UNIVERSITY OF NAIROBI

INVESTIGATION OF FORECASTING POTENTIAL OF AIRCRAFT WEATHER HAZARDS OVER KENYA USING NUMERICAL MODEL

BY

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May the almighty God abundantly bless all of them.

ABSTRACT

The study investigates the forecasting potential of aircraft weather hazards over Kenya using numerical model. The various causes of accidents/incidents are identified using analyzed investigated weather-related aviation hazards data obtained from Kenya Civil Aviation Authority database system from 2008 through 2014. The significance of the contribution by the weather hazards was examined. The parameters analyzed included the Winds, Temperature, Relative humidity, Convective Available Potential Energy (CAPE), Lifted Index (LI), and Dew Point Temperature. Their combined effect is able to provide the means of identifying the areas of strong convection. The China based geostationary Fengyun (FY2E) Satellite and Meteosat Second Generation (MSG) Infrared 10.8 imagery were used to identify the dominant cloud types and the distribution of the convective cells during the dry and wet seasons. A case study was conducted to forecast cumulonimbus clouds on a particular date, and satellite imagery was used to verify that the event occurred as was forecasted. The model was run on a grid point distance resolution of 10 km and runs finite differencing scheme, based on Taylor series. GrADS which is embedded on the model upon installation, was used as the default post processing tool. Key findings revealed that Wind, Fog, Turbulence, Heavy rain showers, and low ceiling influenced aircraft operations. It was shown that the majority of the hazards were linked with cumulonimbus clouds. Landing phase of flight affected aviation most. It was also noted that clouds of all types do not appear in the sky at the same time and a few clouds are rarely ever seen whereas some are only seen during certain seasons.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

Ac	Altocumulus
AMSL	Above Mean Sea Level
AOPA	Aircraft Owners and Pilots Association
As	Altostratus
ASIAS	Aviation Safety Information System Analysis and Sharing
BKN	5 to 7 Octas
CAPE	Convective Available Potential Energy
CAT	Clear Air Turbulence
Cb	Cumulonimbus
Cc	Cirrocumulus
Ci	Cirrus
CLW	Cloud Liquid Water
Cs	Cirrostratus
Cu	Cumulus
CCA	Canonical Correlation Analysis
EL	Equilibrium Level
ENSO	El Nino Southern Oscillation
FAA	Federal Aviation Administration
FEW	1 to 2 Octas
FY2E	China based Geostationary Fengyun 2E
GA	General Aviation
GCM	Global Circulation Model
GDP	Gross Domestic Product
GFS	Global Forecast System
GOES	Geostationary Operational Environmental Satellite
GrADS	Grid Analysis and Display System
IATA	International Air Transport Association
IR	Infrared Spectral Bands
ITCZ	Inter- Tropical Convergence Zone
JKIA	Jomo Kenyatta International Airport
KAA	Kenya Airports Authority
KCAA	Kenya Civil Aviation Authority
KMD	Kenya Meteorological Department
LAMP	Localized Aviation Model Program
LCL	Lifted Condensation Level
LFC	Level of Free Convection

LI	Lifted Index
LIDA	Linear Discriminant Analysis
MAM	March- April- May
METAR	Meteorological Aviation Routine Weather Report
MOS	Model Output Statistics
MPEF	Meteorological Products Extraction Facility
MSG	Meteosat Second Generation
NOAA	National Oceanic Atmospheric Administration
Ns	Nimbostratus
NTSB	National Transport Safety Board
NWP	Numerical Weather Prediction
NWS	National Weather Service
OAEP	Office of Aviation Enforcement and proceedings
OND	October- November- December
OVCST	8 Octas
Q-GIS	Quantum Geographical Information system
RGB	Red Green Blue
RH	Relative Humidity
RWY	Runway
Sc	Stratocumulus
SCT	3 to 4 Octas
St	Stratus
TS	Thunderstorms
UNEP	United Nations Environmental Programme
UPS	United Parcel Service
USA	United States of America
UTC	Coordinated Universal Time
WAFC	World Area Forecast Centre
WAP	Wilson Airport
WMO	World Meteorological Organization
WRF	Weather Research and Forecasting Model

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background of the Study

Aviation provides for fast and convenient the movement of people and goods and contributes significantly to economic growth (Waitz*et al*, 2004), strict adherent to safety measures by airline operators has made air transport the most preferred mode of transport. However, the safety of air transport still faces challenges from weather hazards. Severe weather may impact negatively on air traffic management systems including the ability to ensure timely flight schedules. In 2007, for instance, the Department of Transportation (OAEP, 2008) documented one in four flights delayed due to bad weather.

New data released by the International Air Transport Association (IATA) has shown that the air transport sector in Kenya contributes $3.2bn or 5.1% of the country’s gross domestic product (GDP). It also supports approximately 620,000 job opportunities, including tourism-related employment in the East African nation.

In Kenya the helicopters play a big role as they are used for rescue missions and by politicians when they conduct their campaigns. The helicopters are unlike, the military aircrafts that are designed to endure adverse weather while the commercial aircrafts have to carry optimum capacity to make profit -- they are usually optimized in the best weather. Conducive operations depend on weather which is a crucial component for them to expand in terms of growth. We need to understand the impacts so that key players are aware of this to take necessary precautions to avoid losses.

Aviation hazards during the cumulus stage of thunderstorms are mainly caused by supercooled water (Okoola, 2005). Hazards during the mature stage of the thunderstorms are due to strong winds, lightning and precipitation, while those in the final stage arise from downbursts. Thunderstorms are produced by convective instability, moisture, and a source of lift. In forecasting thunderstorms, it is important to know whether they will occur; their severity; the associated severe phenomena; and the type of storm likely to be observed.

1.2 Research Problem

The research problem is based on Annex 13 – Aircraft Accident and Incident Investigation that is developed by ICAO (International Civil Aviation Organization). According to the provisions laid down in ICAO Annex 13 to the International Civil Aviation Convention – Aircraft Accident and Incident Investigation, the sole objective of the investigation of an accident or incident is to prevent accidents and incidents.

Even though air navigation is considered to be the safest means of transport, it is an activity facing many potential dangers that include weather-related ones. The research intends to address the dangers that are influenced by weather hazards through forecasting using Weather Research and Forecasting (WRF) Model. The aim is to provide timely advisories to aviation stakeholders.
Accurate meteorological information achieved through observation, analysis, and forecasting enable identification of key weather phenomena –severe weather. This is forensic meteorology and the information that is provided is important to aviation stakeholders such as the pilots, airlines, and management as well as to International, Regional, and National Civil Aviation Authorities for better policy and planning, route mapping, and operation schedule. This would enable enhanced safety, enhanced profit, and improved livelihood.

Aircraft weather hazards influence aviation accidents and incidents and may cause or contribute to the following: serious injury to passengers and crew members and damage to aircraft; aircraft experiencing vibrations on landing due to heavy landing; runway excursion – aircrafts go off the runway after landing; and missed approaches. Accidents and serious incidents would therefore result in economic losses.

1.3 Study Objectives

Overall objective of this work was to investigate the predictive potential of severe weather that influences aircraft operations over Kenya.
To achieve the overall objective, the following specific objectives were pursued:

1. Identify the region where the aircraft weather hazards occur over Kenya

2. Determination of weather-related hazards that lead to aircraft accidents and incidents over Kenya.
3. Simulate the weather hazards that occur over Kenya using the Weather Research and Forecasting (WRF) Model.

1.4 Hypothesis

This study is guided by the following hypothesis: the contribution of severe weather to aviation accidents and incidents is significant and may be anticipated in advance.

1.5 Justification and Significance of the Research

The effect of each cloud to aviation varies and understanding the spatial distribution is important so that we get to know of their occurrence or not. Some clouds pilots can penetrate through while others even influence visibility. The weather condition is important as severe weather may influence aviation accidents and incidents. The economic potential of severe weather prediction can be demonstrated that it has an impact and flight schedule avoiding seasons and time when cumulonimbus clouds are prevalent would help to optimize the profits and support the airlines in planning.

1.6 Area of Study

There are four high pressure systems that are strategically placed outside the four corners of Africa that together with the local effects and presence of ITCZ during the wet seasons affect the rainfall patterns over the region of study. The high pressure cells are the Mascarene, St Helena, Azores, and Arabia. The winds associated with the pressure systems are south easterlies, south westerlies, north westerlies, and north easterlies respectively.

The coastal region is hot and humid with annual rainfall of 1000 mm and temperatures ranging between 27 and 32 degrees centigrade; the northern and eastern Kenya is dry and mostly semi-arid with annual rainfall of less than 500 mm and temperatures ranging between 29 and 40 degrees centigrade during the day; the western Kenya is wet throughout the year due to the effects of the Congo air mass and the local effects. The annual rainfall is normally more than

1000 mm and day temperatures range between 25 and 30 degrees centigrade; the central highlands and the rift valley experience annual rainfall of up to 3000 mm over the higher grounds and temperatures range between 20 and 27 degrees centigrade during the day. Stratocumulus and cirrus clouds are the most dominant clouds. Cumulonimbus in extensive spatial coverage is observed during the wet seasons. Other clouds that are observed are cumulus, altostratus, altocumulus, cirrocumulus, cirrostratus, and stratus. Kenya boasts of six airports, two military airbases, and several airstrips located in the 47 counties.

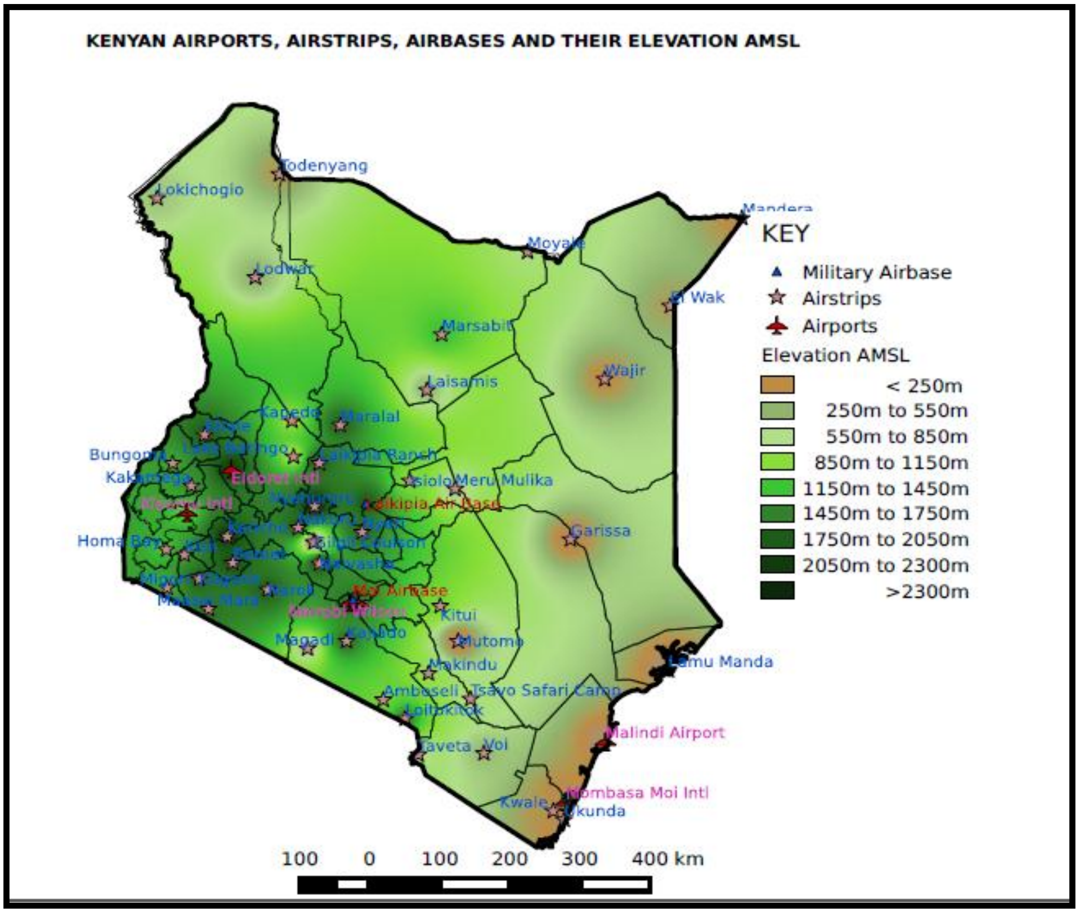

Figure 1: Map of Kenya, showing Airports, Airstrips, Airbases and Topography. Source: Generated using Q-GIS

Table 1: Major Airports and Airbases in Kenya

Airports	Latitude	Longitude
Kisumu	-0.09	34.73
Moi Intl	-4.04	39.59
Wilson	-1.32	36.82
Jomo Kenyatta	-1.32	36.93
Eldoret	0.5	35.3
Malindi	-3.22	40.1

Airbase	Latitude	Longitude
Laikipia	0.033	37.027
Moi Airbase	-1.278	36.862

Table 2: Airstrips in Kenya

Airstrip	Latitude	Longitude
Wajir	1.73	40.09
Laikipia Ranch	0.58	36.43
Tsavo Safari Camp	-2.64	38.37
Amboseli	-2.65	37.25
Bomet	-0.78	35.32
Bungoma	0.58	34.55
El Wak	2.73	40.93
Garissa	-0.46	39.65
Gilgil Coulson	-0.5	36.36
Homa Bay	-0.6	34.47
Kajiado	-1.85	36.78
Kakamega	0.27	34.79
Kapedo	1.16	36.08
Kericho	-0.42	35.25
Kilgoris	-1	34.89
Kisii	-0.67	34.7
Kitale	0.97	34.96
Kitui	-1.37	37.98
Kwale	-4.17	39.43
Laisamis	1.58	37.81
Lake Baringo	0.67	36.1
Ukunda	-4.29	39.57
Maasai Mara	-1.41	35.01
Lamu Manda	-2.25	40.91
Lodwar	3.12	35.61
Loitokitok	-2.91	37.53
Lokichogio	4.2	34.35
Magadi	-1.95	36.28
Makindu	-2.29	37.83
Mandera	3.93	41.85
Maralal	1.1	36.7
Marsabit	2.34	38
Migori	-1.12	34.48
Moyale	3.47	39.1
Meru Mulika	0.23	38.17
Mutomo	-1.85	38.21
Naivasha	-0.79	36.43
Nakuru	-0.3	36.16
Narok	-1.15	35.77
Nyahururu	-0.01	36.37
Nyeri	-0.36	36.98
Taveta	-3.4	37.7
Todenyang	4.53	35.92
Voi	-3.38	38.54
Isiolo	0.34	37.59

CHAPTER TWO

2.0 LITERATURE REVIEW

The chapter discusses weather-related factors that can influence aircraft operations. Specific areas covered are: Visibility/Ceiling and Clouds, Thunderstorms and hazards associated with Thunderstorms such as the following: Lightning, Wind Shear, Icing, and Turbulence.

2.1 Visibility/Ceiling and Clouds

Some clouds are dangerous to aviation as they are capable of producing precipitation, thunder and lightning. Clouds are classified according to general form and the three basic forms are Cumuliform (heaps), Stratiform (layer form) and Cirriform (fibrous) lines. They can also be classified according to average height of base above the ground- Low, Medium, and High clouds (Mwebesa, 1978).

