TOWARDS THE VERIFICATION OF SURFACE WIND FORECASTS AT JOMO KENYATTA INTERNATIONAL AIRPORT, KENYA

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A Research Project submitted in partial fulfillment of the requirements for the award of Postgraduate Diploma (PGD) in Aviation Meteorology,

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DECLARATION

Declaration by candidate

I declare that this research project is my original work and has not been submitted for examination in this or any other university or institution of higher learning.

Signature: ………………………………... **Date: ………………………**

Aliyare Mohamed Warsame
I50/11592/2018

Declaration by the supervisors

This research project has been submitted for examination with our approval as University Supervisors.

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ABSTRACT

The economic progress of civil aviation industry and aircraft operations is largely reliant on the optimum operationalization of the flight schedules. Bad weather and specifically strong winds at the airport may cause interference of the flight schedule when taking off by holding some time or diversions or making u turn when landing. diversions to other airport lead to enormous financial losses to the aviation operators.

Wind speed and direction forecasts are crucial for the flight planning therefore a considerable interest for assessing its accuracy and skill value. The wind speed and direction forecasts are incorporated into the Terminal Aerodrome Forecast (TAF) produced by aerodrome meteorological office. TAF contains the expected conditions of wind speed and direction, visibility, weather and cloud conditions. In this study the forecast of wind speed and direction were verified against the wind speed and direction observation considering for 1hr and 6hr lead times. The highest observed value was compared against the highest forecasted value. Wind speed was sorted into three categories of light covering a range between (1-6) kt, moderate between (7-12) kt and strong above 12kt. Then a 3-category contingency table was developed by considering 1hr and 6hr lead times. Accuracy at 1hr and 6hr lead time was evaluated by using scatter plot and the Root Mean Square Error. Different skill scores were then calculated from the contingency table.

For wind direction verification, significant deviations among observations and the forecasts were investigated. Forecast errors are considered significant when the wind speed attains 7 kts and the deviation is more than 60^0. If the observed wind speed is more or equivalent than the predefined speed threshold, all the forecast errors valid for that hour were calculated. If the observed mean wind speed is less than the speed threshold, the forecast wind direction is regarded as correct since any direction deviation is operationally insignificant. The accuracy of wind direction was assessed by utilizing Percentage Error method. The wind direction was classified into four cardinal directions north, east, south and west. Then a 4-category contingency table was created for both 1hr and 6hr lead times and different skill scores were analyzed.

The accuracy and the skill for wind speed and direction forecasts are high at 1hr lead time as compared to 6hr lead time hence the wind speed and direction forecasts should be utilized quickly after production and limited to not more than six hours since its accuracy and skill drops. The new and the amended forecasts should be used with urgency for flight planning since it has more correct forecasts.

The verification results should be able show the quality and the weakness of the wind speed and direction forecasts thereby acting as an apparatus to promote further improvement for the strong wind forecasting on the part of the forecasters. The skill scores generated from the contingency table will help the management in evolving ways for improving strong wind forecasting by improving the instrument for observing and forecasting strong wind and also opening further training in strong wind forecasting for the forecasters.

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List of Acronyms

AAR:	Airport Acceptance Rate
ACC:	Allowable Crosswind Component
BECMG:	Becoming (Used in TAF)
CSI:	Critical Success Index
FAA:	Federal Aviation Administration
FAR:	False Alarm Ratio
FCST:	Forecast
FM:	From
GDP:	Ground Delay Program
HK:	Hanssen and Kuipers discriminant
HSS:	Heidke Skill Score
IAS:	Indicated Air Speed
ICAO:	International Civil Aviation Organization
ITCZ:	Inter-tropical Convergence Zone
JKIA:	Jomo Kenyatta International Airport
KAA:	Kenya Airport Authorities
KCAA:	Kenya Civil Aviation Authorities
KMD:	Kenya Meteorological Department
LAHSO:	Land and Hold Short Operations
MAM:	March April May
METAR:	Meteorological Aviation Routine weather report
OBS:	Observed
OND:	October November December
PA:	Post Agreement
PC:	Percentage Correct
PE:	Percentage Error
POD:	Probability of detection
PROB:	Probability forecast

RDC:	Runway Design Code
RMSE:	Root Mean Square Error
RVR:	Runway Visual Range
SON:	September October November
SPECI:	Special weather report in METAR code
TAF:	Terminal Aerodrome Forecast
TEMPO:	Temporary
TS:	Threat Score
VRF:	Verification
WMO:	World Meteorological Organization

CHAPTER ONE: INTRODUCTION

1.0 Introduction

This research is aimed at verifying the wind speed and direction forecasts that are being provided at Jomo Kenyatta International airport.

1.1 Background of the Study

Wind forecasts are very important in aviation operation therefore, there is considerable interest in assessing the accuracy, skill, and value. Wind speed and direction forecasts are contained in the Terminal Aerodrome Forecasts (TAF) generated by meteorological office. TAFs provide information about the expected conditions of wind, visibility, clouds and significant weather at airports. Wind speed and direction forecasts in the TAFs are widely used for flight planning by operators, A study done by NavCanada (2002) indicated that an accurate Terminal aerodrome forecast (TAF) at a Canadian airport would contribute $12.5M each year, hence, there is of considerable importance to improve the skill of its forecasting.

One of the most issues which will have an effect on an aircraft is the motion of the wind known as wind effect, the speed and the direction of the wind can alter the progress of any aircraft. Though the aircraft has its own means of propulsion, the pilot must compensate for the wind speed and direction, so as for an aircraft to keep up the desired course. A crucial choice made before any flight is the quantity of fuel to carry. One factor (of many) affecting that choice is the evaluation of the flight time in the light of predicted upper air winds. It is obvious that the amount of fuel carried is very sensitive to the winds provided. Partially as a outcome of studies by Tenenbaum (1991).

Verification of the forecast relies on totally the nature of the observable data. The bone of contention for concern with the exception of the data quality is the treatment of the change groups in the forecast and also the allocation of scores at each time. The TAF utilizes the change gatherings like BECMG for progress inside a period interim, FM for beginning at indicated time, TEMPO for temporary changes and PROB for changes probable with a certain probability typically a 30% or 40% is utilized in the TAF.

