UNIVERSITY OF NAIROBI

EFFECTS OF EXCEEDANCE OF THUNDERSTORM-RELATED PHENOMENA LIMITS ON AIRCRAFT OPERATIONS AT SELECTED AIRPORTS IN KENYA

BY

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A Dissertation submitted in Partial Fulfillment of the requirements for the Award of the Degree of Master of Science in Aviation Meteorology of the University of Nairobi

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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 my own work or that of others has been used, it has been appropriately cited and acknowledged in accordance with University of Nairobi regulations.

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DEDICATION

This dissertation is dedicated to my lovely young family; my wife, Sheila Menin and my son, Scholes Koech. You walked with me through my academic success. Your love, prayers, encouragement and pieces of advice kept me going. Special dedication to my father, Prof. Edward Tanui; you have been there for me all through my studies and given me immense support, God bless you. My mum, Dr. Elizabeth Tanui, siblings and awesome friends, I also dedicate this work to you. Thanks for pushing me positively to the end. Be blessed all of you.

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ABSTRACT

The objective of this study was to investigate the effects of exceedance of thunderstorm-related phenomena limits, including heavy rainfall, surface winds and visibility, on aviation operations at selected airports in Kenya. The rainfall data was obtained from Global Precipitation Measurement (GPM) while the crosswinds, tailwinds and visibility data were obtained from Meteorological Terminal Air Report (METAR) in the Ogimet website. The accidents data were obtained from Ministry of Transport, Infrastructure, Housing, Urban Development and Public Works; State Department of Transport; Air Investigation Department while Information about incidents was acquired from the Kenya Airports Authority (KAA). The methods that were used in this research include; Temporal Trend analysis, Exceedance Value Method, Correlation and Regression Analyses to study the effects of thunderstorm-related phenomena on air transportation in Kenya. The period of study was 2008 to 2017 for MAM season. The findings indicated that western region received more extreme rainfall than any other part of the country. Visibility was worse in Nairobi as compared to the other regions; the reason could have been because of more industrialization and the Capital's urbanization. The study recommends that the airports and airstrips that act as alternate aerodromes to the ones that were studied be assessed for vulnerability to Thunderstorm (TS)-related phenomena and if these aerodromes are less vulnerable to thunderstorm-related phenomena, be expanded so as to accommodate aircraft from those airports that are more vulnerable to TS-related phenomena. This will reduce costs of aircraft operations’ negative effects, enhanced profits, safety and improved employment opportunities. This is expected to cause fast economic growth and sustainable development.

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LISTS OF ACRONYMS

ACC – Allowable Crosswind Component

ATC – Air Traffic Control

EASA - European Union Aviation Safety Agency

EVM – Extreme Value Method

FAA - Federal Aviation Authority

GPM – Global Precipitation Measurement

ICAO – International Civil Aviation Organization

KCAA – Kenya Civil Aviation Authority

KAA – Kenya Airports Authority

KMD – Kenya Meteorological Department

MAM – March, April and May

METAR – Meteorological Terminal Air Report

NTSB – National Transportation Safety Board

OND – October, November and December

TAF – Terminal Aerodrome Forecast

TS – Thunder Storm

LIST OF CODES

HKEL - Eldoret International Airport

HKJK – Jomo Kenyatta International Airport

HKMO – Moi International Airport

HKNW – Wilson Airport

HKKI - Kisumu International Airport

NB: The region is often indicated by the first letter (ICAO subdivided different regions; for example, Africa has five regions, Australia one, USA has five, etc.). The country is identified by the second letter of the ICAO code, and the airport is identified by the remaining letters. Geographic context is provided through ICAO codes. For instance, if one is aware of the fact that Eldoret International Airport's ICAO code is HKEL, they can infer that the airport designated as HKKI is located somewhere in Kenya (it is Kisumu International Airport).

DEFINITION OF CONCEPTS

Aircraft Accident – It is defined as an occurrence connected to the operation of an aircraft that takes place between the time someone boards the aircraft for a flight and the time everyone has disembarked, and in which someone dies, sustains a major injury, or sustains significant damage to the aircraft.

Aircraft Incident – An event connected to an aircraft operation—other than an accident—that has an impact on or has the potential to have an impact on operational safety. For this dissertation, it will represent these; **Flight delays, flight diversions, flight go-arounds/ over shoots** and **flight cancellations.**

Cross winds – These are winds which blow across the runway at an angle.

Heavy Rainfall – This is rainfall when measured in a rain gauge is more than 7.6 mm per hour

Ogimet – This is a website which produces forecasting and air reports. For this study, it produced Meteorological Terminal Air Report (METAR), where the visibility, cross winds and tail winds data were found.

Tail winds – These are winds blowing in the direction of travel of a vehicle or aircraft; winds blowing from behind

Thunderstorm-related Phenomena – **Rainfall**, surface winds (**crosswinds** and **tailwinds**) and **visibility**

Visibility – This is the distance one can see as determined by light and weather conditions.

Source: (ICAA, 2005)

CHAPTER ONE

1.0 INTRODUCTION

1.1: Background

Aircraft accidents that happen in most aerodromes during takeoff and landing are majorly caused by human factors followed by severe weather and technical problems in the aircraft itself in that order (Mussa, 2009). Oxford (2008) observed that thunderstorm-related phenomena is a significant factor in aviation accidents, and can range from hail, fog, mist, turbulence, heavy rainfall, winds, wind shear, micro and macro bursts amongst others. Thunderstorms can reduce visibility up to 100 meters; if there is the presence of drizzle, visibility is seriously reduced especially if mist and/ or fog is/ are also present. It is difficult for pilots to see the runway clearly because of this. If a pilot attempts to take off or land under such conditions, aircraft may crash, resulting in aircraft damage and loss of life. In addition, many thunderstorm threats play a significant part in injuries and accidents in aviation. According to ASIAS (Aviation Safety Information Analysis and Sharing) of the Federal Aviation Administration, FAA, (2010), winds, visibility and precipitation played a significant part in aircraft accidents; thus, it is crucial to look at them in detail especially if they are caused by thunderstorm.

Heavy rains could lead to accidents on board the aircraft by destroying the air navigation system, which is very necessary during aircraft landing; thus, a pilot can lose contact and risk crash landing. There is a high chance of an accident/ incident if a pilot is forced to land under these conditions.

Heavy rainfall often causes an aircraft to be delayed due to flooding resulting in hydroplaning and damage of the airport's facilities, such as the runway; this can lead to delays in take-offs or landings, cancelation of flights, relocation of flights to alternative aerodromes and/ or go-around (Cao, Wu and Xu, 2014).

Surface Winds, especially crosswinds, are dangerous in that if their limits are exceeded, can cause incidents or accidents. Tailwind reduces lift and may make landing difficult especially if the runway is short. Wind gusts and wind shear are also dangerous especially during landings and take offs.

Poor visibility makes the pilot not able to see well and if the flight is on Visual Flight Rules, then delay, diversion or cancellation may be the only option. Accidents have occurred in such weather phenomenon. The worst air accident ever; occurred in fog, in 1977, the Tenerife Air Disaster which killed 583 people (The Telegraph, 2017).

All these Thunderstorm-related phenomena have limits set by International Civil Aviation Organization (ICAO). It is thus critical to study the exceedances of these limits so as to understand and counter the effects that come with going over those edges.

1.2: Statement of the Problem

Air transportation is among the best, efficient and fast forms of travel in Kenya. It has increased air travel of locals for business and/ or personal reasons. It has improved the lives of people socially and economically. Moreover, it has increased the revenue for the country due to the increased air travel (Irandu, 1995).

The goal is to ensure that air transportation in Kenya is improved by eliminating or reducing the effects of thunderstorm related hazards in Aviation.

Due to the various factors including bad weather such as Thunderstorms, it is sometimes dangerous and ineffective. There are many causes of accidents but weather contributes to approximately 10% of aviation accidents worldwide (FAA, 2018). Thunderstorms may lead to aircraft crashing, delaying and/ or go-around, cancellation of flight and/ or diversion of flights to other alternate aerodromes. If crashing occurs, it exposes passengers and crew in the high risk of losing lives or severe injuries and damage to the aircraft, the loss of income for the owner of the damaged aircraft, government though taxes and also loss of man hours which ultimately decreases the GDP of a country. If there are flight incidents and/ or accidents, losses can occur ranging from small to large extent depending on the time lost and the damage incurred. This will impact on the operator(s) who may in turn increase the rates to cater for that, which will eventually hurt the passengers in the long run (Oster, Strong and Zorn, 2010).

In response to this problem, this study proposed to identify the airport operations affected by thunderstorm-related phenomena. Of all the thunderstorm hazards, three phenomena were studied; heavy rainfall, surface winds (both crosswinds and tailwinds) and poor visibility. These three hazards have their limits set by ICAO. The research revealed what happened to the airport operations if those limits were exceeded and the mitigation effects were determined.

1.3: Research Questions

The following research questions were created in response to the indicated research objectives:

1. What are the frequencies/ trends of Thunderstorm (TS) hazards?

2. What are the limits of TS phenomenon exceeded?

3. What are the exceedances of TS phenomenon limits which cause flight accidents and incidents?

1.4: Objectives of the Study

The major goal of the study was to evaluate the effects of exceedance of thunderstorm-related phenomena limits on air transportation in Kenya. The following particular objectives were pursued in order to achieve the overarching goal;

1. To determine the temporal characteristics of thunderstorm-related phenomena at the selected airports in Kenya.
2. To quantify the exceedance of thunderstorm-related phenomena limits at selected airports in Kenya.
3. To establish the relationship between exceedance of thunderstorm-related phenomena limits and aircraft incidents and accidents at the selected Kenyan airports.

1.5: Justification of the Study

The cost of an aircraft accident and/ or incident is very expensive in terms of loss of lives, aircraft damage, loss of man hours et cetera. According to Mariera, (2014), Kenya's average number of annual aviation incidents is 2.11, with aviation accidents being 3 and the average amount of deaths being 4.58. Okorilo *et al*., (2011) discovered that the price range depends on the kind and age of the aircraft as well as the severity of the accident caused by the weather, with the smallest costing 34 million euros and the greatest costing 414-591 million euros.

This shows that weather and especially thunderstorm-related phenomena cause accidents as well as decreasing airport operations efficiency. This results in loss of life and big loss in revenue to persons and to the government. For that reason, it was important to study the effects of exceedance of thunderstorm-related phenomena limits on aviation operations at selected airports and come up with ways of predicting severe weather caused by thunderstorm such as heavy rainfall, surface winds and poor visibility; so that these losses can be reduced significantly. The beneficiaries of this study will be the airline operators, airport staff, the passengers using air transport and the government amongst other stakeholders. This research will guide in issuing advisories and weather forecasts related to aviation to stakeholders and subsequently lead to aviation disaster risk reduction thus revamped airport operations, enhanced profit and safety, improved livelihood and more government revenue.

1.6: Area of Study

The study region was Kenya. Kenya lies between latitudes 4 1/2ºN and 4 1/2ºS and longitudes 34ºE and 42ºE. There are more than 60 airports and more than 450 airstrips in Kenya. Five airports were selected to represent the entire nation. Of these airports, four of them are international airports and one is a local/ regional airport.

Moi International Airport (HKMO), Mombasa, 4.0328° S, 39.6040° E, represented the coastal region airports and airstrips. Kisumu International Airport (HKKI), 0.0819° S, 34.7286° E, represented Lake Victoria region airport and airstrips. Eldoret International Airport (HKEL), 0.4049° N, 35.2239° E, represented the Highlands region airports and airstrips. Jomo Kenyatta International Airport (HKJK), Nairobi, 1.3227° S, 36.9261° E, which is regarded as the 4th busiest airport in Africa, according to data from the latest Airports Council International, (2019) report, formed a basis as the main and busiest airport in Kenya. Finally, Wilson Airport (HKNW), 1.3192° S, 36.8176° E, is one of Africa's busiest hubs on Langata Road. The latter two airports are fewer than 20 kilometers of each other; both are in Nairobi and were included due to their different operations (that is one is a busy international airport while the other is a busy regional airport) and also were studied to determine how different two close airports can be in terms of how extreme weather affect their flight schedules.

No airstrip was chosen as there are few flights there; the data are not stored for long periods and the flights are not scheduled. This won't give the delays, diversions and/ or cancellations of flights as required and therefore, they may not contribute to the study.