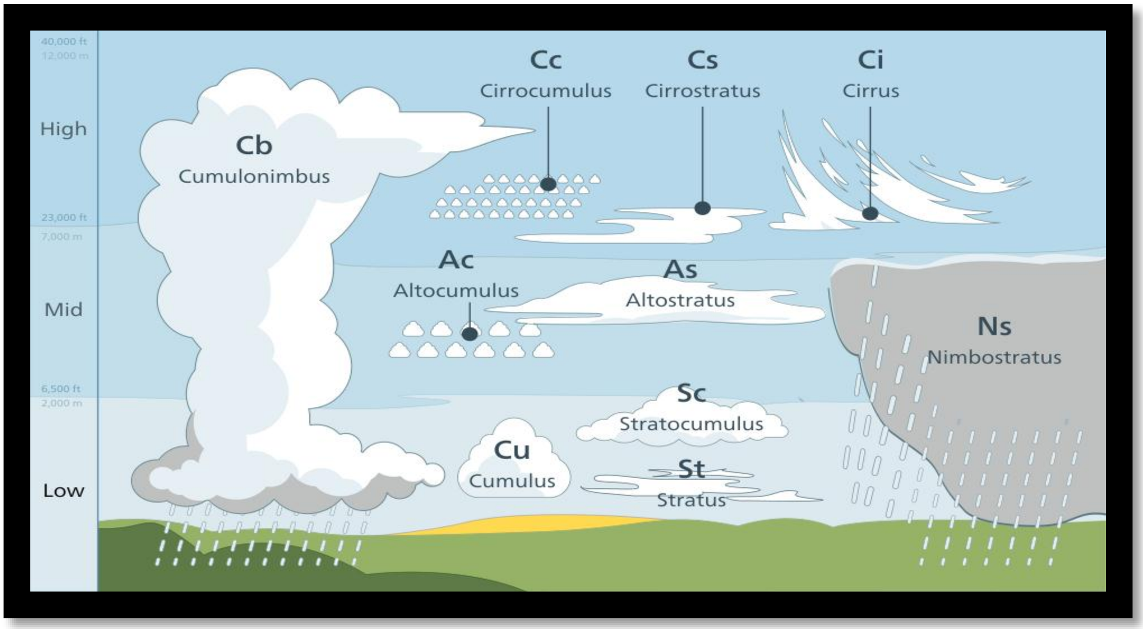

Figure 2: Tropospheric cloud classification by altitude of occurrence.Source:https://en.wikipedia.org/wiki/List-of-cloud-types/media/File:cloud-types-en.svg

In a study by Verlinde *et al.*, (2007), it was found that mixed-phase clouds, such as Arctic stratus and stratocumulus, altocumulus and altostratus, cover approximately 22% of the earth's surface and that the clouds are persistent, with supercooled water existing both within ice clouds and above ice layers at temperatures as lowas-30 ◦C. It was also observed that the clouds contain supercooled water that can be a serious aircraft icing threat. Smith *et al.,*(2009) indicated in a separate study that supercooled water is particularly hazardous for small aircrafts, such as unmanned aerial vehicles, which they noted to have suffered several accidents due to icing during both civilian and military surveillance.

According to Sharman *et al.,* (2015) in their study on the effects of rain to aviation, the investigation concluded that torrential rain has significant effect on an airplane in landing configuration. This is due to effect of poor visibility and flooded runways that may lead to runway excursions.

According to Mahringer (2008), unexpected visibility below minimum threshold (1000m) affects the airport operations to a large extent. The study found that airport operations are adversely affected by adverse weather. It was noted that atmosphere is obscured due to the presence of high concentration of hygroscopic nuclei, small and large water droplets, fine sand, smoke, and smog. The high concentration of these particles tends to reduce the distance through which an observer/pilot can see and identify an object situated some distance away from the observer/pilot. Gultepe *et al.,* (2009), in their study indicated that fog is another troublesome problem. They observed that fog is capable to cause airport delays, and that the major problem with fog encounter is the effect of poor visibility.

2.2Thunderstorms

Murray (2002) in a study about the influence of thunderstorms to aviation state that the storm is formed by convection whereby instability, availability of moisture, and lifting or trigger mechanism are needed for formation. They are associated with convective clouds (cumulonimbus) and are usually accompanied by precipitation.

Maloba (2015) studied thunderstorms over eastern region of Lake Victoria basin in Kenya and in the conclusions found that thunderstorms were most observed in the afternoon from 1200Z to 1500Z when there is maximum heating. It was noted that thunderstorm activities were more intense during the wet seasons of MAM and OND due to the presence of ITCZ. The study indicated that the higher ground areas such as the Mau Hills experienced higher distribution of the storm compared to the lowland areas. It was shown that 850mb and 700mb levels are important when locating areas of convergence and the source of moisture which are conditions necessary to produce thunderstorms. .Showalter (1953) found that unstable air is a necessary ingredient for the development of thunderstorms. It is necessary that the rising parcels to ascend above the level of free convection (LFC).

Galway (1956) found that stability indices are useful tools that can be used to measure convective instability. Moncrieff *et al.*, 1976 state that CAPE is a useful tool in measuring how a parcel of air is ascending relative to the environmental lapse rate and enables researchers to examine the vertical structure of the atmosphere.

Ngaina (2015) modeled aerosol-cloud precipitation interactions for weather modification over East African region. The study found that CAPE is a useful tool that enables identification of areas where energy for convection is available. It was noted that CAPE has both meridional and zonal transitions during MAM season and that at the end of the season, extreme values of 1800 J/Kg were observed over parts of Kenya.

Bothwell (1988) examined surface moisture in terms of mixing ratio while Mahoney (1988) indicate that thunderstorms are mesoscale phenomena, and the source of lift needed to initiate them must be sought on mesoscale space and time scales. The study noted that rising parcels of air move upward through a negatively buoyant layer below the Level of Free Convection (LFC) before positively buoyant upward acceleration is achieved. Upward movement through the negatively buoyant layer is provided by mesoscale mechanical lift produced by low-level convergence.

McNulty (1983) indicates in the conclusions of the study that boundaries are curvilinear discontinuities characterized by cyclonic shear and convergence and include convection (gust fronts) and the best example of differential heating that produces a near-surface convergence zone is the sea breeze.

Bothwell (1988) in the study found that in some cases, thunderstorms occur in the presence of weak synoptic-scale subsidence. They develop due to strong near-surface convergence and high convective instability that compensates for any synoptic-scale downward motion that might impede convection in cases of weak forcing or low convective instability.

2.2.1 Lightning

Hardwick (1999) in a study on lightning in the North Sea region found that helicopters were at higher risks. The study concluded that the protection against the strikes is not foolproof to averting the effects of lightning strikes in the region. The study noted that fixed wing aircrafts flying at the same altitude as the helicopters were equally vulnerable to the strikes and it was further observed that during winter the lightning strikes were stronger and resulted in more damages to aircrafts.

Wilkinson *et al*., (2013) in another study on triggered lightning by helicopters in the North Sea region noted that the phenomenon affected operations during winter. An algorithm was developed based on weather conditions that were observed to be prevailing during past triggered lightning strikes. To locate the convective cells, they used temperatures and precipitation rate of the typical flight levels of helicopters. The study showed that most strikes occurred when cumulonimbus clouds are embedded in stratocumulus clouds and the dangerous regions for the helicopters to fly through are near the base of Cb clouds and underneath the anvil. The algorithm was found to be suitable to warn on Cb occurrence.

2.2.2 Wind shear

Abrupt and rapid changes in wind speed and direction near the surface are at times caused by thunderstorm outflow and may pose adverse effects during landing and takeoff phases of flight- the pilot may find it difficult to maintain control of the aircraft. The Federal Aviation Administration (FAA) Aviation Safety Information Analysis and Sharing (ASIAS) analysts performed a study of the National Transportation Safety Board (NTSB) from 2003 through 2007 and found that most wind shear incidents occurred during the approach and landing phases of flight (NTSB, 2010).

2.2.3 Aircraft Icing

Structural icing disrupts airflow over aircraft surfaces which results in reduced lift and increased drag. Lift is supposed to overcome both the force of gravity and the drag, for the aircraft to takeoff from the runway and to continue with the journey while airborne. (AOPA, 2008).

Vivekanandan *et al.,*(1996) on a separate study, used both visible reflectance and Infrared emittance to estimate cloud properties with the aim of examining the size and path of cloud water droplets. The study was able not only to characterize the location of the cloud systems, but also the size and depth. The study concluded that the cloud -top phase, which they were able to monitor, were important in determining possible icing conditions.

Belo-Pereira (2015) on a study on aircraft icing to predict icing potential and severity of aircrafts flying below 23,000 feet over Eastern United States, used two algorithms based on forecasts of temperature and relative humidity. It was found that the algorithms were most suitable to locate icing and no-icing conditions but were less skillful to predict whether the icing was severe or not. Better results were achieved when the algorithms combined temperature, relative humidity, and vertical velocity when cloud liquid water (CLW) was used in the prediction. The study also stated that the algorithm gave accurate prediction of a severe icing situation that had occurred over mainland Portugal in February 2014.

2.2.4 Turbulence

Gidel *et al.,*(1979) showed that there exist updrafts and downdrafts exceeding 6000 feet per minute in and around thunderstorms. This is turbulence that exceeds the performance capability of most aircrafts. According to the 2010 annual report of the National Transportation Safety Board (NTSB, 2010), turbulence was the main cause of aviation accidents related to weather from 1997 to 2006. In South Korea, turbulence has accounted for about 24% of weather-related aviation accidents since 1957.To reduce these damaging events, the study recommends that adequate prediction of turbulence require knowledge of the generation mechanisms of turbulence that can be established through observational analysis and numerical modeling.

Gill *et al*., (2014) used data for one year from November 2010 through October 2011 to forecast turbulence globally. The turbulence forecasts were verified using 2x2 contingency tables and every forecast was categorized with the corresponding observations. These were as follows: a hit(when the event was forecast and occurred); miss (when the event was not forecast but occurred); false alarm(if the event was forecast but did not occur); and correct rejection (if the event was not forecast and did not occur). 95% confidence interval was used. The study found that the main sources of turbulence are wind shear, convection, and mountain waves. It was noted that most shear induced turbulence was due to jet streams.

2.3 Conceptual Framework

Figure 3 shows the summary of the concept behind the study. The figure highlights data extracted for the study, the methods applied to achieve the major outcome as well as dependent, independent, and intervening variables. This provides the rationale for selection of the study and contribution to research and planning- relationships between methods, factors, and outputs are demonstrated. Meteorological expert services-forensic meteorology, are provided through observation, analysis, and forecasting to the International, Regional, and National aviation authorities – their aim is policy and management. The key weather phenomena that influenced accidents/incidents were identified.

This information is important to aviation stakeholders for better policy and planning, route mapping, operation schedule, and improved aviation meteorological services. Planning leads to enhanced safety, enhanced profit, and improved livelihood- economic benefit.

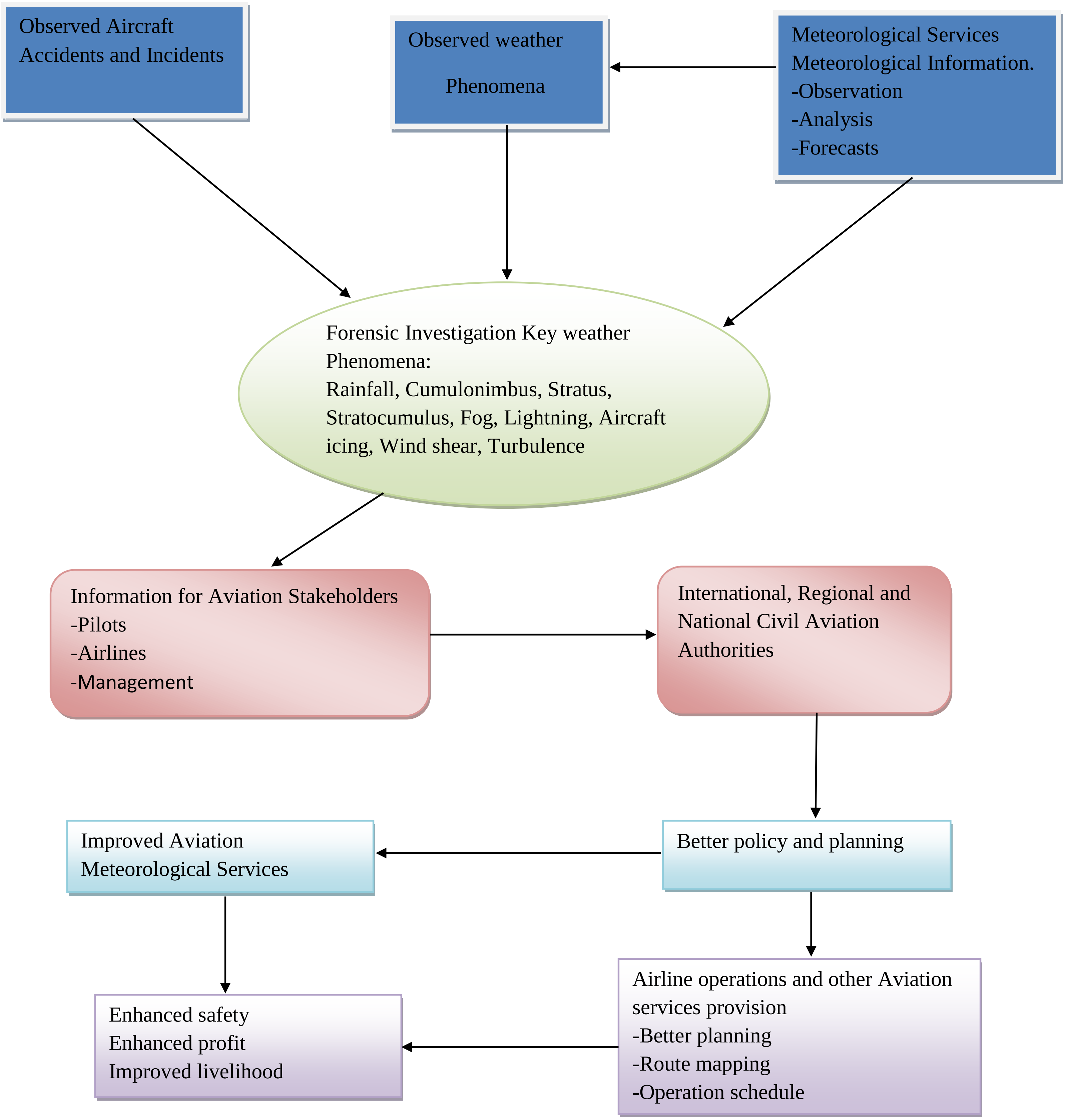

Figure 3: Input, process, output and application of the study

CHAPTER THREE

3.0 DATA AND METHODOLOGY

The data and methods of analysis used to achieve the various objectives of this study are discussed in this chapter.

3.1 Data

The types of data source are discussed in this subsection.

3.1.1 The data for determining the spatial distribution of cloud cover

Satellite data were used in this study. The satellite data include the Meteosat Second Generation data displayed on the Synergie at the Kenya Meteorological Department, a production of the French MeteoFrance. In it, several meteorological products are availed: - Satellite imagery from the USA **GOESW and East** satellites, RGB Composite products for various products, MPEF products from MSG, Aerie weather Models amongst others. In the Synergize, it has been made possible that at every 15 minutes, data is downloaded, saved, and processed for viewing and analysis by the Forecasters on duty.

3.1.2 Data of the Weather-related hazards that lead to aviation incidents/accidents

The aviation weather-related accident/incident data were obtained from Kenya Civil Aviation Authority (KCAA) database from 2008 through 2014.A total of 8 cases of accidents/incidents occurred over Kenyan airspace within this period and they were caused by weather hazards. All accidents and serious incidents conformed to the definition within the 9th edition of the Convention on International Civil Aviation Annex 13 (International Civil Aviation Organization, 2001). There were 8 different types of aircrafts in the accidents/incidents analyzed including commercial airplanes and helicopters.

