015: Modelling Aerosol- Cloud Precipitation Interactions for Weather Modification in East Africa. *Ph.D. Dissertation. Department of Meteorology. University of Nairobi.*

Obiero, K., 2013: Thunderstorm hazards and their impact in the Lake Victoria basin of Kenya. *MSc. Thesis, Department of Geography, Kenyatta University*.

Okoola, R. E., (1999). Mid-tropospheric Circulation Patterns Associated with Extreme Dry and Wet Episodes over Equatorial Eastern Africa during the Northern Hemisphere Spring. *J. of App. Meteo,* **38**, 1161-1169.

Okoola, R.E., 2005: Transition from the Southern to the Northern Hemisphere summer of zones of active convection over the Congo Basin. *Meteorology and Atmospheric Physics*, ***84***, 255-265.

Opiyo F., Nyangito M., O.V. Wasonga and P. Omondi, 2014: Trend Analysis of Rainfall and Temperature Variability in Arid Environment of Turkana, Kenya. *Environmental Research Journal,* **8***: 30-43.*

Oxford Economics, 2011: Economics Benefits from Air Transport In Kenya. *Kenya country report. Oxford Economics*

Pejovic, T., 2009: A Tentative Analysis of the Impacts of an Airport Closure, *Journal of Air Transport Management,* **15**: 241-248.

Pielke, R.A. and Vidale, P.L., 1995: The Boreal Forest and the Polar Front. *Journal of Geophysical Research,* Vol. **100** No. d12, **25**,755-758.

Ranter, H. 2006: Airliner accident statistics 2005. Statistical summary of fatal multi-engine airliner accidents in 2005. *Aviation Safety Network*. http://aviation-safety.net/pubs/. pp.**25**.

Remi, I.F., 1987: Airplane crashes in Port-Harcourt Retrieved from: http//www.aircrashesnig.com. 1-4.

Rowell DP, Booth BBB, Nicholson SE, Good P. 2015. Reconciling past and future rainfall trends over East Africa. *J. Clim.* **28**: 9768–9788.

Sakwa, V. N., (2006). Assessment of the Skill of the High Resolution Regional Model in the Simulation of Airflow and Rainfall over East Africa. *MSc. dissertation, University of Nairobi.*

Sasse, M. and Hauf, T., 2003: A Study of Thunderstorm induced Delays at Frankfurt Airport, Germany, *Meteorological Applications,* **10** (1): 21-30.

Schroeder, M.J. and Buch, C.C., 1970: Fire Weather. Agriculture Handbook 360, U.S. *Department of Agriculture*, *Forest Service*, May 1970.

Stake, R. E. (1995). The art of case study research. Thousand Oaks, CA, US: Sage publication, Inc.

Uman, M.A and Rakov, V.A 2003: The interaction of lightning with airborne vehicles. *Prog. Aerosp*. Sci., **39,** 61-81.

Viste E, Korecha D, Sorteberg A. 2013. Recent drought and precipitation tendencies in Ethiopia. *Theor. Appl. Climatol.* **112**: 535–551.

Wan, T. and Wu, S.W., 2004: Aerodynamic analysis under the influence of heavy rain, *Journal of Aeronautics, Astronautics, and aviation*, vol. **41**, No.3, 173-180.

Williams, E.R. 1995: Meteorological aspects of thunderstorms, in Handbook of Atmospheric Electrodynamics, edited by H. Volland, pp. 27-60, CRC Press, London, UK.

Williams AP, Funk C. 2011: A westward extension of the warm pool leads to a westward extension of the Walker circulation, drying eastern Africa. *Clim. Dyn.* **37**: 2417–2435.

Wu, C, 2005: Inherent delays and operational reliability of airline schedule. *Journal of Air Transport Management,* Volume **11**, Issue 4, 273-282.

WMO, 1992: International Meteorological Vocabulary, WMO/OMM/BMO –NO. 182.

Yin, R. K. (2003). Case study research: Design and methods .3rd Edition. *Thousand Oaks, Calif.: Sage Publications,* - Applied social research methods series; v. **5.**

APPENDICES

Appendix 1: Route Forecast Issued on by KMD on 19th February 2019

ROUTE: HKNW/HKJK TO HKNW/HKJK VIA HKKI, HKKG, HKEL, HUEN, HKKT, HKNO, HKLO
VALID FOR DEPARTURE:19/02/2019 0300 UTC VALID FOR ARRIVAL: 19/02/2019 1800 UTC
WEATHER: Sunny intervals expected in the morning. Showers and thunderstorms expected over few places in the afternoon especially over South Western parts.
HIGHEST CLOUD LAYER AMOUNT AND TYPE … SCT/BKN: AC
CLOUD HEIGHT (BASE TO TOP)- 060-140
LOWEST CLOUD LAYER AMOUNT AND TYPE… FEW/SCT/BKN:CB/CU/SC
CLOUD HEIGHT (BASE TO TOP) 010- 030
SURFACE VISIBILITY: OVER 10KMS UNLESS IN FOG, RAINS, SHOWERS AND THUNDERSTORMS
PRESSURE ALTITUDE OF 0º OF ISOTHERM FL 150
FL050 12010KT
FL070 09015KT
FL100 08020KT
FL140 13020KT
FL180 09040KT
FL240 07030KT
LOWEST MEAN SEA LEVEL PRESSURE (MB)

Appendix 2: Terminal Aerodrome Forecast issued at 4 different times for 19th Feb. 2019