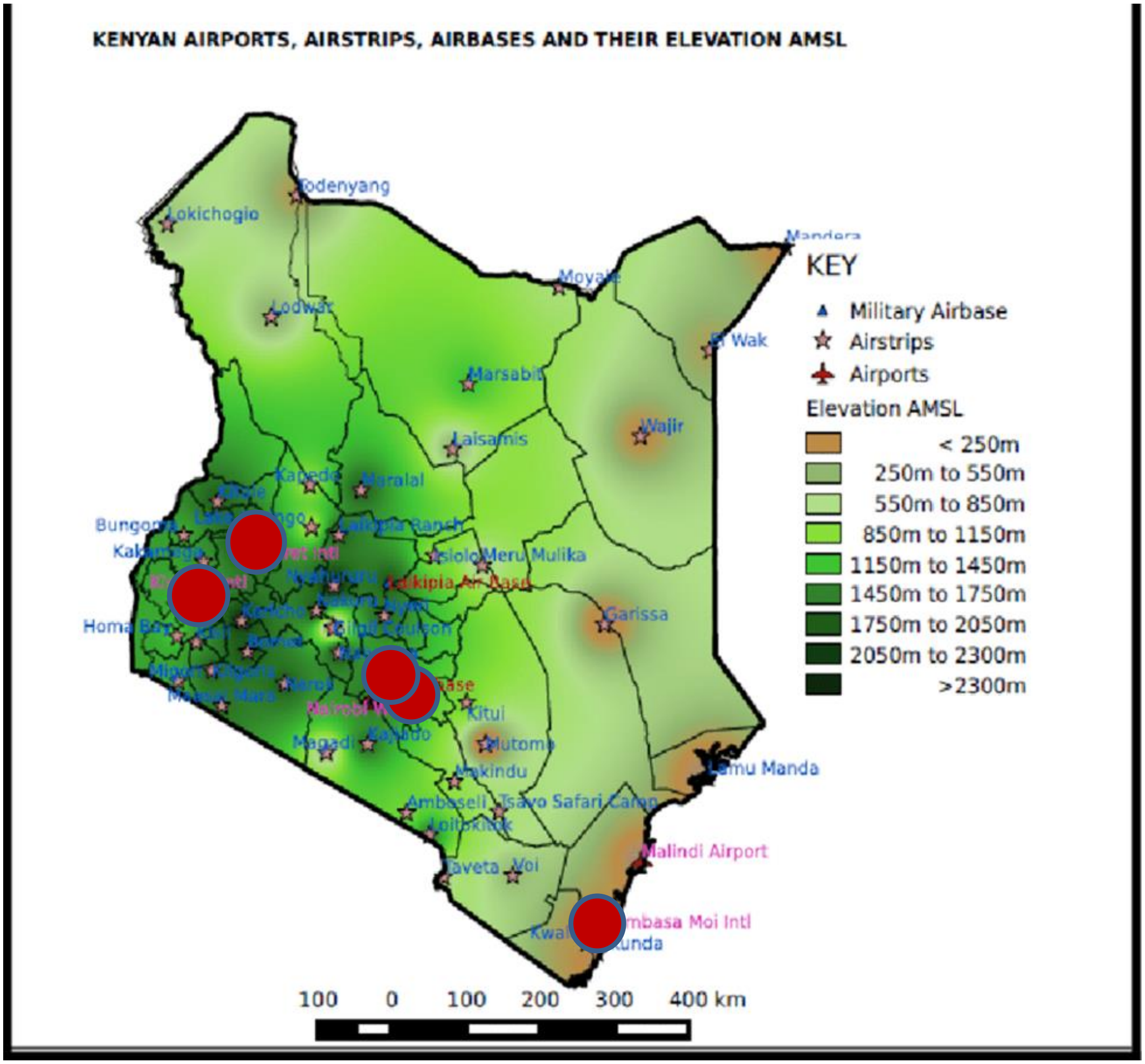

Figure 1. 1: Map of the research area including terrain and the locations of Kenya's main airports, airstrips, and bases. The Maroon circles show the selected airports which were studied. Source: Generated using Q-GIS

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1: Introduction

This chapter discusses literature on extreme or heavy rainfall, visibility limits, crosswind and tailwind limitations and their effects. The chapter looked at how these hazards have effects on airport operations and how to mitigate such effects.

2.2 Effects of Thunderstorm-related phenomena on Flight Incidents and Accidents

According to Nagarajan and Vidyapeetham, (2018), delays due to weather hazards in the aviation sector can occur constantly, but problems and stress caused by delays can be avoided by better forecasting and active delay management. It had been noticed that the most common climate hazards causing these delays were thunderstorms. Certain meteorological factors, including frost, snow and fog may also cause delays. Weather has a key role in many aircraft accidents. In order to decrease weather-related mishaps, it is necessary to identify and classify the meteorological conditions that impair aircraft on the ground or in flight. One can comprehend the direct effects of these conditions on the field to ascertain why they create delays in takeoffs or landings after various weather conditions that are harmful are investigated.

Nagarajan and Vidyapeetham, (2018) discovered that major weather conditions that continue to affect the aviation industry include thunderstorms, turbulence, winds, strong gusts of wind, snow, icing of aircraft and runways, reduced visibility because of fog, haze, and mist, and low cloud ceilings. You can find delays brought on by such weather at the destination or during the flight. In especially when preparing to land, pilots prefer to be aware of the current meteorological conditions. Regional weather services, in addition to ATC management staff, are in charge of delivering airport weather data. Such specifics are used to provide a flight process that is well architectured. Aircraft management at a significantly large airport is pretty demanding, and any kind of weather disruption can cause not only a slight delay, but it can also affect air flights at a humongous level.

In contemporary society, people, goods, and services are all very mobile. Supply chains span continents and nations, and more people are traveling for both business and personal reasons (Borskya and Unterbergera, 2019). Demand for mobility is expanding as a result of population growth and income growth (Schafer and Victor, 1997). The growing need for mobility ultimately results in a high dependence on transportation networks and their infrastructure, with significant expenses paid if mobility is suddenly reduced (Wilson, 2007; Ball *et al*., 2010; Stamos *et al*., 2015).

Conflicts between airlines, airports, and air traffic control organizations as well as external events like bad weather, accidents, and other situations that cause airport congestion typically result in delays (Bendinelli *et al*., 2016).

The main cause of flight operational performance delays is the weather (Okoro *et al*., 2018). For instance, if a flight is delayed, the following flight on the aircraft's itinerary can also be delayed (Schaefer and Millner, 2001). A safe landing or takeoff also requires vision, a minimal cloud ceiling, and certain crosswind maximums.

In the wet seasons, heavy convective weather frequently disrupts en-route or terminal airspace at Nigeria's airports, causing very lengthy delays. Flight delays, cancellations, and diversions brought on by severe weather make it harder for the area's airspace to function. Although it invariably results in delays, detours, and cancellations for airplanes, this safety concern comes at a price (Rodenhuis 2004).

Aderinto and Dahunsi, (2008) found out that the most crucial factor affecting air transport services was the rainfall parameter. Thus, during the long rainfall period (March-October or early November) in Nigeria, flight delay and cancelation becomes very common, extreme and regular.

While air transport seems to be the most ideal method to travel in Tanzania, it has sometimes become dangerous and unreliable due to various factors like bad weather and specifically heavy rainfall. Aircraft accidents, delays, flight cancellations, and flight diversions to other alternative aerodromes can result from bad weather (Mussa, 2009).

Aircraft incidents that occur in most aerodromes during take-off and landing stages are caused by severe weather and technical problems in the aircraft itself. Extreme rainfall is a significant cause of accidents, as it can obscure the view to zero; preventing the pilots from seeing the runway clearly. If the pilot wants to land or take off in such a situation, it can cause aircraft to crash, resulting in aircraft damage and death.

Heavy rain often causes an aircraft to be delayed due to flooding and repairs on its facilities such as runway, which can lead to delays in take-off or landing, flight cancellations and aircraft transfer to alternative aerodromes (Mussa 2009).

Mussa (2009) found out that heavy rains cause some flight cancellations, particularly at Shinyanga Airport, and therefore flight planning should make use of daily weather predictions and TAF to reduce flight delay problems in various aerodromes.

There haven't been many researches on the effects of severe rain on airport operations in Kenya. However, in a study on the effects of rain on aviation, Sharman *et al*. (2015) emphasized that heavy rain has a significant impact on aircraft in landing configuration due to low visibility and flooded runways.

2.3 ICAO-based Thunderstorm-related Phenomena Limits

The following are the limits for different weather phenomena in line with ICAO guidelines (ICAA, 2005).

2.3.1 Rainfall

Rain causes runways to be wet, causing trouble in the take-off and landing performance of aircraft. If a runway accumulates more than three millimeters of water, aircraft may end up in the development of hydroplaning or aquaplaning. This layout provides a higher possibility of aircraft slipping and will eventually increase the necessary runway length for take-off or landing (Nagarajan and Vidyapeetham, 2018). This rainfall translates to more than 7.6 mm of precipitation per hour in the rain gauge; this is the limit, with anything above that considered as heavy rainfall or extreme rainfall amounts.

2.3.2 Surface Winds

2.3.2.1 Crosswind Component

A crosswind factor is the wind blowing across the runway affecting the aircraft's smooth landing (Bellasio, 2014). Manufactured flight test experiments have established a total crosswind component for each aircraft increases in proportion to aircraft size. FAA has developed an allowable crosswind element (ACC) during landing and is based on the runway layout code (FAA, 2012). A letter and a Roman number make up the Runway Layout Code (RDC). The letters A to E refer to the aircraft's approach speed defined as A for low speed up to E for high speed. The Roman numerals I to VI refer to the wingspan or the height of the tail. ('I' being the smallest size to VI the greatest size). Visibility information is also included in the RDC, but it is not taken into account when evaluating the ACC. Table 2.1 shows the ACC as RDC function'

Table 2. 1: Crosswind component permitted under the runway design code

(Source: Kenya Airways-flight crew training manuals, Van Es, 2001)

Runway design code	**Crosswind component allowed, kts**
E I through E VI	20
A IV and B IV, C IV through C VI, D IV through D VI	20
A III, B III, C I up to D III	16
A II and B II	13
A I and B I	10.5

The ACC is also a feature of the minimum required field duration of take-off as defined by ICAO and EASA. The ACC is 10 knots for lengths < 1200 m, 13 knots for lengths <1500 m, and 20 knots for lengths >1500 m. A dry runway surface has the ACC characteristics. For instance, when the runway condition is unfavorable for braking, the ACC for a wet runway surface lowers from 20 knots to 13 knots (EASA, 2011). In general, operators prefer not to exceed the specified crosswinds while in service (Van Es *et al*., 2001). Crosswind restrictions are lowered by operators on dirty and wet runways. Operators are able to utilize different crosswind limits for the same aircraft and runway condition because these limitations are just advisory information on dry runways. Aircraft tires and non-dry runways of varied runways interact in a variety of ways. An airport could set a crosswind limit for all commercial operators using the airport. Heathrow Airport in Europe, for example, has the highest crosswind peak of 25kts. Nonetheless, the recommended limit used by most airports is a total of 15 knots of crosswind (FAA, 2012).

2.3.2.2 Tailwind Component

A tailwind refers to wind blowing in travel direction. As far as tailwinds are concerned, a number of aircraft have a maximum tailwind of 15 knots. Nevertheless, not all operators are authorized to carry out tailwind take-offs or landings of more than 10 knots (Van Es and Karwal, 2001).

Table 2.2 below summarizes the numerical values of the limits required for safe operation under dry runway conditions of a number of different aircraft types. The limits decrease for wet runway or polluted runway (runway containing stagnant water, snow or ice), as runway braking conditions continue to decrease.

Table 2. 2: Aircraft type and respective Allowable Tailwind component

(Source: Kenya Airways-flight crew training manuals, Van Es, 2001)

Aircraft type	**Maximum Allowable Tailwind component during take-off (kts)**	**Maximum Allowable Tailwind component during landing (kts)**
737-300	10	15
737-700	10	15
737-800	10	15

Embraer 190	10	10
Boeing 787	15	15
777-200/ 300	15	15
Embraer 170	10	10

Flight safety and efficiency require wind flow on an aircraft. Headwinds during landing help reduce the aircraft's ground speed while providing a lift at take-off that gives an aircraft a steeper slope that helps clear obstacles. On the other side, tailwinds can raise landing ground speeds needing longer lengths of landing fields. Under these conditions, taking-off means that the slope of climbing out is gentle and not ideal for avoiding obstacles (Van and Karwal, 2001).

2.3.3 Visibility

VFR flights are not permitted to enter the air traffic zone or traffic pattern, or to take off or land in a control zone at an aerodrome: When the ground visibility is less than five kilometers (5000 m) or when the ceiling is lower than 450 meters (1 500 feet).

Table 2. 3: Ranges of Visibility Used in the Study

2,000m-5000 m	slight veil or mist
1,000m–1,999 m	medium haze or mist
Less than 1,000 m	fog or heavy veil of dust

2012 QAM book of the MMIA Lagos meteorological unit

2.4 The Relationship between Thunderstorm-Related Phenomena and Aircraft Accidents and Incidents

Unfavorable weather conditions are a significant external element contributing to delays in the air traffic system (Coy, 2006) and (Koetse and Rietveld, 2009). Depending on the year and month, these can go up to 50% of air traffic delays inside the U.S. national airspace network (Federal Aviation Administration, 2017). The impact of weather-related events on aviation process delays is seldom ever explored in current empirical research. According to a recent study, bad weather has a considerable overall impact on airport and airline operations (Robinson, 1989; Changnon, 1996; Sasse and Hauf, 2003; Hsiao and Hansen, 2006; Markovic *et al*., 2008). At Atlanta Hartsfield International Airport in 1989, Robinson investigated how a number of weather shocks affected the operations of one airline. According to the report, inclement weather results in delays of more than 165,000 minutes annually. Precipitation significantly increased the number of departures at Chicago O'Hare airport that were delayed by more than 30 minutes at the end of the 1970s (Changnon 1996). Hsiao and Hansen (2006) looked at the US domestic transportation system's typical daily latency. They discovered that delays are, on average, 14 minutes longer on days with bad weather than on days with good weather.