3.1.3 Data used to forecast cumulonimbus clouds.

The Weather Research and Forecasting (WRF) Model, is a consortium of the USA based Global Forecasting System (GFS). The GFS is a Global Circulation Model (GCM) at 50km resolution that integrates global observational and satellite data to produce forecasts. WRF, as used in KMD, is a subset of the GFS GCM model, in that it picks its pre-fixed static and initial boundary conditions from the GFS.

The WRF model was run on a grid point distance resolution of 10km. WRF runs finite differencing scheme, based on Taylor series. The length of the run was 48hours, beginning from 14th April, 2017, 0000Z to 16th April 2017, 0000Z.Grid Analysis and Display System (GrADS), embedded on WRF upon installation, was used as the default post processing tool.

3.2 Methodology

3.2.1 Use of satellite to identify the regions

For purposes of this study, two satellite imageries were used. The China based geostationary Fengyun 2E (FY2E) satellite, which is located above the equator at Longitude 105ºE, was usedto classify clouds over Kenya. MSG Infrared 10.8 Imagery was also used to identify cloud temperatures. Areas with cloud temperatures below -40ºC were identified and marked, as they would be zones associated with deep convective cells, and/or raining clouds. Two sets of images from each satellite were picked, from January and April, 2017 to demonstrate and represent dry and wet seasons respectively.

Raw data from GIOVANNI was also used. GIOVANNI is an interactive page for accessing Earth data from NOAA. Atmospheric data can be analyzed, compared, and investigated for various spatial and temporal scales. One of the products, which has been analyzed and used in this study, is time averaged cloud fraction. With appropriate settings, monthly cloud fraction (cloud cover) was obtained for the months of January and April 2016, to demonstrate the dry and wet seasons in Kenya.

Quantum-Geographical Information System (QGIS) is a GIS tool that can read geotiff images as raster layers, hence making it possible for further superimposition, overlaying and extraction. The images from FY2E, MSG IR 10.8, and GIOVANNI, were analyzed further by QGIS so as to enhance the rendering and enable visualization. Kenyan external boundary and counties were labeled and demarcated to depict variables investigated.

3.2.2 Investigation of aircraft accident and incident data

In an attempt of the current study to estimate the true number of accidents/incidents against aviation weather hazards that caused them, an excel table was prepared distributing the considered accident or serious incident with the type of aircraft, departure aerodrome, destination, location of accident or incident, date and time of occurrence, and statement on the damage sustained by aircraft and injuries to persons on board. In each of the cases, weather hazard that influenced an accident or incident is appended.

The data was analyzed to determine the relationships between the type of weather hazard cited in the data and accident or incident caused by the hazard. This was summarized in graphical plots.

3.2.3 Forecasting of cumulonimbus clouds

Cumulonimbus clouds are mesoscale phenomena and the source of lift needed to initiate them must be sought on mesoscale space and time scales (Mahoney, 1988). WRF model is a NWP mesoscale modeling system that is a useful tool in atmospheric research and operational forecast (Skamarock *et al.,* 2008). Several studies globally have used the model.(Wang *et al*., 2009; Ackerman *et al*., 2009) in their studies used the model for large eddy simulations. In their results they indicated that the model was efficient and that the results were in agreement with the observed data.(Ngaina, 2015) evaluated WRF microphysics to simulations of deep convective clouds. The aim of the study was to evaluate the accuracy of the model.

The assessment was based on updrafts and downdrafts and total precipitation. From the various studies that have been carried out using the WRF Model, there is a clear indication that the model gives accurate results and can therefore be relied upon.

A case study was conducted on 14th April 2017 to forecast Cumulonimbus clouds. This date was picked to coincide with April, which is the peak of the March April May (MAM) wet season. It was expected that at this time of the year, many types of clouds would develop, more so of the convective type. WRF model was identified as a suitable model for forecasting of cumulonimbus clouds. Cumulonimbus clouds develop under certain favorable conditions, namely: Convective instability, moisture availability and lifting mechanism.

Surface Convective Available Potential Energy (CAPE) and Lifted Index (LI) at 500mb were simulated to measure instability of the atmosphere as the parcel of air ascends at each time step. Relative humidity at 700mb level was examined since convective processes are best defined at 700mb within the tropics, with Lifted Condensation Level (LCL) located somewhere within this isobaric surface - the level a parcel becomes saturated when mechanically lifted. Surface and 700mb level temperatures were examined alongside the Lifted Index, to determine the vertical gradient of temperature, hence stability and barotropy/baroclinicity of the atmosphere. Surface winds, and streamline analysis, were useful ingredients in determining the areas of convergence and divergence of air. Dew point temperature at 2metres level above the surface was analyzed to tell on the moisture content at the surface.

A nest of the parent domain (Kenya) was created, having its initial boundary conditions as those of Kenya. The nest was used to resolve Mesoscale systems within the Highlands West and East of the Rift valley. This was informed by the climatological zones in Kenya. The length of the forecast was set to 48hrs, so that the model simulation doesn’t default to 24 hour. With the data from GFS downloaded and all settings done, the model was run. The Mathematical and Physical equations of the atmosphere were solved and interpolated to every grid point and then extrapolated to give the future state of the parameters under consideration. The output files were in net.cfd format.

It’s possible to post process the net.cdf data to other formats, for manipulation. Suitable applications can be used to view and post process the model output. However, Grid Analysis and Display System (GrADS) is embedded on the WRF and upon installation, GrADS becomes the default post processing tool.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

Results obtained from the various methods used are discussed in this chapter and they include: weather hazards to aviation; region where the aircraft weather hazards occur over Kenya; and simulated weather distribution over Kenya.

4.1Region Where the Aircraft Weather Hazards Occur Over Kenya

We are short of the mean data but we are using data for a particular year to demonstrate the cloud cover. The spatial pattern was studied for dry and wet seasons for the year 2016 using GIOVANNI tool.

Figure 4 shows the analyzed cloud imagery from GIOVANNI, displaying the cloud fraction for various parts of the country for the month of January, 2016. Significant part of the country still experience coverage of over 50%- the regional systems may have played a role in contributing to weather that may have enhanced formation of the clouds. There could be variation but it is representative of the dry season.

January climatologically marks a dry spell in Kenya. The figure shows higher cloud fraction in central and western parts of Kenya that superseded other parts of the country- the region stretching from Nairobi to Lake Victoria and Mount Elgon have the potential to cause hazards.

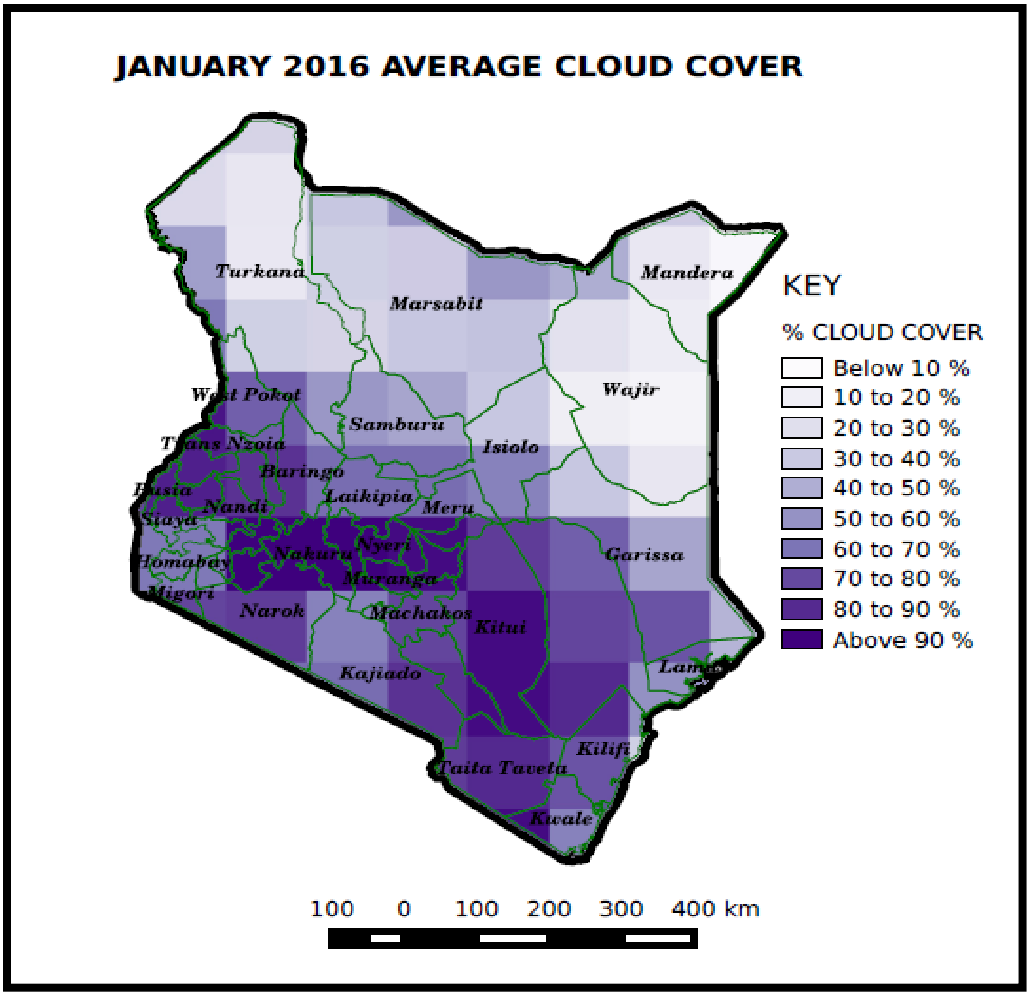

Figure 4: Cloud fraction averaged for the month of January, 2016. Source: Giovanni from NOAA, analyzed using Q –GIS

Figure 5 shows the cloud fraction from GIOVANNI for various parts of the country for the month of April, 2016. April was considered since it marks the peak of the MAM season in Kenya. From the figure western, central highlands and most of the southern sector of the country had over 70% cloud cover. The western and eastern highlands, the coast, and Nairobi areas still had a greater percentage of coverage compared to the other parts of the country. There is increase of the region that is covered by 50%. There are a few areas where either the sky is clear or are covered by few clouds. It should be noted that clear air turbulence could occur and affect aircrafts even over such areas where the sky is clear.

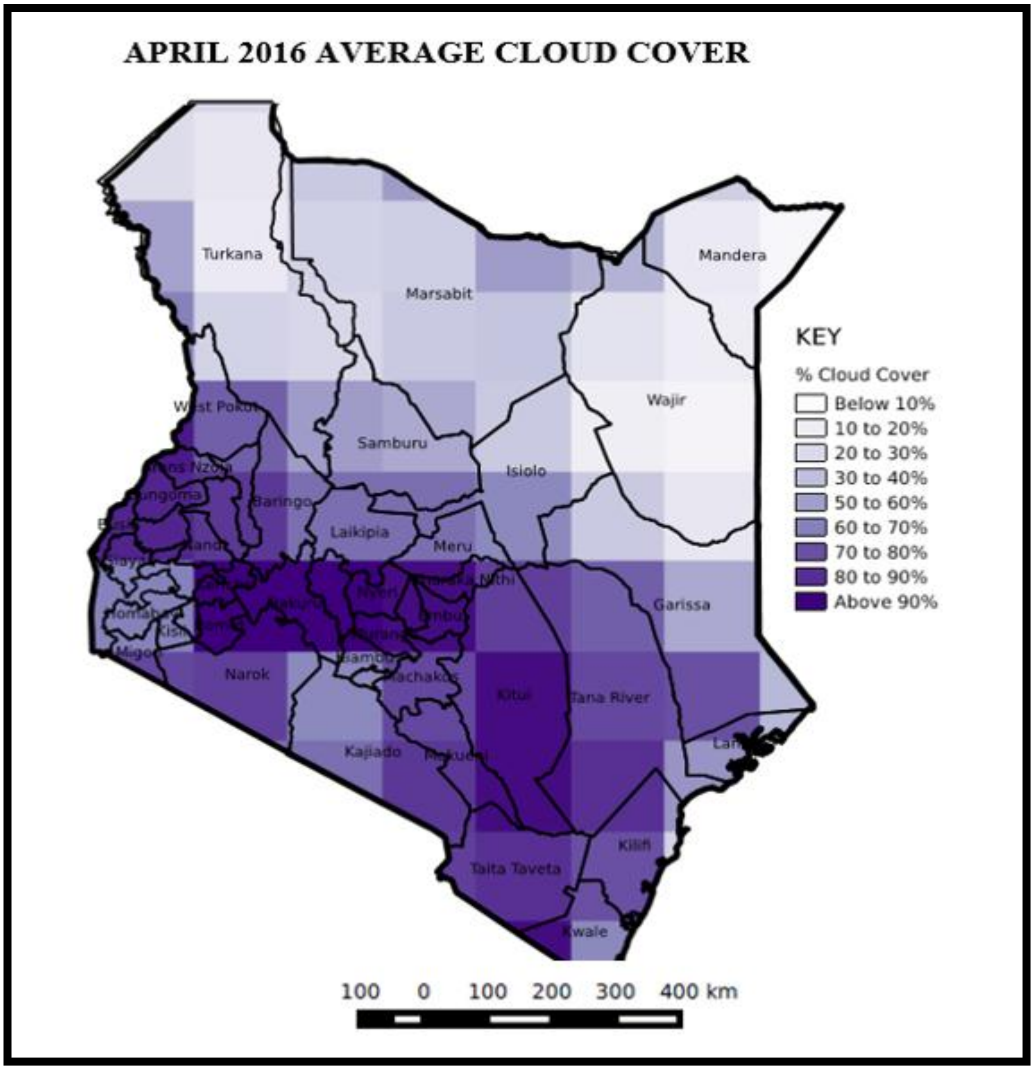

Figure 5: Cloud fraction averaged for the month of April, 2016. Source: Giovanni from NOAA,

The China based geostationary Fengyun 2E (FY2E) satellite was used to identify and classify clouds over the study area during the dry and wet seasons. Figure 6 shows the cloud classification for the month of January, 2017 as observed by FY-2E Satellite, and analyzed using Q –GIS. From the figure, Stratocumulus and Cirrus clouds covered most parts of the sky. Other clouds were majorly along the western corridor-As, St, Cu, Cb and Ac, agreeing with the January distribution from Giovanni averages. The figure tells us that cumulonimbus clouds are not extensive in spatial coverage at this time of the year and this may be due to the absence of ITCZ.

