THE IMPLICATIONS OF WIND AND SHEAR INCIDENCES ON FLIGHT OPERATIONS AT JKIA IN KENYA.

By

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DECLARATION

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

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ABSTRACT

Bad weather is the leading cause of flight delays. This is because it highly affects flight safety especially for aircrafts in approach-landing and take-off-climb out phases owing to their proximity to the ground. Delays affect the economy negatively due to the additional cost attached to them. This study thus analyzed the implications that wind shifts had on operations at JKIA and surrounding areas between 2007 and 2016. Runways are constructed to take advantage of the prevailing wind. However, the erratic nature of wind causes abrupt changes in wind velocities decreasing the optimal performance of an aircraft.

The study examined the effects of wind shear on flight operations. A total of 319 wind shear incidences were reported by pilots. 90% were airborne of which 65% resulted in go arounds due to unstable approach caused by wind shear and turbulence. 2% diverted to other airports. The economic impact due to delays and diversions amounted to approximate USD 79,620 and USD 700,000 respectively. Tailwind shear was the common shear encountered. This is supported by 11% of pilots who specified the nature of shear. Both the allowable tailwind components of 10-15knots and the allowable crosswind components of 10.5-20 knots were encountered. A strong positive correlation was observed between wind shear presence and delays. In entirety, 1 in every 2983 flights encountered wind shear.

Wind shear was reported for the entire year. Over the years wind shears had a downward trend while air traffic had an upward trend. The temporal variability was significant for air traffic as compared to wind shears. The seasonal transition months of February, August and November had high wind shear reports with exception of May. This was based on position of the ITCZ in the tropics. The wind characteristics displayed by seasonal wind roses showed a variability of wind direction in JJA. This can be explained by the influence of southern pressure cells during this season. In the rest of the months north east monsoon winds were dominant.

From predictability analysis it was evident that nocturnal inversion caused wind shearing in the layer 800-750mb in the February case study. Wind speeds were at their maximum at the 800mb level. The wind shear was mainly light to moderate. In the August case study, directional shear was evident from 800mb to middle levels whose cause was convection. It persisted throughout the day. The different directions between the surface and middle levels enhanced instability.

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LIST OF ACRONYMS

ACC- Allowable crosswind component

ASAs: Air Service Agreements

ASRS: Aviation Safety Reporting System

ATSB: Australian Transport Safety Bureau

EAAC: East African Airways Corporation

EASA- European Aviation Safety Agency

ECA: Economic Commission for Africa

FAA- Federal Aviation Authority

GDAS- Global Data Assimilation system

GDP- Ground Delay Program

ICAO-International Civil Aviation Organization

JKIA- Jomo Kenyatta International Airport

KAA-Kenya Airport Authority

KCAA- Kenya Civil Aviation Authority

METAR- Aviation weather routine report

NIPALS- Nonlinear Iterative Partial Least Squares

NTSB: National Transportation Safety Board

NASA: National Aeronautics and Space Administration

PHAK-Pilots Handbook of Aeronautical Knowledge

RDC- Runway Design Code

TAF-Terminal Aerodrome Forecast

WMO-World Meteorological Organization

Aerodrome elevation:	The elevation of the highest point of the landing area.
Airfoil:	Any part of an airplane that is designed to produce lift.
Altitude:	Vertical distance of a point, level, object, considered as a point measured from mean sea level but not fixed on the earth surface.
Angle of attack:	Angle at which the wings meet the flight path
Elevation:	Vertical distance of a point, level, object, measured from mean sea level on/or a fixed object on the earth surface
Height:	Vertical distance of a point, level, object, considered as a point measured from a specified datum.
Incident:	This is an occurrence, other than an accident, which affects or could affect the safety of the flight.
Minimum sector altitude:	The lowest altitude which may be used which will provide a minimum clearance of 300 m (1 000 ft) above all objects located in an area contained within a sector of a circle of 46 km (25 NM) radius centered on a radio aid to navigation.
Weather Standby:	An alert issued when weather conditions render a landing hard or observations are difficult to observe such as during a strong crosswind, poor visibility, ice or snow on the runway.

CHAPTER ONE

1.0 INTRODUCTION

Air transport is a key industry in economic and social processes. Its growth internationally has played a part in the development of a country society. It facilitates the economic development of a region by earning foreign exchange hence influencing national and global economy (Benjamin, 2013). This enhances efficient movement of goods, services and passengers within the domestic and global market hence generating revenue to economies. For instance in 2009 in Kenya, the aviation sector contributed to Kshs 84.0 billion to the Kenyan GDP (3.7% of GDP) of which Kshs 59.2 billion was contribution from tourism (Oxford economics, 2011).

Regardless of these benefits brought about by air transport, there are challenges that affect air transport such as weather. The air transport industry is highly dependent on weather information to economically enhance their daily and strategic decisions on planning and routing (Gruenigen, *et al*., 2014). This weather information is also essential for flight safety. Of interest in this study is low level wind shear, atmospheric turbulence, and gusty winds which are potentially hazardous and negatively impact airlines due to delay cost brought about by unexpected wind shifts encounter. Aircrafts are designed to fly in headwind conditions when landing or taking off for optimal performance (Triet *et al.*, 2015). When tailwinds, gusty winds or crosswinds occur, the lift dynamics of an aircraft are compromised. An aircraft only operates in these conditions if the various tailwind and crosswind thresholds are not exceeded (Van and Karwal, 2001).

In many locations, winds tend to blow more frequently from one direction than any other (Ahrens, 2009). This is what is referred to as dominant wind of a given place. It is this direction of the prevailing wind that is considered in major runway alignments in order to assist in landing and taking off. However airflows on scales just larger than turbulence are always present and can cause considerable variation in wind direction when the large scale wind is weak (Anfossi *et al.*, 2005).

The abrupt changes in wind direction or speed or both in either the horizontal or vertical directions is known as wind shear (Golding, 2005). To a pilot, it is described as the sustained change (that lasts more than a few seconds) in the wind direction and/or speed which causes an abrupt change in altitude of an aircraft when there is considerable increase or decrease in the headwind encountered (Chun, 2004). An aircraft fly's above or below the intended path in this wind changes.

During approach and departure phases of flight, the aircraft is operating at relatively low speeds, (ICAO, 2013). Its proximity to the ground renders the aircraft susceptible to the adverse effects of wind making it difficult to take corrective action. The response of an aircraft to wind shear is dependent on the aircraft type, flight phase, the scale and intensity of wind shear relative to aircraft size and duration of the wind shear encountered (ICAO 9817, 2005). On encountering wind shear, a pilot in most cases performs an emergency go-around procedure and starts a new approach causing delay. A flight is delayed if it arrives 15 minutes after its scheduled arrival time. The 15 minute gap similarly classifies departing flights as delayed (Eurocontrol, 2004). For domestic flights or intra-African routes, the 15 minutes delay is huge considering the time of flight.

In some instances, the effect of wind shear is such that there is no time to properly counter the risk thus a pilot only mitigates the effect of a subsequent loss of control (EASA, 2013). Such was the case in 1985 when a Delta Flight 191 as it descended in the middle of a thunderstorm which produced a microburst along the airline path. The plane encountered an outflow of air at 800 feet above ground level. The plane sank on encountering a downdraft and was subsequently faced by a 46 kt tailwind which denied it crucial lift. At low altitude, the pilots lacked room for recovery. Delta Flight 191 crushed just a mile short of the runway threshold and all people on board perished in the accident (NTSB, 1986). During the 29 year period (1970-1999), aircrafts accidents are summarized in Table 1.

Table 1. A summary of Wind Shear related accidents worldwide (Golding, 2005)

Years	Deaths
1970-74	138
1975-79	112
1980-84	152
1985-89	136
1990-94	37
1995-99	11

Several close accidents have been caused by wind shear in which aircraft recovered just before ground contact. From 1998 to 2003, approximately 1 in 500 flights encountered significant wind shear in Hong Kong airport particularly in the month of March and April. This is defined as a headwind change of 15kt or more (Chun, 2004). Though the number of aircrafts accidents or incidents related to wind shear has reduced, it is still considered as a threat in aviation.

Globally, most aircraft accidents are attributed to severe thunderstorms, low level wind shear and gusty winds as some of the liable weather related events. Due to gust fronts, microburst, mountain waves (in the terminal area), strong surface winds together with local topography, urbanization-manmade structures, sea/land breeze fronts and surface heating, turbulent eddies can occur suddenly especially where wind changes abruptly leading to wind shear.

Accurate and timely weather forecasts thus influence efficiency and safety of flights (Hansen, 2007). These forecasts are used when making tactical decisions such as; how much extra fuel is required before take-off, which runway to use, when to take-off or whether to land, divert or hold within the circuit pattern depending on weather conditions. If convective weather or wind shear is forecasted at a destination airport, then the chance of a flight being diverted to an alternate airport is a higher. In such cases pilots load on extra fuel to extend the flight range of the airplane to reach these alternate airports.

Terminal operations are also impacted by wind shear since the presence of either a crosswind or a tailwind impedes landing and require changing the runway configuration. When occurring in thunderstorm it can lead to airport closures, reduce capability of airports to accept or release planes for departure and hinder or stop ground operations.

This study will mainly focus on determining the implications of wind shear on airline operations at Jomo Kenyatta International Airport (JKIA). JKIA is the busiest airport in Kenya with scheduled flights to over 50 countries.

1.1 PROBLEM STATEMENT

Demand of air transport services has continuously increased due to globalization. As a result airlines are continuously aiming for efficiency in order to achieve consumer satisfaction and retain clients. Timely performance is one of the service that is critical to this industry which is affected by flight delays. Delays are as a result of inclement weather which affects traffic organization especially during peak traffic periods (Wu, 2005). It is a concern to operators and travelers since it brings in additional operational cost and disrupts time schedules.

Muiruri (2011) identified weather as one cause of delays that affect airlines schedules at JKIA. The erratic nature of wind shifts causes difficulty in giving timely warnings for very short range forecast yet it is vital information required during flight planning and operations. Tailwinds on landing increase landing distances especially on wet conditions while crosswinds increase the risk of veering off the runway. Runways are designed to benefit from prevailing winds, thus a wind from a less climatologically preferred direction may result in the air traffic controllers having to rearrange air traffic to depart or land in a different direction. JKIA does not have cross runways to mitigate against excessive crosswind. This means that depending on the strength of the crosswind or tailwind, the air traffic management gives advisories on which direction planes will land from while the pilots decide whether to land or not.

1.2 OBJECTIVE

The main objective of the study is to determine the potential implications of wind shear at JKIA and assess the wind and shear characteristics within Nairobi Airspace

Specific Objectives

i. To determine the effects of wind shear over operations at JKIA.

ii. To determine temporal variations of wind shear.

iii. To determine the wind and shear characteristics of JKIA and surrounding areas.

iv. To establish the predictability of wind shears using analysis data.

1.3 JUSTIFICATION

There are different forms of ground transport. However due to the harsh terrain, they are inadequate in terms of network, poor facilities within transit countries and the heavy investment required in building and maintaining these infrastructures moreso in Africa (ECA, 2005). As a result of these inadequacies, air transport is the most crucial facilitator of the economic and physical integration of the 53 countries and the driving force behind the social and economic growth of the 15 landlocked countries which require an efficient, consistent, fast and safe air transport system (ECA, 2005). An efficient air transport system helps the economic competitiveness of African countries through access to global markets, labor movement, attractiveness to private investment in aviation, and the growth of export sectors that are important in sustaining a strong currency.

Detection and prediction of wind shear occurring at low levels in the surrounding of airports is of particular importance to airlines and control of air traffic. It enables traffic managers to make runway switches using the best possible information about the timing of a wind shift thus plan accordingly. For the airlines, a foreseen encounter with wind shear reduces risk to crew, passenger and reduces cost of air travel. This is because the right action is taken on time avoiding damages likely to be incurred which could remove an aircraft from operations and lead to loss of revenues and extra expenses from maintenance costs. To ensure safety at all times the wind information should be forecasted accurately and timely.

1.4 AREA OF STUDY

The study covers JKIA airport in Nairobi which is the busiest international airport in Kenya. Its’ geographical co-ordinates are $1^0$19’7’’S, and longitude $36^0$55’33’’ E. The airport was opened in 1958 and assigned an ICAO code HKJK. It is located 15km from Nairobi city. It is at an altitude of 1624.5m (5330 ft) above mean sea level. The airport has a single asphalt runway alignment in 060^o-240^0 direction and measuring 4,117m in length. In 2016, JKIA handled over 7 million passengers and has an annual growth rate of 12% pa. This made it the seventh busiest airport in Africa. It is a category 1 (CAT 1) airport meaning that JKIA runway is aided by visual aids and non-visual aids meant for landing operations following an instrument approach operation with a decision height (DH) not lower than 60m (200 ft) and either a visibility not less than 800m or a runway visual range not less than 550m (KCAA, 2014).

Nairobi climatology is determined by the position of the inter-tropical convergence zone. There are 2 rainy seasons namely long rains (MAM) and short rains (OND), a cloudy season (JJAS) dominated by overcast conditions and a dry season (JF). The mean annual rainfall at JKIA is 762mm and the standard level pressure is 844mb.

The study area extends up to a radius of 25 nm (46 km) which is the region considered in determining the minimum sector altitude for safe operations (ICAO, 2013). Within the 25 nm confine is where departure as well as approach paths are situated. These paths are areas with varying terrains. The Mua hills, Kerita hill, Ngong hills, Kiima Kimwe and Ol Donyo Sabuk hills are high ground areas likely to influence the wind characteristics thus will be included in the study. Table 2. shows the location of the high ground areas in the domain of study.

Table 2: High ground areas surrounding JKIA (KAA-Aeronautical Information Publication)

NAME OF PEAK	DISTANCE FROM AIRPORT (NM)	ELEVATION (ft)	LONGITUDE	LATITUDE
Ngong hills	18	8074	0363759E	012603S
Ol Donyo Sabuk	23	7041	0371503E	010802S
Mua hills	20	6800	0371151E	012816S
Kiima Kimwe	22	6970	0371416E	013158S
Kerita	25	8569	0364050E	005854S
JKIA		5330	0365539E	011909S

Figure 1.1: Map of the study Area (Courtesy of Google)

CHAPTER TWO

2.0 LITERATURE REVIEW

In aviation, there are 2 fundamental types of wind shear normally known as to as low level wind shear (LLWS) and low level turbulence. Low-level is defined to be within 2000 ft from the ground. ICAO (2013) Annex 3 document further states that wind shear that could negatively affect an aircraft is that occurring on the approach and take-off paths or during circling approach between runway level and 500m (1600ft) above that level and aircraft on the runway during landing roll or take-off run. The 500m limit is not considered if the local topography produces major wind shears at heights in excess of 500m above runway level. Flight operations near the ground increase their vulnerability to adverse effects of weather. As a result, aircrafts will opt to delay or divert operations in such conditions.

Delays in air traffic can occur while an aircraft is airborne, at destination or arrival airport affecting flight schedules. Schedules in airline industry are essential to proper control and organization of air traffic. They assist in lowering operational cost and maximizing the use of crew and fleet (Wu, 2005). The process of optimizing scheduling will tend to create constricted aircraft routing plans. As a result buffer times are scheduled to solve routing problems. Buffer times help in sustaining flights on time performance and managing small scale delays which makes schedules reliable. A delay of one flight easily spreads to other flights in the network affecting interconnectivity of crew, passengers and aircrafts.

There are different ways of classifying delays. The first classification is based on phase of flight which can be airborne (enroute and holding) delay, taxi-in delay, taxi-out delay and gate delay (FAA, 2001). The other classification is gate to gate delay and network delays (Fergurson, *et al*, 2004). Gate to gate delay is that delay faced by an individual flight based on the environment it meets. Network delay is the influence that it has to the network. Delays can also be tactical or strategic (Cook *et al*., 2004). Tactical delays are encountered in day to day operations such that they last beyond scheduled times while strategic delays are those anticipated days or even months before operations.

In terms of duration the delays can be long (65 minutes or more) or short (15 minutes or less) under tactical delays. Under strategic delays long delays are above 15 minutes. The long delays (>15 minutes) contribute to a massive majority of the cost. From ICAO (2013) Environmental report, the reference times for an airborne delay which involves Approach landing, Climb-out and Take-off Go around commonly referred to as Landing to take-off phase (LTO) performed in a missed approach case is as shown in Table 3. These reference times are general times an aircraft would spend in a missed approach. However, weather conditions and network effect determines how long a delay will be thus the reference times are not explicit.

Table 3. ICAO reference times (ICAO Environmental Report, 2013)

LTO PHASE	REFERENCE TIME (min)
Approach Landing	4
Climb-Out	2.2
Take-Off	0.7

Cook *et al.*, (2004) calculated the cost of delays based on airport charges of 12 European countries. They found that a one minute delay on the ground cost approximately 50€ while on air it is 70€. Ferguson *et al.*, (2004) outlined these cost as fuel cost, extra crew cost, maintenance cost and passenger delay cost. Fuel cost is dependent on fuel burn rates of different aircraft types. Market forces control fuel prices thus will differ with time.

Extra crew cost refers to the additional payments made to crew when they work beyond scheduled hours. Maintenance cost for 1 minute delay is approximated to be 15% of block hour direct operating cost. This cost is calculated by subtracting yearly upkeep cost to fixed cost factors. Passenger delay cost are incurred in terms of hotel accommodation, refreshments and ticket reimbursements (Reichmuth, 2005). A diverted flight means passengers will arrive late at the destination airport hence miss necessary connections. Nieheus *et al.*, (2001) showed that punctuality and operating profit had a positive correlation.

According to Mueller *et al.*, (2002) and Bai (2006), in the Air Traffic Control System, the leading contributors to flight delays is weather which reduces airport arrival or departure rate.

This mainly happens when the runway usability is reduced or when weather conditions are unsuitable for safe operations of aircrafts. Muiruri (2011) conducted a survey of adverse weather hazards that affect flight operations at JKIA and Wilson airports between 2000 and 2009. It was revealed that poor visibility, thunderstorms, wind shear, precipitation and crosswind were the weather hazards that were frequently encountered with a percentage severity of 45.4%, 34.2%, 17.1%, 2.1% and 1.2% respectively. As a result delays and diversions were carried out. At JKIA, the contribution to aircraft delay and diversion by thunderstorms was 15.4% while that of wind shear was 5.4%.

In the US, the Federal Aviation Authority disseminates a ground delay program (GDP) when severe weather conditions are expected at an airport. This increases rate of arrivals to ensure safe operations since airborne flights are more prone to destructive effects of severe weather (Ball *et al.*, 2000). Bad weather causes network delays that affect not only the airport going through the bad weather but to airports holding flights connecting via the said airport. Airport capacity is affected when GDPs are implemented. The capability of an airport to handle traffic is dependent on airport facilities during the given weather event.

Ground stops are also declared when bad weather is predicted for a short while or when weather is not suitable for landing. This implies that aircrafts whose destination is the affected airport are not allowed to depart for a given time. Weather leads to airborne holding for arriving traffic and gate holding or longer taxi times for departing traffic. All these can also be caused by changes in runway configuration. Bai (2006) showed that the correlation between departure and arrival delays and weather at Orlando International airport, between the year 2002 and 2003 was 0.9 which is very high.

Bai (2006) analyzed the relationship between delay in arrival and on-time performance of an airport at Orlando International Airport using multiple logistic regressions. The performance was based on seasons, time (diurnal), precipitation and distance. Delays were categorized into delays ≤ 15 minutes and delays >15 minutes. For those ≤ 15 minutes, the study showed that delays had 24.5% chance of occurring in summer than in any other season while in winter the chance of occurring was 15.4% more. With respect to diurnal cycle, the odds for a delay in the afternoon may possibly be 1.335 times higher while that in the evening may be 2.05 higher than in the morning for both cases.

In precipitating conditions, for every 0.1 inch of increasing precipitation, the probability of having delays for arriving traffic was increasing by 25.3%. In terms of distance, a flight with a distance gap of 750-1000 mile had likelihood of arriving late of 21.2% while that at a distance longer than 1000 miles had likelihood of 3.3% which is a decrease. Delays >15 minutes were also analyzed. In summer and winter the chances of delay are 22% and 10.9% respectively. Diurnally, delay chances are 1.58 and 1.318 times higher in the evening and afternoon respectively than in the morning. For a distance gap of 750-1000 miles, the chance of arriving late increases by 7.5% while for >1000miles the chance increases by 15.9%.

In this cases flights with a longer distance to cover have a higher chance of arrival delay. Wind speeds at Orlando airport were also found to influence delays of arriving aircrafts. Bais' (2006) study showed that time, seasons, weather and distance contribute to delays. Muiruri (2011) assessed how adverse weather affected operations at JKIA and Wilson airports. He showed that the year 2008 recorded the highest frequency of thunderstorms and wind shears. The months of April and December had the highest frequencies of delays and diversions due to the fact they fall under the rainfall seasons. September had the least number of delays and diversions. The cost of delay from all the weather hazards amounted to 3299 minutes which was equivalent to kshs 30 million. Diversion cost of 213 aircrafts was approximated to be Kshs 1.9 billion.

The cost of delays at airborne are determined by decision height, weight, aircraft type and engine type since aircraft models have different engine types which consume different fuel amounts. The point at which a pilot encounters wind shear and decides to carry out a missed approach is the decision height. Once the decision is made, a pilot climbs out to the holding area where the aircraft holds in the circuit pattern till conditions for landing improve. At the holding area the air traffic controller assigns a return vector to the plane in which the pilots will attempt another landing (Mendoza, 2016).

The degradation of airport capacity is highly influenced by wind (Klein, 2009). Airports with parallel runways that are closely spaced or crossing runways are more sensitive even when the winds are weak but from a non-friendly direction that compels an airport into a less favorable runway alignment. Severe convective weather which is associated with destructive winds tend to block terminal and enroute airspace leading to increased delays, diversions, cancellations and extra miles flown that contribute to irregular operating cost. Delays can be avoided or be unavoidable. Unavoidable delays are linked to severe weather and regulations and procedures governing the airport such as consideration of the maximum allowable crosswind.

The avoidable delays are dependent on accuracy of weather forecasts. Under-forecasting causes last-minute disorganization of traffic as players rush to abate the impact of the unanticipated weather. Over-forecasting on the other hand causes unnecessary cancellations, GDPs and rerouting. This creates inefficiencies in the system. Klein *et al*., (2009) computed the impact of various inaccurate weather forecasts to avoidable delays. Wrong forecast of Instrument meteorological conditions (low ceiling/visibility, heavy rainfall) contributed to 33.1% of avoidable delays followed by wind whose speeds/gusts were >15kt at 27.2%, then winter precipitation at 6% , other minor weather events which were winds of <15kt, light rain and drizzles which combined contributed to 32% and lastly, local thunderstorms at 1.6%. It is evident that a correlation between weather forecast accuracy and delays exist.