Bertness (1980) considered that the odds of a delayed departure on a rainy day are several times greater than the chances of a non-rainy day, although the actual cause of the delay could be related to strong winds, low visibility, or regional or surrounding thunderstorms. Heavy rainfall could be expected to result in increased flight delay at Hartsfield Jackson International Airport. In a study comparing rainfall with transport incidents, Changnon, (1996) determined that 57% of the 30-minute flight delays at O'Hare Airport in Chicago occurred during rainy weather. Results suggest that climate in the future with more days of summer rain would result in more total vehicle accidents, more aircraft incidents and delays in flight.

Extreme weather-related delays in transportation services have become more commonplace in recent years. In actuality, weather is the main cause of airline delays in both the United States (Federal Aviation Administration, 2018) and China (Chen *et al*., 2018). (2018). This is due to the direct impact harsh weather has on airport capabilities and aircraft paths, which causes delays to cascade throughout the entire aviation network (Lan *et al*., 2006; Fleurquin *et al*., 2013).

Weather frequently has a key impact in a variety of aviation accidents and events (Okoro *et al*., 2018). Although NTSB studies typically attribute human error as the leading cause of accidents, weather is a significant contributing element in 23% of all aircraft accidents (Kulesa, 2002). Extreme weather events are becoming more frequent and severe, and they cause serious challenges for transportation.

2.5 The Gap on the Research Topic

Different parts of the world including Africa, have significantly researched about the effects of thunderstorm-related phenomena on airport operations in general but not exceedance of it. East Africa's researchers have tried the above study but to a small extent. In Kenya, researches have been mostly on the effects of adverse weather conditions or specific weather condition on the aviation industry or the airport(s).

There was no study on the exceedance of thunderstorm-related phenomena limits on airport operations in Kenya. It was good that the void was filled through this study.

2.6 Conceptual Framework

As shown in Figure 2.1, the thunderstorm-related phenomena were analyzed using time series. Thunderstorm-related phenomena's data was later separated using the extreme value method to get the extremes/ exceedances. The dependent (Airport operations) and independent (thunderstorm-related phenomena) variables were then passed through correlation and regression analyses to determine if there is any relationship between these two variables. After getting the relationships, this can assist the interested parties to be able to improve the flight safety by better flight planning and to reduce the aircraft accidents and incidents.

Figure 2.1 shows this study's conceptual framework; which guided through this research

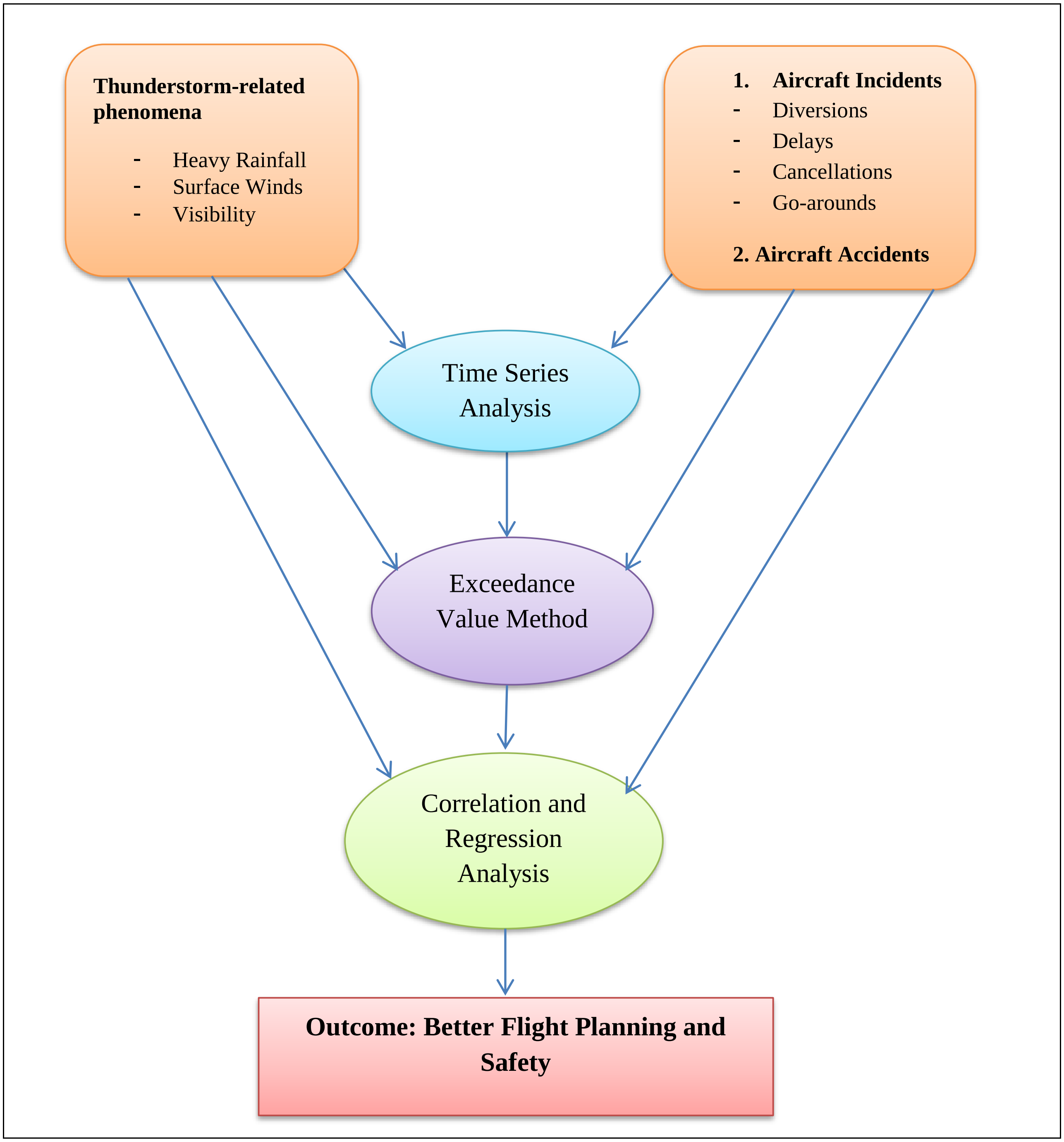

Figure 2. 1: A conceptual framework for the research study. The study's input, methodology, results, and application (Self)

CHAPTER THREE

DATA AND METHODOLOGY

3.0 Introduction

This chapter presents the forms of data that were collected and the specific methods used to achieve the specific objectives.

3.1 Data type and Source

The study's data set consists of collected hourly rainfall totals, hourly wind speeds and directions, hourly visibility sets and aviation flight accidents and incidents components for the selected airports.

All the data collected for both TS related phenomena and Aircraft accidents and incidents were secondary data.

3.1.1 Data for thunderstorm-related phenomena

The rainfall data was obtained from Global Precipitation Measurement (GPM) and were from this site: (www.ogimet.com). These were satellite data. The airport locations latitudes and longitudes were pinpointed then the rainfall amounts for those specific points were found. Half-hourly data were acquired from GPM and these were converted to hourly by addition of every two data components. The rainfall data were measured in millimeters (mm).

Hourly crosswinds, tailwinds and visibility data from the five airports on all runways were obtained from MEteorological Terminal Air Report (METAR) in the Ogimet website. Crosswinds {wind speed (V) multiplied by the sine of angular distinction between runway direction and wind direction}

i.e., Crosswind = V Sin θ (theta) …………………………………. Equation (1)

Where V = wind speed in knots (nautical miles per hour, nm/hr.)

θ = angle between runway direction and wind direction, both from true north

While tail winds {wind speed (V) multiplied by the cosine of angular distinction between runway direction and wind direction}

i.e., Tailwind = V Cos θ (theta) ………………………………….. Equation (2)

Where V = wind speed in knots (nautical miles per hour, nm/hr.)

θ = angle between runway direction and wind direction, both from true north

Wind roses for the five airports were used which were retrieved from (mesonet.agron.iastate.edu/sites/windrose.phtml?station=HKNO&network=KE_ASOS)

Visibility data which were used were the horizontal visibility and were measured in meters.

All the data were from 2008 to 2017 for March, April and May (MAM) season. This season was selected because it is the most thundery period of the year and the study wanted to assess the effects on airport operations when the weather was the most extreme.

3.1.2 Data for Aircraft Accidents and Incidents

An Aircraft Accident is any incident impacting an aircraft's operation that occurs between the times a passenger boards for the purpose of taking off and the time they have all exited that results in a fatality, a major injury, or significant damage to the aircraft. On the other hand, Aircraft Incident is an event connected to an aircraft operation, other than an accident, that has an impact on or could have an impact on operational safety. For this study, it represented flight delays, diversions, cancellations and/ or go-arounds.

The accidents data were obtained from State Department of Transportation; Ministry of Transportation, Infrastructure, Housing, Urban Development and Public Works; Air Investigation Department while the incidents data were obtained from Kenya Airports Authority (KAA). Both of these data were for 10 years (2008-2017) during the MAM season. These data were for the seasonal time steps.

3.2 Methodology

This section outlines the specific methods that were used to analyze the datasets described in Section 3.1 in order to achieve the specific objectives of this study

3.2.1 Temporal Trend Analysis

Investigations were conducted at five airports that represented distinct regions. Time series plots were used to determine if the frequency of thunderstorm-related events was increasing, decreasing, or steady over time on seasonal and monthly timescales. Using the Non-parametric trend test based on Mann- Kendall, it was assessed whether there was a trend for thunderstorm-related incidents during MAM seasons with a 95 percent level of confidence.

The MK test works best when used to pinpoint stations with variances that are significant or widespread and to qualify these results. It is best thought of as an exploratory examination. Furthermore, this test is not dependent on the quantities being evenly distributed and the trend, if any, being linear. Additionally, the MK test can be computed when values are absent or fall below one or more detection limitations. However, such actions have a negative impact on the test's performance. The time between samples must be adequate for there to be no correlation between measurements made at different times and the assumption of freedom (Kendall, 1961; McLeod *et al*., 1990) Equation (1) illustrates the method of computing a statistic that corresponds to the Sen Slope (S).

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k)$$

…………………………………… Equation (3)

Where xj and xk are, respectively, the annual values in years j and k, j>k

Equation provides an estimate of the normal cumulative distribution function's ability to capture the significance of the MK statistic as shown in Equation (4).

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0. \\ \frac{S+1}{\sqrt{VAR(S)}} & \text{if } S < 0 \end{cases}$$ ……………………………………… Equation (4)

Where VAR is the variance and Z is the common test statistic derived from the common normal cumulative distribution tables.

Wind rose analysis was also carried out. They were used to describe the wind analysis and also to explain the wind directions and what affected the directions.

3.2.2 Exceedance Value Method

This method applies to values which have a limit. Any value above or below the limit is used for analysis as shown in Equation (5).

$\{X_i > u \mid X\,i > u\}$………………………………………………………… Equation (5)

Very large limit u

It follows a Generalized Pareto Distribution (GPD)

$Y\,i{:} = X_i - u \mid X\,i$………………………………………………………… Equation (6)

The distribution of exceedances over large limit *u* either upwards or downwards

Limits from ICAO were chosen from data using a Maximum Likelihood Estimate (MLE) (Friederichs, 2007).

$\theta(x) = \arg\max \theta\, L(\theta|x)$ ………………………………………………….. Equation (7)

The days which exceeded rainfall, crosswind and tailwind; and below par visibility data limits were determined.

3.2.3 Correlation Analysis

The statistical technique of correlation analysis is used to determine whether there is a relationship between two variables or datasets and the potential strength of that association. Its equation is as shown in Equation (8).

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}} \quad \text{……………………………………… Equation (8)}$$

Where, r is the correlation coefficient and x_i are the TS-related phenomena values for the x-variable; $\bar{x}$ = the average of the TS-related phenomena values variable's, y_i are aircraft accidents and incidents values and $\bar{y}$ is the average of the aircraft accidents and incidents values variable's. It was necessary to correlate these variables so that the study could find out how one variable affected the other variable and in this case how Thunderstorm (TS) related phenomena affect airport operations. The application was that after knowing their relationships, one could know how to deal with the extreme weather aspects of TS in airport operations.

T-test was then done to examine whether there are significant differences between two group means.

3.2.4 Regression Analysis

Regression analysis is a statistical approach used to evaluate the relationships between a dependent variable and one or more independent variables. It can serve as a model of the long-term relationship between variables and gauge how strongly the relationships between them are. For example, rainfall can have an effect on aircraft delays and diversions; therefore able to predict the future when there is extreme rainfall. The equation is as shown in Equation (9).

$$Y_i = f(X_i, \beta) + e_i \quad \text{... Equation (9)}$$

Where, Y_i: dependent variable, aircraft accidents and incidents

f: the function

X_i: Independent variable, TS-related phenomena

β = unidentified parameters and incorrect words (e_i)

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.0 Introduction

This chapter discusses the specific methods used to get the specific objectives.

4.1 Temporal Trend Analysis of Thunderstorm-related phenomena at the selected airports in Kenya

4.1.1 Rainfall

The daily rainfall amounts during the 2013 MAM season for HKKI, HKJK, HKNW, HKMO and HKEL is as shown in Figure 4.1. This season was selected among the 10 years because this was the season when the accidents at HKNW occurred.