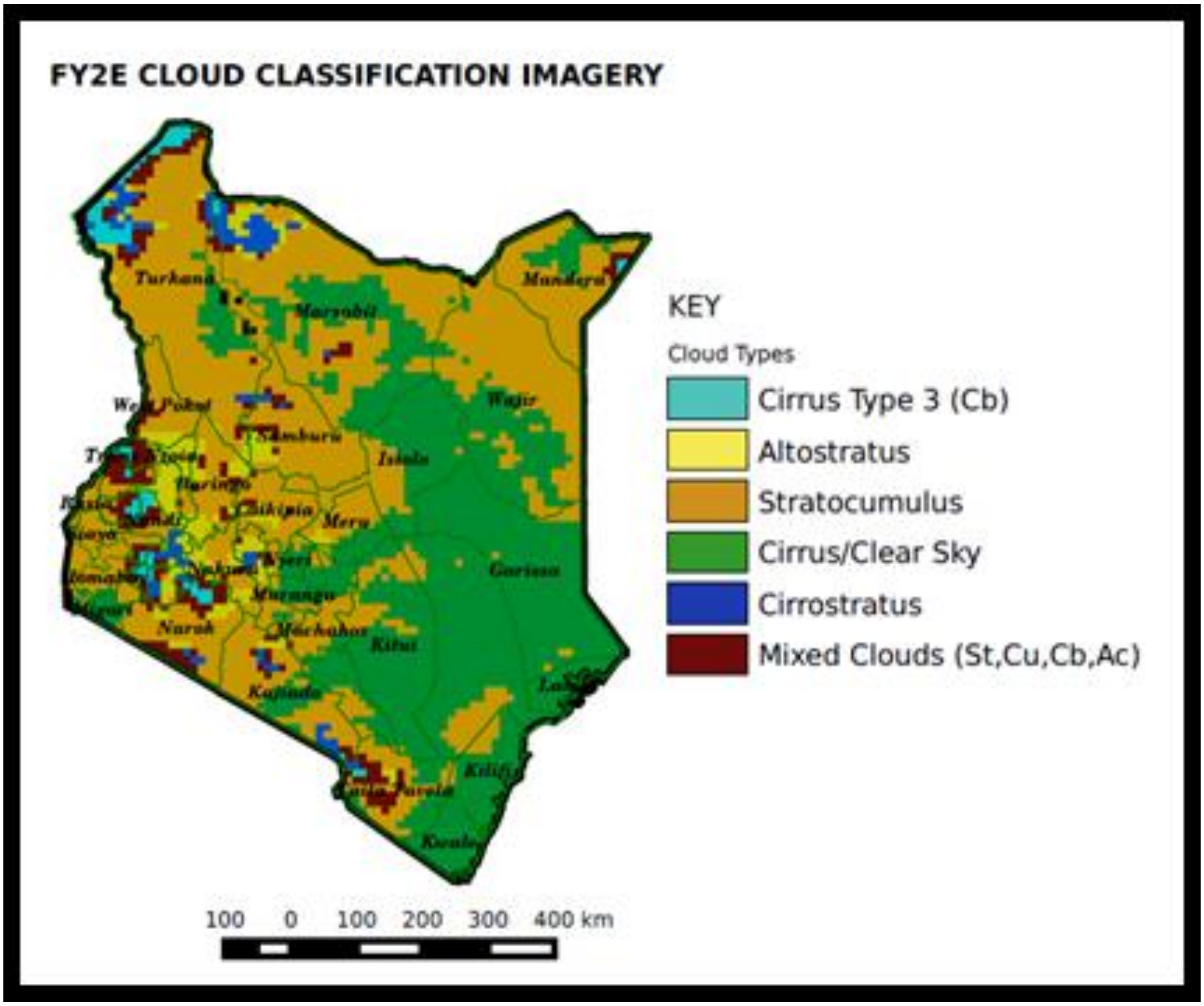

Figure 6: Cloud classification for the month of January, 2017. Source: FY-2E Satellite,

Figure 7 shows the cloud classification for the month of April, 2017as observed byFY-2E Satellite, and analyzed using Q –GIS. The figure shows that the sky was covered by almost all types of clouds during this season. The western part of the country was covered by Altostratus, Cumulonimbus in extensive spatial coverage, and dense Cirrus from Cumulonimbus clouds. The increase in the types of cloud observed during this season may be due to convergence of synoptic scale and local scale winds. This involves circulation due to high ground, synoptic, and the water bodies.

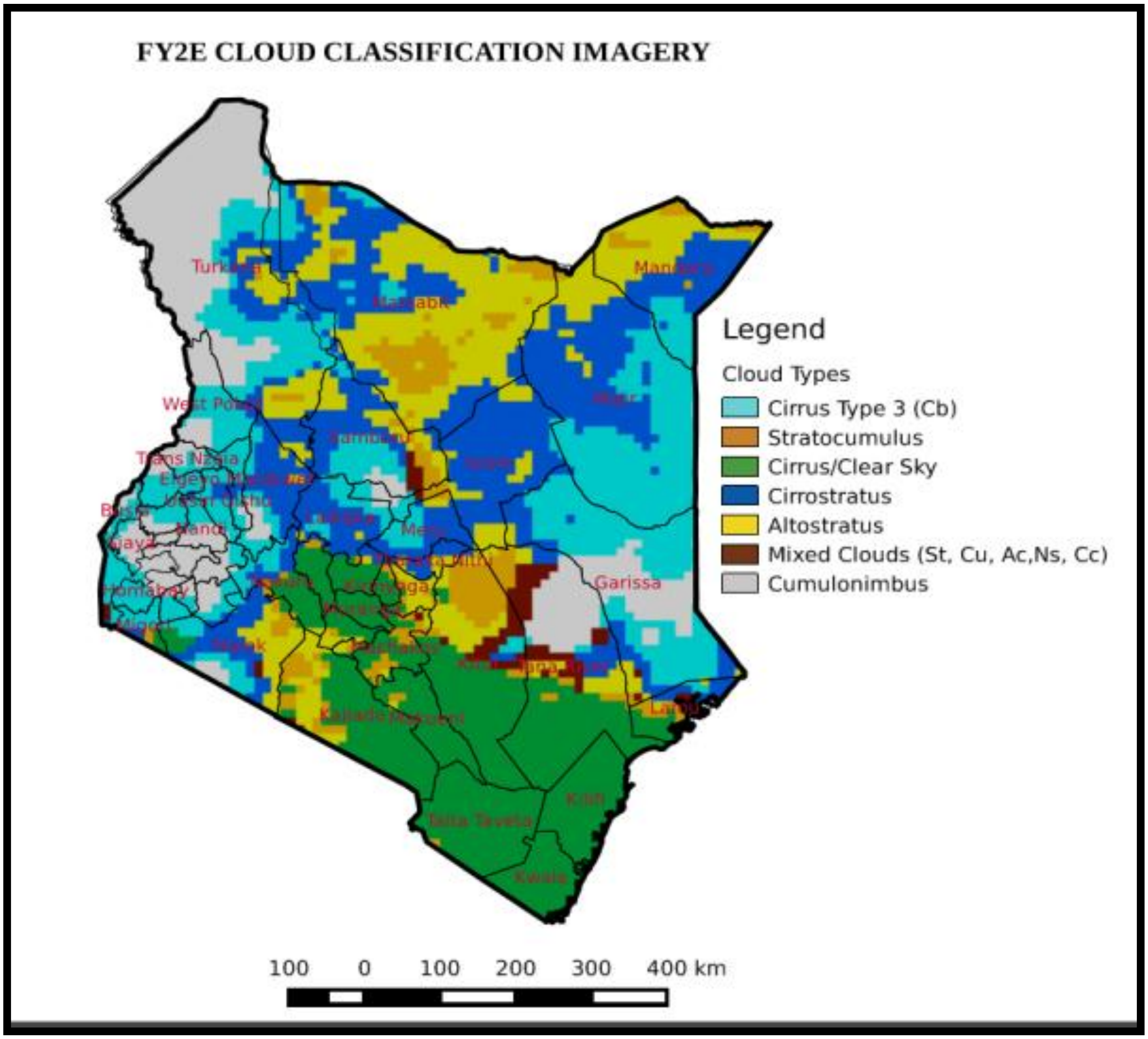

Figure 7: Cloud classification for the month of April, 2017. Source: FY-2E Satellite,

Meteosat Second Generation (MSG) cloud temperature indicates areas where there are deep clouds and a possibility of icing. Such regions can pose a danger to aircrafts.

Figure 8 shows the cloud temperatures as read by the Meteosat Second generation satellite, and analyzed using Q-GIS software. The figure shows that lowest temperatures were observed over western Kenya. Cloud temperatures, less than -40ºC, are associated with deep convective clouds. It therefore implies that even during drier months, Western and Rift Valley regions would still witness development of convective cells.

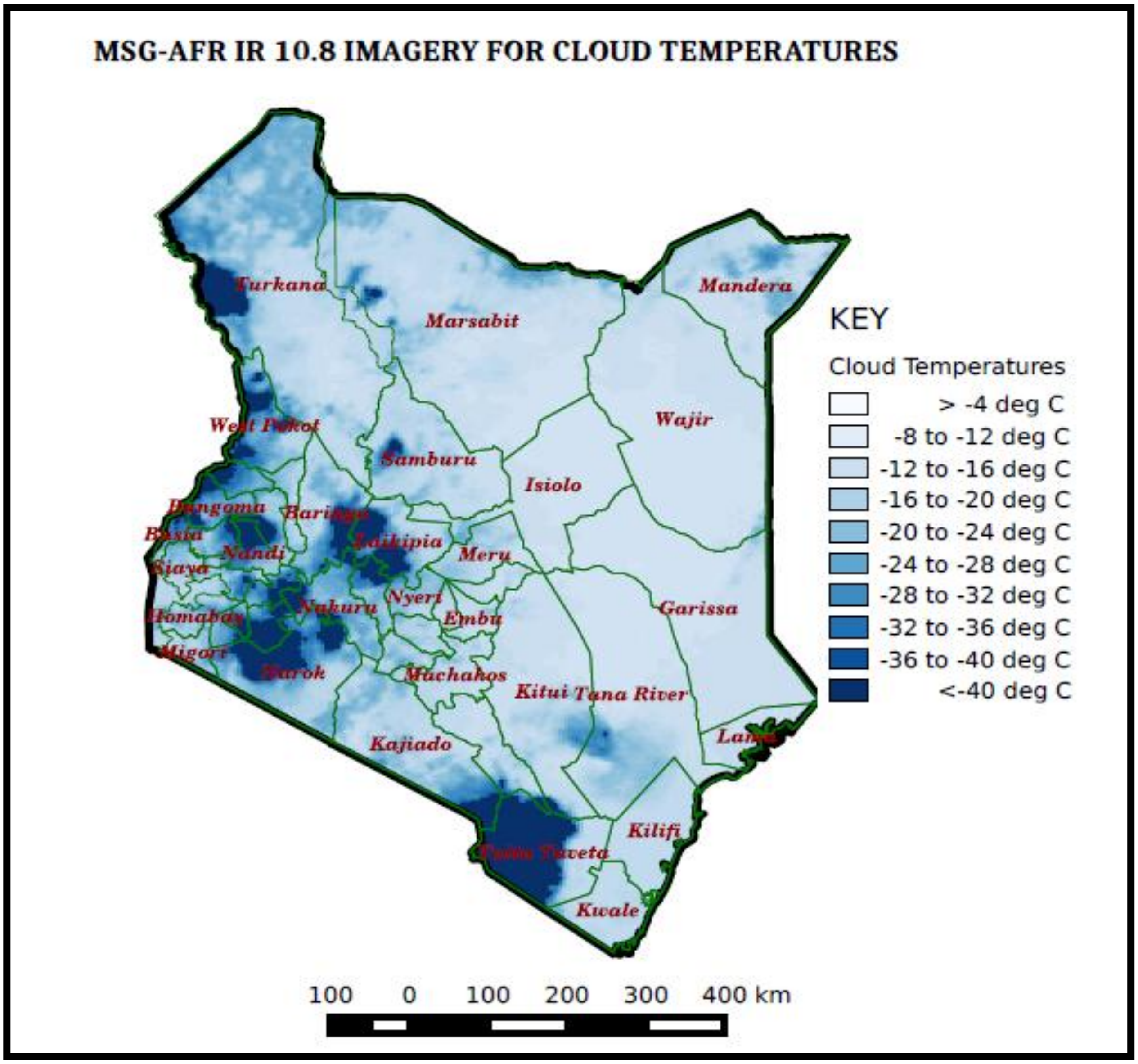

Figure 8: Cloud temperature for the month of January, 2017. Source: MSG,

Figure 9 shows the cloud temperatures as read by the Meteosat Second generation satellite, and analyzed using Q-GIS software. The figure shows that lowest temperatures were recorded over Western Kenya. There is an increase in the spatial coverage where cloud temperatures are less than -40ºC, which are clouds associated with deep convection. There are the darker regions, signifying deeper convective cells during the wet season.

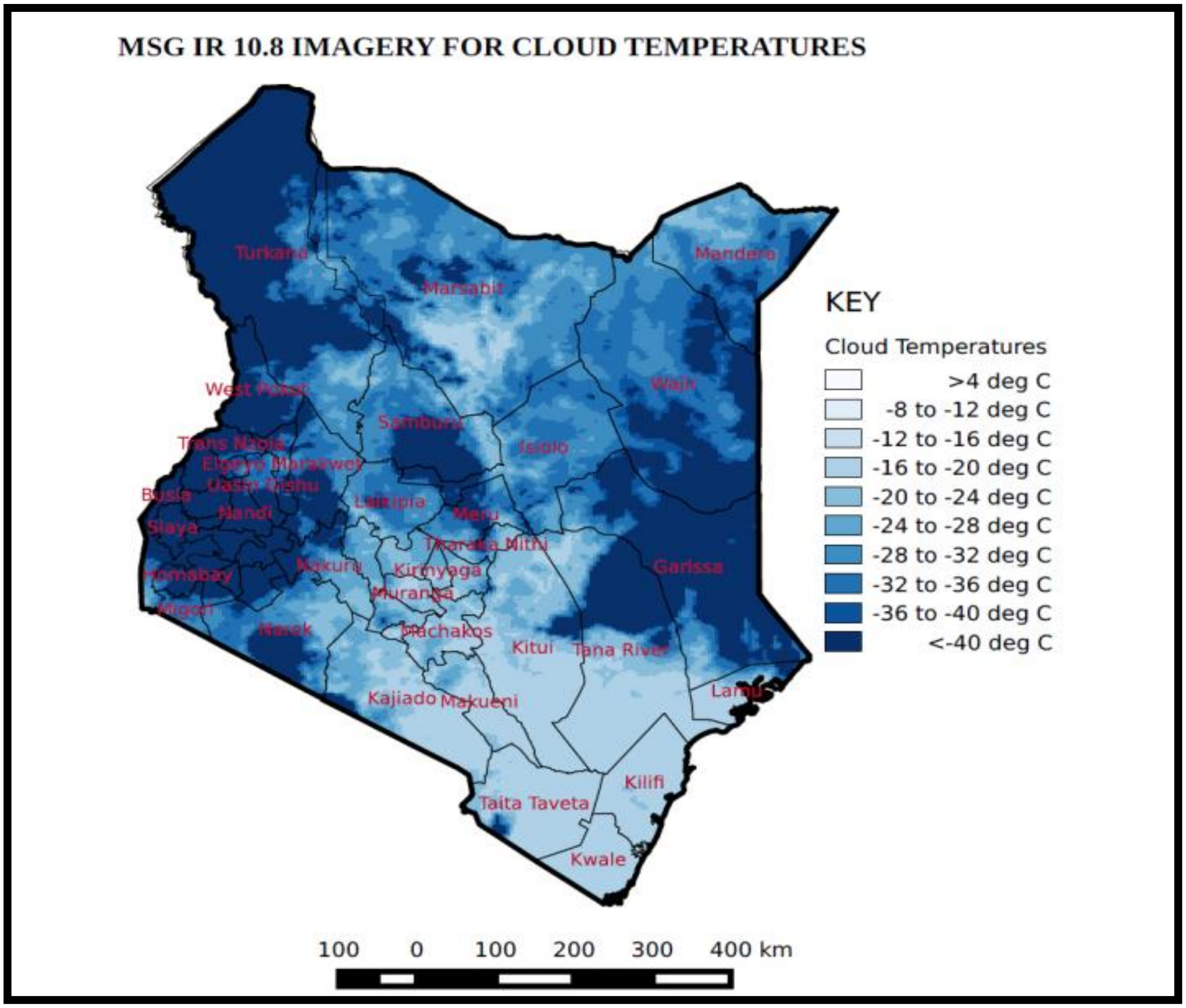

Figure 9: Cloud temperature for the month of April, 2017. Source: MSG,

Figure 10 shows the hotspot areas. The area which is shaded is showing where the aircraft weather hazards occurred in the current study. Nevertheless, as previously discussed, the hazards can occur at any other place over Kenya and the pilots should be cautious and use meteorological information as they fly over other regions which may appear to be safe.