The contention of wind forecast comes with the use of these change groups. The forecast is not for one time but a variety of time interval, therefore one can't straightforwardly relate observed conditions at a single time with what was forecasted since there is more than one forecast state valid for several points of time inside the TAF. This challenge brings the use of time blocks usually six hours for JKIA according to the nature of the forecast. The intense winds are considered in extreme event hence the highest observed during that time interval is related with the highest forecasted during that time interval. Mahringer (2008) states the operational impact forecast as the forecast in effect that is most likely to have a large influence on flight operations subsequently utilizes a very complicated technique to a verification TEMPO.

A forecast is correct as long as the observed value exists in the range opened by TEMPO since the forecast for this case given as a range of possible conditions within a specified time interval. Considering the forecast as a range of possible outcomes within a time interval supports in defeating the issue coming with the idea of point verification. Averaging the observed value within time interval exhibits more noise since the forecast of winds the worst forecasted condition within a time interval and it can occur at any time within the interval. The accuracy is determined basing on the operationally desired accuracy of forecast as contained in the appendix B (ICAO Annex3, 2010).

1.2 Statement of Problem

High intense winds cause flight diversions, delays and flight cancellations which has great economic implications to the aviation operators and based on the available literature that I have reviewed the accuracy and the skill of the wind condition forecasts produced for Jomo Kenyatta International Airport has not yet being verified.

1.3 Research Objectives

The overall objective of this research is to verify the surface wind speed and direction forecast at Jomo Kenyatta International Airport. The specific objectives include to:

- **I.** Assess the temporal variations of surface wind speed and direction at JKIA
- **II.** Assess the accuracy of surface wind speed and direction forecast at Jomo Kenyatta International Airport
- **III.** Determine the skill of forecast of surface wind speed and direction at JKIA

1.4 Research Questions

a) How is the temporal variation of the surface winds at JKIA?

b) What is the accuracy of wind speed and direction forecasts for Jomo Kenyatta International Airport?

c) What is the skill for forecasting wind speed and direction at Jomo Kenyatta International Airport?

1.5 Justification

In Kenya, the tourism sector is heavily dependent on air transport, hence a major contributor of the economy, In the aviation industry, adverse weather contributes to delays in the arrival and the departure of the aircraft, Since wind shear has a significant effect during take-off and landing on aircraft due to its effect on control of the aircraft (Kirishnamurti;2003). Therefore, there is a need of wind speed and direction forecast verification so as to ensure the accuracy and the skill of the forecast.

1.6 Hypothesis

H_0: The wind forecasts produced for Jomo Kenyatta International Airport does not meet the required quality.

H_1: The wind forecasts produced for Jomo Kenyatta International Airport meets the required quality.

1.7 Study Area

The section below presents some brief discussions about the study area.

1.7.1 Location

This study is conducted at Jomo Kenyatta International Airport in Nairobi which is the busiest airport in Kenya. The airport has an ICAO code of HKJK and it is neighbored by the industrial area to the north. It is situated on latitude 01^0 19’S and longitude 36^0 55’E and has an elevation of 1624m above sea level with standard pressure of 840MB at 0600Z. The airport has a single runway alignment in 060^0-240^0 direction and measuring 4,117m in length.

Figure 1: Map of the study Area (Courtesy of Google)

1.7.2 Topography

The airport is located on flat land, adjacent to Nairobi, the airport is surrounded by high ground areas. Table 1. below indicates the position of the high ground zones in the area of study.

Table 1: High ground areas surrounding JKIA (KAA, Aeronautical Information Publication)

NAME OF PEAK	DISTANCE FROM AIRPORT (NM)	ELEVATION (ft)	LONGITUDE	LATITUDE
Ngong hills	18	8074	36^0 37’ 59’’ E	01^0 26’ 03’’ S
Ol Donyo Sabuk	23	7041	37^0 15’ 03’’ E	01^0 08’ 02’’ S
Mua hills	20	6800	37^0 11’51’’ E	01^0 2816 S
Kiima Kimwe	22	6970	37^0 14’16’’ E	01^0 31’58’’ S
Kerita	25	8569	36^0 40’50’’ E	00^{0}58’ 54’’ S
JKIA		5330	036^0 55’39’’ E	01^0 19’ 09’’S

1.7.3 Climatology

Nairobi climate is determined by the position and annual movement of the ITCZ. There are two rain seasons throughout the year, the long rain season from March to May (MAM) and the short rain season from October to December (OND). The two rain seasons occur during the monsoon transition periods. The region has a mean annual rainfall of 762mm and a mean of 27 thunderstorm days in a year (Muiruri, 2011) and the standard level pressure is 844mb.

CHAPTER TWO: LITERATURE REVIEW

2.0 Literature

Wind formation phenomenon is well known as caused by uneven heating/warming of atmospheric air by the sun, forming a 'void' that makes a pressure drop. Direct sun rays reaching the equatorial region make it hotter, causing the hot air to rise, move and settle in the cooler regions in the northern and southern hemispheres, whereas the cold air moves under it to occupy the void left. Wind formation has additionally been attributed to the 'Coriolis' effect caused by the rotation of the planet (earth), shifting the space objects to the right in the northern hemisphere and to the left in the southern hemisphere (Boyle, 1996).

The most common weather citations for aviation accidents are wind, visibility, low ceiling, and high-density altitude, respectively (FAA, 2010). Also, Fultz and Ashley (2016) in a study of Fatal weather-related general aviation accidents in the US demonstrated that the wind was the most commonly cited weather hazard, which was associated with 8,809 of the weather-related accidents from 1982 through 2013.

Weather, specifically the wind speed and direction is typically the main variable to control which runways to use at an airport, in which direction aircraft will take off and land and which flight route will be used. Aircraft should take off and land into the wind or with nominal tail wind. this implies current and forecast wind direction dictates the choice of runway/s in use at any time. Wind direction can change with short notice and this could have an effect on the flight paths and runways used. Wind blowing across the runway is named a cross wind. Generally, aircraft will take off or land the runways which has a low cross wind, typically up to a speed of about 15knots (28 km/h). Cross winds which exceeds that speed could force an aircraft to use another runway or divert to an alternate airport.