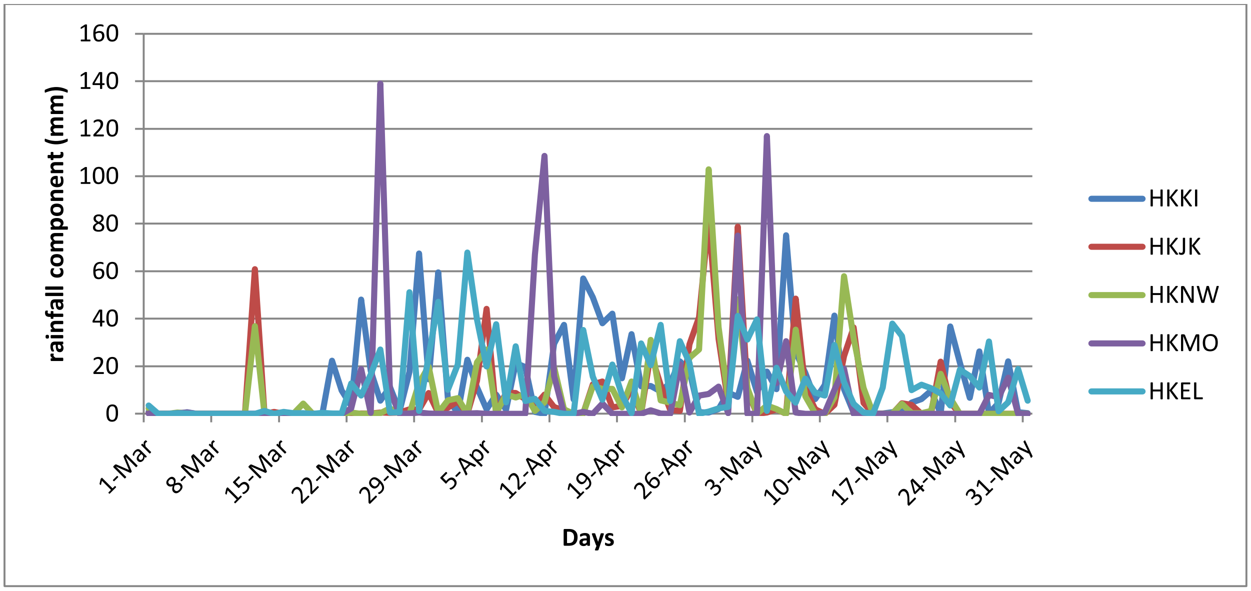

Figure 4. 1: A graph outlining daily rainfall amounts in millimeters during the 2013 MAM season for HKKI, HKJK, HKNW, HKMO and HKEL.

As is evident in Figure 4.1, there was a delayed onset of rainfall in all the airports. They were different in that for a case like HKMO; generally, it had the least rainfall amounts of all the airports but the three of the four highest rainfall amounts came from this airport. This showed that the rains were not frequent but when it did rain; the amounts were very high.

Figure 4.2 shows a graph of all the hourly rainfall data in all the airports for 2008-2017 MAM seasons. There is also a black pointed line indicating the limit for heavy rainfall. The rainfall amounts were measured in millimeters.

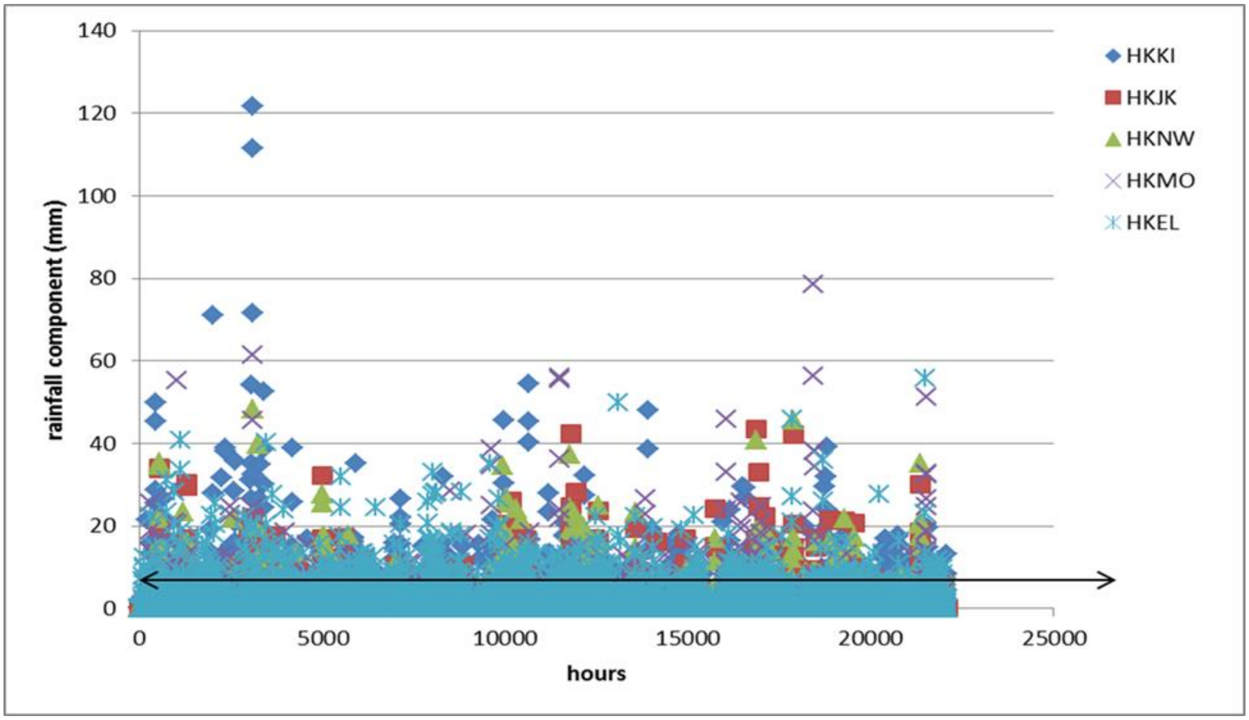

Figure 4. 2: A graph outlining all the hourly rainfall data in mm for HKKI, HKJK, HKNW, HKMO and HKEL from 2008-2017 during the MAM season. The black continuous double-pointed line represents ICAO's 7.6 mm rainfall limit.

The hourly rainfall data for HKKI, HKJK, HKNW, HKMO and HKEL from 2008-2017 during the MAM season is as shown in Figure 4.2. In this Figure, the black continuous double-pointed line represents ICAO's 7.6 mm rainfall limit. Any value above this line is termed as an exceedance. As is evident from Figure 4.2, the results indicated that significant amount of rainfall hours did not pass the limit. It also showed that the five highest rainfall amounts in an hour occurred in HKKI and HKMO, with the former having 80% of them. The least rainfall were very many hours with zero (0) mm of rainfall which implied the days with no rainfall at all.

The results indicated that HKEL and HKKI received more extreme rainfall than HKMO, HKNW and HKJK during the period of study. The reason was the influence of Congo Air Mass; high winds penetrated from the west as the Congo airstream. This airstream is completely unstable and storms easily form and develop (Maloba, 2015). According to Chaggar (1997), Asnani (2005), Obiero (2013), and Maloba (2015), Western Kenya was the region with the most thunderous weather in the entire world. The findings of the current study are consistent with those findings. Another explanation is the lower pressure at the highlands compared to the lower levels. High altitudes experienced low pressure and thus low air density. Since such less dense air does not retain heat, the highlands are always colder than low lands. With respect to orographic precipitation, pressure-gradient driven winds carry warm moist air over the land. When air moves across the highlands, it rises, expands and cools down, thereby leading to condensation and cloudiness usually resulting in precipitation (Ayugi, et al., 2016).

4.1.2 Wind Analysis

In order to understand the climatology of wind over the selected airports, wind rose analysis was carried out. Figures 4.3 and 4.4 depict the wind roses over HKKI and HKNW, respectively.

The outcomes showed that HKKI and HKMO each had two frequent wind directions; one from the most persistence synoptic wind direction and the other one from the mesoscale influence of lake, sea and land breezes.

For HKKI and HKMO, the daytime lake and sea breezes (E) and (SSE) respectively were stronger than the nighttime land breeze of (W) and (NNW), respectively, due to the bigger thermal properties difference of land and water. Land breezes are weaker than sea breezes as a result of temperature differences. Sea breeze typically causes the air temperature to drop.

The wind roses over HKMO, HKJK and HKEL are presented in Appendix 1 in that order

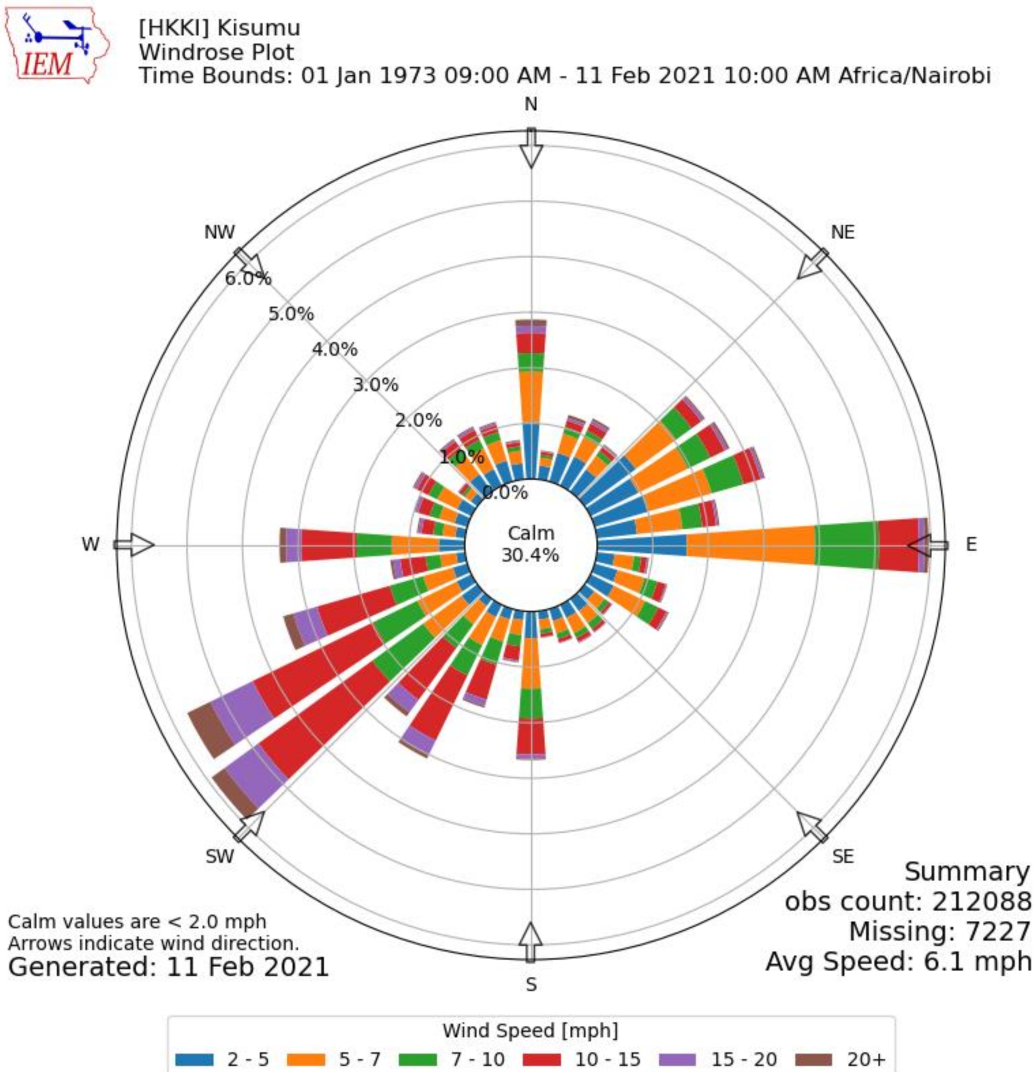

Figure 4. 3: Wind rose diagram for Kisumu International Airport outlining wind direction and wind speed in miles per hour from 01/01/1973 to 11/02/2021

Source: (Akrherz, 2022)