Adams *et al*., (2004) showed that the possible benefits per year of improved non-convective weather forecasts could amount to $600M. Another study by NavCanada (2002) indicated that a Terminal aerodrome forecast (TAF) whose accuracy is 100% at a Canadian airport would contribute $12.5M per year. Gruenigan *et al*., (2014) demonstrated that use of TAFs at Zurich airport in decision making would have economic benefits of estimated $78 to $1906 per landing depending on flight duration. It is noted that these benefits are sensitive to changing fuel prices.

2.1 CROSSWIND COMPONENT

A crosswind component is that wind that blows across the runway thus affecting the smooth landing of aircrafts (Bellasio, 2014). Flight test experiments done by manufactures have developed a maximum crosswind component for each aircraft which increases with aircraft size. An allowable crosswind component (ACC) during landing has been established by the Federal Aviation Administration (FAA) and it is dependent on the runway design code (FAA, 2012). The Runway Design Code (RDC) is made up of a letter and a Roman numeral. The A to E letters relate to the approach speed of the aircraft categorized as A for low speed up to E for high speed. The Roman numerals I to VI relate to the wingspan or tail height (I being small size up to VI great size). Information on visibility is also incorporated in the RDC but it is not considered in determining the ACC. The ACC as function of RDC is shown in Table 4.

Table 4. Allowable crosswind component per runway design code

Runway design code	Allowable crosswind component, kts
E 1 through E VI	20
AIV and BIV, CIV through CVI, DIV through D VI	20
A III, B III, C I up to D III,	16
A II and B II	13
AI and B I	10.5

The ACC is also a function of the minimum required take-off field length as established by ICAO and European Aviation Safety Agency (EASA). The ACC is 10 knots for lengths < 1200 m, 13 knots for lengths <1500 m, and 20 knots for lengths >1500 m. The ACC values refer to a dry runway surface. For a wet runway surface, the ACC decreases for example when the runway condition is poor for braking, the 20 knots ACC reduces to 13 knots (EASA, 2011). KCAA (2014) in their manual of aerodrome standards has adopted this ACC conditions.

Generally, operators prefer not to exceed the established crosswinds during operation (Van *et al.*, 2001). Crosswind limits for contaminated or wet runway are lowered by all operators. Different crosswind limits for the same aircraft and runway condition can be used by operators since this limits on dry runways are advisory information only. Aircraft tires and non-dry runways interact differently for different runways. A crosswind maximum can be set by an airport for all commercial operators which use the airport. For instance in Europe, Heathrow airport has the highest crosswind maxima of 25kts. However a crosswind maximum of 15 knots is the preferred limit used by most airports.

2.2 TAILWIND COMPONENT

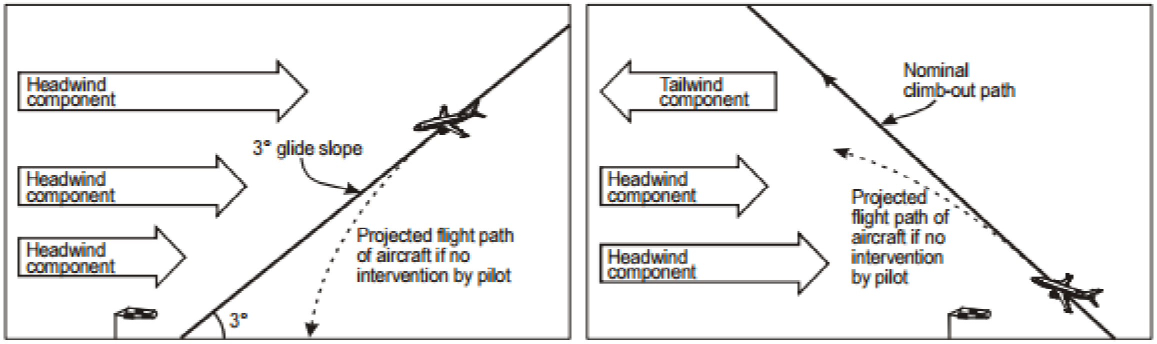
A tailwind refers to wind that blows in the direction of travel. When it comes to tailwinds, a number of aircrafts have a tailwind maximum of 15knots. However not all operators are approved to carry out take-offs or landings with tailwind component greater than 10 knots (Van, 2001). Table 5 below is a summary of the numerical values of the thresholds allowed for safe operations of a sample of different aircraft types under dry runway conditions. For wet runway and contaminated runway (runway containing stagnant water, snow or ice) the thresholds reduce since runway braking conditions tend to lower.

Table 5: 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 (KT)	Maximum Allowable Tailwind component during Landing (KT)
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

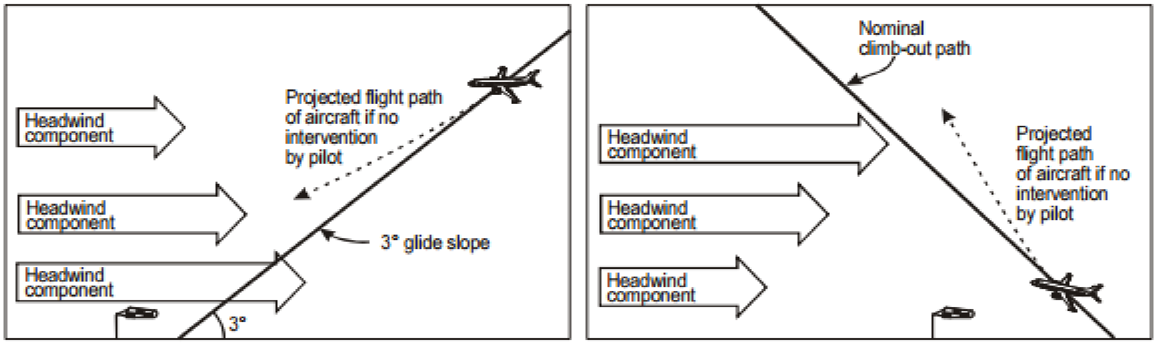
Wind flow on an aircraft is essential to flight safety and performance. Headwinds during landing help reduce the ground speed of aircrafts while at take-off they provide lift giving an aircraft a steeper gradient which is beneficial in clearing obstacles. Tailwinds on the other hand will increase ground speeds on landing requiring longer landing field lengths. Take-off in this conditions means the climb out gradient is gentle and not good for clearing obstacles (Van and Karwal, 2001). How well an aircraft responds to fast changes in wind shear and turbulence is dependent on the pilots' response to perceived and real conditions (Arkell, 2000). The pilot can change the aircrafts' power settings and or its attitude (angle of attack or pitch). These changes in turn revise the aircrafts indicated airspeed (IAS) and/or its rate of climb or descent (ICAO, 1987).

For a tailwind that is increasing, a pilot increases power which in turn increases the indicated airspeed (IAS). This prevents decreased wings lift which reduces the response of control surfaces and drops the aircraft below the desired flight path or glide slope or may even stall the aircraft (ICAO, 1987). If the headwind is increasing, the pilot cuts back on power otherwise the aircraft rises above the desired flight path or glide slope. If the pilot is unsure about the direction of the shear or thinks that the reported or forecasted non-convective low-level wind shear might really be low-level turbulence, the pilot normally increases power to be on the safe side. Figure 2.1 below shows the effect of different wind shear conditions on aircrafts.



a) Landing in decreasing headwind

b) Take-off in decreasing headwind



c) Landing in increasing headwind

d) Take-off in increasing headwind

Figure 2.1: Effect of Head (Tail) wind shear on aircraft. ICAO 2005

During cruising phase the reverse is true. Headwind and tailwind encounters decrease or increase time range respectively as compared to no wind conditions (Byington, 1993). The efficiency of an aircraft is more so reduced when unexpected strong headwinds are encountered. If this condition is not managed well, urgent landing may be required due to insufficient fuel left to complete the journey. This is because more thrust force is required to fly through the strong headwinds increasing the airspeed. On the other hand, strong tailwinds call for reduced airspeed since the aircraft will ride on the tailwind force. As a result less fuel is used and the time travel is less hence advantageous. Palopo *et al*., (2010) affirms that the horizontal wind field in the atmosphere determines the daily variability of time taken and routes chosen by airlines. An optimal flight is one that avoids headwinds as much as possible and utilizes tailwinds.

2.3 WIND SHEAR CALCULATION

The sudden variation of wind direction and/or speed between two vertical levels is referred to as vertical wind shear. This difference in wind can be measured between two points spaced vertically 60 meters (approx. 200 feet) in the direction of the runway (Baynton *et al*., 1965). The difference of winds at two different heights is referred to as thermal wind whose strength is dependent on the vertical wind shear (V.W.S). The strength of the V.W.S is determined by the horizontal temperature gradient.

The behavior of the wind in the final 100 ft. of descent is the most important to an aircraft on its final approach. Wind speed shears greater than 6kts/100ft are categorized as dangerous, while greater changes in wind direction (greater than 40 degrees) are considered hazardous (National Research Council, 1983). The Vertical shear magnitudes are derived by subtracting the wind speed at a lower level from the speed at an upper level, and dividing by the distance between those levels. This relationship is shown below:

$$\frac{V_{upper} - V_{lower}}{d_{u-1}} = \frac{\Delta V}{\Delta d} \quad \text{……………………………………………..………….. 1}$$

V= wind velocity

d_{u-1} = distance corresponding to the velocities measured.

The horizontal wind shear is the wind speed change with respect to the horizontal distance

Wind shear directions are calculated in the same way. Table 6 shows the criteria of wind shear intensity.

Table 6: Criteria of wind shear intensity. (ICAO, 2005)

Wind shear intensity	**Wind shear criteria**
Light	0 to 4 kt inclusive per 30m(100ft)
Moderate	5 to 8 kt inclusive per 30m(100ft)
Strong	9-12 kt inclusive per 30m(100ft)
Severe	Above 12kt per 30m(100ft)

The suitability of this simple approach in classifying wind shear intensity is not complete due to the following reasons:

a) Severity of the intensity of wind shear differs from one aircraft type to another thus what is considered as severe shear may be light or moderate to another aircraft.

b) The wind shear impact on an aircraft is determined by the time the aircraft is exposed to the shear. This is a factor of distance within which wind shear is present and the speed at which the aircraft is moving through the wind shear environment.

c) A pilot thinks in terms of speed of the aircraft in which changes in this airspeed is in terms of acceleration or deceleration. Intensity of wind shear is given in speed and distance units. Flight deck instruments do not relate to these units when flying a 3-degree glide slope hence the wind shear units may not assist the flight crew directly.

d) Thunderstorm related wind shear has all the 3 components of wind changing concurrently making it the most risky and this change is not captured in Table 6.

The separation of the 2 types of wind shear i.e low level turbulence and LLWS is to some degree not real since the shears are a segment of a continuous range of shears in the frictional layer (Arkell, 2000). However, it is possible to distinguish them for operational use, based on temporal characteristics. LLWS is an organized shear as may be found at the leading edge of a thunderstorm outflow boundary, and the latter a disorganized hence turbulent, shear as may be found near the surface on a windy day.

In terms of time, LLWS is the shear that evolves slowly in time and turbulence as that shear that rapidly changes in time. It can be convective or non-convective. Non-convective LLWS evolves slowly within a few hours like in for a of nocturnal inversion case. Convective LLWS changes fast mostly over a few minutes as a gust front evolves. Being able to determine time at which these shears occur as well as distinguishing them is vital to aviation forecasting. Wind shear associated with low-level turbulence usually occur at smaller, more irregular scale than either convective or non-convective LLWS and consist of eddies or waves in the order of a few meters to a few hundred meters across.

Low level turbulence primarily results from mechanical mixing caused by high winds up in the atmosphere mixing down to the surface and interacting with the terrain, solar heating, convection, frontal surfaces and boundaries, gravity waves and aircraft wake effect. Some of these mechanisms also cause LLWS showing the interconnected nature of the two phenomena. Both LLWS and low-level turbulence are observed in thunderstorm environs making it hard to distinguish the two. Any forecast that contains thunderstorms implies presence of convective LLWS. It results from the discontinuity between the ambient environmental winds and gust front and from discontinuities within the outflow region behind the gust front (Arkell, 2000).

Pilots have 5 to 15 seconds of time to respond precisely so as to safely negotiate the hazards as shown from wind shear accident studies. The risks are brought about by rapidly changing headwind and tailwind, strong side gusts and variable lift on the wings, all during a time when an aircraft is most vulnerable (Minor, 2000). Response by a pilot to convective LLWS is not the same as response to non-convective LLWS. Operationally along the flight path, a pilot is presented with one wind shift when the LLWS is non-convective and multiple wind shifts if its convective.

2.4 TYPES OF TURBULENCE AND WIND SHEAR

Motions on scales just larger than turbulence are always present and can cause considerable variation in wind direction when the large scale wind is weak (Anfossi *et al*., 2005). It is mainly noticeable below 600 m (2 000 ft). This is where frictional drag on the air just above the surface of the earth causes changes in both wind speed and direction with height. This layer is largely known as the atmospheric boundary layer and is further subdivided into two as follows:

a) Frictional layer: This is the layer from the earth surface to 100 m (330 ft). In this layer, movement of air is mainly controlled by friction with the surface of the earth

b) Ekman layer: The layer from about 100 m (330 ft) to at least 600 m (2 000 ft). Frictional effect with height though important, reduces gradually, and forces like horizontal pressure gradient and coriolis become increasingly significant.

Wind speed increases with height in the boundary layer. Just above the surface of the earth, in the frictional layer is where the largest change occurs. The wind direction tends to remain constant with height in the frictional layer but tends to veer (back) with height in the northern (southern) hemisphere throughout the Ekman layer. The presence of shear is often visible to an observer such as shearing of plumes of smoke in varying directions with height, clouds at different heights moving in different directions or bending of trees in many directions (ICAO, 2005).

Vertical motion is as a result of vertical distribution of momentum and determines atmospheric stability. It can be stratified when the vertical motion is suppressed (cooled from below), unstable when there is enhanced vertical motion (heated from below) or neutral when the layer is adiabatic (no heat exchange) (Archer *et al.*, 2016). When there is distribution of momentum, turbulence and wind shear occurs. Turbulence is categorized as Clear air turbulence (CAT), orographic turbulence, mechanical turbulence, convective turbulence, wake turbulence and Low level wind shear. They are discussed below.

a) Clear-air turbulence and Orographic turbulence

Clear air turbulence (CAT) is a meteorological threat whose scale is small and formed through the following mechanisms. Kelvin-Helmholtz Instability (KHI), horizontal deformation (Ellrod and Knapp, 1991), anticyclonic flow and the gravity wave breaking (Jiang and Doyle, 2004; Doyle and Bartels, 2005).

- KHI is when the vertical wind shear within a stable layer exceeds a critical value-Richardson number, which is the ratio of buoyancy to shear forces (Ellrod, 1991). The primary cause of CAT is the vertical shear of the horizontal wind. However according to Dutton (1980) moderate to severe CAT predominantly forms in regions where the flow changes significantly in all three spatial directions hence large magnitudes of $\delta u/\delta z$ by themselves are not the best CAT indicators.

- Horizontal deformation of the horizontal components of wind (zonal and meridional) is another mechanism of CAT formation (Ellrod, 1991). Deformation is a fluid property in which a circular shaped area is changed into an elliptical shape. Such flow patterns are like in cols, troughs and jet stream exit regions. In cirrus type of clouds, deformation will show stretching motion at the cloud edges.
- Inertial instability associated with anticyclonic flow is another source of CAT although it is less frequent in anticyclonic flow than in cyclonic flow.
- Mountain waves are created when layers of air flow through topographical obstacles. This airflow flow is displaced by the topography where large amplitude waves are formed and propagated away from the original level (Doyle and Bartels, 2005). The air density decreases with altitude causing the growth of these amplitudes with height. An increase in atmospheric stability reduces the vertical wavelength breaking the waves. This steepens and overturns the waves causing backward wind shear (Hines, 1968). The waves tend to return the airflow to its original level. The presence of a layer of vertical wind shear and a small Richardson number layer in the ambient flow favors gravity wave breaking (Doyle and Jiang, 2004). Mountain waves are classified under **orographic turbulence.** Turbulence prone areas are near wave crest and troughs while the flow is smooth at mid-levels of the waves.

CAT is therefore dominant in regions with strong vertical and horizontal wind shear, strong thermal gradients, lapse rate discontinuities, horizontal deformation and convergence in upper levels which leads to subsidence or in lower levels leading to divergence above mesoscale convective systems creating strong vertical wind shear (Chun and Kim, 2010). It occurs in patches, often near jet-streams, mountains and land than over water or flat terrain (Reiter, 1969). It is revealed as bumpy flight conditions in clear air (Audrey *et al*., 2011). Its occurrence in clear air makes it sudden hence leading to serious damage and additional cost to airlines.

Terrains and obstacles near airports affect the flight path. As a result, orographic turbulence degrades the climb capability of an airplane during take-offs or go-arounds. Similarly there are limits on take-off weight since the climb gradient is less steep for heavier aircrafts thus obstacle clearance height may be compromised. The effect of orographic induced wind shear is thus serious to aviation (Shanzer, 1966).

b) Low-Level Jet

- Inertial oscillation: Light or calm winds are dominant near the surface under clear sky conditions at night and weak synoptic winds (Cuxart and Jimenez, 2007). However, just above ground level, the wind speed may have supergeostrophic values a phenomenon known as nocturnal jet or low level jet (LLJ). This is when a surface temperature inversion decouples the surface winds from the winds aloft, which due to the Coriolis force turns around the geostrophic value forming a LLJ. Prabha *et al*., (2011) further emphasizes that nocturnal flow decoupling from the surface and an imbalance between the pressure gradient and Coriolis forces introduces an inertial oscillation of winds and is considered to be a major contributing factor for LLJ formation. Its occurrence reaches its peak just before dawn hours. At daytime the atmospheric boundary layer is coupled with the surface (Strensrud, 1996). The frictional effects cause the winds to be subgeostrophic. At night the turbulent mixing and frictional effects are reduced and winds above the shallow nocturnal inversion are decoupled from the surface layer and are no longer in balance.

- Shallow baroclinicity: This is where the surface and terrain characteristics vary significantly with diurnal cycle (Strensrud, 1996). The horizontal temperature gradients arise which produce a shallow baroclinicity. The geostrophic wind varies with height (thermal wind) giving rise to pressure gradient inducing a Low Level Jet (Prabha *et al*., 2011). Frontogenesis where a front is passing is another means of creating LLJ.

How a nocturnal Inversion grows.

A nocturnal inversion grows when at just above the surface (approximate a meter), the rate of cooling is enormous to be justified by conduction or radiation fluxes hence, the upward spread of the inversion surface is by mainly turbulent transfer (Blackadar, 1957). This turbulence is produced by the wind shear that grows within the inversion and has ability of weakening the stability if the turbulent energy is abundant. Once the nocturnal inversion sets in, turbulent mixing decreases above the inversion reducing mass exchange. Some turbulence is maintained in the growing inversion due to the large wind shear. There is transfer of heat downwards to the surface and lost by radiation. This loss of heat is not compensated in the upper layers leading to upward growth of the inversion. In the same way, momentum is removed from upper part of the inversion, carried downwards by the turbulence to the surface and dissipated.

At the upper level of the growing inversion, cooling is not yet considerable thus little loss of momentum. Once the wind profile with the jet is evident, turbulent mixing may be generated by the negative wind shear above the wind maximum. When the geostrophic wind decreases upward, the wind maxima sharpness is enhanced. The reverse is true. If the decrease is rapid, the jet profile can occur at daytime. Momentum loss at every level is comparative to heat loss thus wind speed profiles and temperature profiles are expected to be similar within the nocturnal inversion.

c) Mechanical Turbulence

The flow of wind on the ground is affected by obstructions such topography and large buildings which is a hidden danger. Wind flow is disrupted by these obstructions creating wind gusts that change rapidly in direction and speed. Natural barriers like hills to man-made structures like hangars are some of the obstructions to wind flow. It is necessary to be cautious when flying in and out of airports that have large buildings or natural obstructions located near the runway. The obstacle size and wind velocity determines the intensity of the turbulence. Thermal and mechanical turbulence occur together in the atmosphere.

d) Convective turbulence

Convective turbulence occurs hand in hand with thermal and mechanical turbulence (Ahrens, 2009). When the earth surface heats, wind speed increases, instability develops; eddies become large and the rising side of these eddies extend through a greater depth of the atmosphere. The slow moving air on the surface is carried by the rising side upward causing a frictional drag on the faster flow of air aloft. The descending part of the eddy brings down some of the faster moving air, producing a short-lived gust of wind. Strong, gusty surface winds have a high possibility of occurring in an unstable atmosphere because of the increased depth of circulating eddies in the unstable air.

Near the surface, the average wind speed is increased by this exchange. This explains why in the afternoon there are usually stronger surface winds. Thermal turbulence is at a minimum during early mornings when the air is most stable and eddies are non-existent or small. If the rising thermals are moist, convective clouds are formed and are associated with updraughts and down draughts whose impact is not only below the clouds but also aloft. The down draughts can be dry or wet thus not necessarily associated with precipitation.

2.5 THEORETICAL CONCEPT

Provision of wind characteristics and projection of the short and long term behavior at the airport is important in ensuring safety for aircraft operations. In order to understand the impact of wind characteristics on the aircraft operations there is need to gather information from the pilots, meteorological observations, simulations and air traffic controllers. Low level wind characteristics depend largely on physical structure which can be natural (topography) or manmade structures e.g tall buildings and weather phenomena occurring near the airport such as thunderstorms.