Headwinds and crosswinds at the surface determine the possibility of use for a specified runway. Surface winds may determine the possibility of a certain air traffic control operational procedures such as Land and Hold Short Operations (LAHSO). Surface headwinds can also have an effect on the ground speed of aircraft on final approach, which is closely related to the attainable arrival rate. Surface wind impacts may be intensified by adverse ceiling and visibility conditions (DeLaura, *et al*, 2014).

Excessive wind speeds (up to 15 knots) and/or vertical wind shear aloft are currently not considered in making the choice of runway configuration. In fact, planners have restricted access to data about winds aloft. However, adverse winds aloft can cause the Airport Acceptance Rate (AAR) to decrease due to the increased difficulty of merging arrival traffic streams and sustaining acceptable ground speeds and spacing as aircraft descend and change heading through strong or varying winds. Especially, winds aloft may introduce in compression, in which the spacing between the arriving aircraft decreases rapidly as they descend to final approach (Delaura, *et al*, 2014). Compression arises when headwinds increase significantly along the arrival trajectory, causing the lead aircraft ground speed to decrease much faster than the ground speed of the following aircraft. The greater than expected difference in ground speed between lead and following aircraft results in a reduction in aircraft spacing that can make it tough for controllers to satisfy the required aircraft separation. High winds aloft may also result in abnormally high or low aircraft ground speeds, which may make it hard to increase or decrease efficiently to the desired ground speed on final approach.

Wind speed and direction forecasting is of interest in the aviation industry as wind speeds have an effect on to a larger extent aircraft safety during landings and take offs. This prompts for forecasting or rather 'nowcasting' and communicating the outcomes to the flight crew from a range of a couple of minutes to a number of days into the future (Nicolus, 2012). Adams *et al*., (2004) demonstrated that the viable profits per year of improved non-convective weather forecasts could sum to $600M. Another study by NavCanada (2002) showed that a Terminal aerodrome forecast (TAF) whose precision is 100% at a Canadian airport would provide $12.5M per year. Gruenigan *et al*., (2014) exhibited 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 Tailwind and headwind component

A tailwind refers to wind that blows towards the direction of travel. With regard to the tail winds, many aircrafts have a tailwind maximum of 15knots. However not all operators are permitted to carry out take-offs or landings with tailwind component greater than 10 knots (Van, 2001).

Table 2 below shows the thresholds allowed for safe operations of a sample of some aircraft types under dry runway conditions. For wet runway and contaminated runway, the thresholds decrease since runway braking conditions tend to lower.

Table 2: Aircraft type and 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 stream on an aircraft is crucial to flight safety and performance. Headwinds during landing help decrease the ground speed of aircrafts while at take-off they provide lift giving an aircraft a steeper gradient which is valuable in clearing obstacles. Tailwinds on the other hand will increase ground speeds on landing requiring longer runway lengths. Take-off in this case means the climb out gradient is gentle and not good for clearing obstacles (Van and Karwal, 2001). How well an aircraft responds to quick changes in wind shear and turbulence is reliant on the pilots' response to the perceived and actual conditions (Arkell, 2000). The pilot can adjust the aircrafts' power settings and or its approach (angle of attack or pitch). These adjustments 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 rises the power which in turn increases the indicated airspeed (IAS). This avoids 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 reduces the power otherwise the aircraft rises above the desired flight path or glide slope.

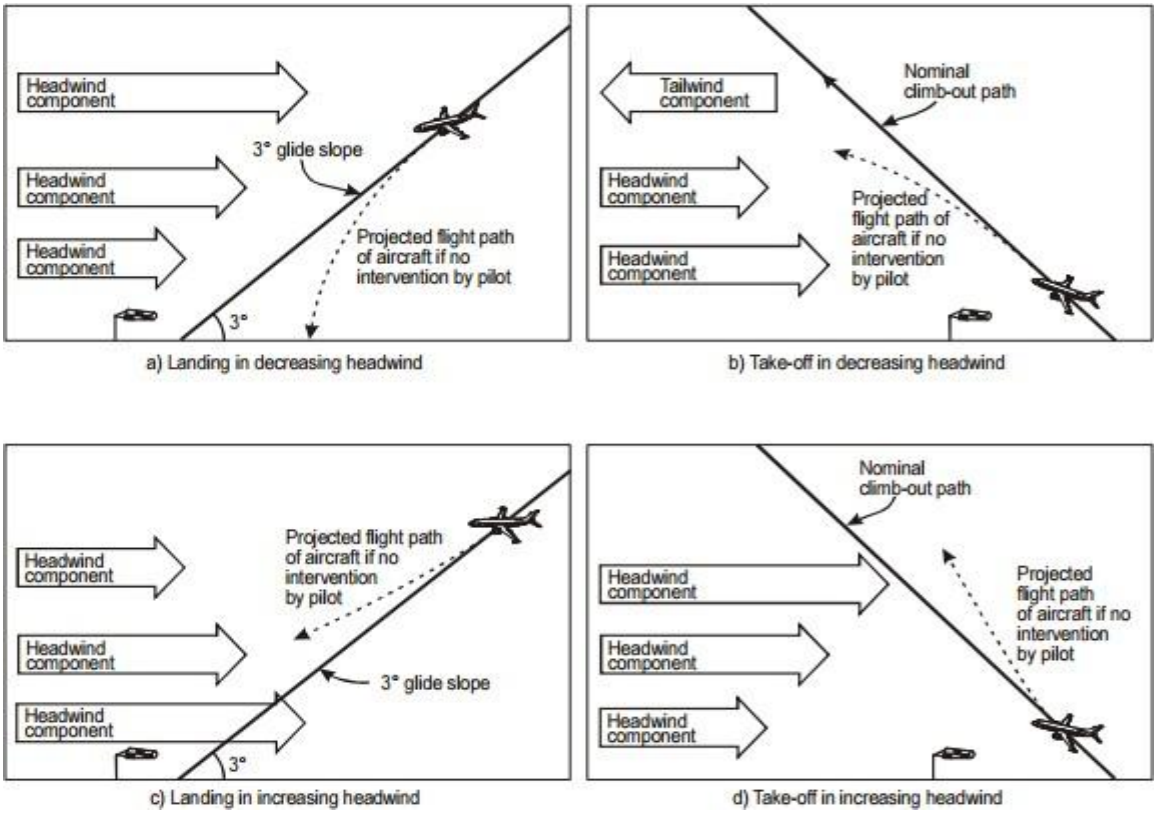

Figure 2: Effect of Head (Tail) wind shear on aircraft. (Source ICAO 2005)