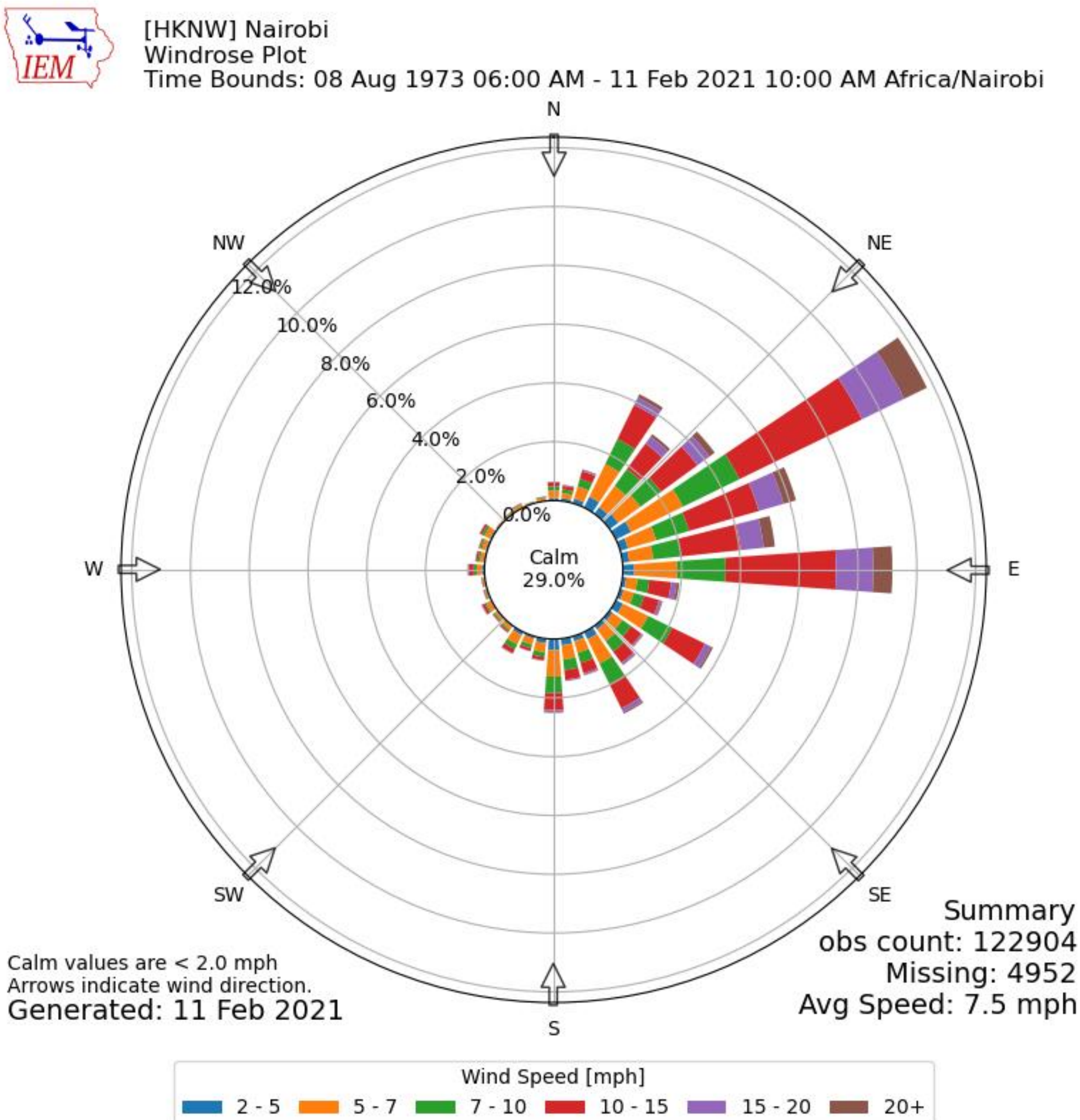

Figure 4. 4: Wind rose diagram for Wilson Airport outlining wind direction and wind speed in miles per hour from 08/08/1973 to 11/02/2021

Source: (Akrherz, 2022)

4.1.2.1 Crosswinds

The hourly cross winds which exceeded the limits during the period of study for HKKI, HKJK, HKNW, HKMO and HKEL is as shown in Figure 4.5.

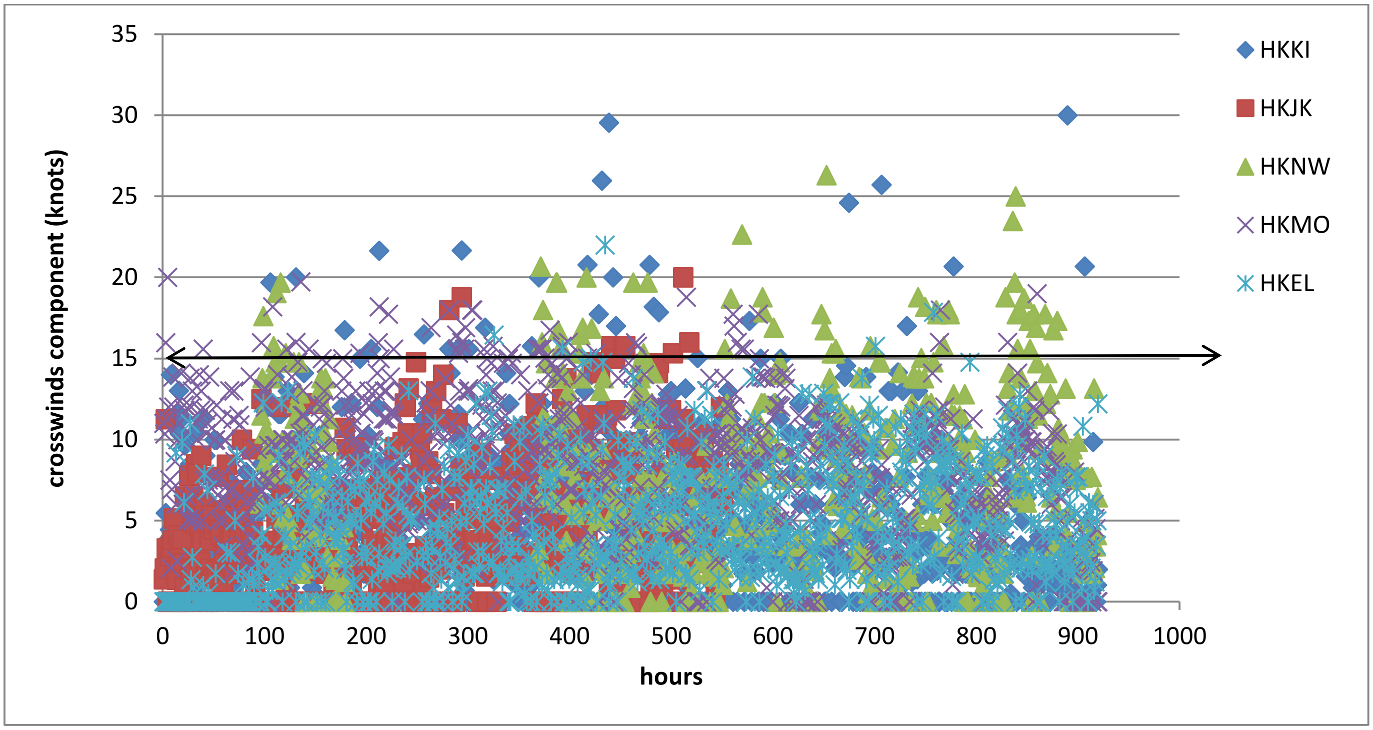

Figure 4. 5: A graph outlining crosswind hours presented in the graph the highest for each day during the MAM season from 2008-2017 for HKKI, HKJK, HKNW, HKMO and HKEL. The black continuous double-pointed line represents ICAO's 15 knots cross winds limit.

The hourly cross winds data for HKKI, HKJK, HKNW, HKMO and HKEL from 2008-2017 during the MAM season is as shown in Figure 4.5. In this Figure, the black continuous double-pointed line represents ICAO's 15 knot cross wind limit. Any value above this line is termed as an exceedance. As is evident from Figure 4.5, the results indicated that many small figures including zero being the majority. This showed that in a typical situation, the wind direction of those five airports were consistent and more or less constant thus giving a majority of these small figures. Most crosswinds hours had 15 knots or below as shown.

For HKKI, the most persistence wind direction was the one from South West (SW) while the one influenced by the land and lake breezes was from the East (E). For HKMO, the most persistence wind direction was from South South-West (SSW) while the one influenced by the land and sea breezes was from South South-East (SSE). The study showed that there were more incidents of crosswinds from both stations. HKKI had the most occurrences of crosswinds; followed by HKMO due to the above reasons. The crosswinds were much significant between 11 am and 4 pm. This is the time when land was heated most and significant lake and sea breezes were experienced.

4.1.2.2 Tailwinds

The hourly tail winds which exceeded the limits during the period of study for HKKI, HKJK, HKNW, HKMO and HKEL are as shown in Figure 4.6.

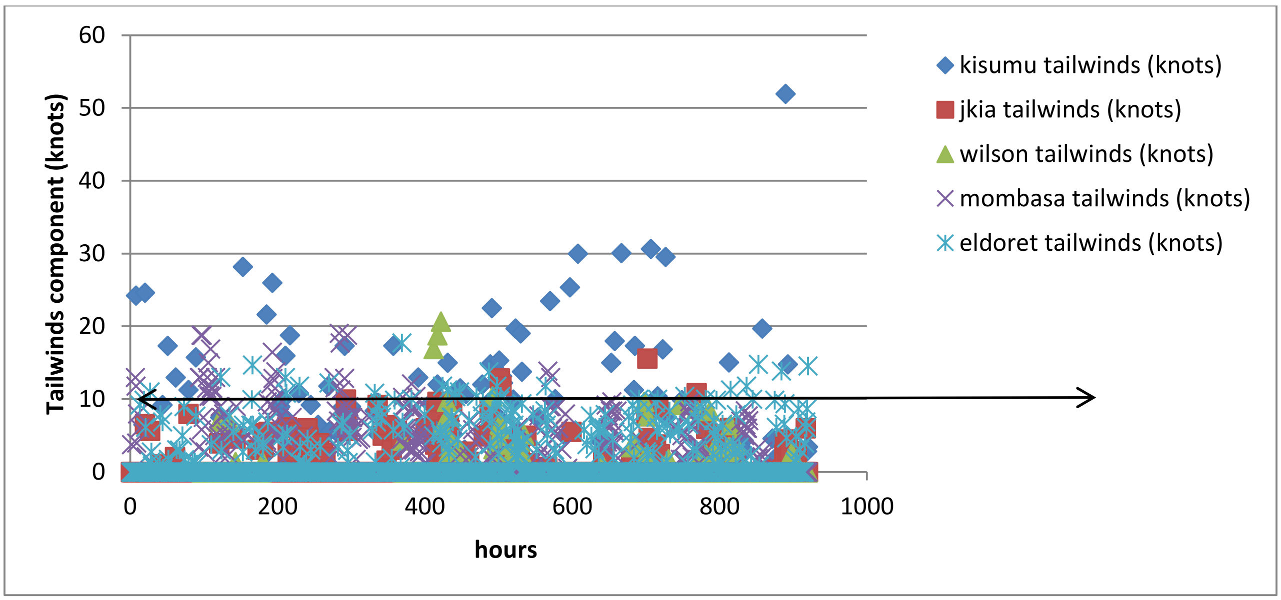

Figure 4. 6: A graph outlining tailwind hours presented in the graph the highest for each day during the MAM season from 2008-2017 for HKKI, HKJK, HKNW, HKMO and HKEL. The black continuous double-pointed line represents ICAO's 10 knots tail winds limit.

The hourly tail winds data for HKKI, HKJK, HKNW, HKMO and HKEL from 2008-2017 during the MAM season is as shown in Figure 4.6. In this Figure, the black continuous double-pointed line represents ICAO's 10 knot tail wind limit. Any value above this line is termed as an exceedance. As is evident from Figure 4.6, the results indicated that most tailwind hours were zero (0) knots and very few were above the limit of 10 knots depicted by the black pointed line. The reason was that, as discussed above, the wind direction is usually constant and consistent with the runways at the airports being constructed to be on the path of wind direction. Therefore, instances of having wind direction moving directly opposite to its normal routine were extremely rare bar few special cases. There was one extreme hour in HKKI which had greater than 50 knots of tailwinds. This was caused by wind gusts, which were mainly generated by a strong change in wind direction and speed. In addition, HKKI regularly experiencing intense thunderstorms could have been a major contributing factor.

Uneven heating and subsequently pressure gradients affects HKMO and HKKI more than the other three airports due to the thermal properties of water bodies; and therefore more instances of tailwinds may be significant. For HKEL, topography and land features e.g., the adjacent forests bring significant changes in wind direction. This may have had an effect on HKEL wind direction. For HKNW and HKJK, urban-rural circulation from Urban Heat Island (UHI) causes changes in wind direction. This may have affected the wind direction thus caused tailwinds to occur. HKNW experiences more effects of UHI than HKJK because the former is nearer to the city than the latter.

4.1.3 Visibility

The hourly visibility components which were below par limits during the period of study for HKKI, HKJK, HKNW, HKMO and HKEL is as shown in Figure 4.7.