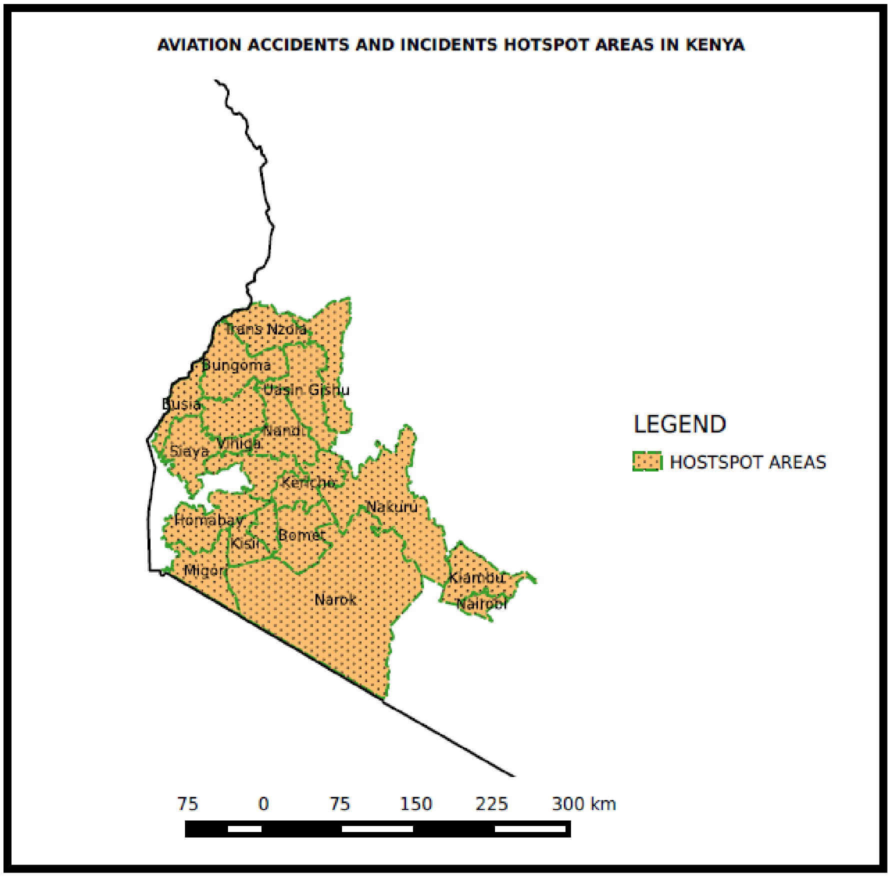

Figure 10: Hotspot areas for aviation related accidents and incidents Generated using Q-GIS.

4.2 Weather Hazards to Aviation

Severe weather that caused or contributed to aircraft accidents and serious incidents over Kenyan airspace from 2008 through 2014 is discussed. Figure 11 shows level of injury resulting from aircraft accidents. Analysis show that 12 percent resulted in fatality and damage to aircraft, 25 percent resulted in serious injury to passengers and crew members and damage to aircraft, and 63 percent resulted in minor injury to passengers and crewmembers or damage to aircraft due to severe weather condition. Some of the cases that were cited in the data include the ones that occurred at Maasai Mara, the right wing of the aircraft hit a tree and there was substantial damage sustained to fuselage, wings, tail section and main landing gear; near Wilson/Dagoretti, the pilot was fatally injured and the aircraft completely destroyed; at Kaptarkok primary school in Eldoret the aircraft was substantially damaged but no fatal incident reported; runway excursions- the aircrafts went off the runway after landing at JKIA RWY 06 and at Wilson Airport RWY 07;an aircraft experienced vibrations due to heavy landing at Eldoret Airport RWY 26; and two cases of missed approach during approach at JKIA RWY 06 on different occasions.

With regard to the figure, although the cases categorized to fatal are less than 50%, the impact is significant. In an analysis of injuries among pilots involved in fatal general aviation airplane accident- accident analysis and prevention, the study indicated that the primary objective of aircraft accident investigation is important for prevention of reoccurrences. On the other hand, the information about the nature of injuries sustained should also be given equal attention. This is because an analysis of injuries sustained during an accident can help to determine whether it was due to design of aircraft or it resulted from the prevailing environmental conditions. Such determination can guide and help establish crashworthiness standard and issues regarding a possibility of survival during a crash (Desjardins *et al.*, 1979).

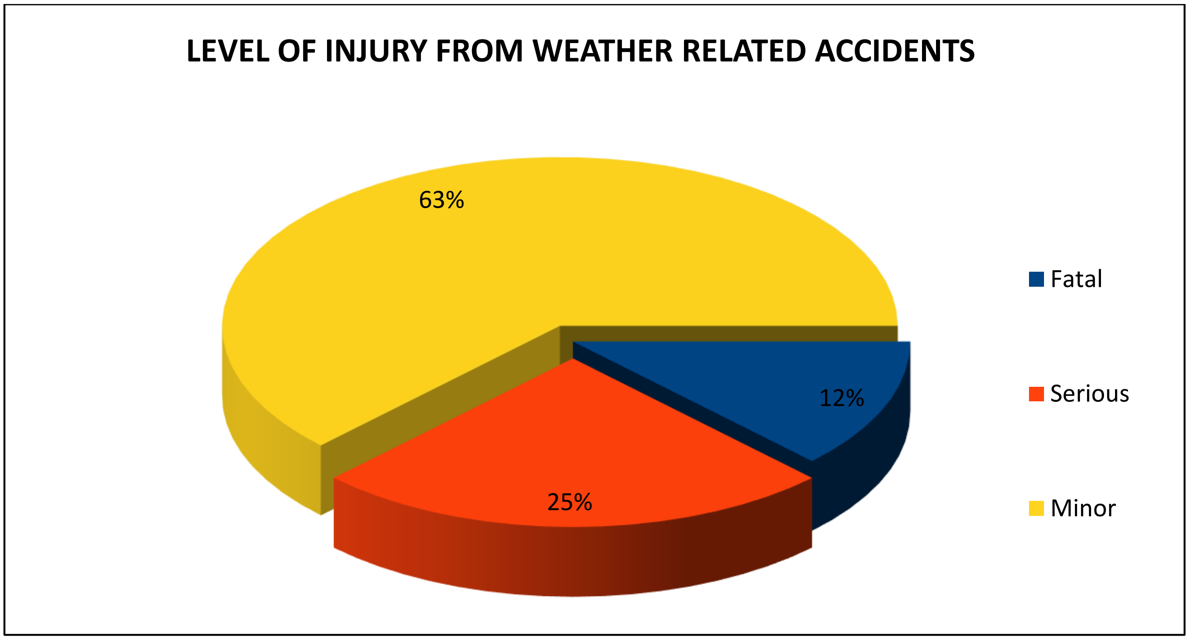

Figure 11: Weather-related Accident and Incident Injury and damage to aircraft over Kenyan airspace; 2008-2014.Source: KCAA Aviation Accident and Incident Database

Figure 12 shows breakdown of weather hazards over Kenyan airspace. The figure tells us which one is dominant. Overall it can be noted that most of these hazards were associated with severe weather that were linked with cumulonimbus cloud. The factors that influenced the accidents and incidents were crosswind 11 %, turbulence 11 %, and visibility/ceiling 78 %.

From the data it was cited that the aircraft experienced vibrations on landing at Eldoret Airport RWY 26 due to heavy landing resulting from crosswind and heavy rain showers that were produced by cumulonimbus clouds. Another incident occurred on the same runway during takeoff due to turbulence encounter near the surface and caused damage to aircraft but no fatal incident. Majority of accident and incident cases were due to visibility/ceiling and clouds. At Wilson Airport RWY 07 runway excursion occurred due to low cloud base. Thick fog encounter at JKIA RWY 06 caused another runway excursion-the aircrafts went off the runway after landing.

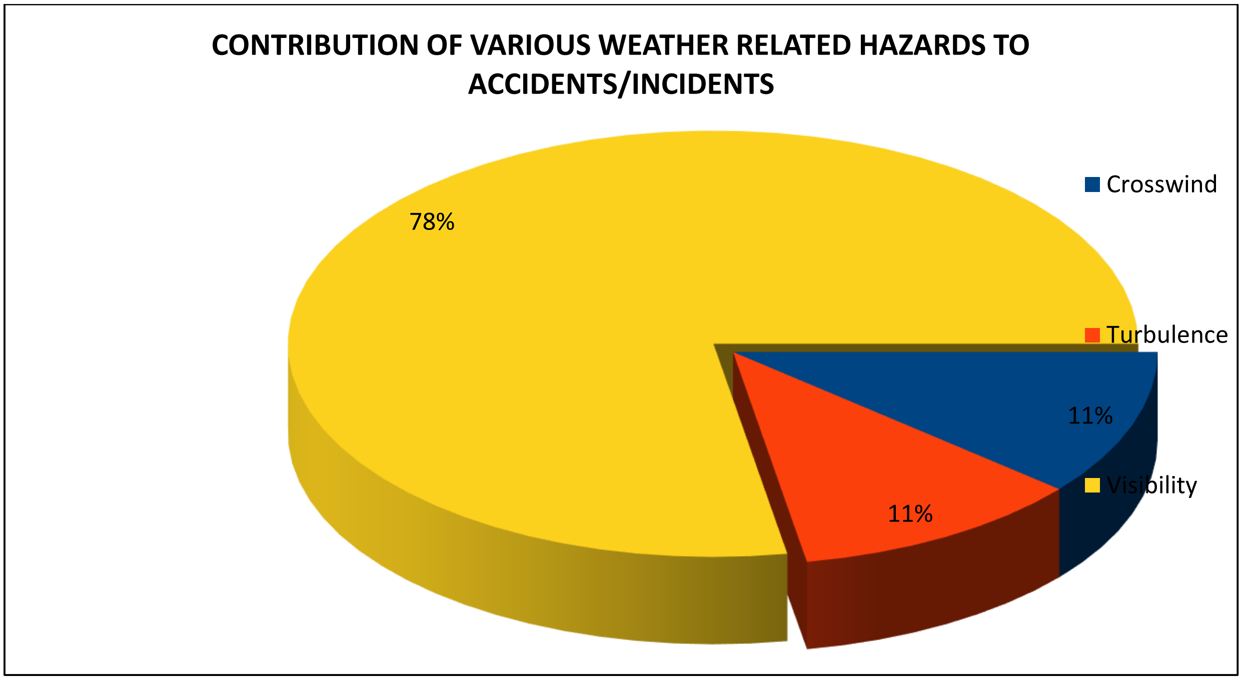

Figure 12: Breakdown of Weather-related Accident and Incident Citations over Kenyan airspace 2008-2014. Source: KCAA Aviation Accident and Incident Database.

Figure 13 shows the distribution of accidents and incidents over Kenya according to the phase of flight. The figure shows that the accidents and incidents were common when the aircrafts were landing, taking off and during Go-Around/Missed Approach. Other phases of flight cited are Approach and Emergency landing after takeoff due to fog, heavy rain showers, turbulence, and crosswind encounters. The figure tells us that landing is the most dangerous phase of flight.

The figure shows the lowest kilometer of the atmosphere referred to as atmospheric boundary layer where there are more weather activities. The aircraft has come where turbulence is generated as the wind blows over the earth's surface. There is also a possibility of the presence of thermals associated with clouds or generated as a result of uneven heating of the earth's surface by the sun. The pilot having managed coming near the ground may opt to land-set for landing. Landing becomes the appropriate action but the condition of the runway and the weather could cause mishaps.

Sharman *et al*,. (2015) in a study on the effects of rain to aviation noted that torrential rain, due to the effect of poor visibility and flooded runways, has significant effect on airplane in landing configuration. This may explain why landing phase of flight is most affected by weather hazards when compared with other phases.

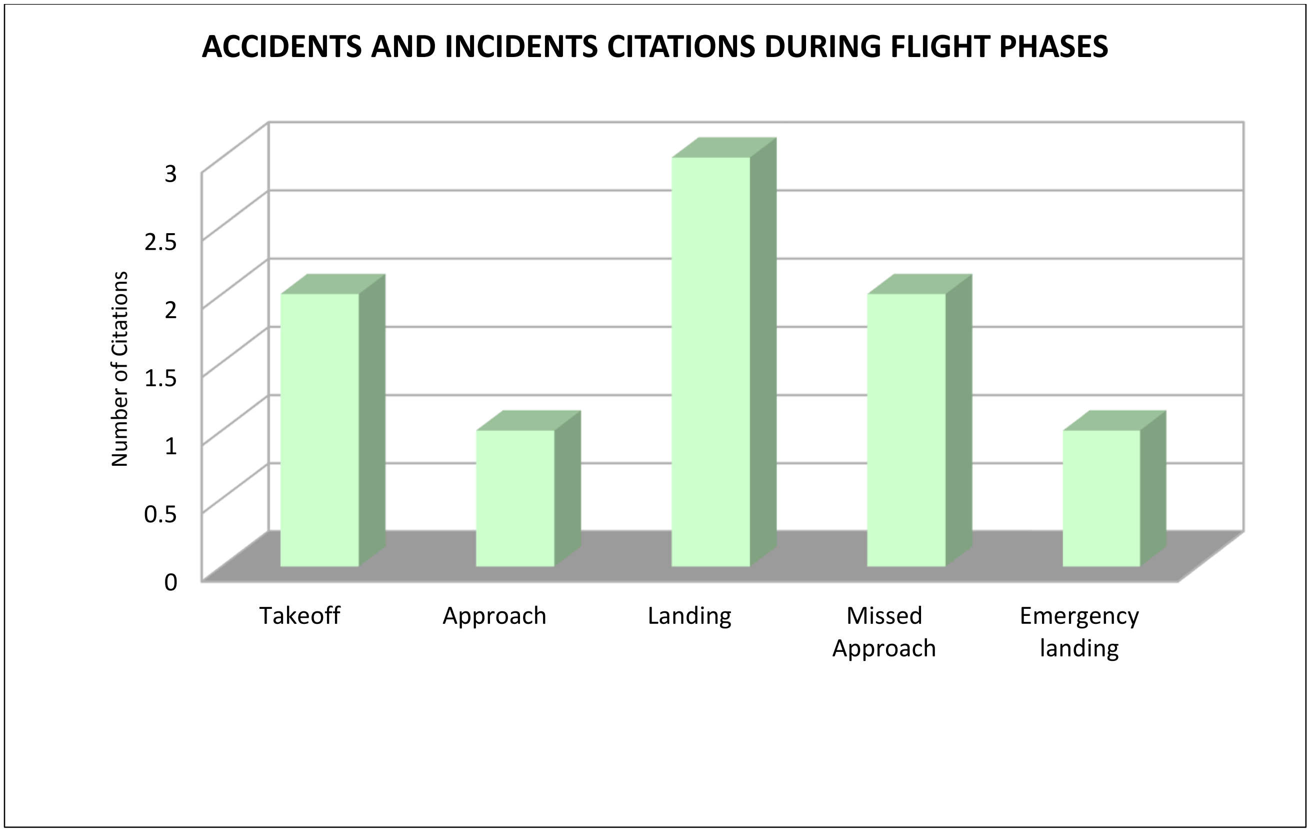

Figure 13: Accidents and Incidents Citations by Phase of Flight over Kenyan airspace 2008-2014.Source: KCAA Aviation Accident and Incident Database.