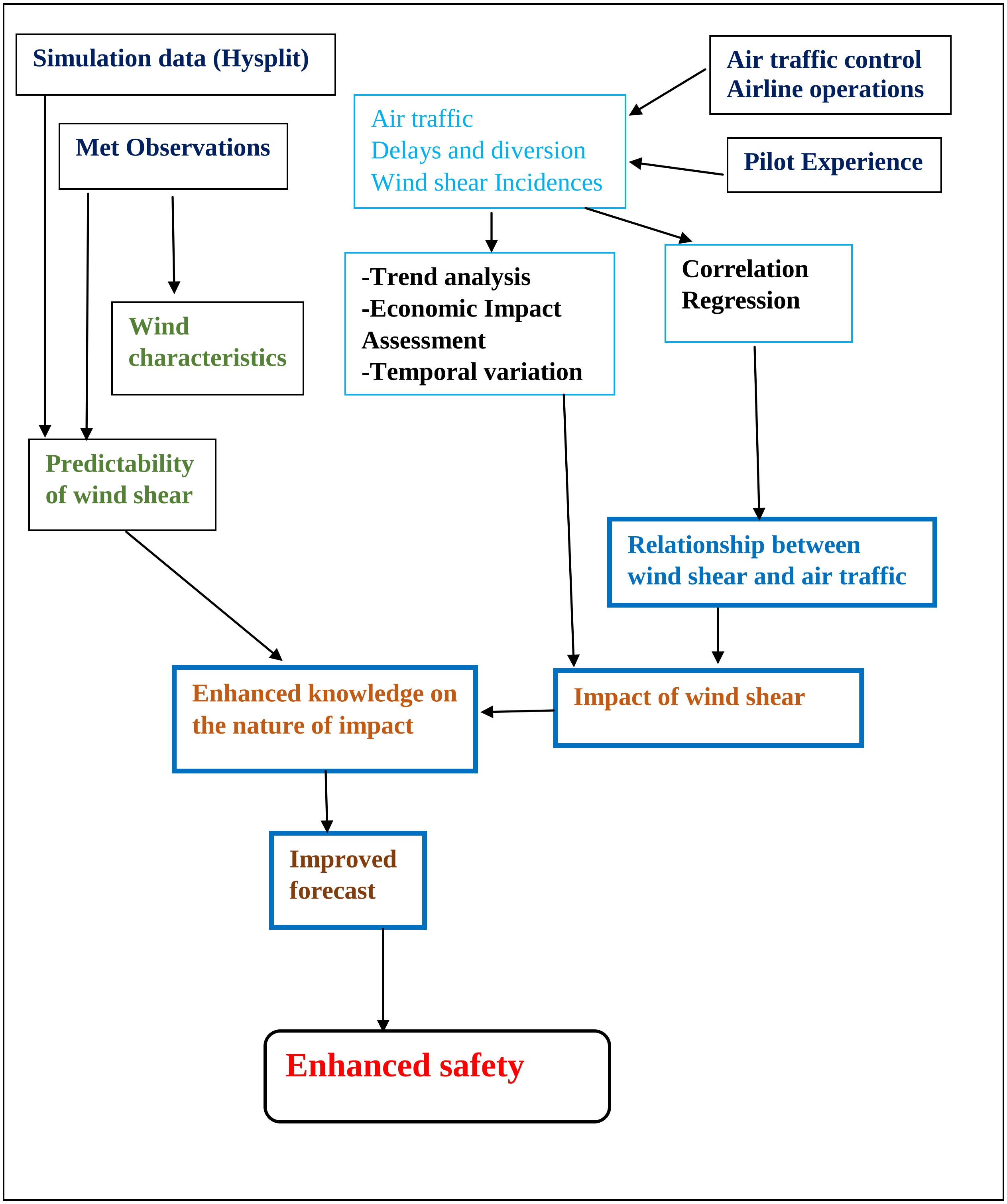


Figure 2.2 Theoretical framework

CHAPTER THREE

3.0 DATA AND METHODOLOGY

This chapter presents the data and methods of data collection and analysis which were adopted to achieve the specific objectives.

3.1 DATA

3.1.1 Aviation data

Flight data used in this study was for the years 2007 to 2016. It included air traffic data, wind shear incidences, delays and diversion incurred, date and time of occurrence of aircraft delays or diversions and duration of delays. These data was sourced from Kenya Civil Aviation Authority (KCAA) Database. The incidences are from what was reported by the pilots to KCAA. Data from Flight data recorder would have been ideal however it is not possible to get the data hence only reported incidences will be considered which is mainly based on the pilots subjective assessment of the intensity of the wind shear encountered.

In ICAO (2013) Annex 3, Appendix 6, 6.2.4, Note 2, it is accepted that pilots will possibly use the terms “moderate, light or severe” to describe the magnitude of the wind shear they have encountered. These descriptions are included in reports as conveyed thus remain unchanged.

3.1.2 Economic data

This includes data on aircraft type, fuel consumption and time-taken in delays for the missed approaches performed. These records were sourced from Kenya Airways and KCAA. In the absence of actual data on cost on aircrafts delays and diversion due to wind shear, simulated data from previous studies was used (Sands *et al*., 2009; Warren, 2009).

3.1.3 Meteorological data

Mean sea level chart, medium level chart, wind and temperature vertical profiles of 2 case studies of when wind shear was present were used. They were obtained from hysplit model. This model uses gridded meteorological data on either of the three map conformal projections (Polar, Lambert or Mercator) or on a latitude-longitude grid at regular time intervals. The data is analyzed by the Global Data Assimilation system (GDAS) (Draxer and Hess, 2010). The routine meteorological data fields required for the calculations are obtained from existing archives or from forecast model outputs already formatted for input to HYSPLIT. It contains surface observations, balloon data, wind profiler, aircraft reports, buoy observations, radar observations, and satellite observations. The data assimilation system has been designed with advanced quality control and monitoring components. GDAS 1 degree, 3 hourly, Global was used.

In showing wind characteristics within Machakos, Kabete, Thika and JKIA, data for 5 years 2005-2015 was used to generate seasonal wind roses.

3.1.4 Data Quality Control

Ascertaining data quality enables sound interpretations from analysis made. Quality management implementation in all meteorological aviation weather providers guarantees the quality of the data due to examination for completeness and consistency before transmission and storage for future use (ICAO, 2013). Wind data used to generate wind roses was of good quality. Wind shear incidences, delays and diversions data was retrieved from KCAA logbooks as reported by the pilots hence is reliable.

3.1.4.1 Estimating Missing Data

The Nonlinear Iterative Partial Least Squares (NIPALS) method was used to estimate missing air traffic data. NIPALs method estimates missing data from 3 contexts. Data that is missing completely at random (MCAR), missing at random (MAR) and not missing at random-NMAR (Severnson *et al*., 2017). When the data is missing due to data mishandling or failure of sensors at random, MCAR is applicable. In circumstances where the data is acquired in sequence then MAR applies. An example would be a test that is only performed based previous results. Thirdly when measurements are not recorded owing to controls, where the value is beyond the limits of detection then NMAR applies. The missing air traffic data is categorized under MCAR.

The NIPALS algorithm, an application on XLSTAT was applied on the dataset and the obtained PCA model used to estimate the missing values corresponding to cell (i,j).

3.1.4.2 Homogeneity Test

Pettitt’s test was used to determine the homogeneity of wind shear incidences and air traffic data. This test is able to detect a point at which a shift in dataset occurs or whether there is a change with the trend in a time series. It is a nonparametric test that needs no assumption about the distribution of data.

Significant shifts in the data show homogeneity through computing p values and comparing them with significant value α =0.05. The p value determines whether a null hypothesis i.e data is homogeneous) or alternative hypothesis i.e data not homogeneous should be adopted. If the computed p-value is greater than α =0.05, the dataset is said to be homogeneous between two given times meaning there is no shift in average or distribution between the data sets. The p value gives the percentage risk of rejecting the null hypothesis thus adopting the alternate hypothesis.

Alternative hypotheses could be a change in average, change in distribution or presence of trend. The computed p-values are provided using Monte Carlo resampling from XLSTAT statistical software.

3.2 METHODOLOGY

3.2.1 ASSESSMENT OF EFFECTS OF WIND SHEAR ON AIR TRAFFIC AT JKIA

The effects that wind shear had on flight operations were analyzed. The magnitude of the wind shear as reported by pilots, the type of wind shear and the outcome of this encounter was determined. The economic impact of wind shear to airlines is also discussed. Diversions, delays, respective cost in form of extra fuel and time spent is similar analyzed.

3.2.1.1 Assessment of the Intensity and Type of wind shear/turbulence encountered

- Wind speeds retrieved from wind shear reports were used to establish the intensity and frequency of occurrence of the wind shear. They were compared to allowable tailwind and crosswind thresholds to show whether flight operations are affected by wind shear.
- The nature of wind shear was also deduced from the wind shear reports to establish the type of wind shear that is encountered.

3.2.1.2 Assessment of Flight Delays and Diversion due to Wind Shear

- Flight delays and diversions were categorized to indicate the extent to which delays/diversion occur due to wind shear. Delays were categorized as airborne which lead to go-arounds and delays in take-offs. The delays were also compared to total air traffic to establish the impact of wind shear to air traffic at JKIA.

3.2.1.3 Assessment of Economic Impacts of Wind Shear on Operations at JKIA.

- The method used to determine costs incurred due to delays was derived from previous studies (Sands *et al*., 2009, Warren, 2009, Muiruri, 2011). Cook *et al*., (2004) in the Eurocontrol report determined that the cost per aircraft delay was approximately €72 per minute. This is delay that is 15 minutes after the scheduled arrival/departure times. For short haul flights, 15 minutes delay is massive. The study thus included delay below 15 minutes to scheduled departure or arrival of flights.
- In assessing costs related to aircraft diversion, the approximate cost was also derived from previous studies (Sands *et al*., 2009; Warren, 2009 and Muiruri, 2011) which revealed that the costs per diversion ranges between \$30,000 and \$150,000. This cost is dependent on aircraft size, diurnal and seasonal weather characteristics and nature of operations. This study used \$100,000 conservatively as adopted by Muiruri (2011) based on the fact that aircraft size of planes operating JKIA maybe smaller compared to American and European aircraft sizes. The cost include holding of aircraft before diverting, flight time to diverted airport, fuel burn, landing fees, ground handling fees, meals to passengers, accommodation, ferrying passengers as well as lost opportunities by both aircraft operators and the passengers.
- Fuel consumption data from few aircrafts are shown indicating amount of fuel an aircraft burns for every missed approach procedure performed. Different aircrafts will consume different amounts of fuel. This is dependent on engine type, weight of aircraft and decision height.

3.2.1.4 Correlation Analysis

Correlation analysis was used to measure the association between reported wind shear incidences and total air traffic as well as delays and diversions. It is used to show whether the incidences have any influence on diversions or delays. Similarly the association between the wind shear incidences and air traffic over time will be correlated to establish whether there is any influence to air traffic operating at JKIA. Pearson's correlation coefficient, r, showing the strength of the relationships is given by:

$$r_{xy} = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{(\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2(\frac{1}{n}\sum_{i-1}^{n}(y_i - \bar{y})^2)}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4$$

r_{xy} is the correlation coefficient between x and y,

x_i, y_i are x and y values for observation i and j respectively,

$\bar{x}, \bar{y}$ are the mean values of x and y respectively and

n is the total number of observations.

The coefficient r only shows the linear relationship between variables. The positive or negative signs of r indicate the direction of the relationship. The magnitude lies between 1 and -1 which indicate strong correlation while 0 being the weakest.

The value, $\alpha < 0.05$ is used to establish the statistical significance of the comparisons.

T-test technique is used to determine the significance of computed correlation coefficient, r. The r^2 indicates the percentage of the dependent variable that can be explained by the independent variable. The t-test is given by:

$$t_{n-2} = r\sqrt{\frac{n-2}{1-r^2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5$$

n is the total number of observations.

n-2 is the number of degrees of freedom,

r^2 is the coefficient of determination where

$r^2=1$ shows perfect fit.

$r^2=0$ shows lack of fit

3.2.2 ANALYSIS OF TEMPORAL VARIATION OF WIND SHEAR

3.2.2.1 Trend Analysis

Mann-kendall test was used to determine whether an increasing or decreasing trend exist over time. It was preferred because it is able to show whether the trend is significant, locate the period with the trend and detect sudden changes in a time series (Sneyers, 1990). In carrying out the Mann Kendall test, the difference between the latter measured value and all earlier measured values ($y_i > y_j$) where j>i was computed. The integer values were assigned -1, 0, 1 for negative differences, no change and positive differences respectively. The test statistic, S is then computed as the sum of the integers;

$$S = \sum_{i-1}^{n-1}\sum_{j=i+1}^{n} sign\left(y_j - y_i\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 6$$

Where sign(y_j-y_i), is equal to -1, 0, +1

When S is a larger positive number, latter measured values tend to be larger than earlier values. An upward trend is indicated. When S is a larger negative number, later measured values tend to be smaller than earlier values and a downward trend is indicated. When the absolute value of S is small, no trend is indicated.

3.2.2.2 Monthly and Diurnal Variation of Wind Shear Incidences

Wind shear reports were plotted against time. Monthly bar graphs indicated months in which wind shear was prevalent. Diurnal variation indicated times of the day in which wind shear is prevalent.

3.2.3 WIND CHARACTERISTICS

Wind roses for JKIA and the surrounding hilly regions within the approach and departure phases were generated using Systat. These phases of flight have high ground areas likely to influence the wind direction and speed. Seasonal wind roses will display wind characteristics of meteorological stations near these hills. They represent wind characteristics at 10m above ground level.Wind roses in seasons of March, April and May, June, July and August, September, October and November and December, January and February are displayed. Wind rose spikes show frequency of occurrence in terms of direction. Longer spikes indicate higher frequencies. Partitions within the spikes indicate wind speed. The percentages show the percentage time wind blows from the shown direction at the given speeds. December component in DJF season could not be included due to operational difficulties from data source.

3.2.4 WIND SHEAR PREDICTABILITY

Two cases studies of convective and non-convective scenarios were chosen for illustration in this study. Prevailing conditions that led to wind shear conditions were analyzed. Observed data from METARs and model data were relied upon. The case studies are based on highest frequency of occurrence. The months which have high wind shear reports and times in which occurrence of wind shear are high are considered for illustration.

Hysplit model was used to generate wind grams and temperature profiles. The vertical profile indicates heights at which wind shear is prevalent and relates them to reported wind shear occurrence. Temperature profiles were also generated to analyse behavior of temperature with height and time. Weather charts with wind patterns and pressure behavior were used in analyzing the convective case. Observations from METARs was used in support of model data. The cause was then established through analysis of observed data from METARs and GDAS products within the region of study. A 3 hourly time period was used since it gives better temporal resolution.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSIONS

This chapter presents the results and discussions of the findings based on the methods used to achieve the objectives.

4.1 DATA QUALITY CONTROL RESULTS

4.1.1 Homogeneity Test Analysis using Pettitt test

Figure 4.1 shows the results of the pettitt test carried out on wind shear incidences which gave a p-value of 0.0725. This value is greater than the significance value of α=0.05. It reveals that the risk of the data been declared inconsistent is 7.25% thus the homogeneity of the data cannot be rejected. This implies that the wind shear data was consistently homogeneous.

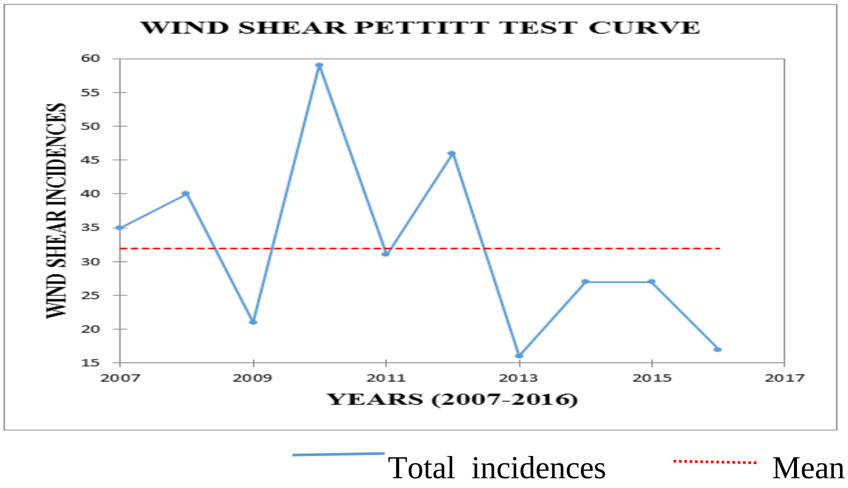
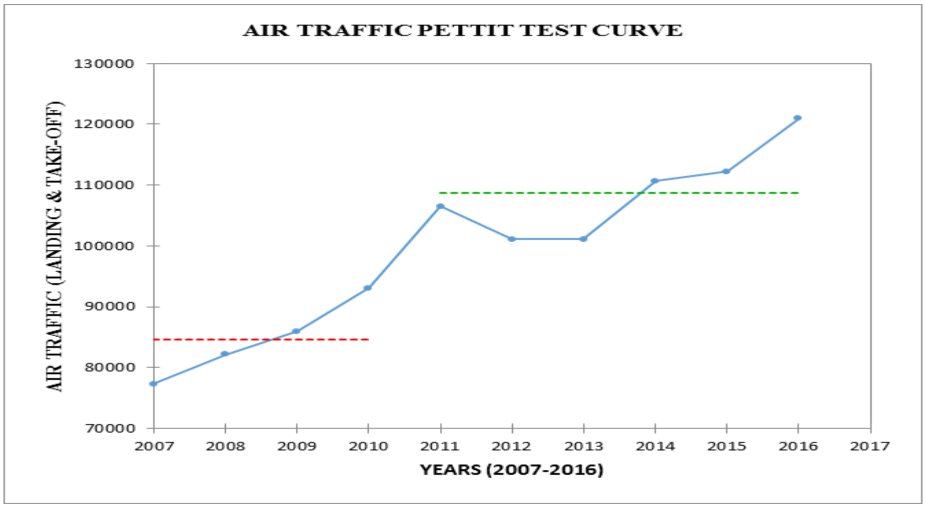


Figure 4.1: Pettitt test for wind shear incidences encountered between 2007-2016 during landing and take-off phases at JKIA.

Figure 4.2 shows the pettitt test computed on air traffic totals which gave a p-value of 0.0062. This value is lower than the significance value of α=0.05. There is a positive shift in air traffic numbers that happens at the end of 2010 this implies that the alternative hypothesis in this case is the change in mean. However the risk of rejecting the null hypothesis (data is homogeneous) is 0.62% which implies the change is not significant hence the null hypothesis cannot be rejected.



Total incidences- —— Mean 1- ⋯⋯ Mean 2- ⋯⋯

Figure 4.2: Pettitt test for Air traffic landing and taking off at JKIA between 2007 and 2016.

This indicate that the data is of good quality and the results derived from the corresponding analysis are reliable as used in the rest of this study.

4.2 EFFECTS OF WIND SHEAR ON AIR TRAFFIC AT JKIA

This section discusses the effects of wind shear to flight operations. It contains the magnitude of the wind shear as reported by pilots, the type of wind shear and the outcome of this encounter. This is in terms of wind direction and speeds encountered in comparison to allowable thresholds. The economic impact of wind shear to airlines is also discussed. Diversions, delays, respective cost in form of extra fuel consumption and time spent is analyzed.

4.2.1 Assessment of the Intensity and Type of Wind Shear/Turbulence Encountered

Figure 4.3 shows wind speeds associated with reported crosswinds and tailwinds. Wind shear and turbulence incidences were reported at speeds ranging from less than 10 knots to 40 knots. Speeds of 10 to 15 knots were the majority followed by 16-20. When compared to the allowable crosswind threshold in the manual of aerodrome standards (KCAA, 2014), it is assumed that landing or take-off of airplanes is, in normal circumstances prohibited when the crosswind component exceeds 20 knots for airplanes whose reference field length is 1 500 m or over. When the runway surface is wet, the allowable crosswind component decreases to 13 knots due to poor runway braking conditions. JKIA runway length is 4.117 km.

Maximum allowable tailwind conditions range between 10 to 15 knots depending on aircraft type. From the results, tailwind thresholds are easily surpassed by most aircrafts.

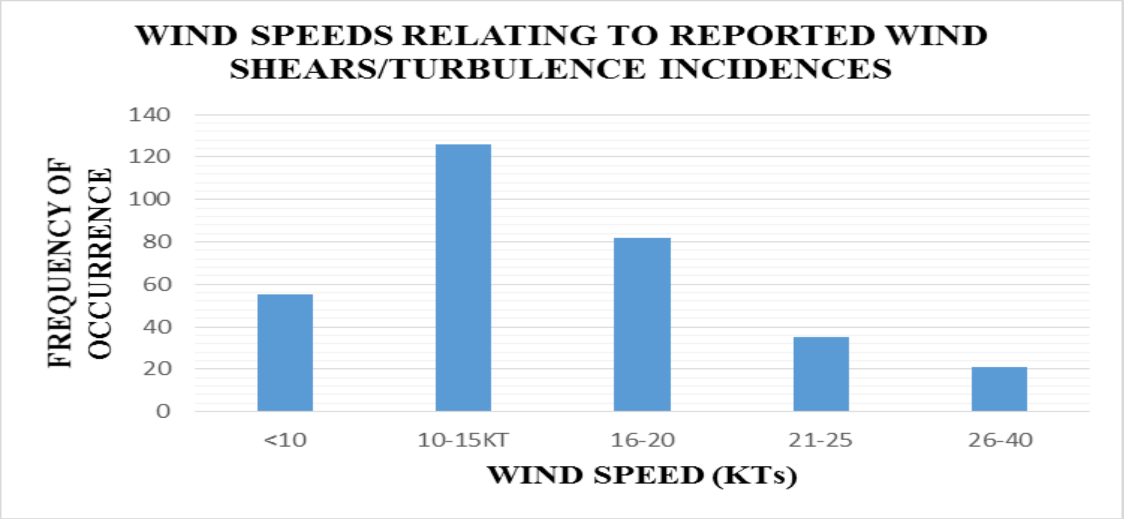


Figure 4.3: Wind speed frequency distribution relating to Wind shear/Turbulence reports for aircrafts that landed/took off at JKIA from 2007 to 2016.

The reported wind shear incidences are further categorized in terms of tailwinds, crosswinds and turbulence. In a majority of cases, the pilots reported experiencing wind shear with no classification of whether it was a crosswind or tailwind. This is shown in Figure 4.4 below. Weather standbys due to crosswinds are also presented. A weather standby is issued by air traffic controllers when crosswinds have speeds greater than 10 knots. They serve us warnings to incoming and outgoing aircrafts in which a pilot is able to make a decision on whether the conditions are safe to land/take-off.

61% of pilots reported encountering wind shear without specifying whether it was a crosswind or tailwind. 11% encountered tailwinds, 3% encountered crosswinds while 7% said the conditions were turbulent. From air traffic controllers, 18% weather standbys due to crosswinds were issued.