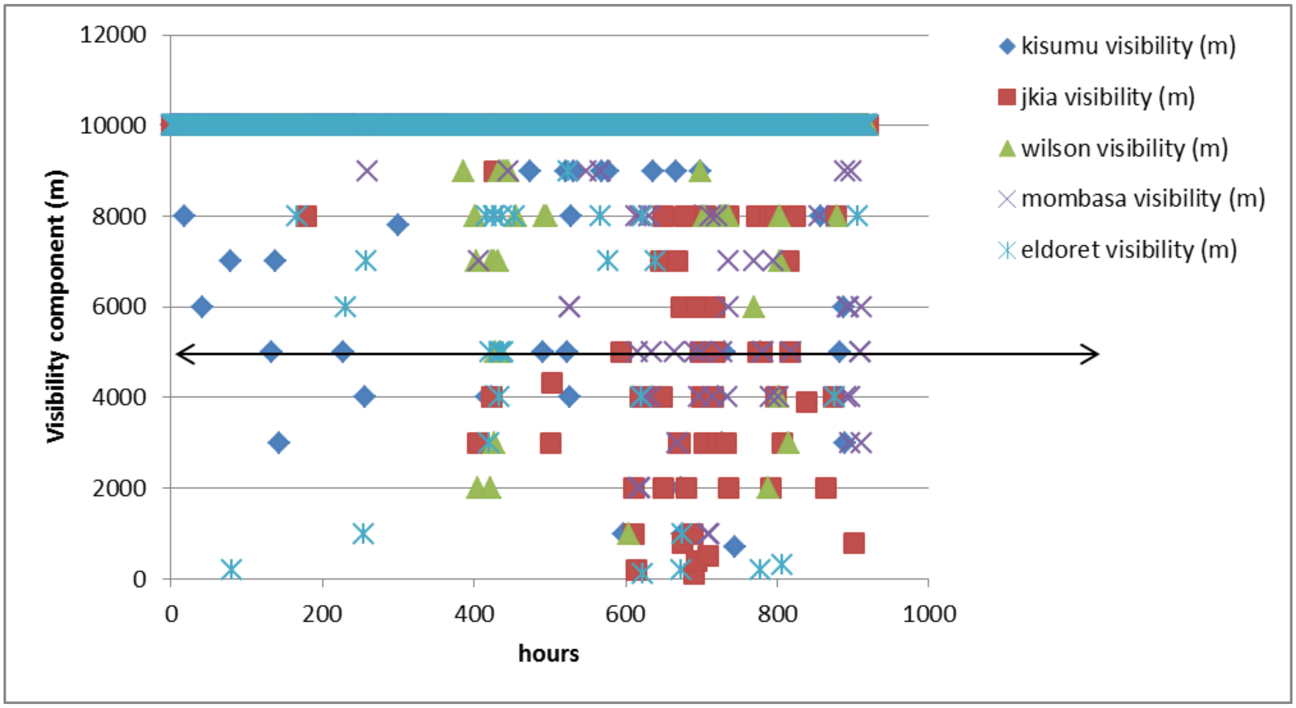

Figure 4. 7: A graph outlining visibility hours presented in the graph the highest for each day during the MAM season from 2008-2017 for HKKI, HKJK, HKNW, HKMO and HKEL. The black continuous double-pointed line represents ICAO's 5000 m visibility limit.

The hourly visibility data for HKKI, HKJK, HKNW, HKMO and HKEL from 2008-2017 during the MAM season is as shown in Figure 4.7. In this Figure, the black continuous double-pointed line represents ICAO's 5000 m visibility limit. Any value below this line is termed as an exceedance. As is evident from Figure 4.7, the results indicated that majority of the hours during the period of study were CAVOK (Clouds And Visibility OK) and this is usually given a figure of 9999; thus at the 10000 mark, it shows a bold blue line representing the majority clear day hours. The extremes for visibility were the lowest values as opposed to the other thunderstorm related components whose extremes were the highest values. The findings also indicated that there were visibility hours with as low as 100 m from a number of airports and instances; which were extremely low and dangerous for Visual Flight Rules (VFR). The limit of 5000 m depicted by a black line pointed. There were few hours below that line.

The results indicated that HKJK had the worst visibility followed by HKNW. HKMO had the best visibility followed by HKKI. For HKJK, there are cement industries in East section of Nairobi that is Kitengela and Athi River; an average distance of 15 kms between those industries and the airport. As the winds moved from ENE to WSW according to the windrose, the particles are advected by the winds hence reduced visibility in this airport.

HKNW may have been affected significantly by the UHI. Urban areas with many buildings have higher temperatures. If moisture is sufficient, and dew point temperature favorable, condensation will occur then advection fog will form. This reduces visibility significantly. HKMO had the best visibility. The reason could be because the sunlight/ heating dispersed any fog that could have formed. The same reason applies to HKKI. HKEL was mostly affected by radiation fog in the mornings but after sunrise, visibility improved.

4.2 Histograms of events for Aircraft Accidents and Incidents during the MAM 2008-2017 for the five airports

In order to determine the characteristics of aircraft accidents and flight incidents at four of the five selected airports, flight delays, diversions, overshoots/ go-arounds, cancellations, and accidents were retrieved from the available records throughout the duration of the MAM season from 2008 to 2017. These counts are shown in Table 4.1. Note that aircraft accidents and incidents data from HKEL was not accessible from the source; the data could not be traced from where they were stored.

Table 4. 1: Aircraft accidents and incidents that occurred during MAM from 2008 to 2017 for HKKI, HKJK, HKNW and HKMO against the total flights in brackets at those respective airports.

Event/ Occurrence	HKKI	HKJK	HKNW	HKMO
Flight delays	2	39	5	0
Flight diversions	8	46	6	0
Flight overshoots/ go-arounds	1	5	0	0

Flight cancellations	0	8	2	0
Aircraft accidents	0	0	3	0
Total	**11 (360)**	**98 (3478)**	**16 (2198)**	**0 (1238)**

As is evident in the Table 4.1, HKJK had the most occurrences with 98 incidents. This was due to being a very busy airport; among the first in the region (Airport Council International, 2019). HKNW had a few incidents despite being the one of the busiest hubs in East and Central Africa (KCAA 2014). This could be due to the fact that the airport majorly handles unscheduled but regular flights. For a scheduled aircraft, one can get flight delays and cancellations because one can know after how long from the scheduled time has the delay occurred. When a plane takes off or lands later than expected, there has been a delay. The Federal Aviation Administration (2018) states that if an aircraft is more than 15 minutes behind schedule, it is deemed to be delayed. A cancellation occurs when the airline decides not to operate the flight at all for a certain reason. That is the rationale why HKNW does not have many incidents because 95% of the flights are not scheduled (KCAA, 2014). Moreover, most of its flights are the General Aviation (GA) aircrafts which are training aircrafts. These aircrafts fly after observing if the weather is convenient for flying. An example can be students may be due to fly the next day at 8 am but these times are not noted down; meaning that these flights are not scheduled. The next morning, the students delay or cancel their training flights due to heavy rainfall or fog but because these flights were not scheduled, they cannot be considered as delays or cancellations on paper. Apart from General Aviation aircrafts, most of the government agencies for instance Kenya power, Kenya Wildlife, Kenya forest amongst others, operate their aircrafts in an ad hoc situation; that is anytime they are ready to go, therefore, flights incidents were difficult to determine.

HKNW was the only airport out of the five that experienced aircraft accidents during the period of study. The accidents occurred due to tailwinds in thunderstorm (KCAA, 2014). During the third and final stage of thunderstorm formation (dissipating stage), there occur downdraught. These downdraughts are downward current of air moving in all directions, creating wind shear. When an aircraft landing meets these wind shear, it initially gets a headwind which is beneficial for landing as it reduces landing distance due to drag. As the aircraft proceeds, it subsequently gets a tailwind which is unfavorable; this increases the landing distance which eventually push the aircraft towards the end of the runway and crash at the fence ahead. The strengths of the tail winds at the time of the three accidents were 13, 17 and 24 knots. The aircraft which crashed were; two Cessna-182 and a piper aircraft all of them being General Aviation flights for training.

The histogram for aircraft accidents and incidents during the period of study for HKKI is as shown in Figure 4.8 in time steps.

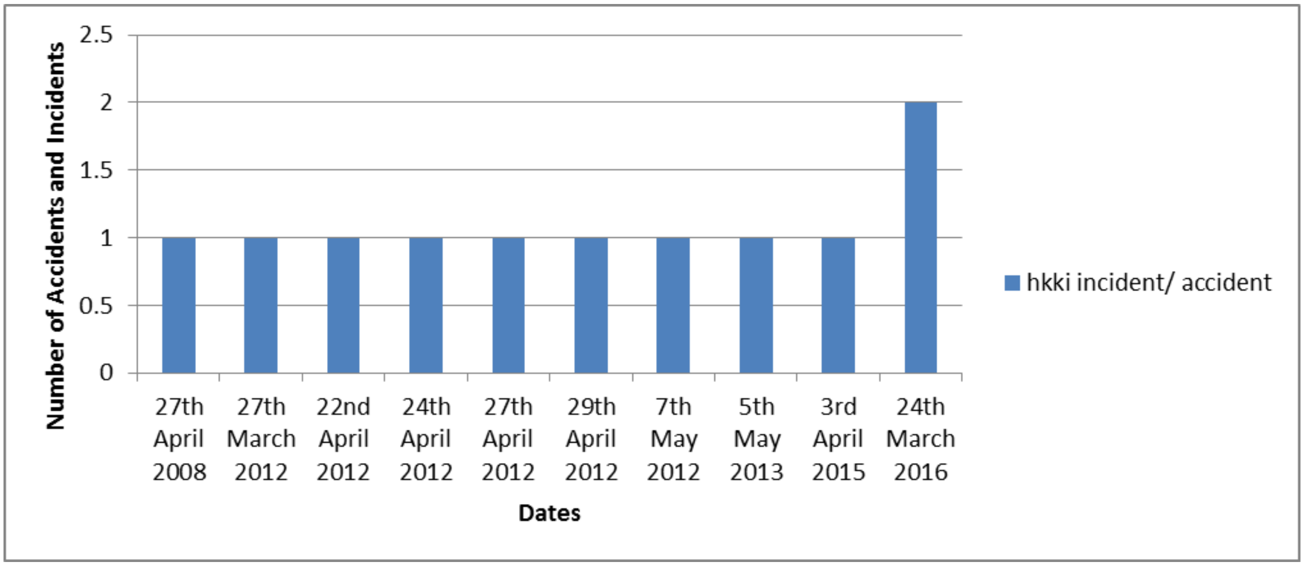

Figure 4. 8: A graph outlining aircraft incidents and accidents during MAM from 2008-2017 at HKKI

As is evident in Figure 4.8, the results indicated that there was only one day which had more than one instance of an incident; the other nine days had one incident per day. During the period of study, 10 days experienced incidents. The month of April had six of the 10 days with these incidents; this could have been contributed by a higher rainfall amount during that month in the MAM season. March and May each had two incidents.

As shown in Figure 4.8, 2012 had six incidents of the total 11 for the period of study. The reason for this many incidents in 2012 as opposed to the other years was that; expansion started in 2008 to make this airport an international airport. In late 2011 to mid-2012, there was an upgrade of instruments from the old ones to the more advanced ones which was to enable the airport get the international airport status. The upgrade involved structural maintenance. During this period, most instruments were affected and probably led to low accuracy readings of the weather elements. Many flights were affected as a result and this is the reason this particular year reported a lot of incidents.

The histogram for aircraft accidents and incidents during the period of study for HKJK is as shown in Figure 4.9

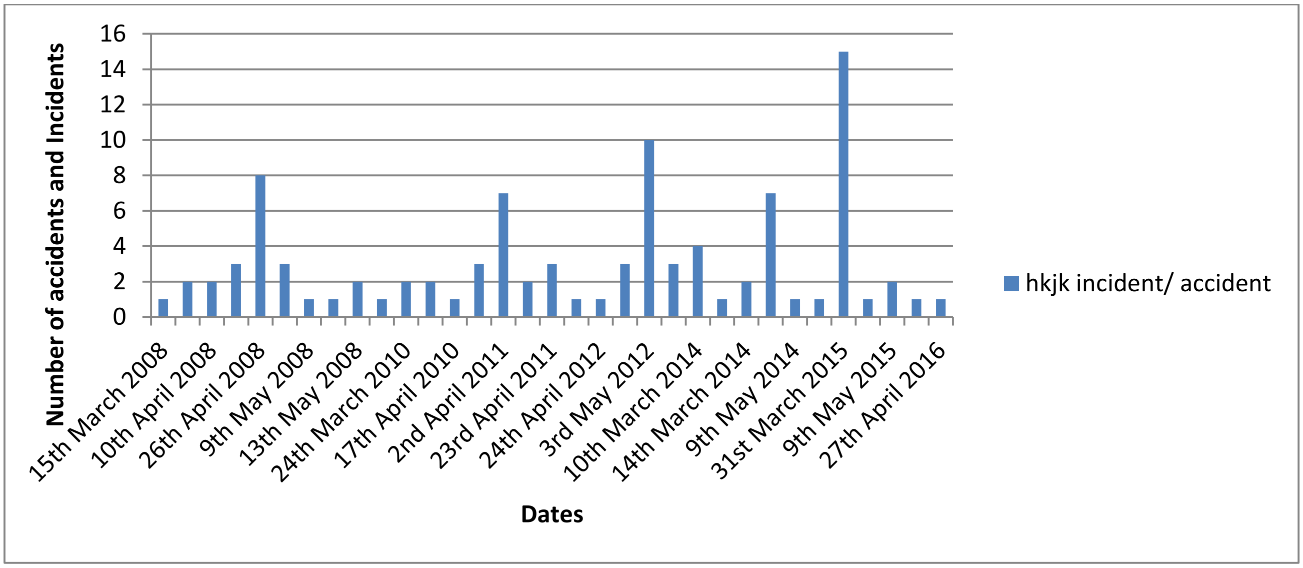

Figure 4. 9: A graph outlining aircraft incidents and accidents during MAM from 2008-2017 at HKJK

As is evident from Figure 4.9, the outcomes showed that many days had one instance of aircraft incident while other days, the frequency was higher. There was a day; 31st of March, 2015, which had 15 incidents. This day experienced a lengthy period of rainfall as well as an intense one which rained from 2pm to 10pm and had a total of 101 mm of rainfall. This greatly affected the flights and thus many incidents experienced. April had most days of incidents with 17 then March with nine and May with seven.