Figure 14 shows that low ceiling, heavy rain showers, and fog caused accidents/incidents over Kenyan airspace. Low ceiling was the overall leading type of phenomena related to visibility that influenced weather-related accidents/incidents from 2008 through 2014.The data cited low clouds as either being broken or overcast and this has an impact when a pilot is on the landing phase of flight- the runway cannot be viewed by the pilot due to obscuration by low clouds.

Wilkinson *et al.,* (2013) in a study noted that stratocumulus clouds are not only dangerous because they can limit view of runway but the potential danger lies in the fact that cumulonimbus clouds are at times embedded in the stratocumulus clouds and this would mean that the pilots can unknowingly fly through the dangerous cloud both when landing or taking off. The study warned that cumulonimbus clouds should be avoided by pilots due to the hazards that are associated with the cloud.

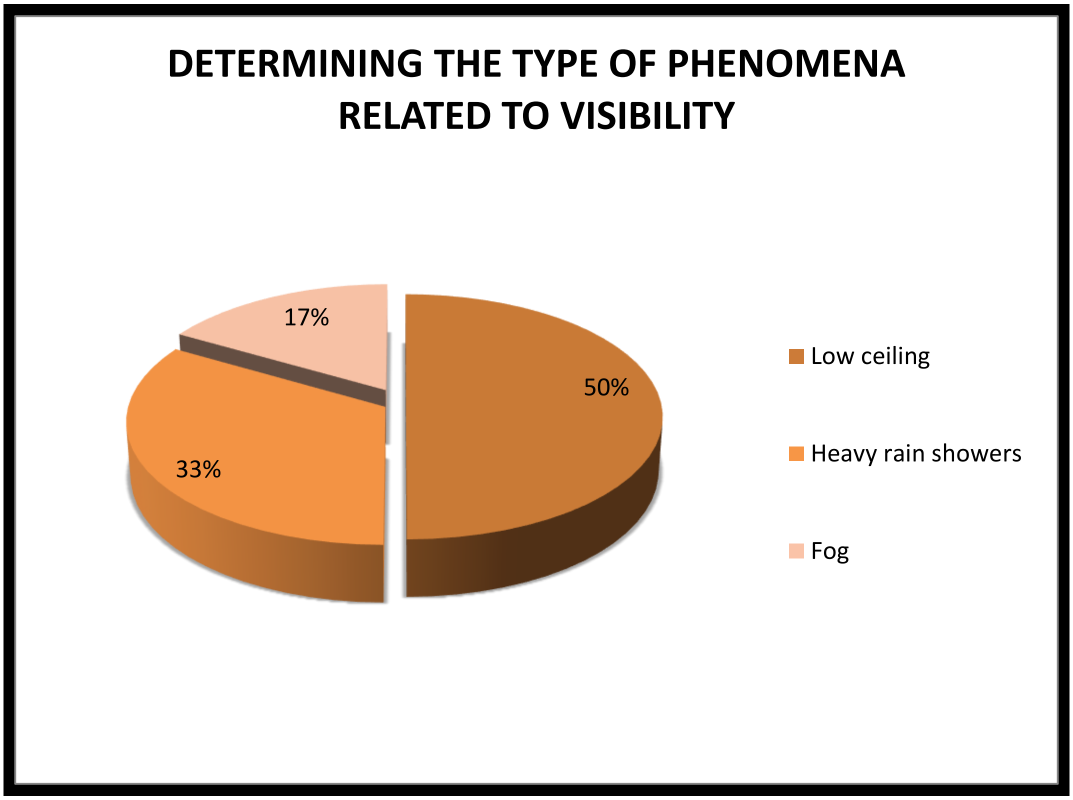

Figure 14: Visibility/Ceiling Citations over Kenyan airspace 2008-2014; Source: KCAA Aviation Accident and Incident Database

4.3 Simulated Weather Distribution over Kenya

The results from the simulation using the Weather Research and Forecasting (WRF) Model are discussed in this section. The weather parameters analyzed include Wind at 10m level, Surface temperature, Lifted Index (LI) at 500mb level, Convective Available Potential Energy (CAPE), Relative Humidity (RH) at 700mb level, and Dew point temperature at 2m level.

Figure 15 shows the 1200Z Surface temperatures drawn together with the 10m winds. From the figure, the surface winds are predominantly South Easterlies over most parts of the country. The winds converge over the central and western highlands. The temperatures are high over the Coast, Eastern and North Western sectors of the country, and low over the western, southwestern and central parts of Kenya. From the figure, it is noted that enhanced surface convergence is witnessed over the high ground areas. The wind convergence is giving us the lifting mechanism. If other conditions are available we should expect the area to be active.

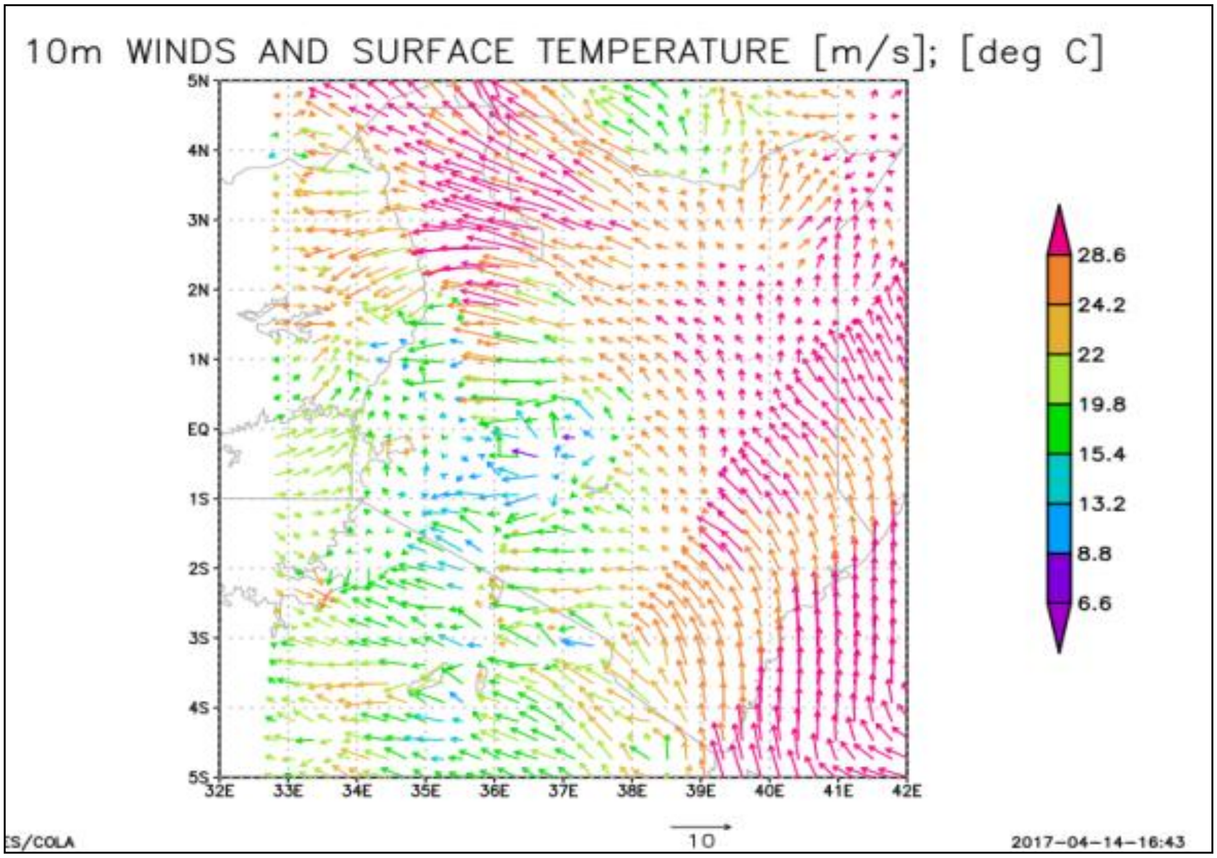

Figure 15: 12Z Surface Temperatures superimposed on 10m winds. Source: WRF model run on the 14-04-2017**.**

Figure 16 shows Lifted Index at 500mb level. Values between -4 degrees to -6 degrees would favor thunderstorm development; negative 6 degrees of LI or lower, usually yields severe thunderstorm; and Positive values of LI imply no major convective development. From the figure, most of the places, especially over the western half of the country, had LI indices above 0ºC. This implied stability, with minimal activities at this particular hour over the western part of the country. Much of the eastern half had negative indices, suggesting that the region would benefit from convection instability.

Lifted index shows that the static stability was generally stable despite the convective mechanism over a large area. The mechanism is there but we can also see the convective energy is low. This could be attributed to low temperatures over the region.

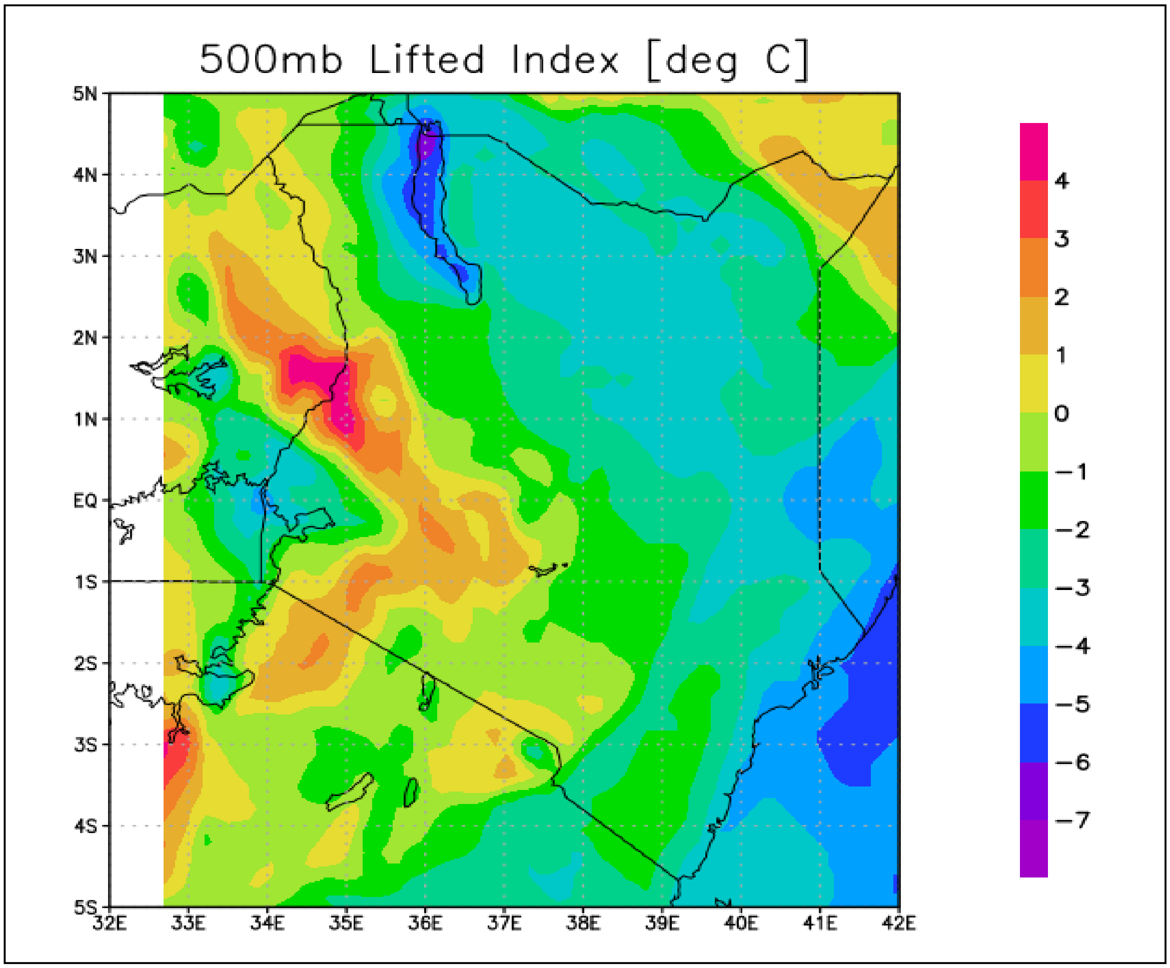

Figure 16: 500mb level Lifted Index. Source: WRF model

Figure 17 shows the distribution in space of the Convective Available Potential Energy. From the figure, most places over the central and western parts of the country were stable at this hour. We see that these areas with less trigger mechanism have higher convective energy. CAPE gives us energy of the whole depth which is telling us that most of the areas did not have convective potential energy.

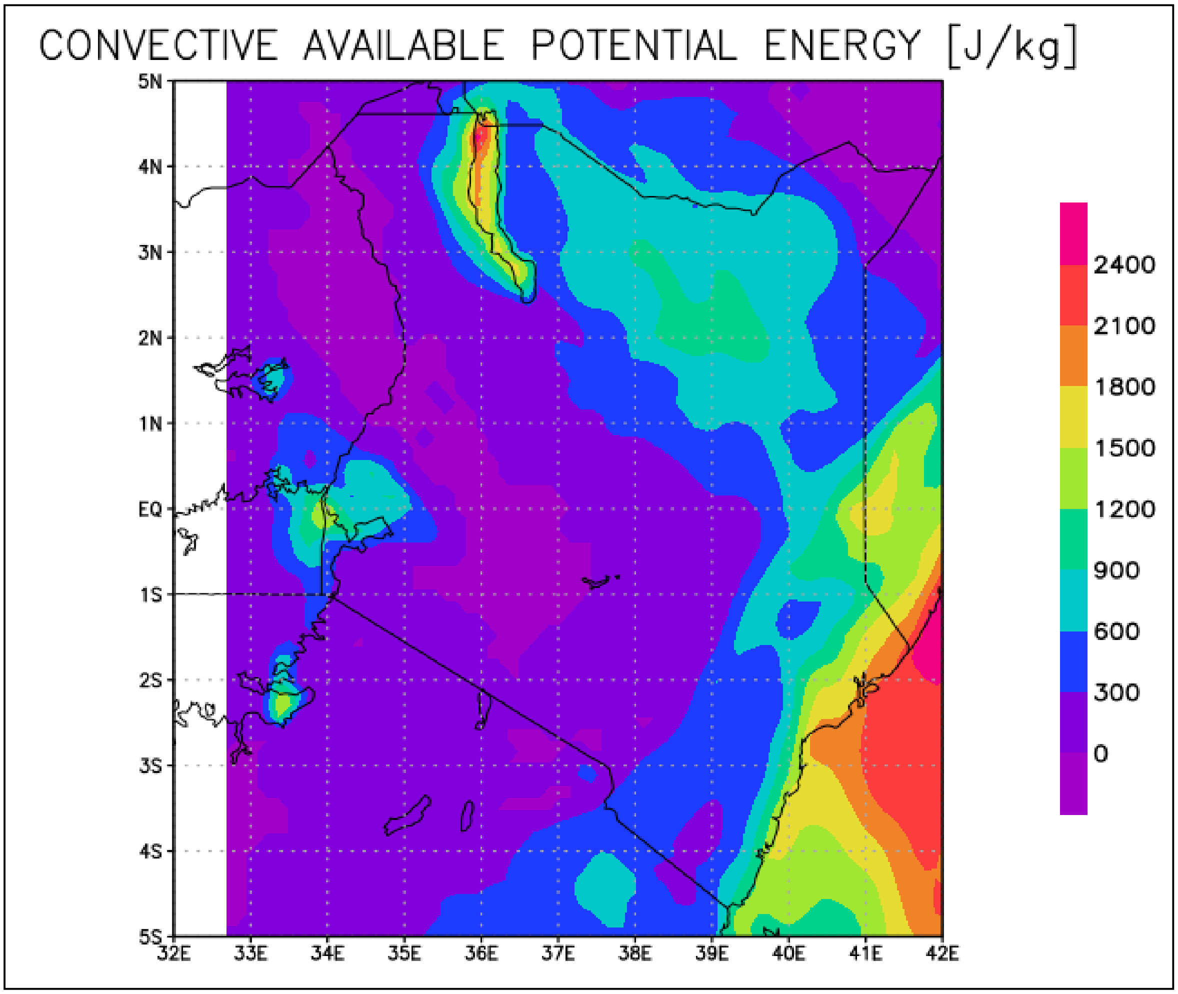

Figure 17: CAPE. Source: WRF model

Figure 18 shows relative humility profile at 700mb level. Relative humidity was generally above 50% over most parts of the country, hitting 80-100 % over the western and central and northern parts of the country. These values, especially over the western, central and northern parts, should supply sufficient moisture. There seems to be more supply over the lake region while other areas are generally low- there was less moisture supply over most parts of the country.