FTKN32 HKJK 182300 TAF HKKI 182300Z 1900/2000 00000KT CAVOK BECMG 1906/1909 VRB05KT BECMG 1909/1912 20010KT BECMG 1915/1918 09005KT FEW022CB BKN023 BECMG 1921/2000 08005KT BKN019=
FTKN32 HKJK 191117 TAF HKKI 191100Z 1912/2012 24010KT 9999 FEW028 TEMPO 1912/1918 FEW029CB BECMG 1920/2004 24005KT CAVOK BECMG 2003/2006 24010KT 9999 FEW024CB=
FTKN32 HKJK 191636 TAF HKKI 191700Z 1918/2018 24010KT 9999 FEW024 BECMG 1920/2004 24005KT CAVOK BECMG 2003/2006 24010KT 9999 FEW024CB TEMPO 2012/2018 -TS EW028CB SCT029=
FTKN32 HKJK 192306 TAF HKKI 192300Z 2000/2024 06005KT 9999 SCT018 BECMG 2000/2006 24005KT CAVOK BECMG 2008/2011 24010KT 9999 FEW024CB TEMPO 2012/2018 -TSRA FEW025CB SCT026 BKN080 BECMG 2020/2023 08005KT SCT020=

Appendix 3: Flight Schedules from Nairobi to Kisumu International Airport on 19th Feb. 2019

FLIGHT	CARRIER	TAKE-OFF TIME (NAIROBI)	LANDING TIME (KISUMU)
KQ650	Kenya airways	0315Z	0405Z
JM8650	Jambojet	0320Z	0420Z
KQ654	Kenya Airways	0625Z	0715Z
JM8654	Jambojet	1005Z	1105Z
KQ674	Kenya airways	1035Z	1125Z
KQ670	Kenya airways	1410Z	1500Z
5H1409	Fly 540	1540Z	1640Z
JM8656	Jambojet	1600Z	1700Z

Appendix 4: Route forecast of en-route conditions issued by KMD on 26th March 2019

ROUTE: HKNW/HKJK TO HKNW/HKJK VIA HKKI, HKKG, HKEL, HUEN, HKKT, HKNO, HKLO	
VALID FOR DEPARTURE: 26/03/2019 0300 UTC VALID FOR ARRIVAL: 26/03/2019 1500 UTC	
WEATHER: Mainly sunny intervals expected in the morning with rains expected over few places (Migori). Mainly sunny intervals expected in the afternoon with showers and thunderstorms expected over few places. Issued on 25th 2019 at 2.00 P.M (Valid from 9.00pm that night to 9.00pm of 26th March 2019	
HIGHEST CLOUD LAYER AMOUNT AND TYPE - SCT/BKN: AC	
CLOUD HEIGHT (BASE TO TOP)- 060-140	
LOWEST CLOUD LAYER AMOUNT AND TYPE- FEW/SCT/BKN:CB/CU/SC	
CLOUD HEIGHT (BASE TO TOP)- 010- 030	
SURFACE VISIBILITY: OVER 10KMS UNLESS IN FOG, RAINS, SHOWERS AND THUNDERSTORMS	
PRESSURE ALTITUDE OF 0º OF ISOTHERM FL 150	
FL050	03005KT
FL070	03010KT
FL100	03010KT
FL140	06015KT
FL180	09015KT
FL240	09030KT
LOWEST MEAN SEA LEVEL PRESSURE (MB)	

Appendix 5: Terminal Aerodrome Forecast at 4 different times on 26th March 2019

TAF HKKI 252300Z 2600/2624 VRB05KT CAVOK BECMG 2608/2611 23010KT 9999 FEW026CB SCT027 TEMPO 2612/2618 VRB10KT -TSRA FEW023CB BKN024 BKN080 BECMG 2620/2623 VRB05KT NSW CAVOK=
TAF HKKI 260500Z 2606/2706 23010KT 9999 FEW026CB SCT027 TEMPO 2612/2618 VRB10KT -TSRA FEW023CB BKN024 BKN080 BECMG 2620/2623 VRB05KT NSW CAVOK=
TAF HKKI 261100Z 2612/2712 24015KT 9999 FEW029CB SCT100 TEMPO 2612/2618 VRB10KT -TSRA FEW023CB SCT024 BKN080 BECMG 2620/2623 VRB05KT NSW CAVOK TEMPO 2700/2706 9999 FEW020CB BECMG 2708/2711 22010KT 9999 FEW028CB SCT090=
FTKN32 HKJK 261744 TAF HKKI 261700Z 2618/2718 28010KT 9999 -RA FEW018CB BKN080 BECMG 2620/2623 VRB05KT NSW CAVOK TEMPO 2700/2706 9999 FEW020CB BECMG 2708/2711 22010KT 9999 FEW028CB SCT090 TEMPO 2712/2718 VRB10KT –TSRA FEW023CB SCT024 BKN080 =

Appendix 6: Flight schedules from Nairobi to Kisumu International Airport on 26th Mar. 2019

FLIGHT	CARRIER	TAKE-OFF TIME (NAIROBI)	LANDING TIME (KISUMU)
KQ650	Kenya airways	0315Z	0405Z
5H407	Fly 540	0500Z	0550Z
JM8652	Jambojet	0610Z	0710Z
KQ654	Kenya Airways	0625Z	0715Z
KQ656	Kenya airways	0935Z	1025Z
JM8654	Jambojet	1005Z	1105Z
KQ674	Kenya airways	1100Z	1150Z
KQ670	Kenya airways	1305Z	1355Z
5H409	Fly 540	1325Z	1415Z
JM8656	Jambo jet	1345Z	1448Z