The histogram for aircraft accidents and incidents during the period of study for HKNW is as shown in Figure 4.10

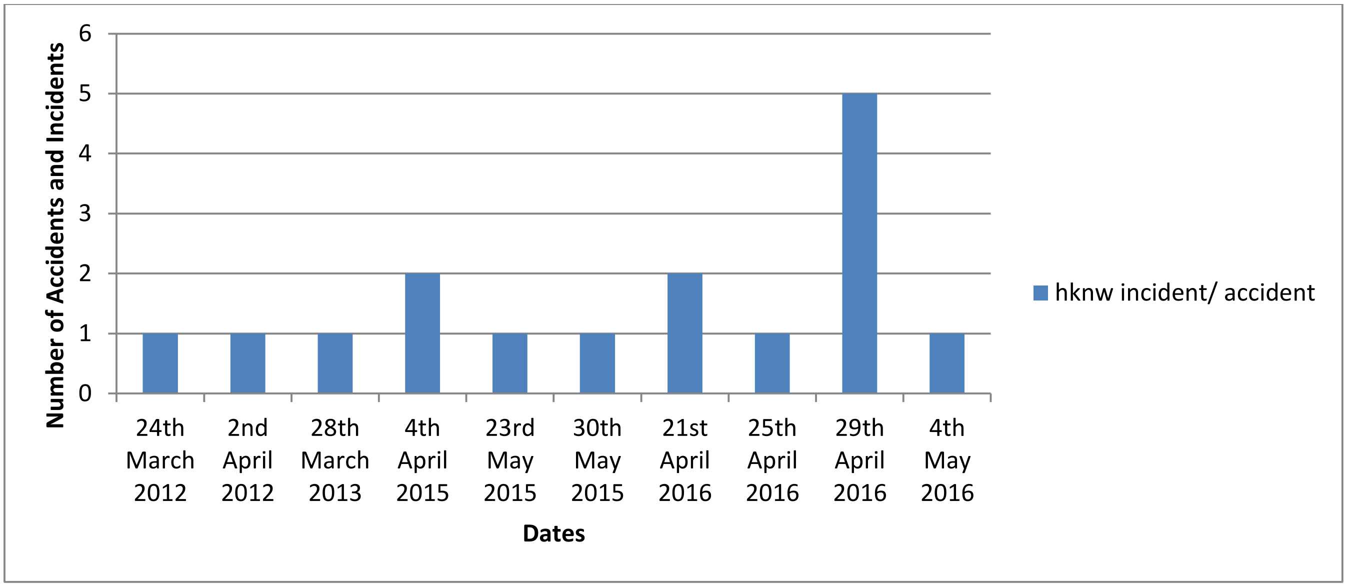

Figure 4. 10: A graph outlining aircraft incidents and accidents during MAM from 2008-2017 at HKNW

As is evident in Figure 4.10, the results indicated that many days had one incident and/ or accident with few days with more than one. This airport could potentially have had the most incidents because of its busy nature but because the flights were not scheduled, these incidents were not captured. This airport was the only one with aircraft accidents of all the five airports. These accidents were caused by tailwinds in thunderstorm (KCAA, 2014). There was a two week period in 2016 between April 21st and May 4th where there were a lot of incidents. This was caused by a go slow from KCAA workers regarding pay hike. This affected weather information transmission to pilots thus worsened the airport operations and led to many incidents. April was once again the month with the most days of incidents/ accidents with five followed by May with three and March with two.

In conclusion, the results indicated that western region received more extreme rainfall than any other part of the country. Secondly, visibility was worse in HKJK and HKNW as compared to the other airports under study; the reason could have been because of more industrialization and urbanization in the Capital City. HKJK had the most incidents while HKNW was the only airport with accidents. The lake, sea and land breezes affected wind components at HKMO and HKKI.

Rainfall peaked in April for all the years during the period of study for all the airports under study apart from HKMO. April was also the month with the most accidents/ incidents. This can be concluded that extreme weather affects airport operations.

4.3 Thunderstorm-related phenomena exceedances over a particular limit

There were exceedances of all TS-related phenomena limits from all the airports and all the years of the period of study. The exceedances were few as shown in Table 4.2 which confirms that the extremes of weather are usually not normal to experience but when they do happen, may cause significant hazards.

Table 4. 2: Exceedances of thunderstorm related phenomena during MAM from 2008 to 2017 for HKKI, HKJK, HKNW, HKMO and HKEL.

AIRPORT	% of frequency of rainfall exceedances	% of frequency of crosswind exceedances	% of frequency of tailwind exceedances	% of frequency of visibility exceedances
HKKI	1.83	0.04	0.21	0.05
HKJK	0.83	0	0.01	0.15
HKNW	0.87	0.01	0.03	0.03
HKMO	0.78	0	0.15	0.08
HKEL	1.76	0	0.11	0.05

The outcomes showed that all the stations had rainfall hours of less than 2% which exceeded the limits; as is depicted in table 4.2 and in figure 4.2, by the 7.6 mm mark shown by a black line pointed at both ends. Anything above that line was an exceedance of rainfall hour.

As is evident in table 4.2 and in figures 4.5, 4.6 and 4.7, all the stations had crosswind components of less than 0.05%, tailwind components of less than 0.25% and visibility components of less than 0.20% which exceeded the limits. These components were the exceedances

In conclusion, it was observed that all the ICAO thunderstorm-related phenomena (i.e. rainfall, crosswinds, tailwinds and visibility) limits were exceeded at all the five selected aerodromes. All the exceedances were less than 2% of the total observations. This study concurs with Aderinto and Dahunsi, (2008) which found out that the rainfall which exceeded the limits in Nnamdi Azikiwe International Airport, Nigeria, was less than 2.2%.

4.4 Relationship between exceedance of thunderstorm-related phenomena and aircraft incidents and accidents at the selected airports in Kenya

The correlation between days with extreme weather events and the days with aircraft accidents and incidents was carried out as shown in Table 4.3. The correlation was for both the thunderstorm related phenomena and the aircraft accidents and incidents. In addition, there were the tests of significance of the correlation coefficient for each aspect.

Table 4. 3: Correlation between thunderstorm-related phenomena and aircraft accidents and incidents at HKKI, HKNW and HKJK

Incidents/ Accidents	Airport	Heavy Rains	Crosswinds	Tailwinds	Visibility
Delays	HKKI	**0.158**	-0.002	**0.21**	-0.287
	HKNW	**0.369**	0.384	0.09	0.235
	HKJK	**0.454**	0.583	0.313	**-0.309**
Diversions	HKKI	**0.481**	-0.004	0.097	-0.285
	HKNW	**0.339**	0.52	0.328	0.481
	HKJK	**0.386**	**0.042**	0.04	**-0.193**

Go-arounds	HKKI	**0.459**	-0.02	**0.004**	-0.002
	HKJK	**0.277**	**0.192**	**0.04**	**-0.074**
Cancellations	HKNW	**0.134**	0.286	**0.21**	**0.004**
	HKJK	**0.145**	**0.042**	**0.081**	**-0.334**
Accidents	HKNW	-0.009	0.232	**0.17**	-0.005

NB: The values that were statistically significant (The p-value must be less than 0.05 for the values to be considered statistically significant) are bolded in table 4.3.

For most of them, the correlations were moderate. A test of significance was conducted on all components parameter-wise and station-wise. It showed that in more than half of them, the p values were less than 0.05 (as shown in the bolded numbers above); hence the correlation coefficients were statistically significant at those levels.

As is evident in Tables 4.3, at HKKI, there were no cancellations and accidents. At HKNW, there were no Go-arounds and at HKJK, there were no accidents. Delays in HKKI, HKNW and HKJK airports were caused by heavy rains as indicated by 0.158, 0.369 and 0.454 respectively. HKKI delays were also affected by Tail winds as shown by 0.21; this comes as a result of the water body nearby which causes the lake and land breezes. HKJK delays being affected also by visibility as shown by -0.309 due to the cement industries active during the day. Diversions in HKKI, HKNW and HKJK airports were affected by heavy rains as indicated by 0.481, 0.339 and 0.386 respectively; with HKJK diversions being affected also by crosswinds (0.042) and visibility (-0.193). Go-arounds in HKKI (0.459) and HKJK (0.277) and cancellations in HKNW (0.134) and HKJK (0.145) were all affected by heavy rains. Cancellations and Go-arounds in HKJK were affected by all the four thunderstorm-related phenomena.

Generally, heavy rains affected all the airport operations. Visibility, crosswinds and tailwinds also had significant effects on airport operations as is evident in Table 4.3. This means that the more the thunderstorm related phenomena leaned towards the extremes; the higher the number of accidents and incidents were experienced. This is in line with the past studies; (Kulesa, 2002), (Rodenhuis, 2004), (Mussa, 2009), (Koetse and Rietveld, 2009), (Cao *et al*., 2014), (Sharman *et al*., 2015), (Coy, 2016) and (Nagarajan and Vidyapeetham, 2018).

Regression analyses for the three airports were also done as shown in Table 4.4.

Table 4. 4: Regression Analysis summary based on the selected Airports

Incidents/ Accidents	Airport	Heavy Rains	Crosswinds	Tailwinds	Visibility	Variance
Delays	HKKI	**		**		**6.73%**
	HKNW	**				**13.98%**
	HKJK	**			**	**23.95%**
Diversions	HKKI	**				**23.68%**
	HKNW	**				**11.68%**
	HKJK	**	**			**21.35%**
Go-arounds	HKKI	**				**21.15%**
	HKJK	**	**			**9.5%**
Cancellations	HKNW	**		**		**6.07%**
	HKJK	**				**2.57%**
Accidents	HKNW			**		**3.07%**

****** (the double stars) show the relationship between the thunderstorm-related phenomena and aircraft accidents and incidents that were significant

From Table 4.4, Extreme rainfall affects aircraft flight operations. At HKNW, it was observed to explain 13.98 % and 11.68 % of aircraft delays and diversions respectively while in HKKI, it was observed to explain 23.68% and 21.15% of diversions and go-arounds respectively. Go-arounds and cancellations were also observed to be affected by heavy rains.

Aircraft operations were also reported to be affected by extreme tailwinds. Extreme tailwinds accounts for about 3.07% of all the accidents at HKNW. Extreme rainfall can be concluded to have affected most of the airport operations at all the airports while visibility least affected the airport operations. This is the case in all the other airports.

HKNW and HKJK were affected mostly by delays and diversions. HKKI experienced diversions and go-rounds mainly. HKNW was the only airport which reported an accident which is associated with extreme tailwind. Extreme rainfall played a role in the incidents at all these three airports. In other words, incidents at all the airports were associated with the occurrence of extreme rainfall alone or accompanied by another extreme thunderstorm-related phenomenon. Poor visibility only affected delays at HKJK. Extreme crosswinds affected diversions and go-arounds at HKJK. Extreme tailwinds affected cancellations and accidents at HKNW and delays at HKKI. From this, it can be concluded that heavy rainfall majorly affects airport operations more as compared to the other thunderstorm-related phenomena.

In conclusion, from the above results, the study showed that whenever there was an extreme of thunderstorm related phenomena ranging from rainfall, surface winds (crosswinds and tailwinds) to visibility, chances were high that it would lead up to an aircraft accident and/ or an aircraft incident. This has been pointed out from the correlation and the regression analyses results.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The study's main objective was to assess the effects of thunderstorm-related phenomena limits on air transportation in Kenya. This was accomplished through achieving three particular goals, which included reviewing temporal characteristics of thunderstorm-related phenomena at the selected airports in Kenya, quantifying the exceedance of thunderstorm-related phenomena limits at selected airports in Kenya and analysing the relationship between exceedance of thunderstorm-related phenomena limits and aircraft incidents and accidents at the selected airports in Kenya.

The study established that exceedance of thunderstorm related phenomena limits affected air transportation negatively in that they caused aircraft accidents and incidents to increase. This leads to loss of life, severe injuries and big loss in revenue to persons and to the government in terms of aircraft damage, flight delays, diversions, cancellations and go-arounds. These airport operations, when they occur, more aircraft fuel is used which goes to waste and many man hours wasted which would have done something constructive and brought in revenue in one way or another.

Given the relative cost of an aviation accident or incident, improved model outputs, additional research and development, the installation of weather radars, monitoring and verification will all lead to significant financial savings.

The majority of this study is in agreement with Jagero's (2017) study, which demonstrated that turbulence and visibility lead to accidents and significant occurrences, with an examination of injuries and damages demonstrating that they were caused by weather-related hazards.

The remedy for this problem is to avoid flying in a thunderstorm. If the forecasts give that a particular time, thunderstorm(s) will be experienced; the flight schedules should be reorganized to avoid the thunderstorm effects. This is so because the effects of thunderstorm cannot be averted wholesomely; there is need to avoid flying at these times.