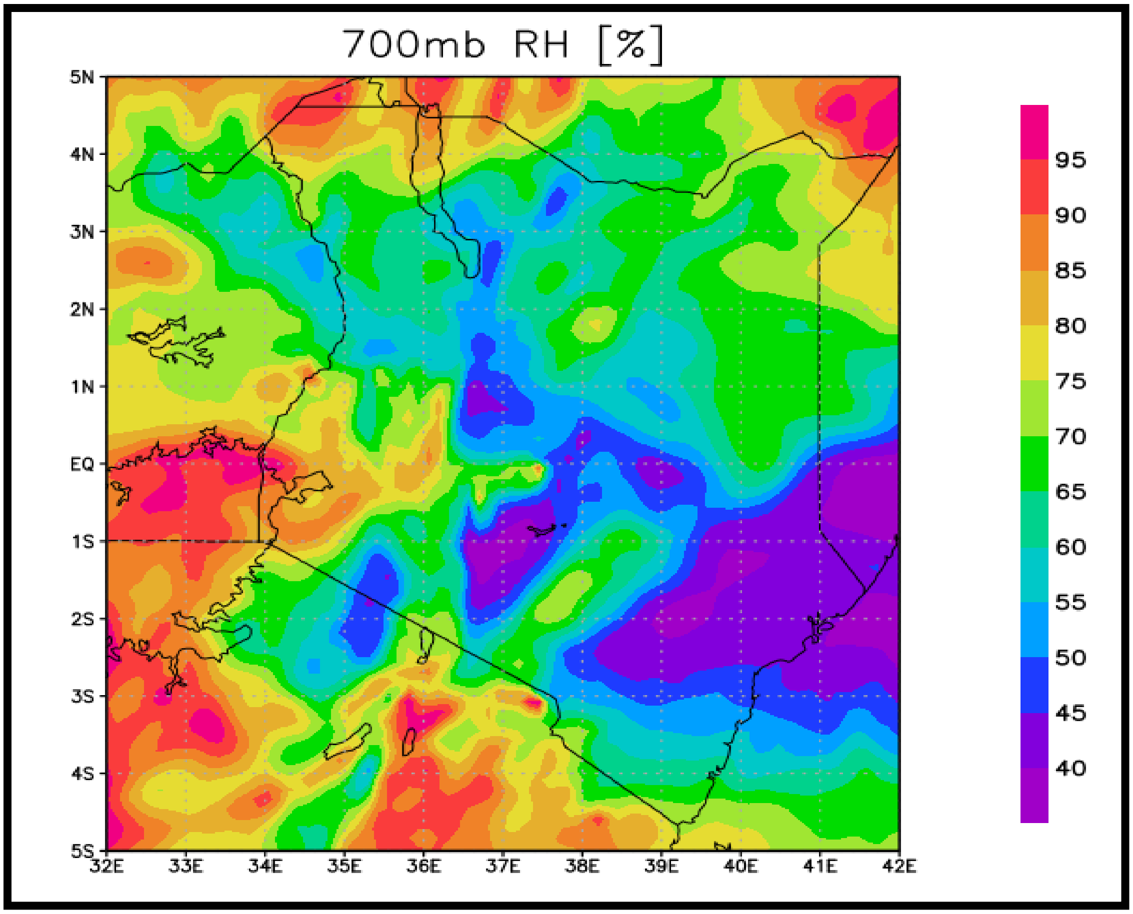

Figure 18: RH at 700mb. Source: WRF Model

Figure 19 shows the contours of dew point temperatures at 2m. Dew point temperature is a measurement of low-level moisture content. The distribution map shows high values of dew point temperature on the eastern parts of the country and relatively low values on the western parts. The lower the value of the dew-point temperature the lower the saturation state of the air. From the figure it can be seen that at this time, the eastern part of the country had relatively higher values, with the western half of the country reporting lesser values.

It therefore implies that the western part of the country is less humid and the eastern region more humid. At the surface the lower the dew point the lower the moisture- the higher the dew point the higher the moisture.

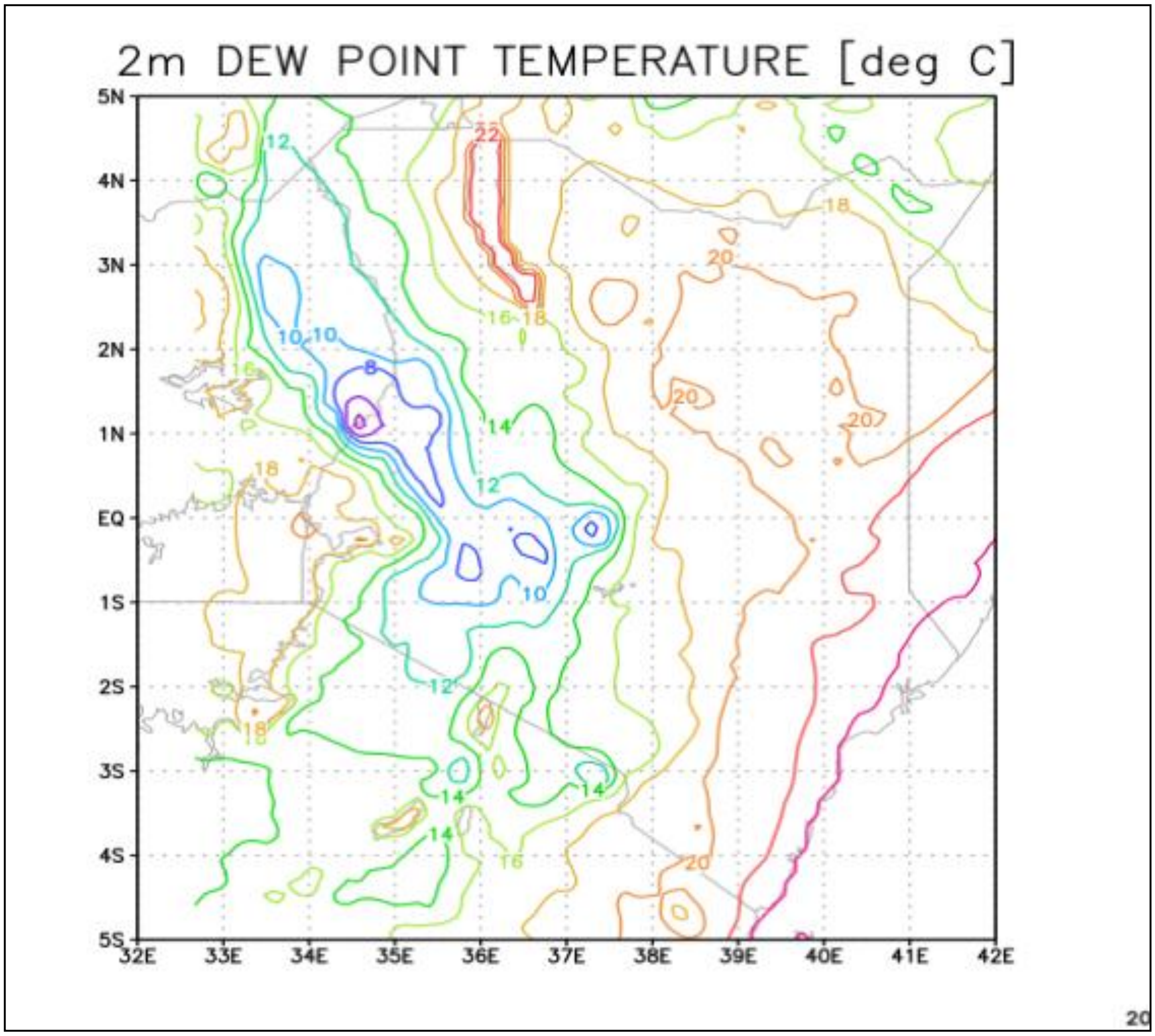

Figure 19: 2m Dew Point Temperature. Source: WRF model

The parameters that are aforementioned are useful in identifying areas where aircraft weather hazards occur over Kenya. What was observed is agreeing with the indices in the model thus telling us the model can identify these hotspots. We have seen that generally areas of cumulonimbus clouds are limited. Where there was strong lifting mechanism, moisture was deficient and where moisture was available the lifting mechanism was slightly weaker. Wind patterns tell us the areas where hazards are likely to occur. Based on the winds, the wind convergence is giving us the lifting mechanism. Most areas did not have convective potential energy which is supported by the lifted index. The cold environmental temperature seemed to have lowered the static instability.

Energy is a function of moisture andif the dew point temperature is low we have to raise moisture to a higher level since the Level of Free Convection (LFC) ishigh. We need to lift the parcel of air until this level is attained to enable it to have buoyancy to rise on its own. The area to be integrated between the level of free convection and the equilibrium level is high hence the area of CAPE is small-convective available potential energy is small. This is the positive buoyant energy which is the buoyant heat a parcel of air has between Level of Free Convection(LFC) and Equilibrium Level (EL).

There are areas where conditions of potential are available but it lacks a push due to diffluence-trigger mechanism was lacking in such regions. We have to combine the potential, trigger mechanisms, and moisture cumulatively. The accumulated effect seem to point that we should expect intense activity over the lake region as is informed by the cloud imagery on figure 20.It shows that if we assimilate the parameters even without the cloud imagery they should tell us what to expect. These various parameters when analyzed we should be able to identify the hotspots.

The widespread coverage of clouds and increase of cloud types during the wet season with minimum activity may be due to lack of potential convection and other conditions are not enhanced. When all the parameters were put together they were able to give us the resultant which is the type of clouds we are looking for- the amount of clouds that covered the sky was ranging from 1 to 2 octas (few) over the lake. Nevertheless the aim was to see whether the combination of the parameters could identify the areas. The areas where they agree is over the lake region where we observe cumulonimbus clouds. This is confirmed with the cloud image shown below.

Figure 20 shows the FY2E satellite cloud genera over the area of current study. The figure places most convective cloud types, majorly over the western region of the country, just as the model had captured.

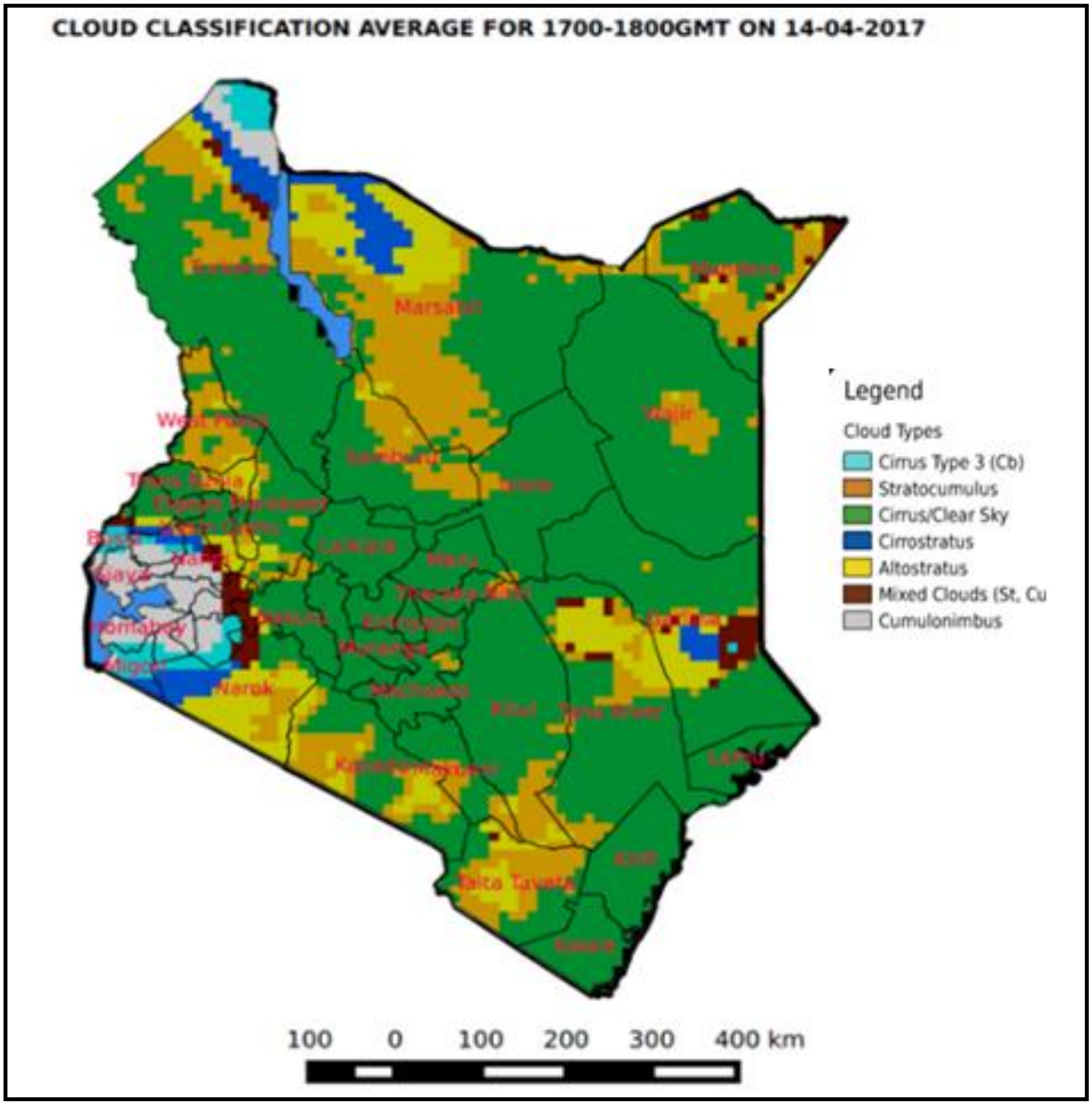

Figure 20: Cloud classification averaged between 1700 and 1800 UTC on 14-04-2017. Source. FY2E Satellite

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The study showed that from the occurrences turbulence, and visibility contributed to various accidents and serious incidents with visibility being the most commonly cited as being associated with the majority of the incidents. The analysis of injuries/damages indicated that they were caused by weather-related hazards. Although the fatal and serious levels associated with weather is less than 50%, it is nonetheless significant.