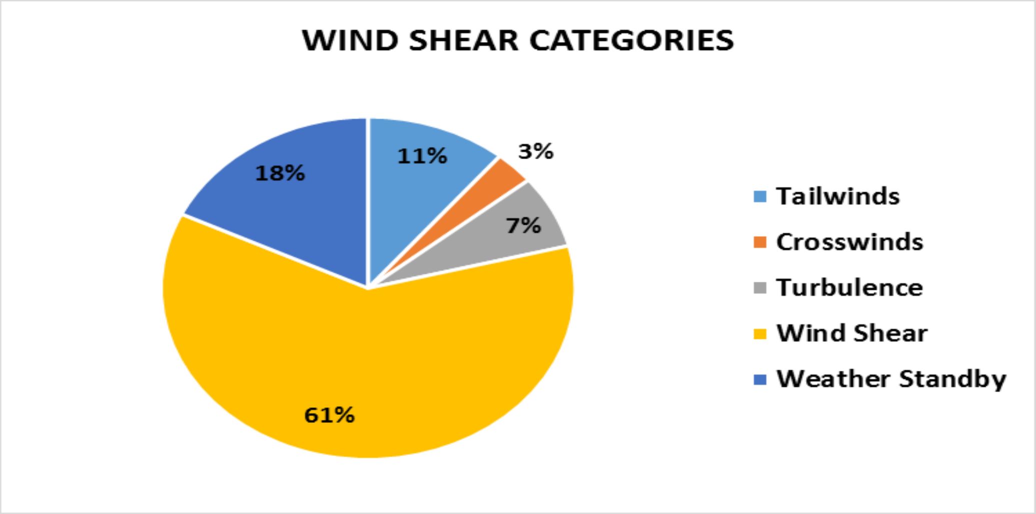


Figure 4.4 Type of Wind shear encountered at landing and take-off phases at JKIA

We can thus deduce that tailwinds are the likely common cause of shear as shown by those who specified the nature of wind shear.

4.2.2 Assessment of Flight Delays and Diversion due to Wind Shear

Delay of aircrafts has been classified into two; missed approaches and hold take-off. 90% of the aircrafts that encountered wind shear experienced it while airborne of which 65% carried out a missed approach as shown in Figure 4.5. This is where an aircraft on approach aborts landing and goes around to attempt another landing when the conditions have improved. If the wind shear conditions persist, a pilot may choose to divert to another airport as revealed by the 2%. 23% of the aircrafts that experienced wind shear landed irrespective of the wind shear conditions present. 10% of aircrafts delayed take-off till wind direction and speeds were favorable for take-off.

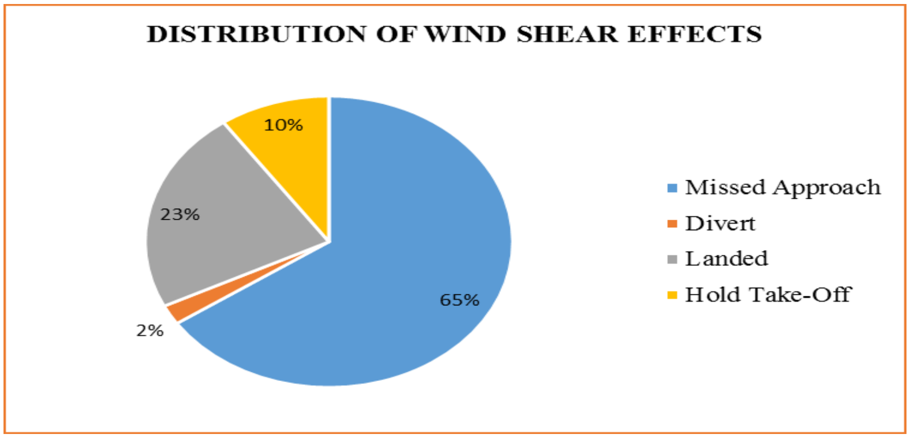


Figure 4.5: Distribution of delays and diversions due to wind shear conditions during landing/take-off at JKIA

In establishing the implication of wind shear on flight operations, the ratio of wind shear to total flight numbers was calculated. Total air traffic from 2007 to 2016 was 951,435. Reported wind shear incidences were 319. This suggests that every 1 in 2983 flights landing and taking off from JKIA experience wind shear.

4.2.3 Assessment of Aircraft Cost due to Delays and Diversions related to Wind Shear

Aircraft Delay Cost

To assess the costs related to delays due to wind shear, computations were estimated at 72 Euro per minute as shown in Table 7. I Euro was equivalent to 111.43 as at 31/12/2015.

Table 7. Composition of Aircraft Delay Cost per Minute (€)

ITEM	DELAY COST PER MINUTE
Cost of Fuel	0
Maintenance Cost	1
Crew costs	10
Airport Charges	0
Aircraft ownership costs	-
Passenger compensation	24
Direct cost to airlines	36
Overall cost	**72**

Total number of delay minutes were 1014. Hence total cost incurred was approximate Kshs 8.14 million. In dollars at an exchange rate of 1$≈ Kshs 102.2355, the loss is equivalent to 79,620 US dollars.

Table 8. shows the fuel consumption in a missed approach maneuver of some of the aircrafts. Losses encountered by 65% of aircrafts that carried out missed approaches were dependent on decision height, weight, aircraft type and engine type since aircraft models have different engine types which consume different fuel amounts. Fuel prices are calculated at approximately 40 US cents per litre and may vary from time to time depending on market forces. Extra distance covered from the missed approach landing in comparison to a successful landing consumes extra fuel.

Table 8: Aircraft type and respective fuel consumption during a missed approach manouvre

Aircraft Type	Fuel consumption in a missed approach maneuver (kg)
E 170/175	73
E 190/195	89
B787-800	265
B787-900	336/332 depending on engine
747-8 freighter	785
747-8	694
777 Freighter	445
777-300	430
777-200	445
737-700/300	130

(Source of data: Kenya Airways, European Environment Agency, Report No 21/2016)

The highest losses are due to missed approaches based on their frequency. According to Boeing, a comparison between normal landing and missed approach procedure showed that upto 28 times more fuel can be consumed when the latter is performed (Robertson and Johns, 2010). This shows how expensive executing a missed approach is.

Aircraft Diversion Cost

KCAA data revealed that 7 aircrafts diverted between 2007 and 2016 due to wind shear conditions. The cost of diverting an aircraft was estimated through previous studies (Sands *et al*, 2009; Warren, 2009 and Muiruri, 2011). Using an average estimate cost of diversion of $100,000 and a conversion rate of 1$ to Kshs102.236 as at 31/12/2015, the resultant cost due to diversion was approximate Kshs 71,565,200 (USD 700,000).

4.2.4 Correlation Analysis results

This section discusses the results of linear correlation. Pearson correlation was performed to measure and interpret the strength of the linear association between wind shear occurrence versus delays, diversions and air traffic.

4.2.4.1 Wind shear Occurrence effect on Delay/Diversions

Mendenhall (1971) stated that the coefficient of determination (r^2) provides a more meaningful interpretation of the strength of the relation between two variables than the corelation coefficient itself. From figure 4.6 (a) it is clear that delays had a stronger correlation with wind shear presence. This means that pilots are more likely to carry out a missed approach or delay take-off if wind shear conditions are prescent. Diversions in Figure 4.6 (b) on the other hand have a very weak correlation impling that the prescence of wind shears may not lead to diversions.

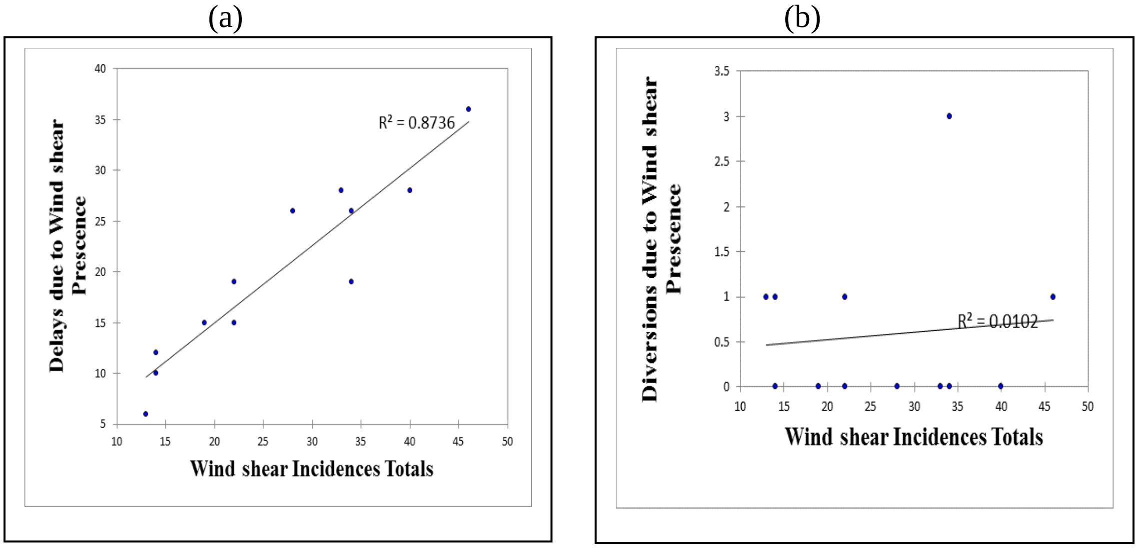


Figure 4.6: Scatter plot of the relationship between wind shear occurrence and (a) Delay and (b) Diversions of aircrafts landing or taking off at JKIA

4.2.4.2 Wind shear Occurrence effect on Flight Numbers

Total wind shear incidences were also correlated with the flight numbers to establish the strength of wind shear occurance to flight numbers. From Figure 4.7 wind shear has an influence on 0.23% of flights landing and taking off .

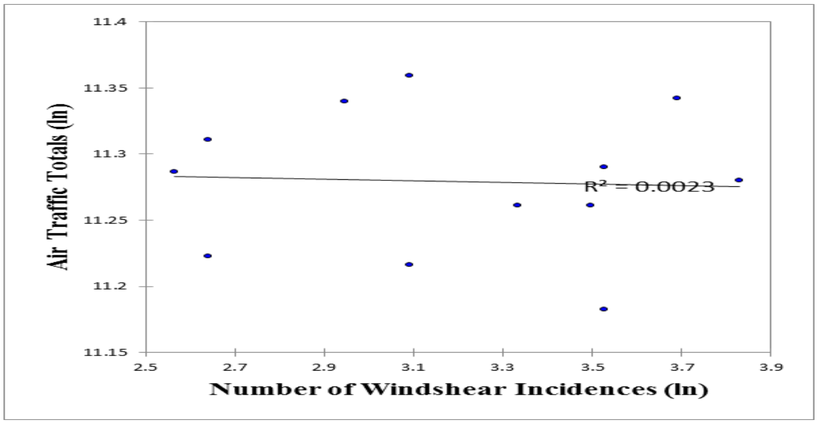


Figure 4.7: Scatter plot of the relationship between wind shear occurrence and Flight Numbers

4.3 TEMPORAL VARIATION OF WIND SHEAR RESULTS.

This section discusses how wind shear incidences and air traffic totals have behaved over the period between 2007 and 2016.

4.3.1 Trend Analysis Results

Trend of past wind shears and air traffic totals were computed and results are as shown in Table 9. Wind shear incidences indicate a downward trend based on the S negative value. Air traffic landing and taking off at JKIA on the other hand indicates an upward trend due to the positive S value. Air traffic had a higher temporal variability as compared to wind shear incidences.

Table 9. Computed S values for past wind shear incidences and Air traffic totals

ITEM	S value
Wind Shear incidences	-16
Air traffic	39

Button (2006) attributes the upward trend to globalization which has led to increased demands for the movement of people and goods between countries as a result of the growing overall economic activity. Airlines are able to more effectively feed their routes and coordinate their activities thus increasing their geographical market being serviced and also generate economies of scope and scale. ICAO journal (2007) projected an annual average growth rate of 4.6% worldwide in passenger traffic upto 2025. From oxford economics (2011), Growth in air transport is reliant on airline cost and world trade which is influenced by fuel prices and political environments for government regulated airlines.

4.3.2. Monthly distribution of Reported wind shear incidences and Traffic totals

Figure 4.8 shows the monthly reported wind shear incidences over 10 years (2007-2016). Wind shears encountes were reported throughout the year. The month of November had the highest reported cases. Traffic distribution over months is shown in Figure 4.9. Aircrafts landing and taking off from JKIA are between 71,000 in Feb and 86,000 in december

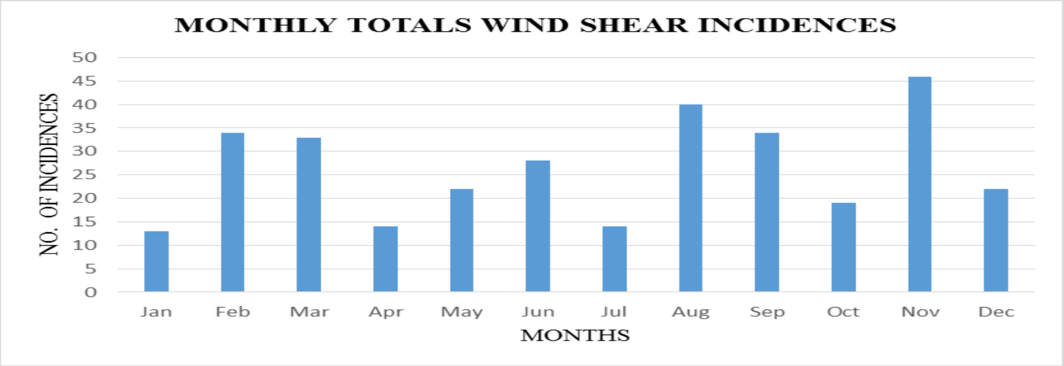


Figure 4.8: Monthly wind shear incidences reported between 2007-2016 at approach landing, take-off and climbout phases of JKIA

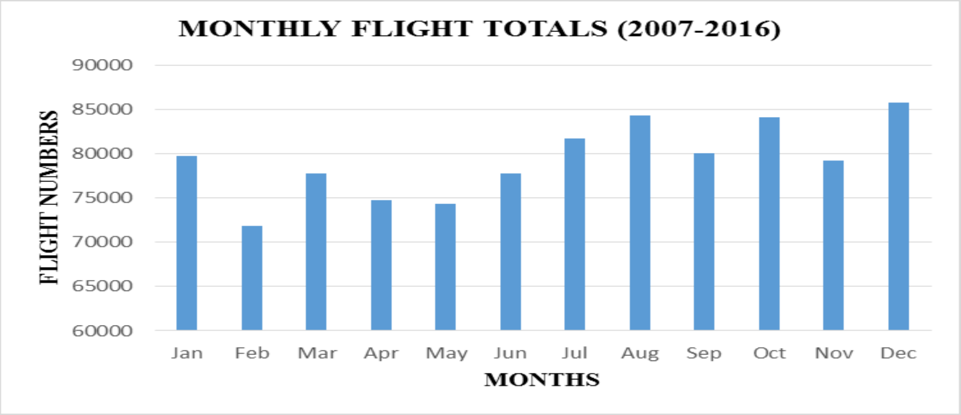


Figure 4.9: Monthly Air traffic between 2007-2016 at JKIA.

The seasonal transitional months; February, August and November were the most problematic months other than may. These is attributed to changes in the direction of trade winds which are controlled by the shifting position of the sun whose insolation creates pressure differences. November is also a rainy month hence convective turbulence contributed to reported shears. Of interest is less shears reported in the long rain season (March to May). Months in the middle of a season (January, April. July and October) had the least reported windshears. This can be attributed to stability of wind regimes. As discussed in section 4.3.1, air traffic to a region is influenced by factors such as political state and trade thus the varying monthly totals cannot be conclusively attributed to wind shear.

4.3.3. Mean Hourly distribution of Reported wind shear incidences

The distribution shows time at which the vulnerability of wind shear is high. Tailwinds and crosswinds were mainly reported in late afternoons to midnight. The few wind shear reports in the early morning to early afternoon can be attributed to a decrease in vertical eddies. The turbulent layer shrinks as nighttime progresses till early mornings. During day time, solar insolation causes vertical eddies to increase and are maximum in late afternoons to early night. It is at these times that deep convection systems have their peak around this region. This explains the high wind shear encounters in the evenings upto midnight as shown in Figure 4.10.

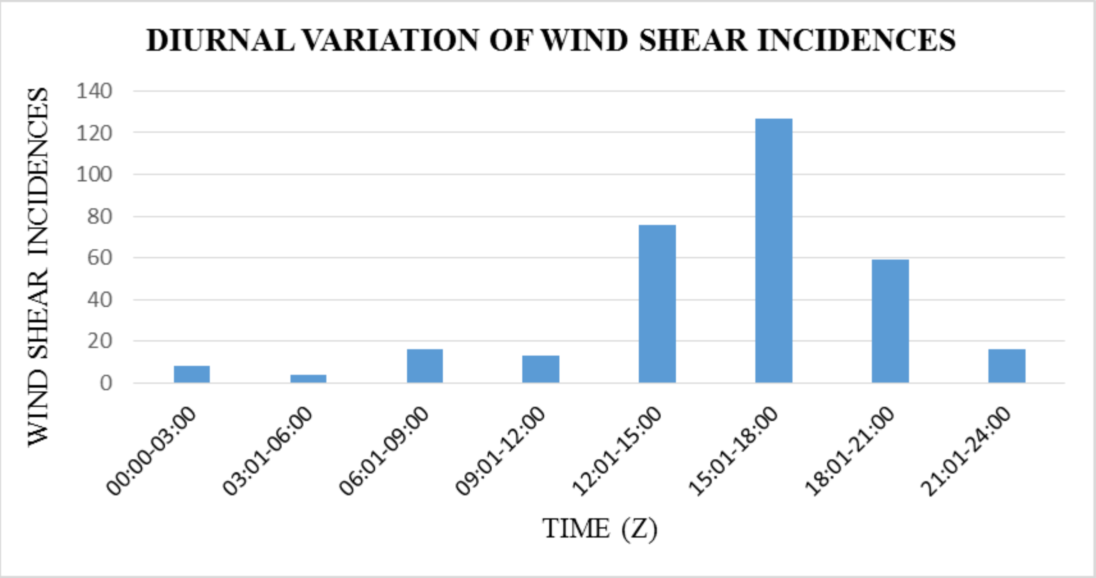


Figure 4.10: Diurnal variation of Wind Shear Incidences.

4.4 RESULTS FROM ANALYSIS OF WIND CHARACTERISTICS

Wind characteristics at JKIA and over the approach and take-off paths are represented in this section by wind roses.

4.5.1 Seasonal Wind roses for Jomo Kenyatta International Met Station

Figures 4.11 a), b), c) and d) show wind roses indicating JKIA and Ngong hills seasonal winds behavior. In JF,MAM and SON, the main wind direction is in the first quarter with wind speeds upto 22kts. The runway is aligned in 060^0-240^0 direction hence beneficial to landing/Take-off which requires a headwind. The challenge of tailwinds will come in if runway configuration is not changed to reflect wind direction. Convective activity during these seasons bring in gusty winds which cause turbulence, tailwinds and crosswinds. In the JJA season, winds are distributed within the 4 quarters with the fourth quarter having the lowest frequency. Wind speeds vary from calm to 17 knots. During this season, flights are more prone to crosswinds and tailwinds whose impact depends on size of aircraft.

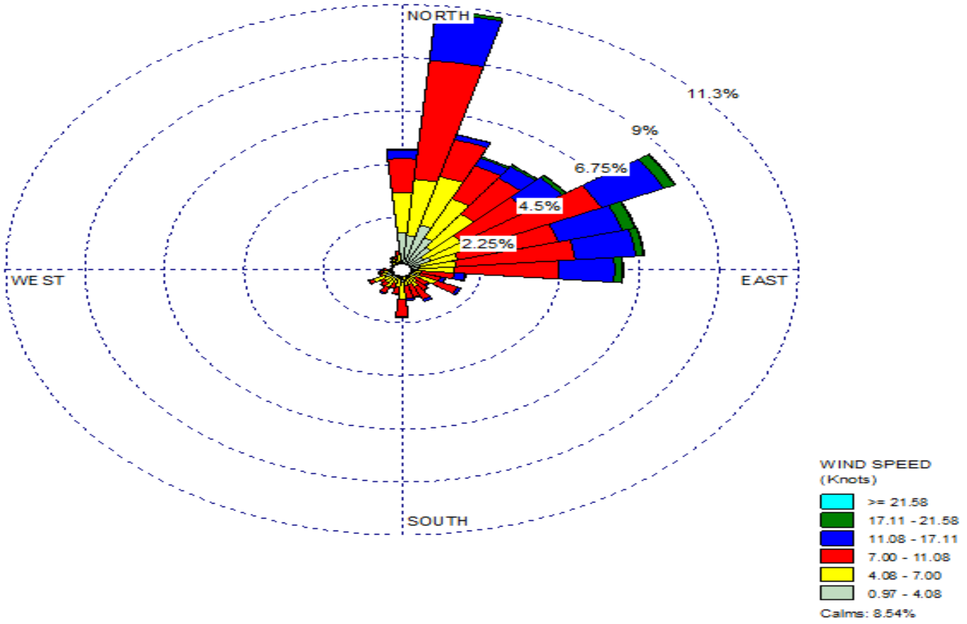


Figure 4.11a: JKIA Wind rose for March to May.

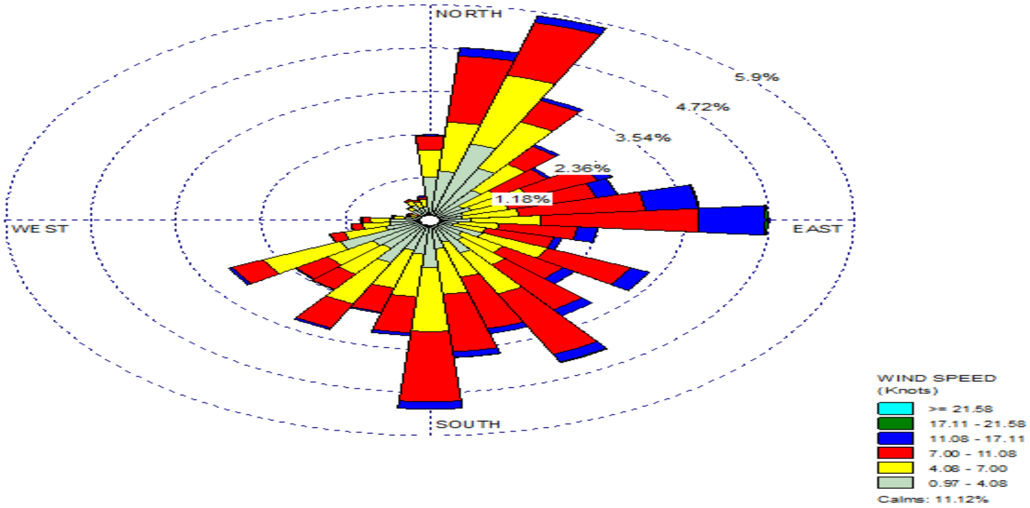


Figure 4.11b: JKIA Wind rose for June to August.