5.2 Recommendations

The following recommendations are offered to various sectors based on the findings, discussions, and conclusion taken from this study.

5.2.1 To the Researchers

- This study focused on the effects of exceedances of thunderstorm-related phenomena limits on aircraft operations in Kenya. An assessment of the relationship of these weather elements (rainfall, tailwinds, crosswinds and visibility) and the aircrafts incidents/ accidents were done. The investigation has to be repeated for other thunderstorm-related factors including turbulence, wind shear, temperature, etc. because the findings demonstrated the impact TS-related phenomena had on airport operations.
- There is also need for accurate and timely forecasts of these TS-related phenomena which were studied. Timely forecasts will ensure that the flight schedules will be done in such a way to avoid the thunderstorm effects thus reduce its impacts on aviation

5.2.2 To Socio-economic Planners

- The study recommends that the airports and airstrips that act as alternate aerodromes such as Isiolo, Nakuru and Garissa be assessed for vulnerability to TS-related phenomena to the ones that were studied and if they are less vulnerable to thunderstorm-related phenomena be developed as backup landing strips in the event that inclement weather causes problems in Nairobi.

5.2.3 To Aviation Sector

- KCAA have attributed what caused the accidents at HKNW. A study to understand the causes of these incidents at different airports will be a plus.

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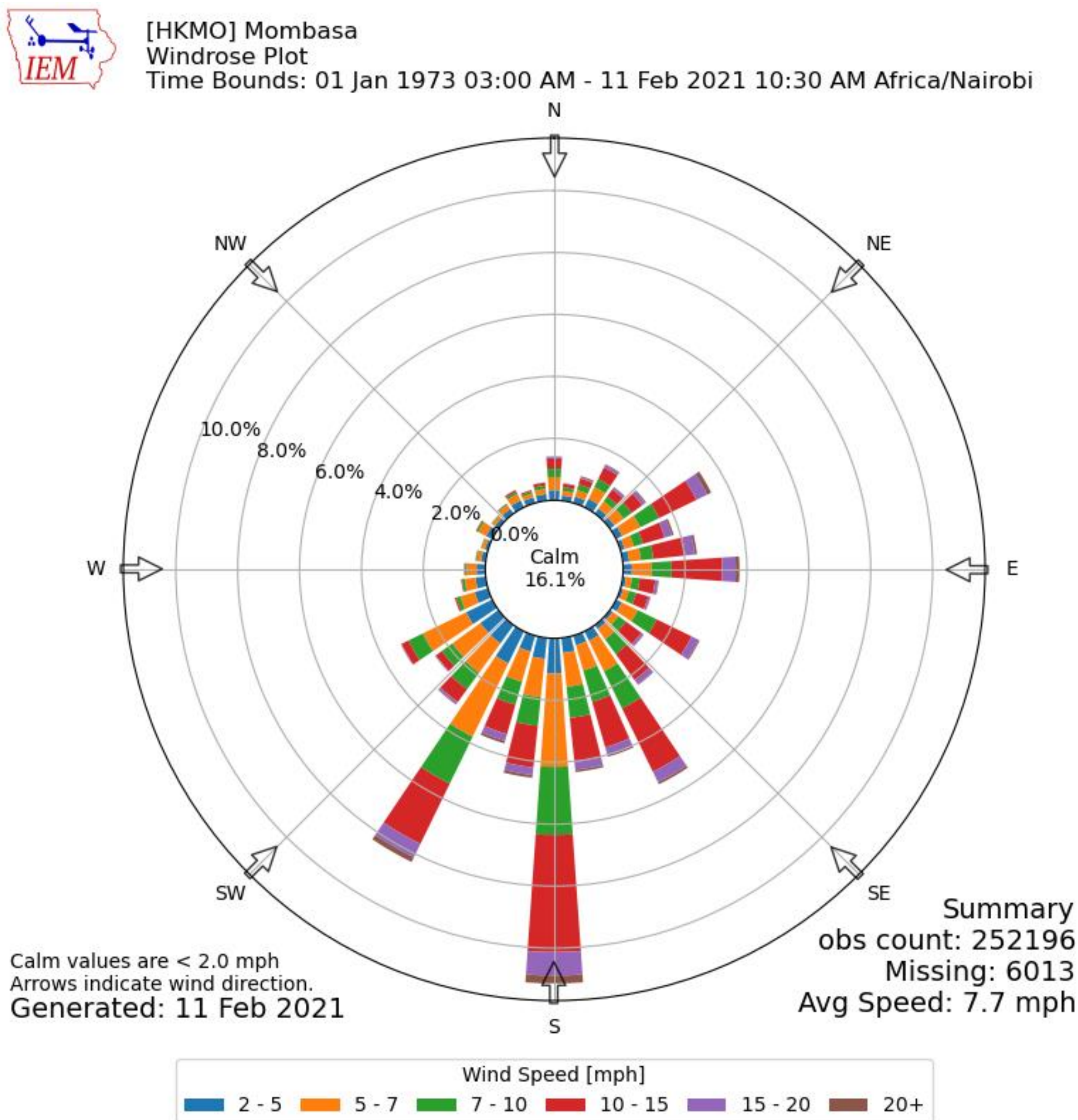
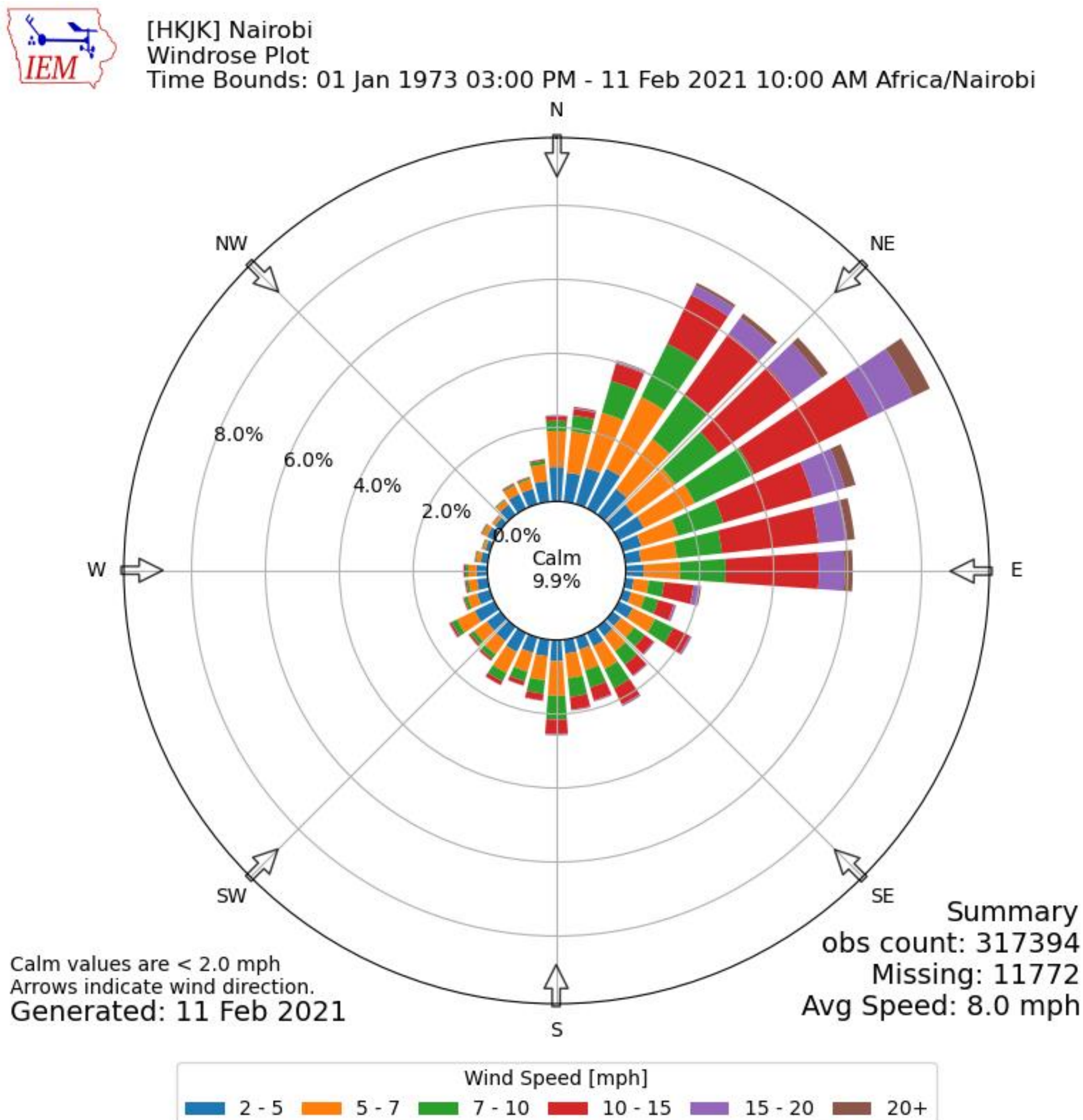
APPENDICES

Appendix 1: Wind rose for HKMO



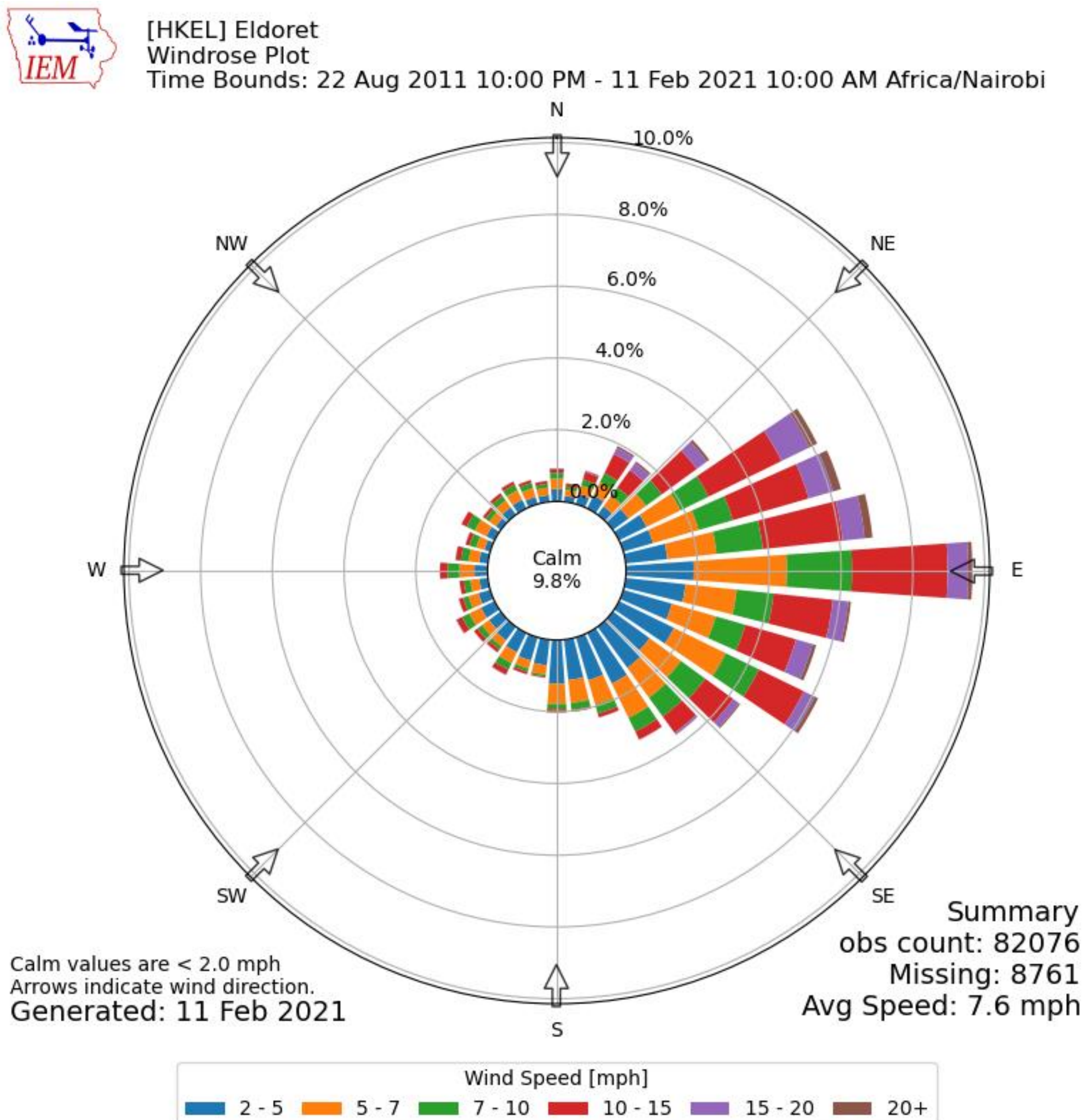
Source: The data are from "Iowa Environmental Mesonet", by Iowa State University, 2022.

Appendix 2: Wind rose for HKJK



Source: The data are from "Iowa Environmental Mesonet", by Iowa State University, 2022.

Appendix 3: Wind rose for HKEL



Source: The data are from "Iowa Environmental Mesonet", by Iowa State University, 2022.