Highest incidents occurred during the landing phase of flight suggesting that landing is the most vulnerable phase of the flight. The most prevalent cause of visibility during this phase is low ceiling due to low level clouds that cover the whole sky hence obscure the view of the runway during landing configuration. Crosswind and turbulence though together they contribute about 20%, the incidents associated with them are the most serious. The observed turbulence are associated with deep convective clouds which can easily be identified from the satellite imagery. From the information pilots can be warned and the most dangerous cloud is cumulonimbus.

The study showed that Highlands West and East of the Rift Valley experienced most clouds most parts of the year. The frequencies of the most dangerous clouds are observed over these regions. The result from the simulation using Weather Research and Forecasting (WRF) Model showed that the parameters such as Winds at 10m level, Surface temperature, Lifted Index(LI) at 500mb level, Convective Available Potential Energy (CAPE), Relative Humidity (RH) at 700mb level, and Dew Point Temperature at 2m level can be used to identify the areas where the particular clouds occur.-when we combine them they are able to tell us the area of convection and hence provide the means of prediction.

5.2 Recommendations

The following are the recommendations, having considered the results of the study.

5.2.1 To Aviation Sector

The hotspot areas have been identified. The study has shown that most of the cumulonimbus clouds are frequent over the routes to the main destination of the local flights. They can however avoid the weather hazards if the planners properly schedule their flights at the time when we have more likelihood.

5.2.2 To Researchers

In the current study the hotspot areas were identified in respect to cumulonimbus clouds but we also need a map to mark other areas in respect to other hazards. The China based Geostationary Fengyun 2E (FY2E) satellite was used to identify and classify the clouds during wet and dry seasons over the study area and the Meteosat Second Generation (MSG) Infrared 10.8 satellite was used to determine the cloud temperatures and areas where there were deep convective clouds - development of convective cells were easily identified. The results from the two tools were in agreement however we need facilities for characterization of clouds to be obtained for finer details - the Fengyun in certain cases could not give finer details and a number of clouds were grouped as mixed clouds.

5.2.3 To Socio-economic Planners

This study recommends that airstrips situated in other areas which are less vulnerable can be expanded as alternative landing aerodromes when there is problem in Nairobi due to bad weather. Expansion of airstrips that are not located within the area of problem but are nearby such as Isiolo and Garissa can then be better options for aircrafts to be diverted to the aerodromes when severe weather condition is observed or reported.

5.2.4 To Kenya Meteorological Department

The department needs to invest into modeling by training more personnel in modeling; to buy high speed computers; and to invest into data initialization (regional data analysis) on finer resolution. In order to achieve this they need to improve the grid to provide information not only to pilots but also to other users.

They can undertake pilot observation to help improve in the data resource because there are many things that happen on mesoscale that we cannot capture on synoptic scale. They can undertake intense network for 6 months or 1 year and use the data in improving the analysis. This would enable them to capture the patterns that occur to be able to capture sub-synoptic scale features.

The study has demonstrated the potential of the model and I recommend that the department take a step and it becomes operational.

REFERENCES

Ackerman A.S., Van Zanten M.C., Stevens B., Savic-Joycic V., Bretherton C.S., Chloud A., Golaz J.C., Jiang H., Khairoutdinov M., Krueger S.K., Lewellen D.C., Lock A., Moeng C.H., Nakamura K., Petters M.D., Snider J.R., Weinbrecht S., and Zulauf M., 2009: *Large-eddy Simulations of a drizzling , Stratocumulus-topped Marine boundary layer, Mon.Weather* Rev.**137**: 1083-1110.

AOPA(Airport Owners and Pilots Association)s, 2008:*Weather- Related Aviation Accident Study 2003-2007 Aircraft Icing.*

Barnett T.P., 1981: *Statistical Prediction of North American air temperature from Pacific Predictors. Mon.Wea.Rev*. **109**:1021-1041

Banett T.P., and Hasselmann K., 1979: *Techniques of linear prediction, with application to oceanic and atmospheric fields in the tropical pacific.Rev.Geophys.Space* Phys.**17**: 949-968.

Belo-Pereira M., 2015: *Comparison of in-flight icing algorithms based on ECMWF(European Centre for Medium-Range Weather Forecasts) forecasts. Meteorological Applications.22:705*-715

Bothwell P.D., 1988: *Forecasting Convection with the AFOS Data Analysis Program (ADAP).NOAA Tech.Memo.SR-122, NWS Southern Region, Fort Worth, TX*. 92pp.

Desjardins S.H., Laananen D.H., Singley G.T., III, 1979:*Aircraft Crash Survival Guide (USARTL-TR-79-22A). Applied Technology Laboratory, US Army Research and Technical Laboratory (AVRADCOM), Ft Eustis, VA.*

Galway J.G., 1956: *The lifted index as predictor of latent instability. Bull, Amer, Meteor.Soc.***37**:528-529.

Gidel L.T., and Shapiro M.A., 1979: *The role of clear air turbulence in the production of potential vorticity in the vicinity of upper tropospheric jet stream-frontal systems. J. Atmos. Sci.***36:**2125–2138.

Gill P.G. and Buchanan P., 2014: *An ensemble based turbulence forecasting system. Meteorological Applications.***21**: 12-19

Gultepe I., Pearson G., Milbrandt J.A., Hansen B., Platnick S., Taylor P., Gordon M., Oakley J.P., and Cober S.G., 2009:*The fog remote sensing and modeling field project. Bull. Am. Meteorol. Soc.* **90**: 341–359.

Hardwick C,J., 1999:*Assessment of Lightning Threat to North Sea Helicopters: Final Report. Paper 99007. Civil Aviation Authority: London.*

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

Li G., Baker S.P., 1999:*Correlates of pilot fatality in general aviation crashes.Aviat. Space Environ. Med.* **70**: 305–309.

Mahoney W.P., III, 1988: *Gust front characteristics and the kinematics associated with interacting thunderstorm outflows. Mon. Wea. Rev.***116**: 1474-1491.

Mahringer G., 2008:*Terminal Aerodrome Forecast Verification in Austro Control Using the Windows & Ranges of Forecast Conditions.Meteorologicalapplications.* **Vol.** 15: 113-123

Maloba S., 2015: *Spatial and Temporal Characteristics of Thunderstorms over the Eastern Region of Lake Victoria Basin in Kenya.MSC Project Report. Department of Meteorology*.

McNulty R.P., 1983: *Some basic elements of thunderstorm forecasting. NOAA Tech. Memo.NWS CR-69*. 13 pp.

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

Mwebesa M.N., 1978: *Elementary Meteorology for Observers. Meteorological Training and Research (IMTR).* 88-105 pp.

Ngaina J.N., 2015: *Modeling Aerosol-Cloud Precipitation Interactions forWeather Modification in East Africa Ph.D.Project Report. Department of Meteorology.*

NTSB (National Transportation Safety Board), 2010:*U.S. air carrier operations -Annual review of aircraft accidentdata.NTSB/ARC-10/01. Washington,DC*. 57 pp.

OAEP(Office of Aviation Enforcement and Proceedings), 2008: Air *Traffic Consumer Report, Department of Transportation.*14–23.pp.

Okoola R.E., 2005: *Aeronautical Meteorology (SMR 312).University of Nairobi Press.* 42-49 pp.

Pane G.A., Mohler S.R., Hamilton G.C., 1985:*The Cincinnati DC-9 experience: lessons in aircraft and airport safety. Aviat. Space Environ.Med*. **56**: 457–461.

Pantley P.F., Lester K.C., 1990:*Observations of severe turbulence near thunderstorm tops. J. Appl. Meteorol. Climatol.* **29**: 1171–1179.

Pike W.S., 1995:*Extreme warm frontal icing on 25 February1994 causes an aircraft accident near UttoxeterMeteorol.Appl.***2**: 273–279.

Rauber R.M., Tokay A., 1991:*An explanation for the existence of supercooledwater at the top of cold clouds. J. Atmos. Sci.* **48**: 1005–1023.

Saito K., Fujita T., Yamada Y., 2006: *The operational JMA non hydrostatic mesoscalemodel.***Vol.** 134, no. 4, 1266–1298 pp.

Scanlon, Charles H., 1992: *A Graphical Weather System Design for NASA Transport Systems Research Design for NASA Transport Systems Research Vehicle B-737.NASATechnicalMemorandum 104205.*

Schowalter A.K., 1953: *A stability index for thunderstorm forecasting.Bull.Amer.Meteor.Soc*. **34:**250-252.

Shapiro M.A., 1980: *Turbulent mixing within tropopause folds as a mechanism for the exchange of chemical constituents between the stratosphere and troposphere. J. Atmos. Sci.,* **37:**994–1004.

Sharman H.,HarsheS.,Vekaria S., Singh M.,Damodaran M., Beo Cheong, Khoo., 2015: *Computational Assessment of Rainfall Effects on Aircraft Aerodynamic Characteristics*. *33rd AIAA Applied Aerodynamics Conference.*

Sharman R.D., Cornman L.B., Meymaris G., Pearson J., Farrar T., 2014:*Description and derived climatologies of automated in situeddy-dissipation-rate reports of atmospheric turbulence. J. Appl.Meteorol. Climatol.* **53**: 1416–1432.

Skamarock W.C., Klemp J.R., Dudhia J., Gill D.O., Barker D.m., Duda M., Huang H., Wang W., and Powers J.G., 2008: *A description of advanced research WRF Version.***3**:53.NCAR.Tech.Note.

Smith A.J., Larson V.E., Niu J.,Kankiewicz J.A., Carey L.D., 2009:*Processes that generate and deplete liquid water and snow in thin mid-level mixed-phase clouds. J. Geophys. Res.***114**: D12203, DOI: 10.1029/2008JD011531.

Verlinde J., Harrington J.Y.,Yannuzzi V.T., Avramov A., Greenberg S.,Richardson S.J., Bahrmann C.P., McFarquhar G.M., Zhang G., Johnson N.,Poellot M.R., Mather J.H., Turner D.D., Eloranta E.W., Tobin D.C., HolzR,Zak B.D., Ivey M.D., Prenni A.J., DeMott P.J., Daniel J.S., Kok G.L., SassenK.,SpangenbergD.,MinnisP.,ToomanT.P.,Shupe M., HeymsfieldA.J., Schofield R., 2007:*The mixed-phase Arctic Cloud Experiment. Bull. Amer.Meteorol. Soc.***88**: 205–221.

Vivekanandan J.G., Thompson and Lee T., 1996: *Aircraft icing detection using satellite data and weather forecast model results.*FAA.365-373 pp.

Waitz I., Townsend J.,Cutcher-Gershenfeld J., Gereitzer E., Kerrebrock J., 2004: *Aviation and the environment. A national Vision Statement, Framework for Goals and Recommended Actions.*1-52 pp.

Wang H. and Feingold G., 2009: *Modeling Mesoscale Cellular Structures and Drizzle in Marine Stratocumulus Part 1: Impact of Drizzle on the Formation and Evolution of Open Cells.Journal of the Atmospheric Sciences* **66** (11): 3237-3256.

Wilkinson J.M., Wells H., Field P.R., and Agnew P., 2013*: Investigation and Prediction of helicopter-triggered lightning over the North Sea. Meteorological Applications.***20:** 94-106

Wilson J.W., and Entrekin H.D., 1967: *Diagnostic Studies of fog and low cloud in the Atlantic City mesonetwork.Tech. Note (Paper B), Contract FA 66WA-1536, TheTravelers Research Center, Inc*. 27 pp.

Wolff J.K., Sharman R.D., 2008:*Climatology of upper-level turbulenceover the contiguous United States. J. Appl. Meteorol. Climatol.***47**:2198–2214.

Wong W.K., Chan P.W., 2011: *Aviation applications of a new generation of mesoscale numerical weather prediction system of the Hong Kong Observatory, in Proceedings of the 24th Conference on Weather and Forecasting and 20th Conference on Numerical Weather Prediction, American Meteorological Society, Seattle, Wash, USA.*

WMO (World Meteorological Organization), 1998: *Code forms. Section A, Part A-Alphanumeric codes, International codes.Manual on codes,WMO-No 306.***Vol.** 1.1. Geneva, Switzerland, 169 pp.

PUBLISHED ARTICLE(S)

INVESTIGATION OF THE INFLUENCE OF SEVERE WEATHER ON AIRCRAFT OPERATIONS OVER KENYA

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ABSTRACT

The study investigates the influence of severe weather on aircraft operations over Kenya using analyzed investigated weather-related aviation accident and incident causes data extracted from Kenya Civil Aviation Authority database system from 2008 through 2014. The China based geostationary Fengyun (FY2E)Satellite and MSG Infrared 10.8 imagery were used to identify the dominant cloud types and the distribution of the convective cells during the dry and wet seasons. Key findings revealed that Wind, Fog, Turbulence, Precipitation, and Thunderstorms influenced the accidents and incidents over Kenyan airspace.. Other factors were as a result of Fog encounter and Low Ceiling due to Stratus and Stratocumulus clouds being reported as Overcast or Broken. It was also noted that clouds of all types do not appear in the sky at the same time and a few clouds are rarely ever seen whereas some are only seen during certain seasons.

Keywords: Severe Weather, Aircraft Operations, Clouds, Aviation

APPENDICES

1. Script Used to Extract Data from WRF Model output file: 201704140600_arw_wrfout_d01.ctl

```
‘c'
‘set display color white’
‘open 201704140600_arw_wrfout_d01.ctl’
‘setmpdset hires’
‘setgxout shaded’
‘setlev 500’
‘sett 13’
‘setlat -5 5’
‘setlon 32 42’
‘d lftxl100_100’
‘cbar’
‘draw title 500mb Lifted Index [0°C]’
‘printim 500mb_Lifted_Index.png’
‘c'
‘Reset’
‘set display color white’
‘setmpdset hires’
‘setgxout shaded’
‘sett 13’
‘setlat -5 5’
‘setlon 32 42’
‘dcapesfc’
‘cbar’
‘draw title CONVECTIVE AVAILABLE POTENTIAL ENERGY [J/kg]’
‘printim CAPE.png’
‘c'
‘reset’
‘set display color white’
‘setmpdset hires’
setgxout shaded’
‘setlev 700’
‘setlat -5 5’
‘setlon 32 42’
‘sett 13’
‘drhprs’
‘cbar’
‘draw title 700mb RH [%]’
‘printim 700mbRH.png’
‘c'
‘open 201704140600_arw_wrfout_d01.ctl’
```

```
‘setmpdset hires’
‘sett 13’
‘setlat -5 5’
‘setlon 32 42’
‘setgxout vector’
‘d skip(ugrd10m,2,2);vgrd10m;tmpsfc-273’
‘cbarn’
‘draw title 10m WIND AND SURFACE TEMPERATURE [m/s]; [0°C]’
‘printim 10m_Wind.png’
‘c’
‘open 201704140600_arw_wrfout_d01.ctl’
‘setmpdset hires’
‘sett 13’
‘setlev 700’
‘setlat -5 5’
‘setlon 32 42’
‘setgxout stream’
‘d skip(ugrdprs,1,1);vgrdprs;tmpsfc-273’
‘draw title 700mb STREAMLINES AND TEMPERATURE [0°C]’
‘cbarn’
‘printim 700mb_STREAMLINES.png’
‘c’
‘open 201704140600_arw_wrfout_d01.ctl’
‘setmpdset hires’
‘sett 13’
‘setlat -5 5’
‘setlon 32 42’
‘setgxout contour’
‘d dpt2m-273’
‘draw title 2m DEW POINT TEMPERATURE [0°C]’
‘printim DP.png’
‘c’
```