2.2 Crosswind Component

A crosswind component is the wind that blows across the runway thus affecting the smooth landing of aircraft (Bellasio, 2014). Flight test experiments done by manufacture have established a maximum crosswind component for every aircraft which raises with airplane size. An allowable crosswind Component (ACC) during landing has been settled by the Federal Aviation Administration (FAA) and it is subject to the runway design code (FAA, 2012). The Runway Design Code (RDC) is comprised of a letter and a Roman numeral. The A to E letters identify with the approach speed of the aircraft sorted as A for low speed to E for high speed. The Roman numerals I to VI identify with the wingspan or tail height (I being small size up to VI large size). information on visibility is also incorporated in the RDC but it isn't considered in establishing the ACC. The ACC as function of RDC is appeared in Table 3.

Table 3: Allowable crosswind component per runway design code (FAA, Airport Design)

Runway design code	Allowable crosswind component, knots
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

Table 4: 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 fittingness of this basic method in classifying wind shear intensity isn't complete due to the following reasons:

a) Severity of the intensity of wind shear differs from one aircraft type to another therefore what is considered as extreme might be strong or moderate to another aircraft.

b) The wind shear impact on an aircraft is controlled by when the airplane is presented to the shear. This is a factor of distance within which wind shear is available and the speed at which the airplane is traveling through the wind shear condition.

c) A pilot thinks with regard of speed of the airplane 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 with these units when flying a 3-degree glide slope thus the wind shear units may not help the flight crew directly.

d) Thunderstorm related wind shear has all the 3 components of wind changing simultaneously making it the least secure and this change is not presented in Table 5.

CHAPTER THREE: DATA AND METHODOLOGY

3.0 Data and Methodology

This chapter presents the data and the methods which is used to achieve the overall and specific objectives of this study.

3.1 Data Sources

The data was collected from the METARs and TAFs obtained from the Jomo Kenyatta International Airport meteorological office. A METAR is a weather observation from ground level usually originating from an airport or permanent weather observation station, it stands for Meteorological Terminal Aviation Routine weather report or Meteorological Aerodrome Report. The Terminal Aerodrome report (TAF) is a concise statement of the expected meteorological conditions at an airport during a specified period (usually 24 hours). The data contains a period of 1 year from March 2019 to February 2019.

3.2 Method of Determining the Accuracy

To determine the accuracy of the forecast, the forecasted values of wind speed and direction extracted from the TAFs was checked alongside the observed values extracted from the METARs. The temporal variability of wind observations of an interval of 6 hours were plotted to determine the interval which there is high frequency of strong wind occurrences. The accuracy was determined basing on the operationally desired accuracy of forecasts as contained in the appendix B (ICAO Annex3, 2010). The accuracy at 1hr and 6hr lead times was measured by using Root Mean Square Error (RMSE) and Percentage Error (%Error) for the speed and direction respectively. The formula of both the RMSE and PE is as follows:

$$\textbf{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(Predicted_i - Actual_i)^2}{N}} \qquad \textbf{Equation 1}$$

$$\textbf{\%Error} = \sum_{i=1}^{N} \frac{|\, Predicted_i - Actual_i \,|}{Actual_i} \qquad \textbf{Equation 2}$$

3.3 Method of Determining the Skill

The surface wind speed was categorized into the following ranges

a) Light between 0-6 kt.

b) Moderate between 6-12 kt.

c) Strong above 12 kt.

These ranges are established based on the ICAO (2005) criteria of wind shear intensity. The category for light represents the wind conditions which has a speed of less than 6 Knots, occurrence of this category indicated by light may not lead to disruption to the flight schedules. The range indicated by moderate may or may not lead disturbance depend on the condition of the runway and the type of the aircraft. The category with Strong wind may lead to diversion, holding, and delays for some aircraft types, although some aircraft have been designed to maintain this range of wind speed but most of the aircrafts based on JKIA does not have the capability to avoid this type of strong winds especially if there is a wind shear, hence affecting the flight schedule.

Wind speed is verified using contingency tables. In accordance with ICAO Annex 3, Appendix 5. The contingency table can be used to draw conclusions regarding the forecast quality from the verification process. It is the best way of evaluating the type of errors being made by the forecaster. A perfect forecast would produce only hits and correct negative events only. The accuracy of wind speed and direction forecasts from TAFs were checked alongside the observed values from METARs and based on the ranges discussed above. A 3-category contingency table was created as shown in table 5.

Table 5: Three category contingency table

		OBSERVED			
		Light	Moderate	Strong	Total
FORECAST	Light	A	b	c	M
	Moderate	D	e	f	N
	Strong	G	h	i	O
	Total	J	K	L	T

A contingency table is basically a display format used to analyze and record the relationship between two or more categorical variables and determine the forecasting skill by calculating various skill scores including the following:

a) **Hit Rate or Percentage of Detection (POD)**: The Hit Rate is the fraction of observed events that is forecast correctly. It is calculated as follows:

$$\textbf{POD} = \frac{\mathbf{a}}{\mathbf{J}} \qquad \textbf{Equation 3}$$

It ranges from zero (0) at the poor end to one (1) at the good end.

b) **False Alarm Ratio:** is the fraction of "yes" forecasts that were wrong, i.e., were false alarms. It is calculated as follows:

$$\textbf{FAR} = \frac{\mathbf{b+c}}{\mathbf{M}} \qquad \textbf{Equation 4}$$

It ranges from zero (0) at the good end to one (1) at the poor end.

c) **The Threat Score (TS) or Critical Success Index (CSI):** combines Hit Rate and False Alarm Ratio into one score for low frequency events. It is calculated as follows:

$$\textbf{CSI} = \frac{\boldsymbol{a}}{\mathbf{JM}} \qquad \textbf{Equation 5}$$

This score ranges from zero (0) at the poor end to one (1) at the good end. It does not consider "not forecast/not occurred" (d) events.