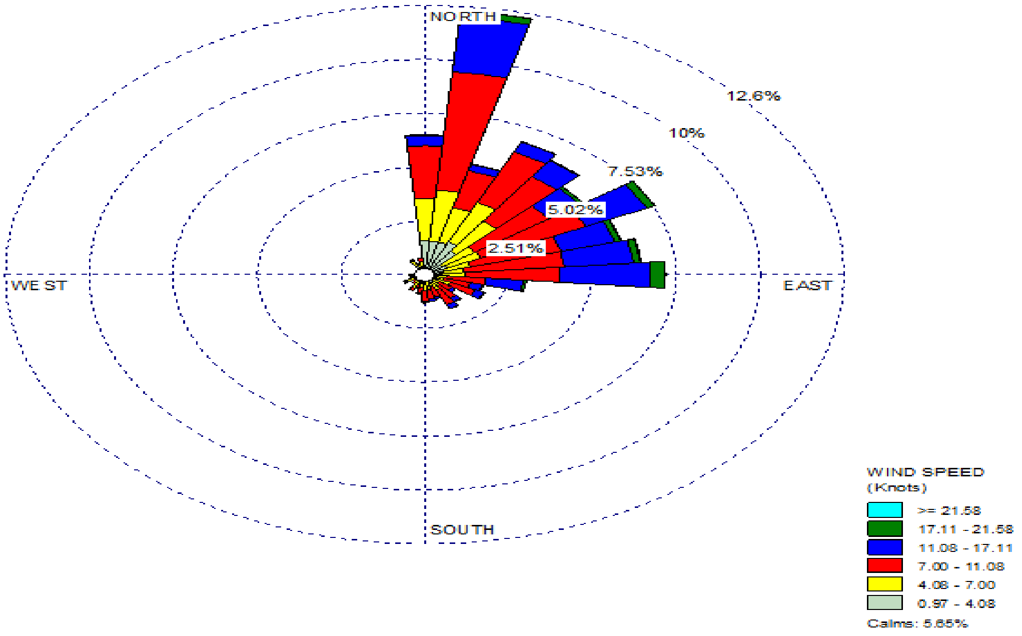


Figure 4.11c: JKIA Wind rose for September to November.

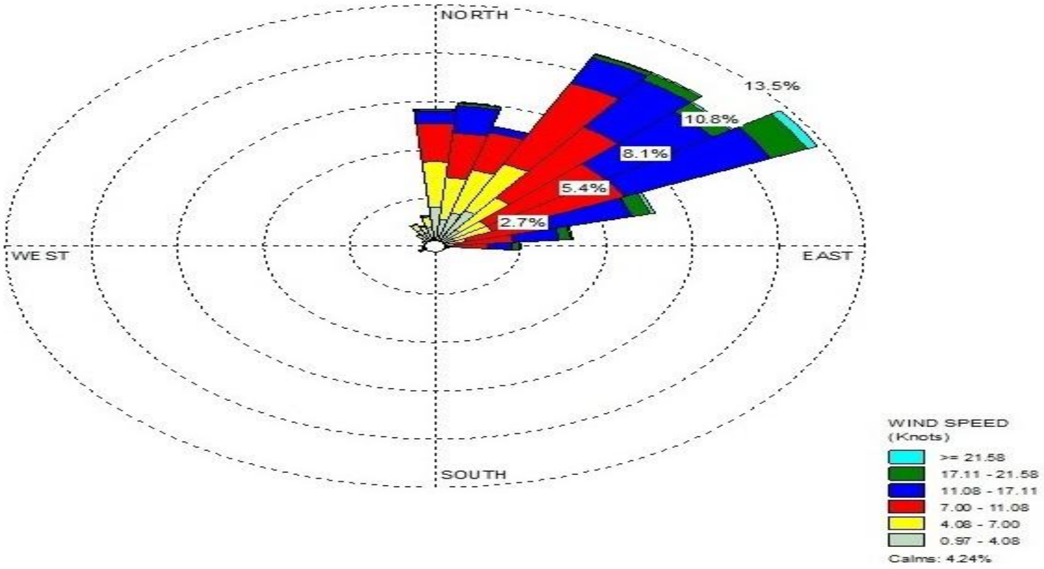


Figure 4.11d: JKIA Wind rose for January and February.

In the large scale, wind direction is influenced by atmospheric pressure. Insolation at any given place creates pressure differences where rising warm air is replaced by cold air. The Inter tropical convergence zone is a zone of low pressure due to heating. Its position is determined by the position of the sun. It also affects and the strength of the subtropical high pressure cells (Arabian, Azores, Mascarene and St. Helena) which bring in air to replace the rising air. In figures 4.11a, c and d, it is seen that winds are mainly in the first quadrant. Fig. 4.11a (DJF season) the sun is located in the southern hemisphere. In Fig 4.11c (SON), the position of the sun is transitioning from southern to northern hemisphere while in Fig. 4.11d (MAM) the position shifts from north heading south. This positions also show the location of ITCZ. Winds tend to flow from high to low pressure zones hence the observed behavior. In these 3 seasons, the Arabian high pressure cell is predominantly strong hence the main control of wind direction. Fig. 11b shows the variability of wind in JJA which is attributed to position of the ITCZ in the northern hemisphere and the subsequent strengthening of the southern pressure cells. The heating of the land mass over the Tibet plateau in the Asian continent creates the heated air to rise creating a low pressure zone. Once in the upper troposphere, the air flows southwards where it sinks over the South Indian Ocean strengthening the mascarene high. The mascarene high pushes the descending air northwards towards the low pressure zones in the north. This explains the wind variation during JJA.

Ongoma *et al*., (2013) showed that wind speeds within cities were decreasing with time due to urbanization. Increase in construction of large buildings increased the frictional effects of airflow over the surface.

4.5.2 Seasonal Wind roses for Kabete Agro-meteorological Station

Kabete agro-meteorological station represented Kerita hills in Kiambu. In Kabete, wind direction is distributed in all quarters as shown in Figures 7.1a, b, c and d in appendix 3. However the first quarter has a higher frequency of wind direction in which wind blows from. This is for the entire year. In JF and JJA strong crosswinds have a higher possibility of occuring due to high wind speeds for winds blowing from the south. For MAM and SON winds are mainly in the first quarter with a lower frequency in the remaining quarters..

4.5.3 Seasonal Wind roses for Thika Agro- meteorological Station

Thika agro- meteorological station represents Oldonyo Sabuk hills. Wind direction is mainly North north east from March to November with wind speeds between calm to 11 knots. In the JF season, the frequency of wind is well distributed between North and East. In reference to runway allignment, the winds throughout the year do not cause any danger. Figures 7.2a), b), c), and d) in appendix 4 show Thika and Oldonyo Sabuk hills seasonal windroses.

4.5.4 Seasonal Wind roses for Machakos Agro-meteorological Station

Mua and Kiima Kimwe hills are represented by Machakos wind roses. Between March to August as shown in Figures 7.3 a and b in appendix 5, wind direction is distributed between the first quarter and second quarter (North to south) with the highest frequency being in the North North East. Winds range from calm to 17 knots. In January,February, September to November months, winds mainly blow from the NNE. This is shown in Figures 7.3c and d respectively. The respective wind roses are also shown in appendix 5.

Windrose over Thika, Kabete and Machakos represent wind characteristics at 10m above ground level thus cannot account for variations of winds in higher levels that may directly affect an aircraft in approach or climb-out phases. Winds are mainly in the first quadrant for all the stations. This is in line with the usability of the the runway which is aligned in NE-SW direction to utilise headwinds while taking off and landing.

4.6 RESULTS ON PREDICTION OF WIND SHEARS USING ANALYSIS DATA.

The results of simulation of the wind shears are presented. Two case studies of convective and non convective scenarios are chosen for illustration in this study.

4.6.1 Case with No Convection

On 16/02/2016, wind shear was reported at 2115Z. Appendix 6. is an aviation routine weather report showing the raw data of weather conditions observed on 16/02/2016 from 6 pm at JKIA. From observations made, a north easterly wind blew turning to a northerly wind from 2000Z. North east winds do not cause any danger to landing or take-off at JKIA since they are in allignment with the runway. The Northerly winds are not suitable for both landing and take-off since they are beyond the operational desirable forecast for winds which is +/- 20^0 of the runway allignment (ICAO, 2013). Notably is the clear sky conditions that set in from 1630Z (7.30PM).

This condition is suitable for radiation cooling where the earth surface cools faster than air above it inducing temperature inversion.

Figures 4.12a,b,c and d represent wind vertical profiles for JKIA, Oldonyo Sabuk, Mua hills and Ngong Hills respectively from 15Z on 16/02/2016 to 03Z 17/02/2016. The monthly mean pressure for JKIA in February at maximum temperatures is 836.9 mb while at minimum temperatures is 839.2mb. The surface wind direction for the 4 places is generally backing with time. From 18Z, there was discontinuity of wind where surface winds were turning to northerlies with 5 knot speed while those at 800mb level were east north east with speeds of 15 knots with the exception of Ngong. The highest wind speeds at Ngong were at 750mb level at 18Z but from 21Z the wind behaviuor is nearly the same as the rest.

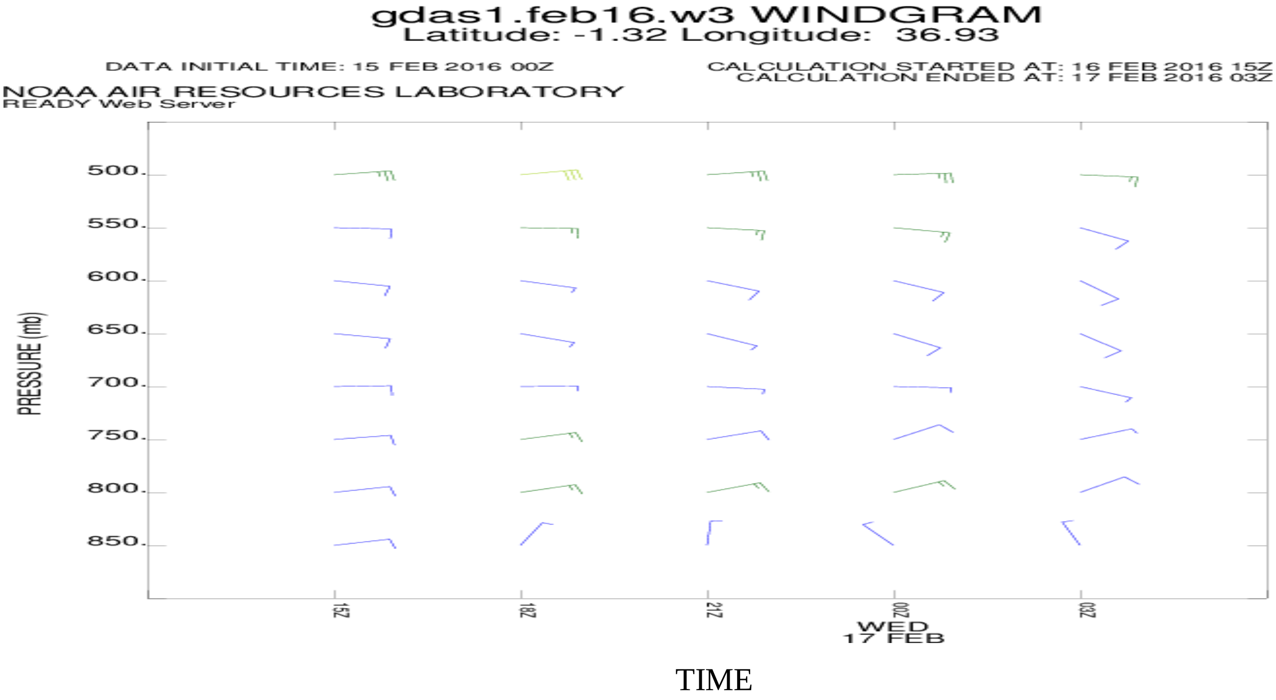


Fig 4.12 a) Wind vertical profile at JKIA between 15Z, 16/02/2016 and 03Z, 17/02/2016

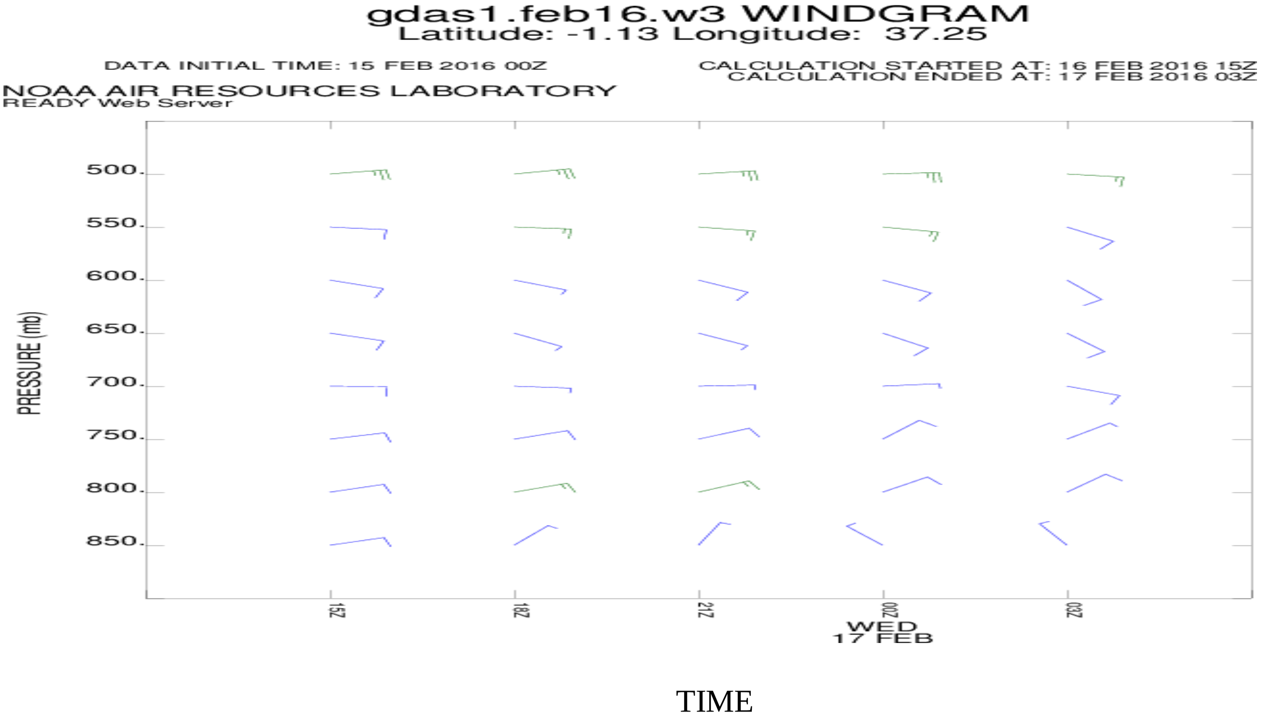


Fig 4.12 b) Wind vertical profile at Oldonyo Sabuk hills on 16/02/2016, 15Z to 03Z 17/02/2016

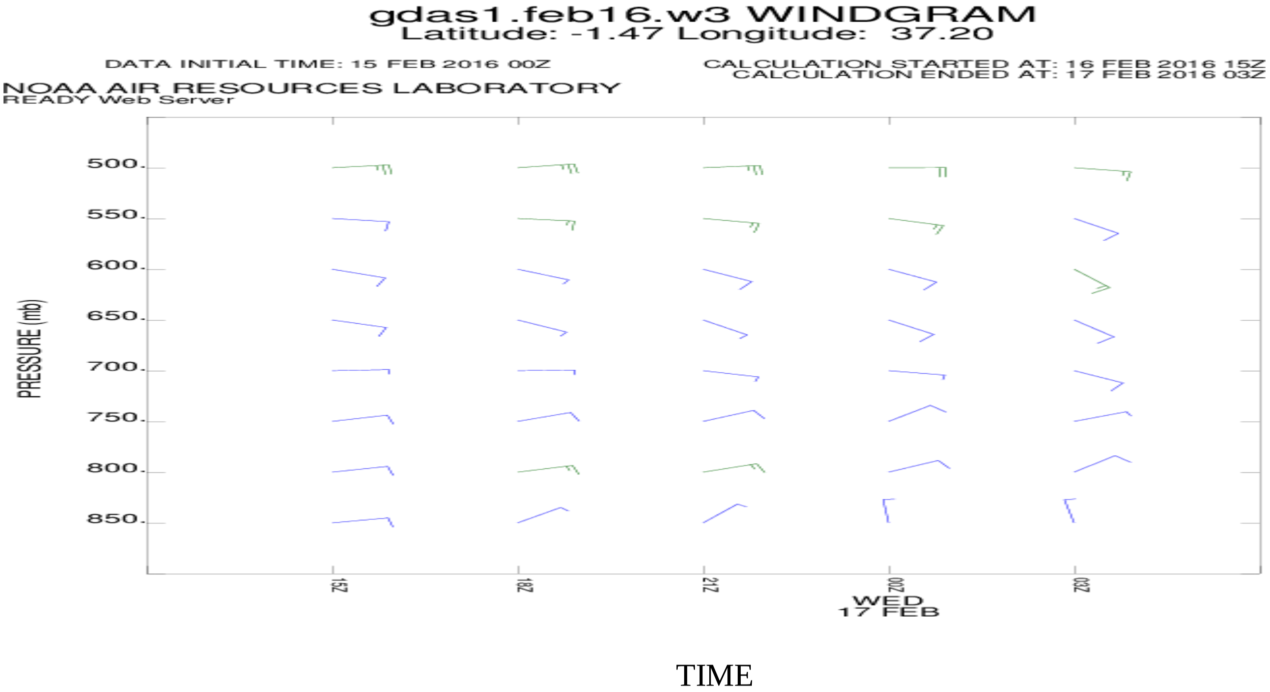
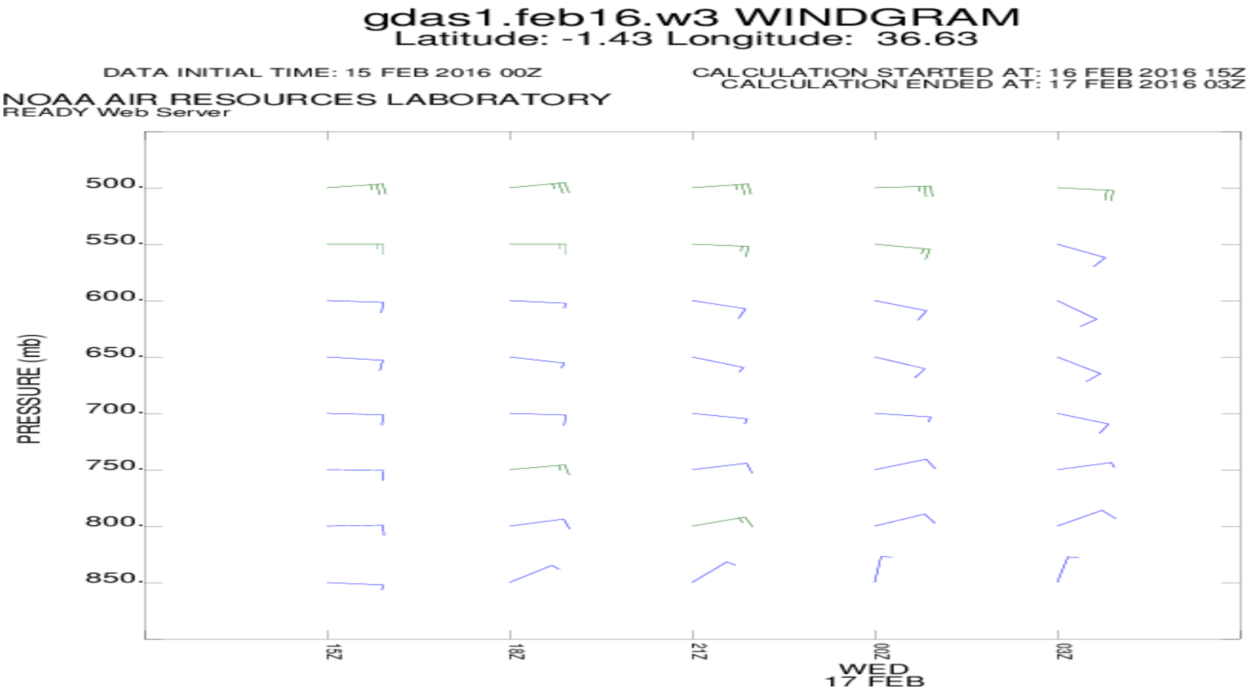


Fig 4.12 c) Wind vertical profile at Mua hills on 16/02/2016, 15Z to 03Z 17/02/2016



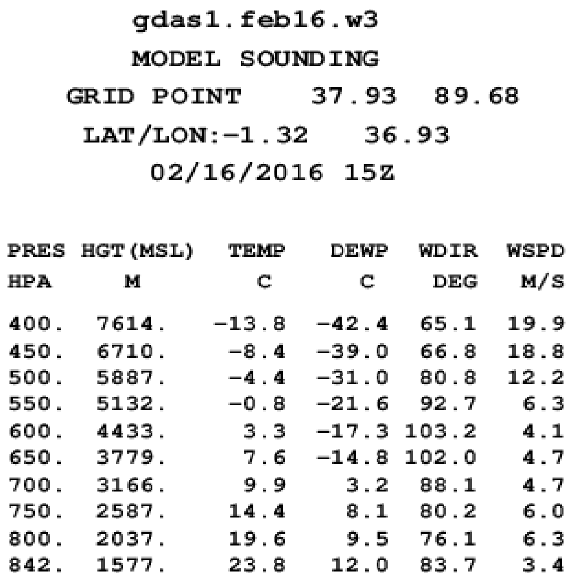
TIME

Fig 4.12 d) Wind vertical profile at Ngong Hills on 16/02/2016, 15Z to 03Z 17/02/2016

Tables 10 a, b and c show the vertical temperature profiles for JKIA from 15Z to 21Z on 16/02/2016. From the JKIA profile, there was formation of surface inversion from 18z. These conditions continued in the next 3 hours where by at 21Z the negative lapse rate was still present. This surface inversion is attributed to the clear sky conditions as shown in observed raw data in Appendix 6 that led to radiation cooling thus faster cooling of the surface than the air at 800mb level which was the warmest as shown in Tables 10 b and c.