d) **BIAS**: Bias compares the number of times an event was forecast to the number of times an event was observed. Specifically,

$$\textbf{BIAS} = \frac{\mathbf{M}}{\mathbf{J}} \qquad \textbf{Equation 6}$$

i. If BIAS = 1 (unbiased), the event was forecast the same number of times that it was observed
ii. If BIAS >1 (over forecast), the event was forecast more than it was observed
iii. If BIAS < 1 (under forecast), the event was forecast less than it was observed.

e) **Heidke skill Score (HSS):** HSS skill score shows the accuracy of the forecast relative to that of random chance. It ranges from -∞ at the poor end to 1 at the good end. This skill score measures the fraction of correct forecast after removing the forecasts which would be correct due purely to random chance. The HSS can be determined by applying the formula below.

$$\textbf{HSS}= \frac{\mathrm{a}+e+i-\frac{JM+KN+LO}{T}}{T-\frac{JM+KN+LO}{T}} \qquad \textbf{Equation 7}$$

f) **Pierce skill score/ Hanssen and Kuipers discriminant (HK):** HK skill score indicates how well the forecast is separated the yes events from the no events, it ranges from -1 to 1. With the perfect score being 1. This score does not depend on climatological event frequency. For rare events the score is unduly weighted hence more useful for more frequent events and it is determined by the following formula

$$\textbf{HK} = \frac{a}{J} - \frac{b}{K} + \frac{c}{L} \qquad \textbf{Equation 8}$$

For the wind direction, a 4 category contingency tables were generated based on the four cardinal directions north, east, south and west to analyze the skill of the forecast. Then a similar method and skill scores were used to assess the skill of forecasting the wind direction.

CHAPTER FOUR: RESULTS AND DISCUSSIONS

4.0 Results and Discussions

This chapter presents and discussions the results obtained from the methods described in chapter three to achieve the objectives outlined in section 1.4

4.1 Temporal Distribution of wind speed Observations at Jomo Kenyatta International Airport

The temporal variability of the wind speed observed at Jomo Kenyatta International Airport during the study period was plotted in this section.

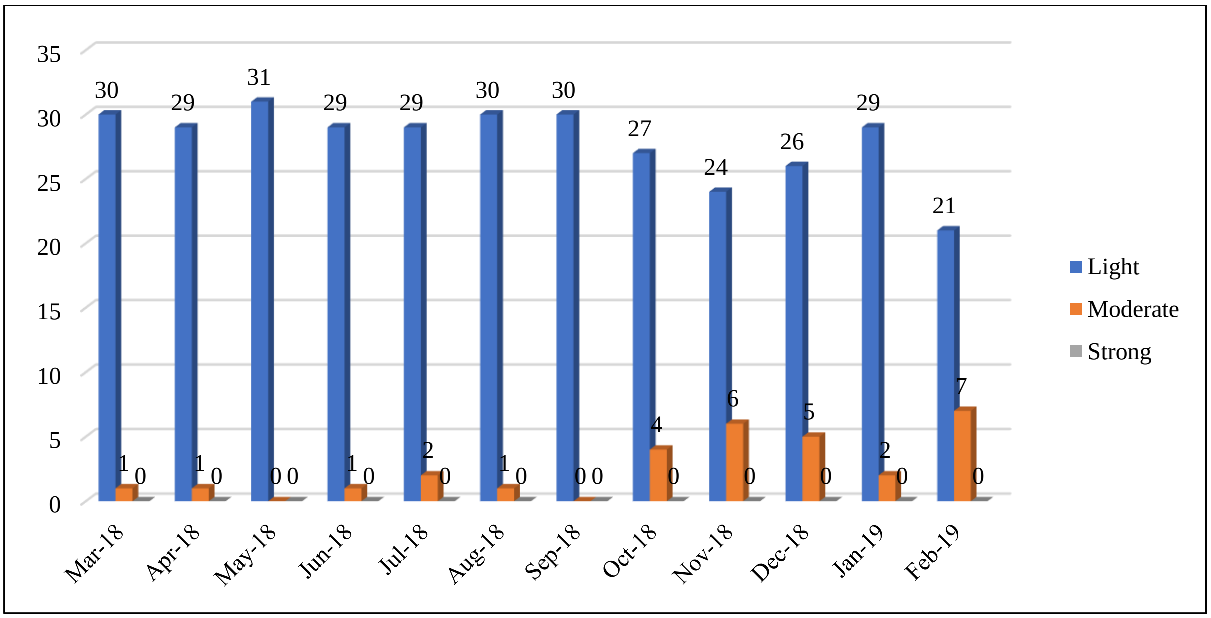

Figure 3: Wind speed observation between 00Z and 06Z

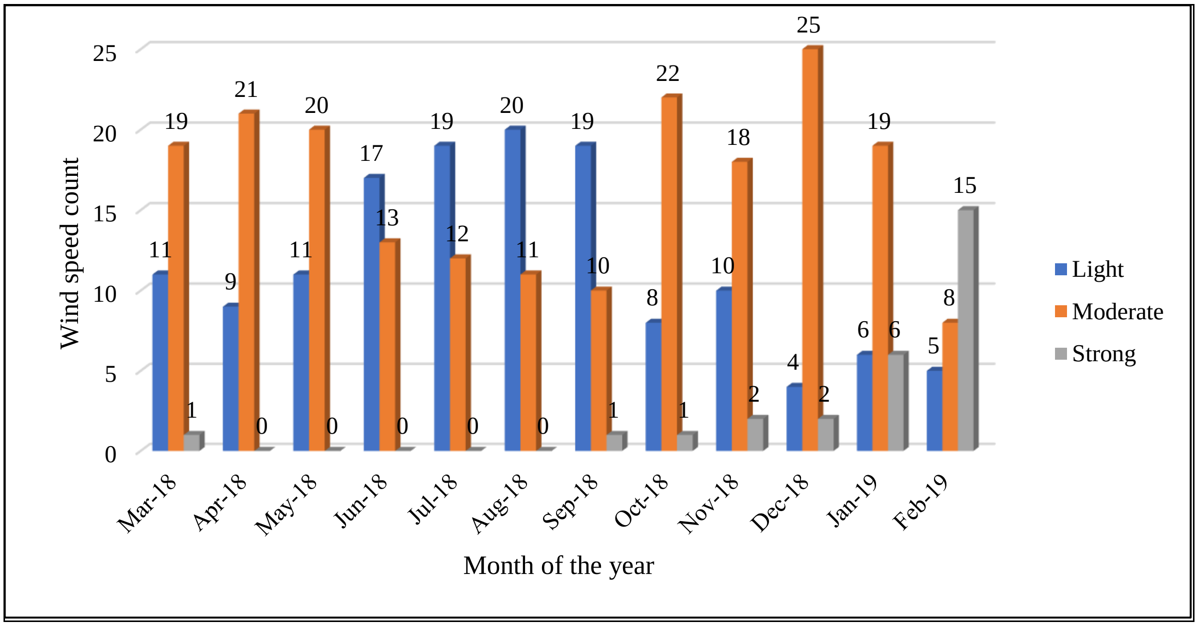

Figure 4: Wind speed observation between 00Z and 06Z

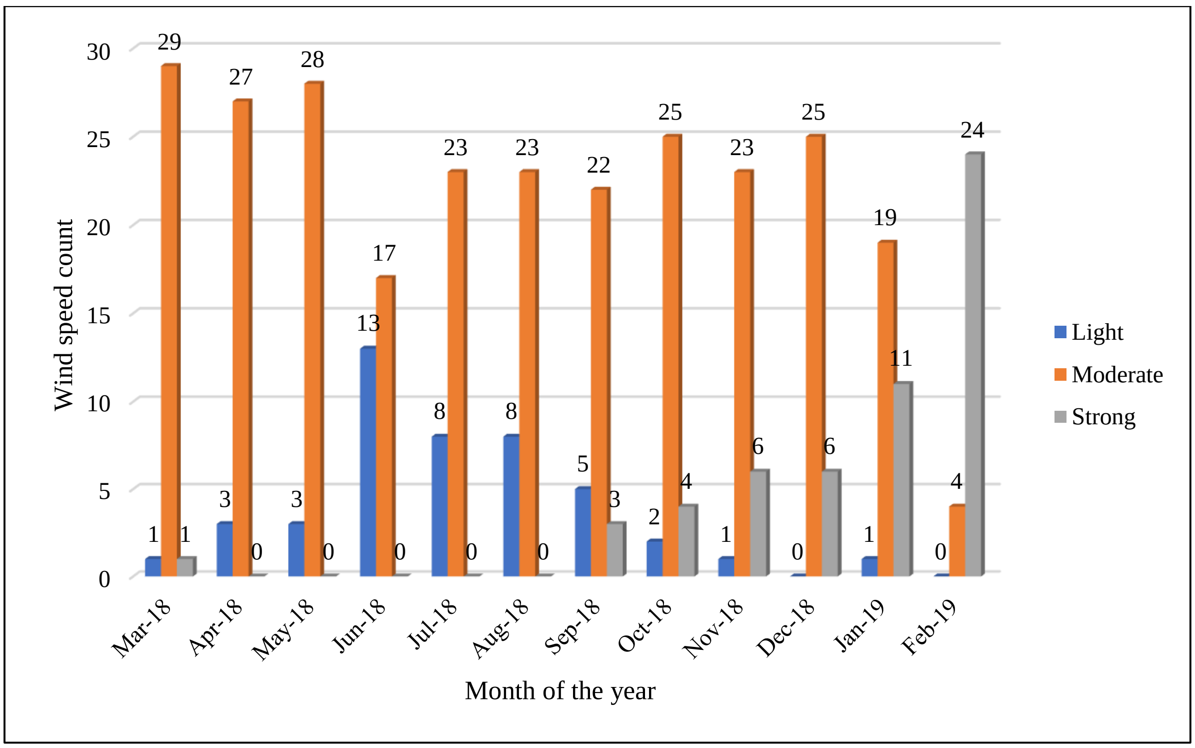

Figure 5: Wind speed observation between 12Z and 18Z

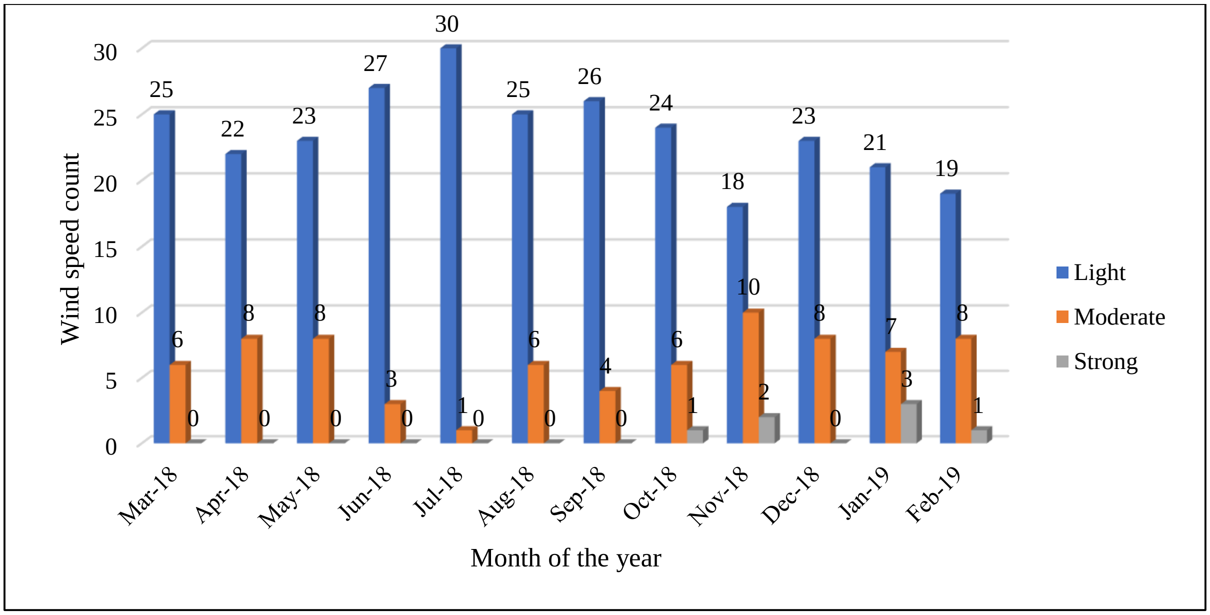

Figure 6: Wind speed observations between 18Z and 24Z

From figure 3, figure 4, figure 5 and figure 6, high frequency of strong wind occurrence was observed between 06Z and 12Z and again between 12Z and 18Z. The high frequency is generally attributed to the increase of the temperature as the sun's heating is the strongest during these periods which destabilizes the atmosphere and allows the cold strong winds moving above the surface to bring down. The strong winds are frequently observed during the months of September to February. The strong winds during this season is brought about by the fact that the SON season there is a short rain

4.2 Temporal distribution of wind speed and direction observations at Jomo Kenyatta International Airport

The temporal variation of wind speed and direction observed at JKIA was plotted, the wind speed was first categorized into three categories Light (1-6) knot, Moderate (7-12) knot and strong above 12 knots as described in section 3.3.