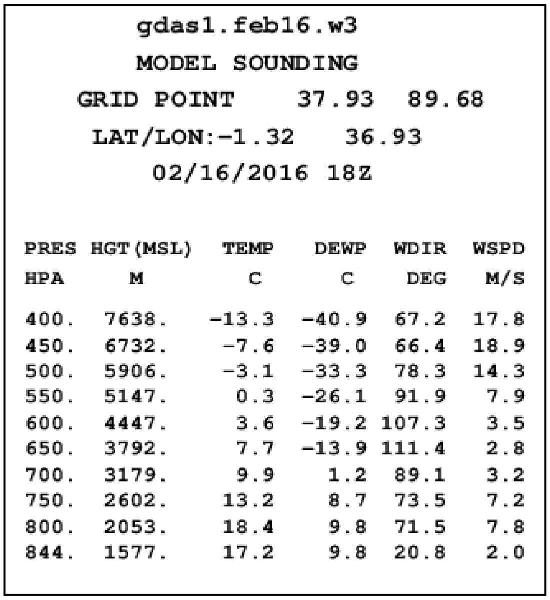
Tables 10. JKIA Temperature Sounding at (a) 15Z, (b) 18Z and (c) 21Z on 16/02/2016

(a)



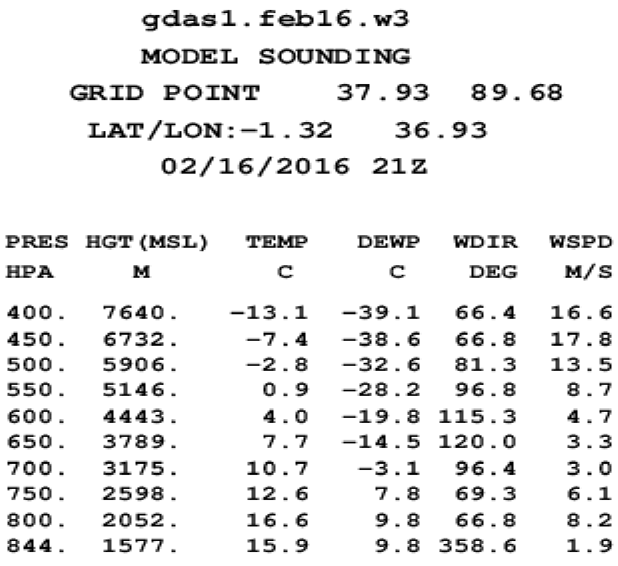
```
          gdas1.feb16.w3
          MODEL SOUNDING
      GRID POINT     37.93   89.68
       LAT/LON:-1.32    36.93
           02/16/2016 15Z

PRES HGT(MSL)   TEMP    DEWP   WDIR  WSPD
HPA     M         C       C     DEG   M/S

400.  7614.   -13.8  -42.4   65.1  19.9
450.  6710.    -8.4  -39.0   66.8  18.8
500.  5887.    -4.4  -31.0   80.8  12.2
550.  5132.    -0.8  -21.6   92.7   6.3
600.  4433.     3.3  -17.3  103.2   4.1
650.  3779.     7.6  -14.8  102.0   4.7
700.  3166.     9.9    3.2   88.1   4.7
750.  2587.    14.4    8.1   80.2   6.0
800.  2037.    19.6    9.5   76.1   6.3
842.  1577.    23.8   12.0   83.7   3.4
```

(b)



```
          gdas1.feb16.w3
          MODEL SOUNDING
      GRID POINT     37.93   89.68
       LAT/LON:-1.32    36.93
           02/16/2016 18Z

PRES HGT(MSL)   TEMP    DEWP   WDIR  WSPD
HPA     M         C       C     DEG   M/S

400.  7638.   -13.3  -40.9   67.2  17.8
450.  6732.    -7.6  -39.0   66.4  18.9
500.  5906.    -3.1  -33.3   78.3  14.3
550.  5147.     0.3  -26.1   91.9   7.9
600.  4447.     3.6  -19.2  107.3   3.5
650.  3792.     7.7  -13.9  111.4   2.8
700.  3179.     9.9    1.2   89.1   3.2
750.  2602.    13.2    8.7   73.5   7.2
800.  2053.    18.4    9.8   71.5   7.8
844.  1577.    17.2    9.8   20.8   2.0
```

(c)

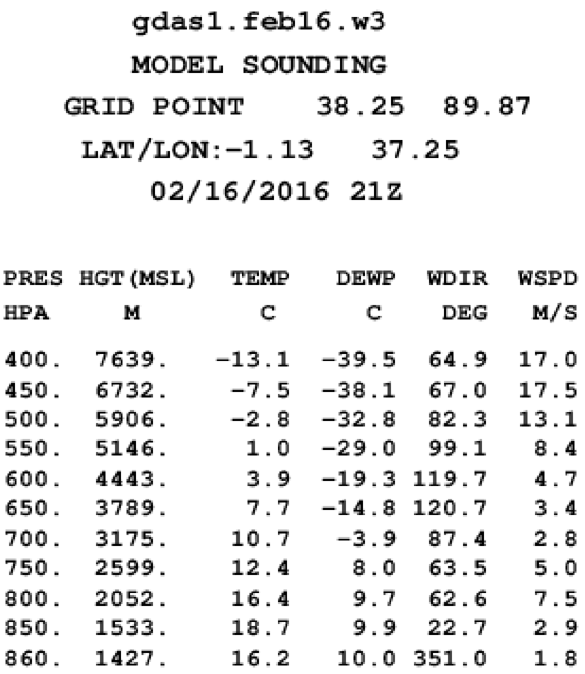


```
          gdas1.feb16.w3
          MODEL SOUNDING
      GRID POINT     37.93   89.68
       LAT/LON:-1.32    36.93
           02/16/2016 21Z

PRES HGT(MSL)   TEMP    DEWP   WDIR  WSPD
HPA     M         C       C     DEG   M/S

400.  7640.   -13.1  -39.1   66.4  16.6
450.  6732.    -7.4  -38.6   66.8  17.8
500.  5906.    -2.8  -32.6   81.3  13.5
550.  5146.     0.9  -28.2   96.8   8.7
600.  4443.     4.0  -19.8  115.3   4.7
650.  3789.     7.7  -14.5  120.0   3.3
700.  3175.    10.7   -3.1   96.4   3.0
750.  2598.    12.6    7.8   69.3   6.1
800.  2052.    16.6    9.8   66.8   8.2
844.  1577.    15.9    9.8  358.6   1.9
```

Similarly, Tables 11 a), b) and c) represent temperature profiles at 21Z for Oldonyo-Sabuk, Mua and Ngong hills respectively where the surface inversion is also observed.

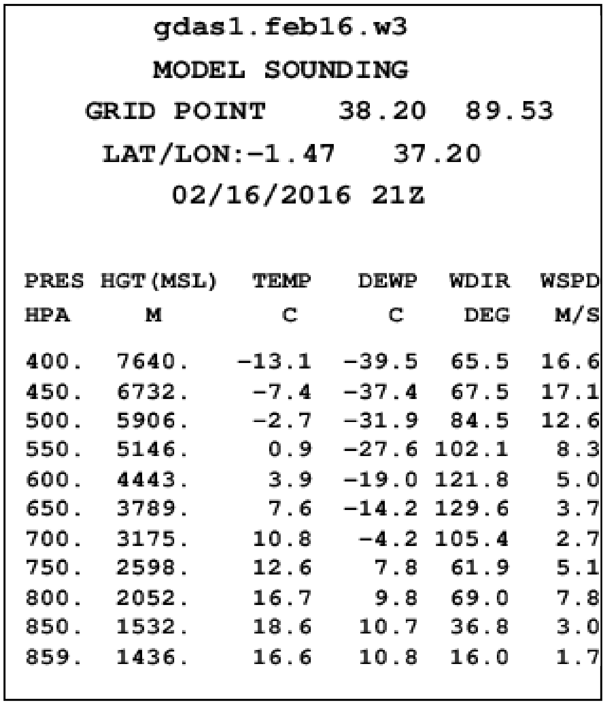
Tables 11. Oldonyo-Sabuk, Mua and Ngong Hills Temperature Sounding respectively at 21Z on 16/02/2016

11a) Oldonyo-Sabuk Temperature sounding



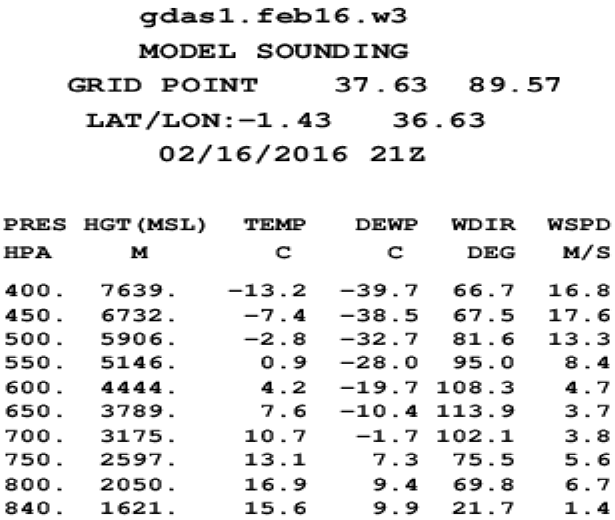
```
        gdas1.feb16.w3
        MODEL SOUNDING
    GRID POINT    38.25  89.87
     LAT/LON:-1.13    37.25
         02/16/2016 21Z

PRES HGT(MSL)  TEMP   DEWP  WDIR  WSPD
HPA     M        C      C    DEG   M/S

400.  7639.   -13.1  -39.5  64.9  17.0
450.  6732.    -7.5  -38.1  67.0  17.5
500.  5906.    -2.8  -32.8  82.3  13.1
550.  5146.     1.0  -29.0  99.1   8.4
600.  4443.     3.9  -19.3 119.7   4.7
650.  3789.     7.7  -14.8 120.7   3.4
700.  3175.    10.7   -3.9  87.4   2.8
750.  2599.    12.4    8.0  63.5   5.0
800.  2052.    16.4    9.7  62.6   7.5
850.  1533.    18.7    9.9  22.7   2.9
860.  1427.    16.2   10.0 351.0   1.8
```

11b) Mua Hills temperature sounding



```
        gdas1.feb16.w3
        MODEL SOUNDING
    GRID POINT    38.20  89.53
     LAT/LON:-1.47    37.20
         02/16/2016 21Z

PRES HGT(MSL)  TEMP   DEWP  WDIR  WSPD
HPA     M        C      C    DEG   M/S

400.  7640.   -13.1  -39.5  65.5  16.6
450.  6732.    -7.4  -37.4  67.5  17.1
500.  5906.    -2.7  -31.9  84.5  12.6
550.  5146.     0.9  -27.6 102.1   8.3
600.  4443.     3.9  -19.0 121.8   5.0
650.  3789.     7.6  -14.2 129.6   3.7
700.  3175.    10.8   -4.2 105.4   2.7
750.  2598.    12.6    7.8  61.9   5.1
800.  2052.    16.7    9.8  69.0   7.8
850.  1532.    18.6   10.7  36.8   3.0
859.  1436.    16.6   10.8  16.0   1.7
```

11 c) Ngong Hills temperature sounding



```
        gdas1.feb16.w3
        MODEL SOUNDING
    GRID POINT    37.63  89.57
     LAT/LON:-1.43    36.63
         02/16/2016 21Z

PRES HGT(MSL)  TEMP   DEWP  WDIR  WSPD
HPA     M        C      C    DEG   M/S

400.  7639.   -13.2  -39.7  66.7  16.8
450.  6732.    -7.4  -38.5  67.5  17.6
500.  5906.    -2.8  -32.7  81.6  13.3
550.  5146.     0.9  -28.0  95.0   8.4
600.  4444.     4.2  -19.7 108.3   4.7
650.  3789.     7.6  -10.4 113.9   3.7
700.  3175.    10.7   -1.7 102.1   3.8
750.  2597.    13.1    7.3  75.5   5.6
800.  2050.    16.9    9.4  69.8   6.7
840.  1621.    15.6    9.9  21.7   1.4
```

From the analysis, the surface was cooling faster than the air at the immediate upper levels from 18Z. The 800mb and 750mb levels had higher wind speeds than the immediate surrounding layers; 700 in the upper atmosphere and 850 the surface whose winds were light. A discontinuity due to change in wind direction existed from 18Z at 800mb level at JKIA. It thus can be concluded that the surface inversion with moderate to light winds in the layer 750-850mb contributed to vertical wind shear on 16/02/2016 from 18Z. The formation of surface inversions is favoured under clear-sky light wind conditions (Baynton, 1965).

4.6.2 Case with Convection Present

On 23/08/2014, wind shear was reported by 4 aircrafts en route to JKIA between 1300Z and 1400Z. 2 of the aircrafts encountered the wind shears at 5 miles and 2 miles to touchdown. At around 1328Z, KQA483 reported experiencing strong winds which made the aircraft to veer slightly as it landed. Of these 4 aircrafts, two performed a missed approach and 1 diverted.

Appendix 7. shows the observed weather conditions on 23/08/2014 at JKIA. Convective clouds were present indicating presence of updrafts and downdrafts. The changing wind directions from earlier on even though not strong is a sign of instability. Wind direction and speed varied with crosswinds and gusty winds been evident between 13Z and 14Z. Convection occurred from 1330Z to 1500Z.

Figures 4.13 a, b,c and d shows windgrams for JKIA, Oldonyo Sabuk, Mua and Ngong hills fom 06Z to 18Z. The surface wind direction was generally easterly with the exception of 09Z when it was a south easterly wind. With height, winds completely reversed their direction from an easterly to a westerly component in the middle levels. Considerable variability is observed.

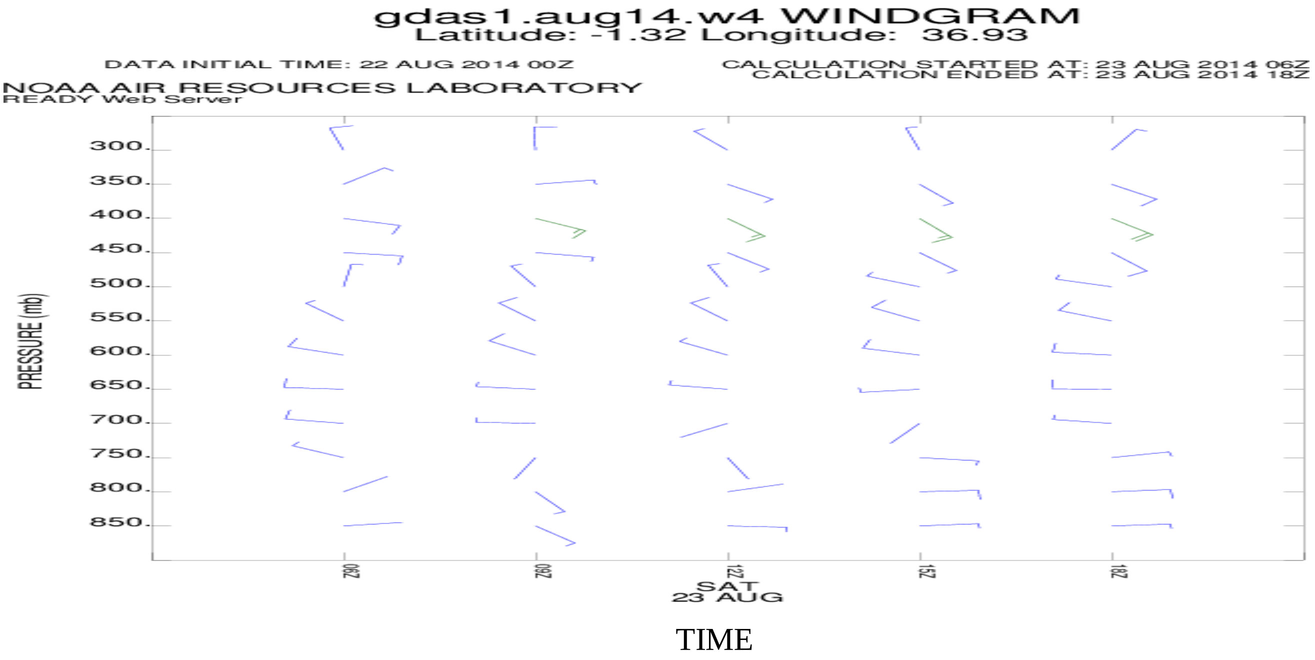


Fig 4.13a) Vertical wind profile at JKIA between 06Z and 18Z on 23/08/2014

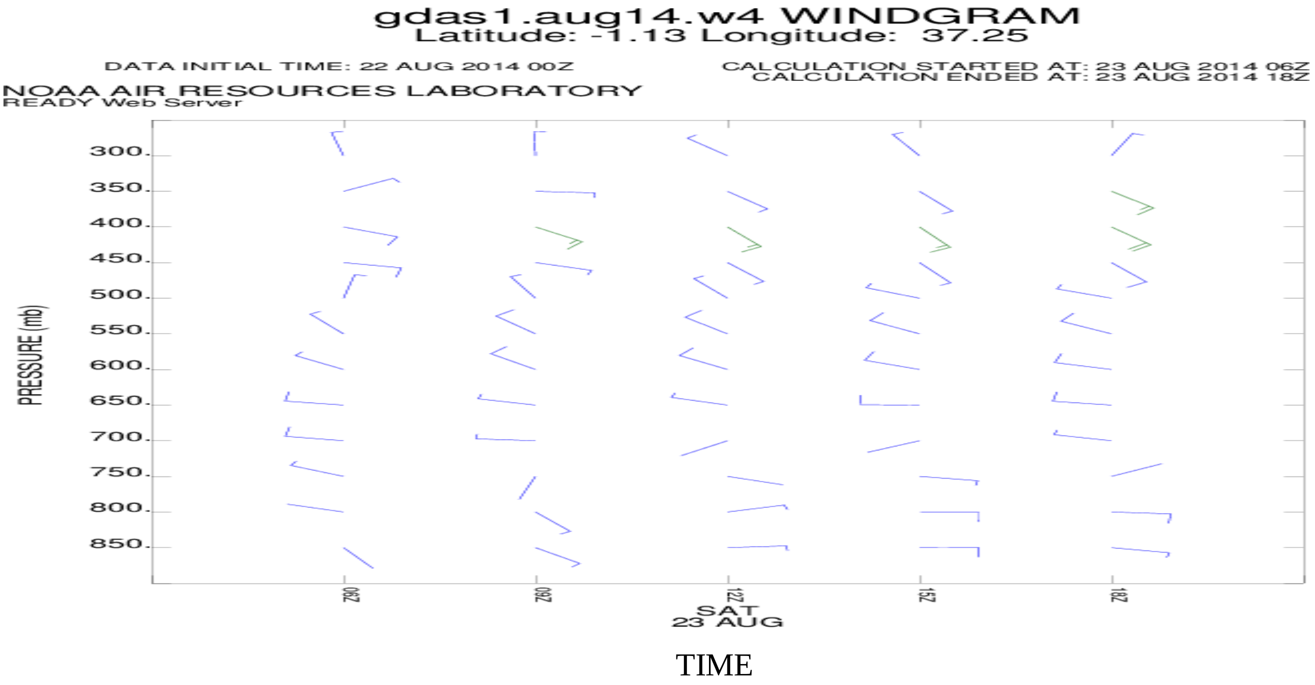


Fig 4.13b) Vertical wind profile at Oldonyo-Sabuk hills between 06Z and 18Z on 23/08/2014