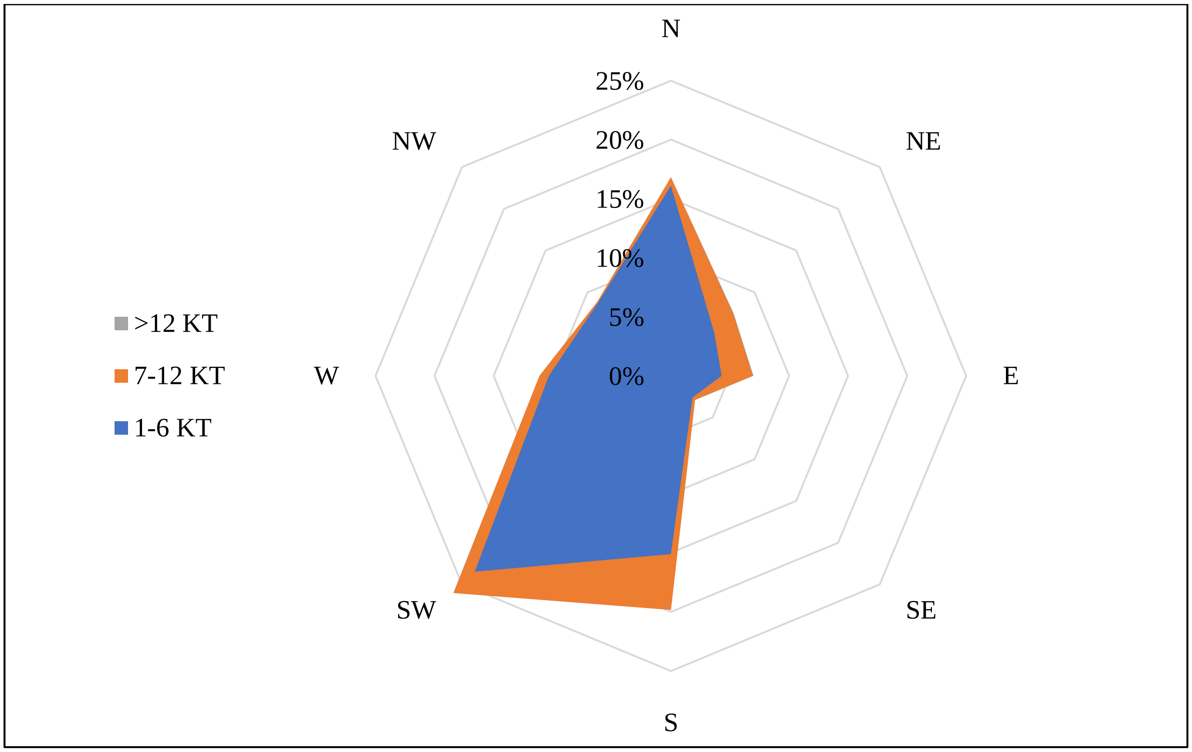

Figure 7: Wind rose between 00Z and 06Z

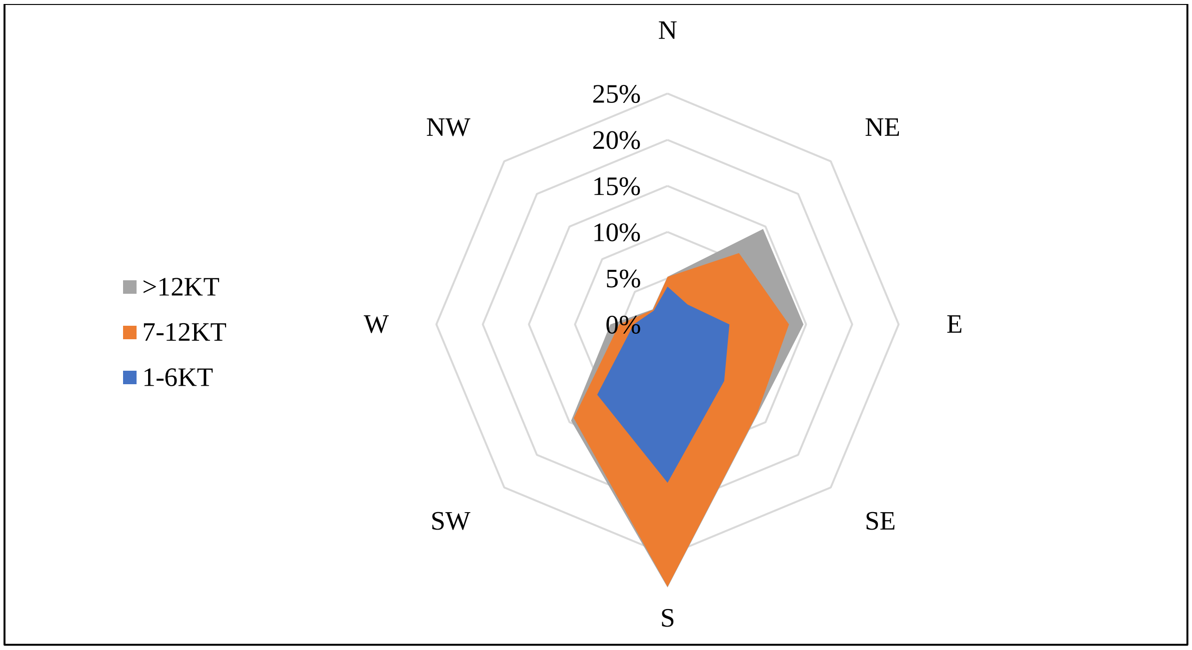

Figure 8: Wind rose between 06 to 12Z