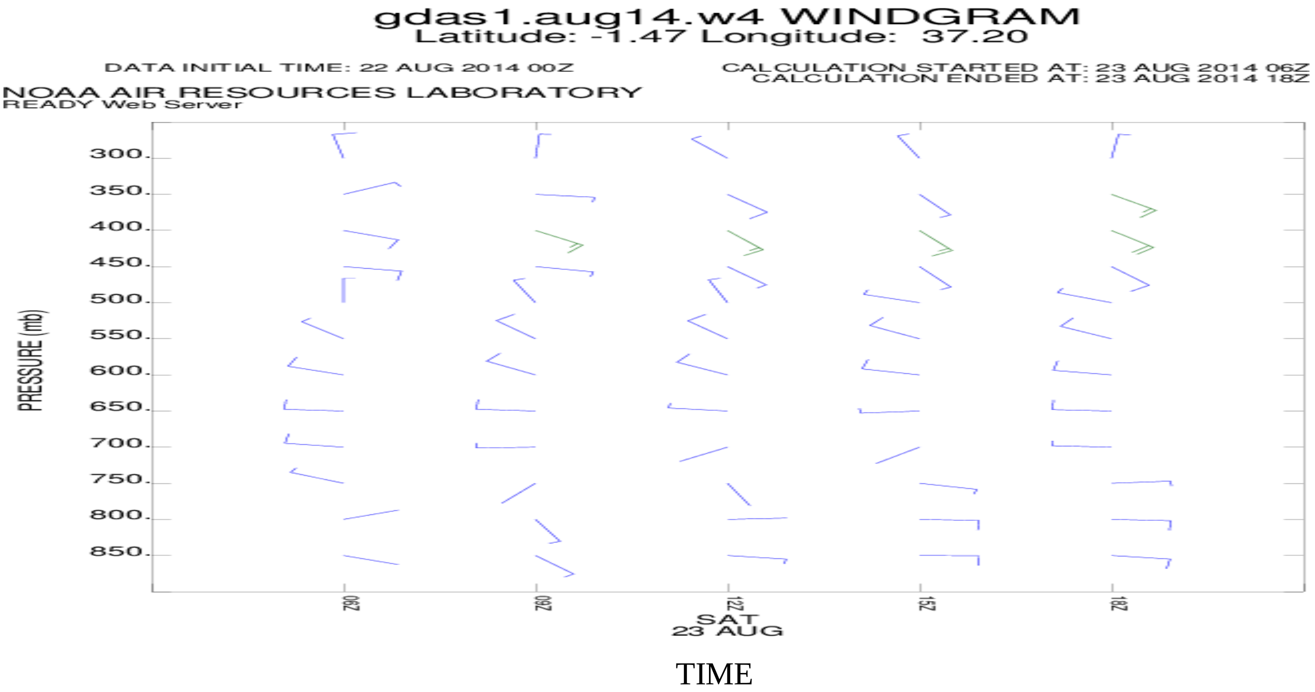


Fig 4.13c) Mua hills vertical wind profile between 06Z and 18Z on 23/08/2014

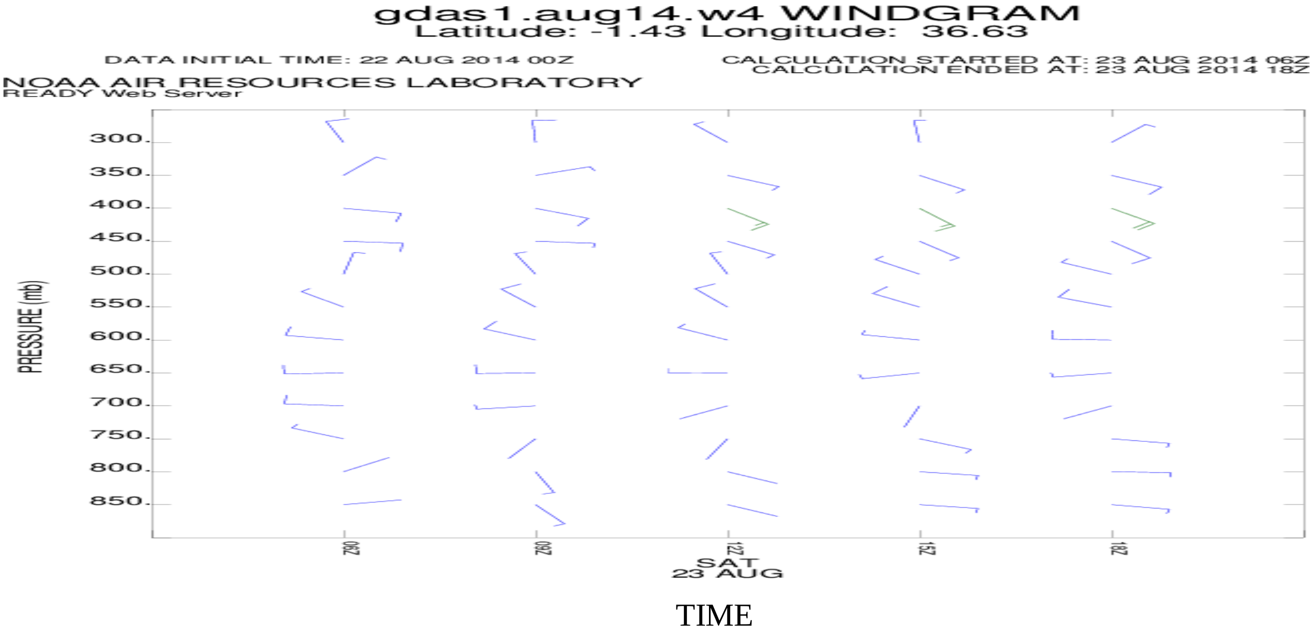


Fig 4.13d) Vertical wind profile at Ngong hills between 06Z and 18Z on 23/08/2014

Figure 4.14 is a mean sea level pressure chart covering East Africa region on 23/08/2014, 12Z valid for 6 hours. From this chart, Mascarene high was predominantly controlling winds at the study region which are mainly easterlies and south easterlies. During Northern summer, South east monsoons are dominant within most parts of the country which are mostly moist and cold (Anyamba, 1983). Slight insolation as from observed data in appendix 7 lead to development of convective clouds. Westerly winds in the middle and lower troposphere are associated with rainfall in the east African region (Camberlin and Wairoto, 1997). The medium level winds shown in Figure 4.15 clearly show westerlies were present on this particular day.

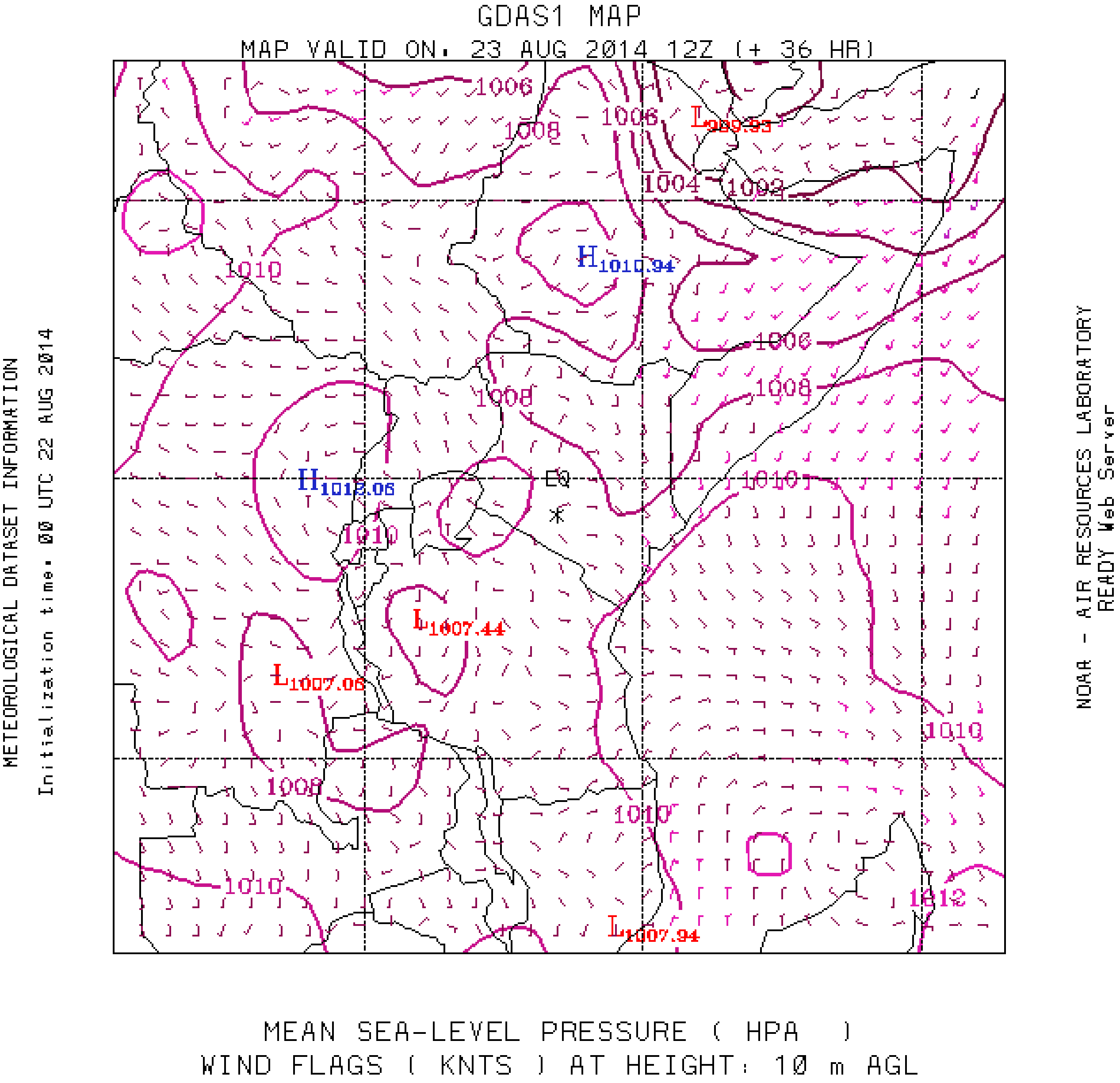


Fig 4.14. Mean Sea Level Pressure chart for East Africa region on 23/08/2014 valid from 12Z for 6 hours

* -JKIA location

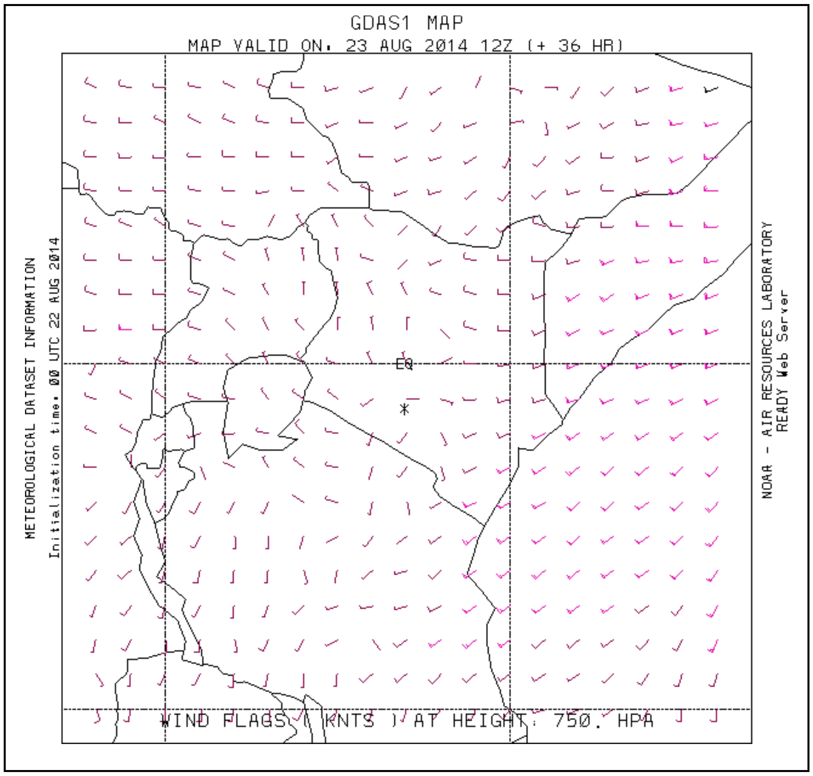


Fig 4.15. Medium level chart showing winds observed at 12Z on 23/08/2014.

Directional shear is present in the layer 800-700mb throughout the day. This implies that when convection is expected to occur the wind variability is expected to be present for an extended period of time leading to convection. Instability is enhanced by the different wind directions between the surface and middle levels-700mb.

5.0 CHAPTER FIVE

CONCLUSIONS AND RECOMENDATION

This chapter provides a summary of the findings obtained from various methods used to achieve the objectives of the study. Conclusions drawn and recommendations for further study are also provided.

5.1 Conclusions of the Study

The study has shown that wind shear is a phenomena that affects operations at JKIA based on flight delays experienced. It was mostly reported when aircrafts were airborne which lead to go arounds and diversions. Delays in taking off are also a commom implication of wind shear on aircraft operations. Tailwinds were the most encountered supported by 11% of wind shear reports. 61% of reports did not specify the nature of wind shear. Wind speed conditions from shear reports easily surpass the allowable tailwind thresholds of 10-15 knots for most aircrafts. It thus can be concluded that directional shear and not the high speeds is the problem at JKIA.

0.03% of air traffic within 10 year study period were affected by wind shear of which 65% of pilots carried out a missed approach which lasted approximately 10-20 minutes. Corelation between wind shear incidences and delays and diversions showed that 87.4% of aircrafts are likely to perform a missed approach or delay take-off while 1% will divert if wind shear conditions are present. The total number of minutes that flights delayed were 1014. The cost incured as a result was approximate USD 79,620. 7 aircrafts were diverted due to wind shear conditions within the 10 year period. This resulted in the resultant cost due to diversion being approximate USD 700,000.

During missed approach procedures, different aircrafts consume different amounts of fuel depending on aircraft weight, size and decision height. A missed approach can consumes 28 times more fuel than a normal landing.

The trend analysis showed an upward trend for air traffic and downward trend of wind shear based on the S positive (+39) and negative (-16) values respectively. Air traffic had a higher temporal variability as compared to wind shear incidences. In terms of seasons, it was revealed that november was the month which had the highest wind shear incidences. The transitional months from one season to the other also recorded high incidences of windshear encounters. This is attributed to the seasonal shift of the the position of the sun whose heating creates pressure differences that controls wind patterns in the large scale. Months in between seasons (Jan, April, July and October) had the least incidences. A majority of these incidences were reported from late afternoon to midnight.

From the windroses, the usability of the runway is not affected most of the year. It is designed to utilise both NE moonsoon winds and SW winds. However windshear in short time spans may not be captured especially if it happens in between hours since data used is hourly. Similarly wind flow on the surfacemay vary with wind flow in upper layes. It thus does not negate the awareness of windshear occurrence especially in the approach landing and take-off paths. Windshear is thus a challenge within the airspace that impacts airlines negatively.

In analysis of simulation of wind shear,the non-convection case study showed that surface inversion from 18Z in 16/02/2016 with light to moderate winds existed. It was favoured by clear sky conditions which lead to vertical wind shear occuring. Levels 800mb and 750mb had fastest wind speeds than surrounding upper and lower levels, temperatures were also highest at this layer.

In the convection case, variability of winds between lower and middle levels indicated an unstable atmosphere throughout the day. The vertical wind shear existed from the surface to 700mb level. The easterlies and south easterlies in the low levels brought in moisture from the indian ocean. Westerlies in the middle levels are associated with rainfall in E. Africa. Insolation thereof caused development of convective activity which lead to diversion and missed approaches.From both illustrations, directional wind shear was dominant. The convective case had notable negative effects such as diversion.

Flight planning utilizes weather forecast in the most optimal way to ensure flights remain safe and on schedule. Given the relative costs of occurrence of the wind shear and protection from the event, it is of utmost importance to issue timely and accurate forecast. This will ensure the correct amount of fuel is carried as well as ensure a pilot does not substitute passengers or cargo for extra fuel due to wrong forecast. Wind shears and turbulent environments should thus be well forecasted.

5.3 Recommendations

Based on this study, the following recommendations have been made.

- Future research should incorporate actual flight data from flight data recorders to clearly outline heights at which wind shear is predominant.
- Pilots are encouraged to specify the nature and intensity of wind shear in their reports. This is for proper categorization of the shears.
- Future research should use wind data from the hills themselves since this will present the actual wind characteristic of the raised terrain.
- Conditions that lead to wind shear occurrence at JKIA are not conclusively discussed since only 2 case studies were considered. Other times when wind shear occurred can be studied to outline weather conditions that would lead to wind shear at JKIA. Further studies in the month of february that was chosen for the case study should reveal whether surface inversions are common.
- Research of any overruns if occurred should be done from aircrafts that landed or took-off with tailwinds conditions to further classify the impact of wind shear.
- Wind shear reports are mainly from Pilot encounters. Predictability results should enable wind shear warnings to be issued in future to improve flight operations. In addition Kenya Meteorological Department is encouraged to invest in a wind profiler which will assist in early warning of wind shear conditions during take-off and landing.

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APPENDICES

APPENDIX 1

Table 1. Tailwind limits for a few aircrafts from available Aircraft Manuals (Van Es G.W.H and Karwal A. K., 2001) NLR-TP-2001-003

Model	Tailwind Limits (Knots)
B737-300/400/500	10
B747-400	15
B757-200	15
B767-200/300	15
B777-200	15
A319/A320/A321	15
A310-200/300	10
F100/70/50	10
MD80/MD11/MD90	10
146-200-steep approach, take-off, landing	5, 10, 15
Dash 7-take-off, Landing	15, 20
RJ70, RJ85,RJ100	15
146-200 (Steep approach)	5
146-200 (Take-off)	10

APPENDIX 2

Table 2. Overview of demonstrated crosswinds of western-built aircraft.

Model	Demonstrated crosswinds kts
EMB-120	30
EMB-145	30
F28-all series	30
F100	30
F70	35
F50	33
F28-all series	25
B727-100/200	29
B737-100/200	29
B737-300/400/500	35
B747-100/200	28
B747 SP	34-Take off, 32-Landing
B747-400	30
B757-200	30
B767-200	29
B767-300	33
B777-200	38

Cessna 500	25
Cessna 560	23
Cessna 650	20
Cessna 750	25
Bae146-100	25-Take off, 30-Landing
Bae146-200	30-Take off, 35-Landing
Canad air CL-65 RJ	24
Canad air CL-600/601/604	24
DC-8-61	17
DC-8-61	32
DC-8-71/72/73	28
DC-9-30/34/40	38

Source: Faa and manufacturers; NLR-TP-2001-217 (Van Es, Geest V and Nieuwpoort T.M.H)

APPENDIX 3: Seasonal Wind roses for Kabete Agro-meteorological Station

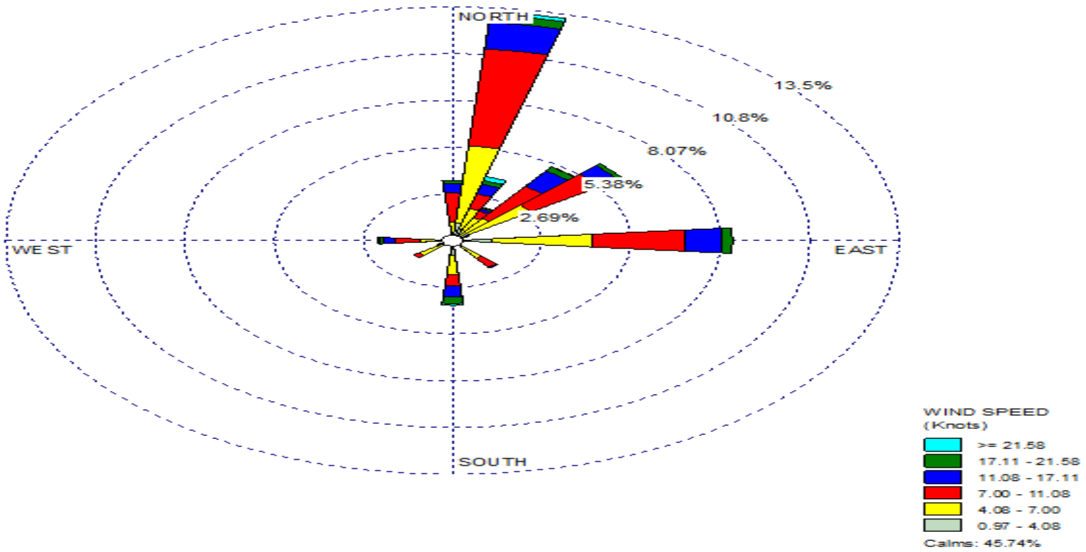

Figure 7.1a: Kabete Wind rose for March to May.

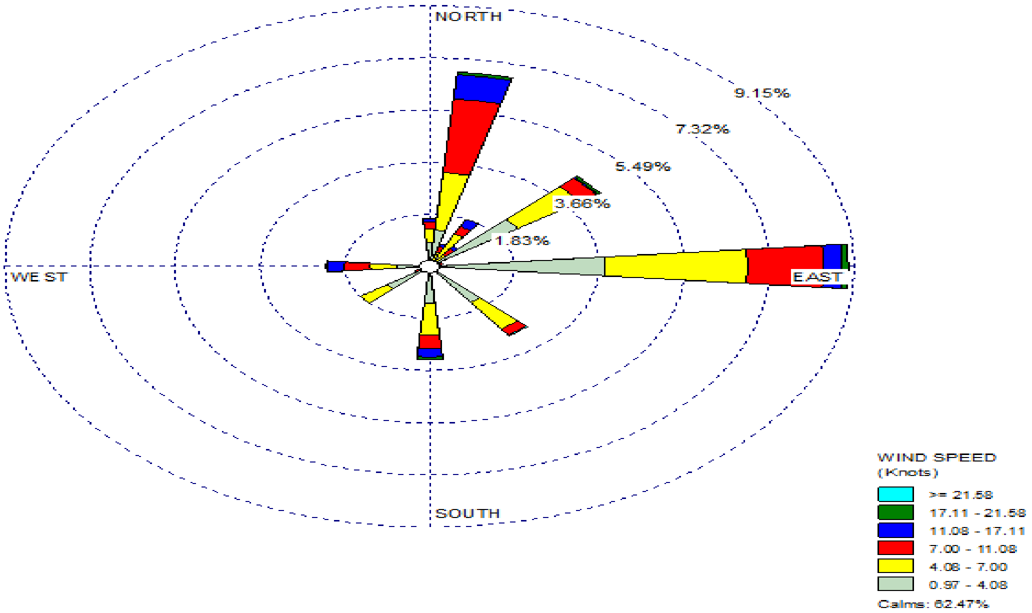

Figure 7.1b: Kabete Wind rose for June to August.

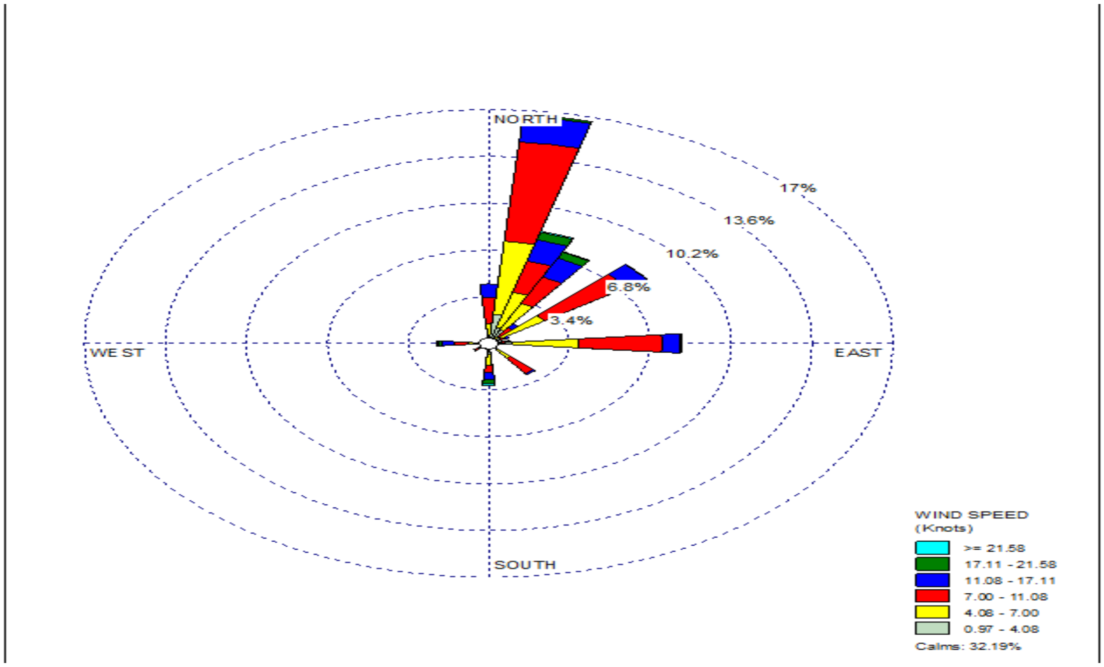

Figure 7.1c: Kabete Wind rose for September to November.

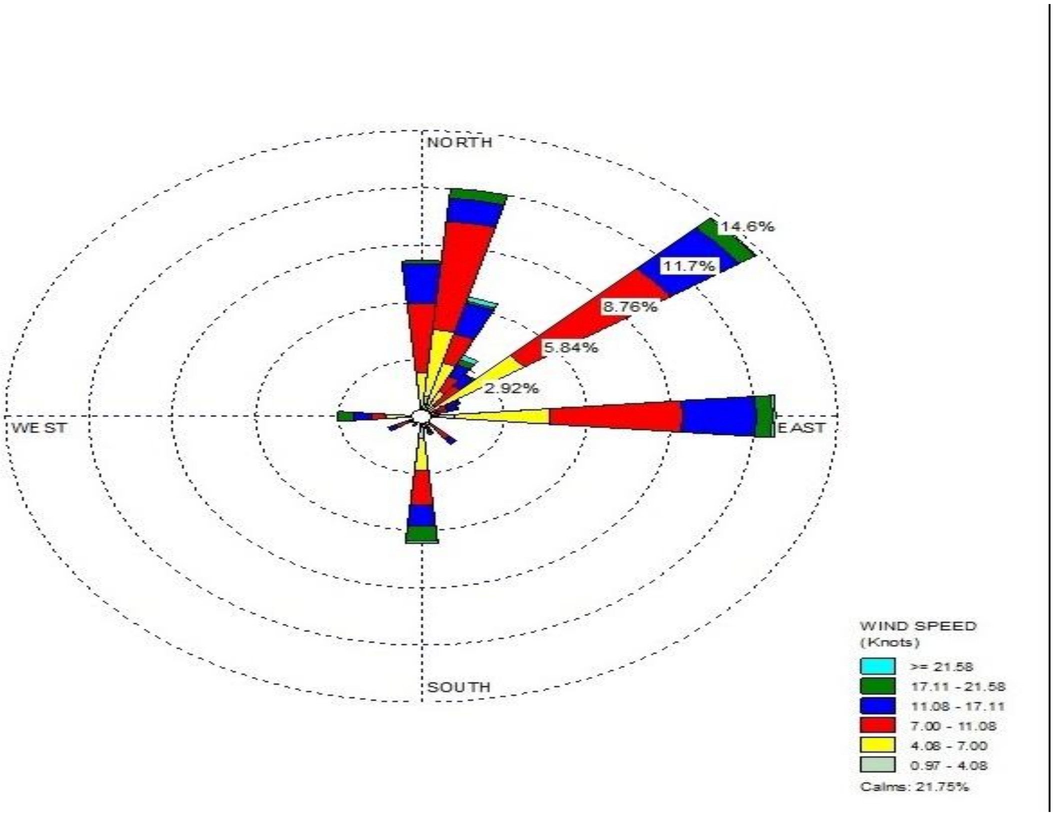

Figure 7.1d: Kabete Wind rose for January and February.

APPENDIX 4: Seasonal Wind roses for Thika Agro-meteorological Station

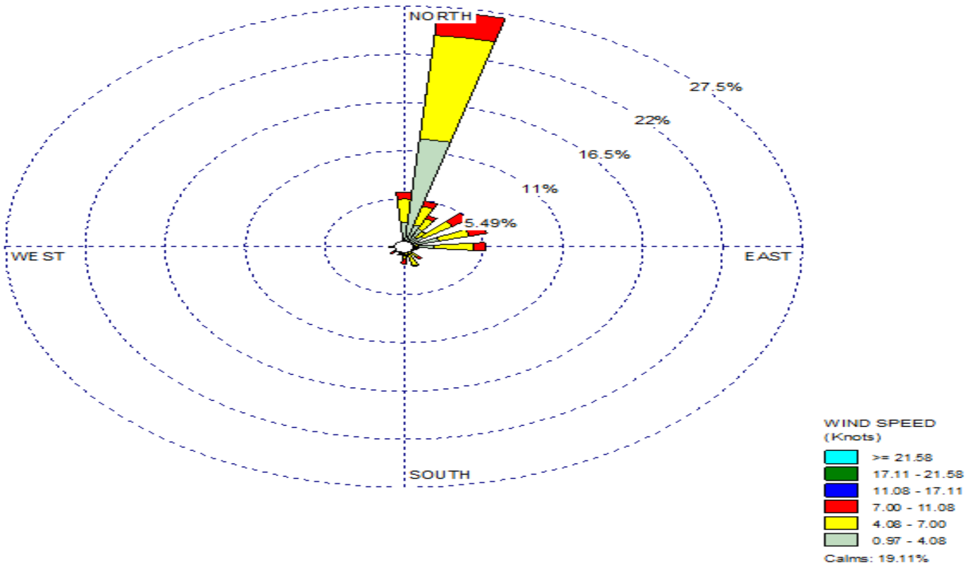

Figure 7.2a: Thika Wind rose for March to May.

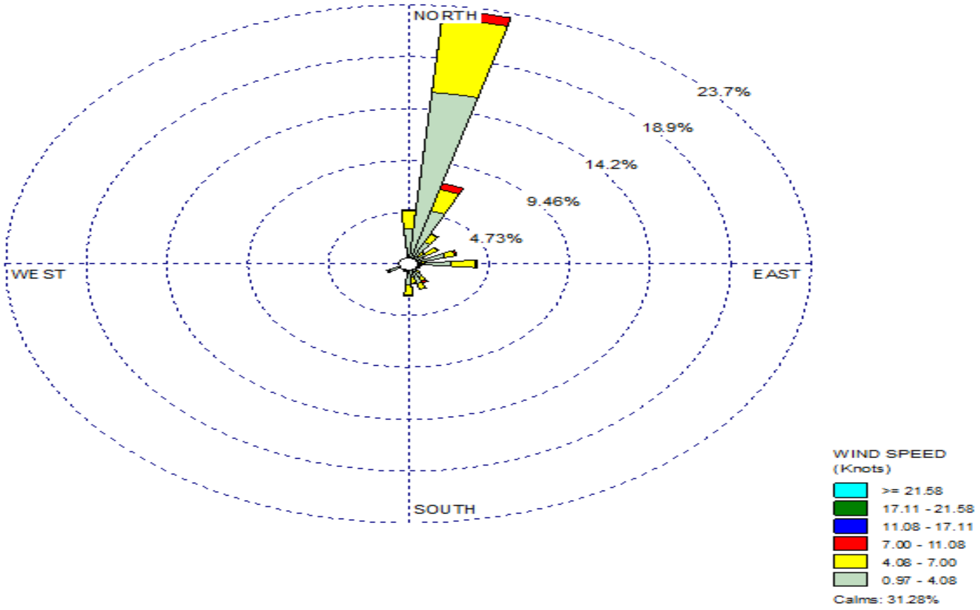

Figure 7.2b: Thika Wind rose for June to August.

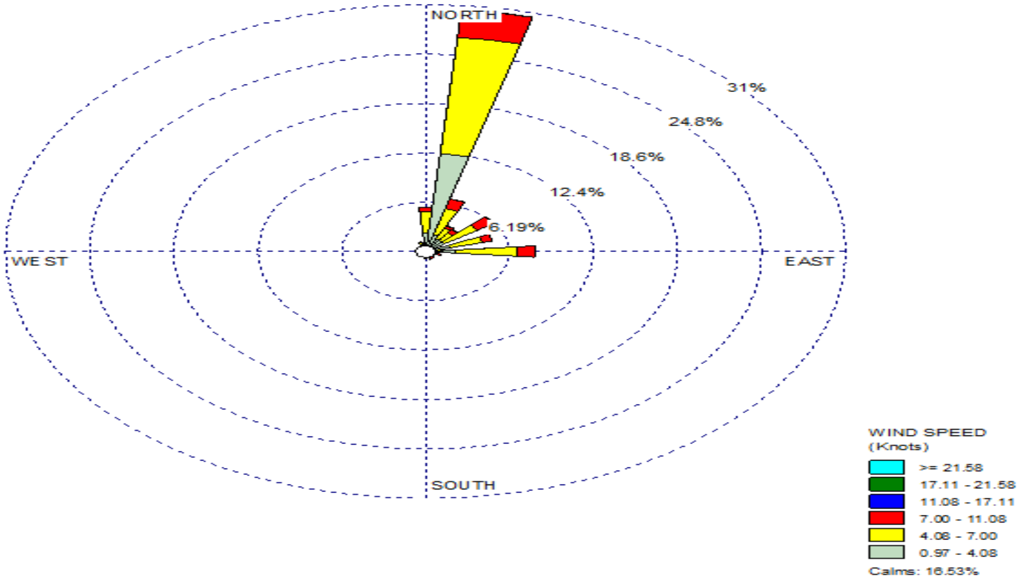

Figure 7.2c: Thika Wind rose for September to November.

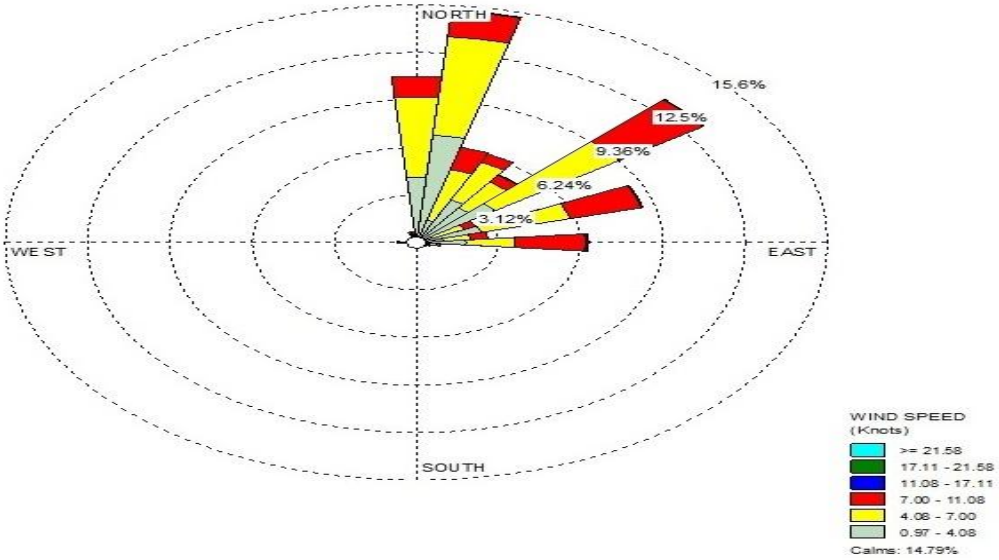

Figure 7.2d: Thika Wind rose for January and February.

APPENDIX 5: Seasonal Wind roses for Machakos Agro-meteorological Station

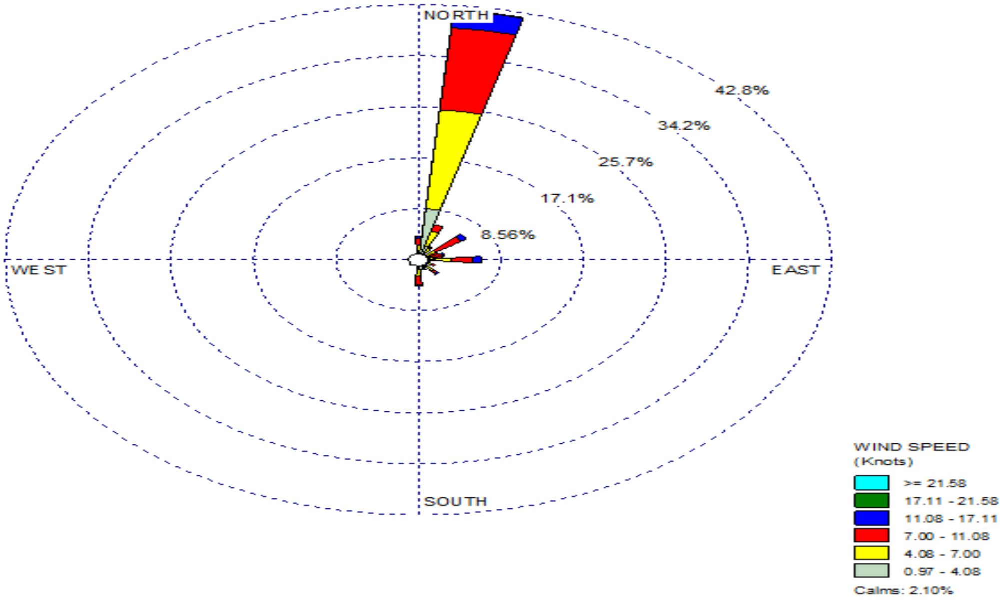

Figure 7.3a: Machakos Wind rose for March to May.

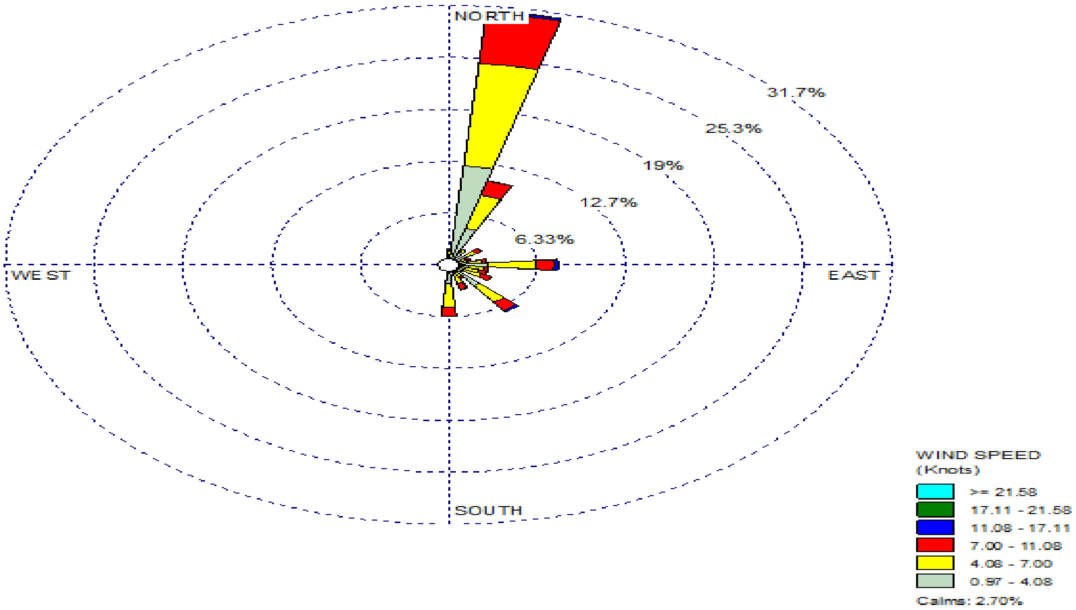

Figure 7.3b: Machakos Wind rose for June to August.

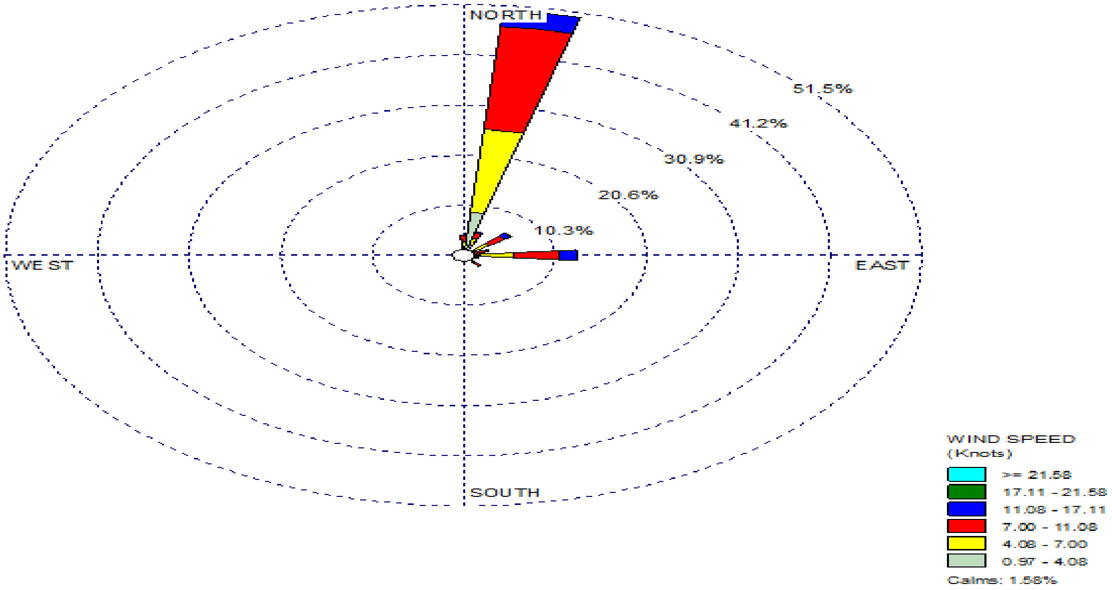

Figure 7.3c: Machakos Wind rose September to November.

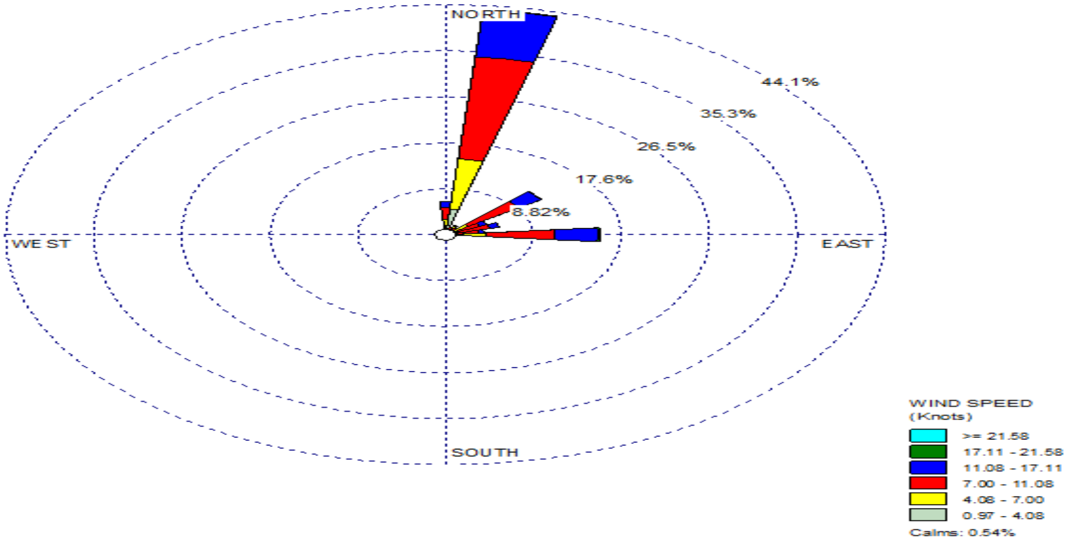

Figure 7.3d: Machakos Wind rose for January and February.

APPENDIX 6

Table 11: JKIA METARs observed on 16/02/2016 from 15Z to 23Z

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.METAR HKJK 161500Z 04015KT 9999 FEW025 25/12 Q1021 NOSIG=
METAR HKJK 161530Z 05011KT 9999 FEW025 24/11 Q1021 NOSIG=
METAR HKJK 161600Z 04009KT 9999 FEW024 23/12 Q1021 NOSIG=
METAR HKJK 161630Z 03007KT CAVOK 21/13 Q1022 NOSIG=
METAR HKJK 161700Z 02007KT CAVOK 19/12 Q1022 NOSIG=
METAR HKJK 161730Z 02006KT CAVOK 19/13 Q1022 NOSIG=
METAR HKJK 161800Z 03006KT CAVOK 19/13 Q1023 NOSIG=
METAR HKJK 161830Z 05004KT CAVOK 18/13 Q1023 NOSIG=
METAR HKJK 161900Z 03004KT CAVOK 18/13 Q1024 NOSIG=
METAR HKJK 162000Z 01006KT CAVOK 18/13 Q1023 NOSIG=
METAR HKJK 162030Z 02005KT CAVOK 18/14 Q1023 NOSIG=
METAR HKJK 162100Z 01006KT CAVOK 18/14 Q1023 NOSIG=
METAR HKJK 162130Z 34005KT CAVOK 17/14 Q1023 NOSIG=
METAR HKJK 162200Z 35006KT CAVOK 17/13 Q1022 NOSIG=
METAR HKJK 162230Z 35006KT CAVOK 17/13 Q1022 NOSIG=
METAR HKJK 162300Z 35005KT CAVOK 17/14 Q1022 NOSIG=
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APPENDIX 7

Table 14: JKIA METARs observed on 23/08/2014 from 09Z to 15Z

METAR HKJK 230900Z VRB03KT 9999 SCT025TCU 25/13 Q1020 NOSIG=
METAR HKJK 231000Z VRB03KT 9999 FEW026CB BKN027 27/13 Q1019 NOSIG=
METAR HKJK 231100Z 00000KT 9999 FEW027CB BKN028 29/13 Q1017 NOSIG=
METAR HKJK 231130Z 24007KT 9999 FEW027CB BKN028 28/12 Q1017 NOSIG=
METAR HKJK 231200Z VRB03KT 9999 FEW027CB BKN028 29/13 Q1016 NOSIG=
METAR HKJK 231230Z 06010KT 9999 FEW027CB BKN028 28/11 Q1016 NOSIG=
METAR HKJK 231300Z 15016KT 9999 FEW026CB BKN027 27/13 Q1016 NOSIG=
METAR HKJK 231330Z 06016G35KT 1000 +RA FEW022CB BKN023 BKN080 22/18 Q1016 BECMG 1530 9999 -RA FEW024CB BKN025 BKN080=
METAR HKJK 231400Z 04018KT 1000 +RA FEW020CB BKN021 BKN080 15/14 Q1018 BECMG 1600 9999 -RA FEW024CB BKN025 BKN080=
METAR HKJK 231430Z 02009KT 5000 TSRA FEW020CB BKN021 BKN080 17/15 Q1018 BECMG 1630 9999 -TSRA FEW023CB BKN024 BKN080=
METAR HKJK 231500Z 04003KT 9999 -RA FEW020CB SCT021 17/16 Q1018=