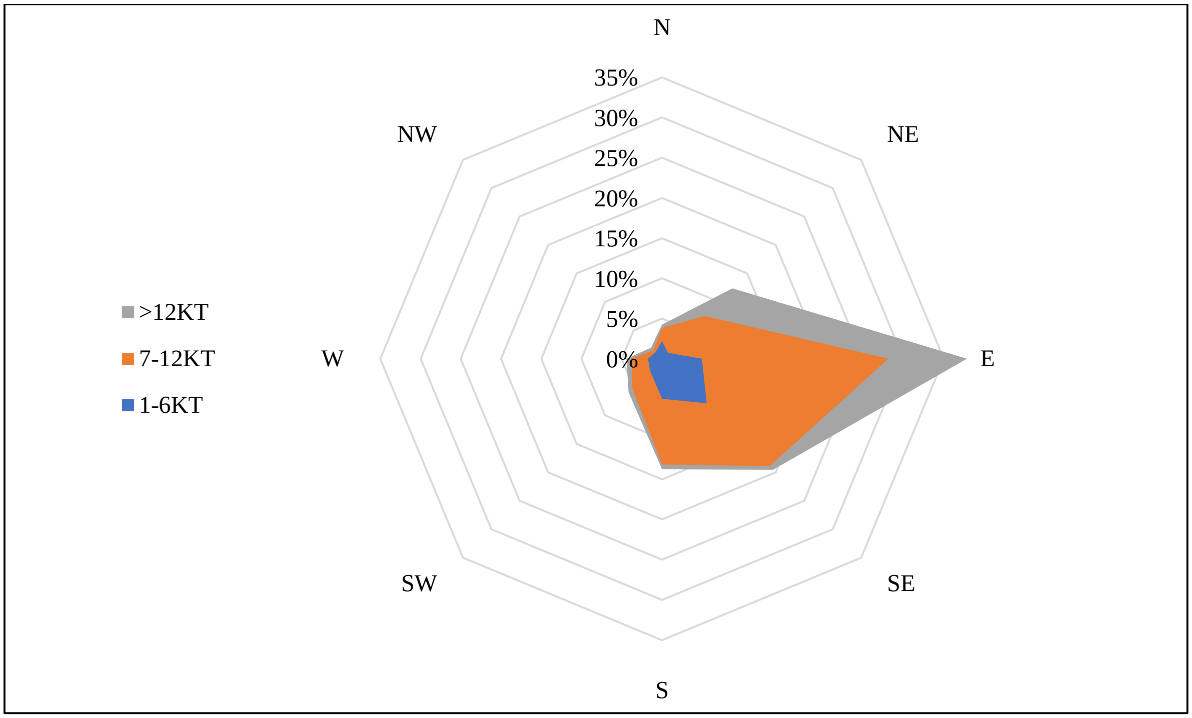

Figure 9:Wind rose between 12 to 18Z

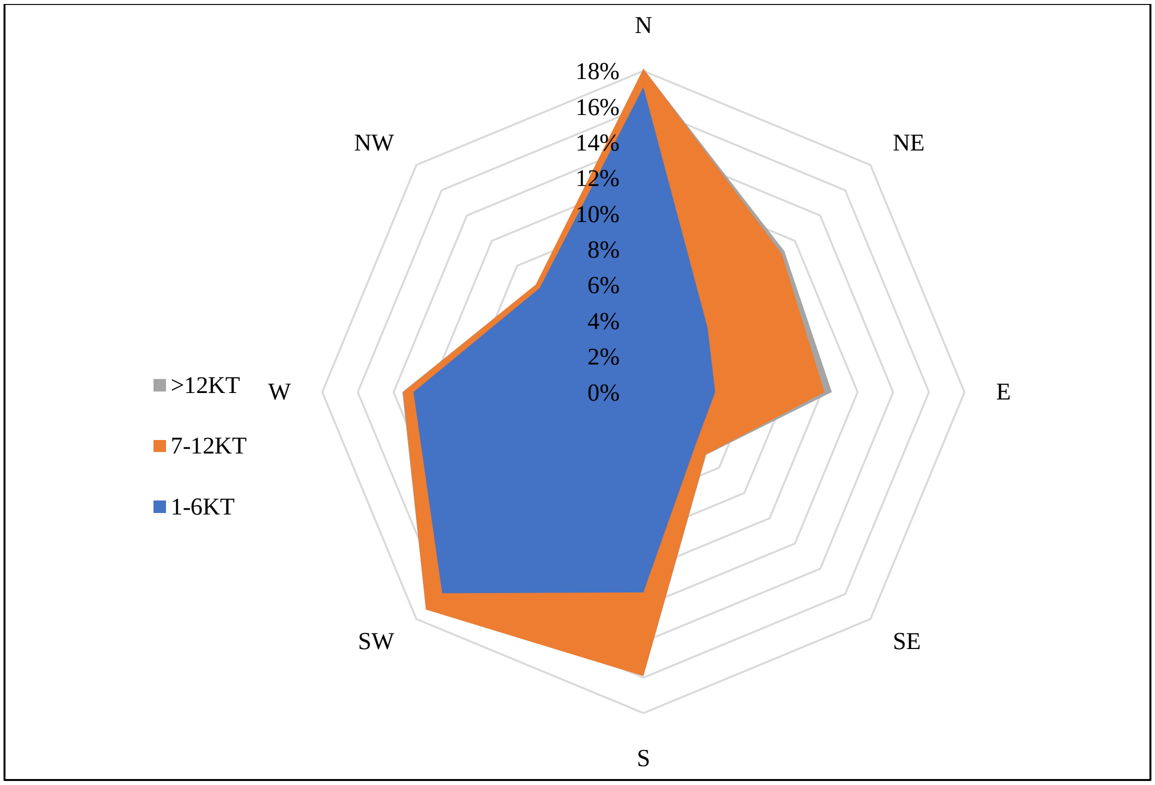

Figure 10: Wind rose between 18 to 24Z

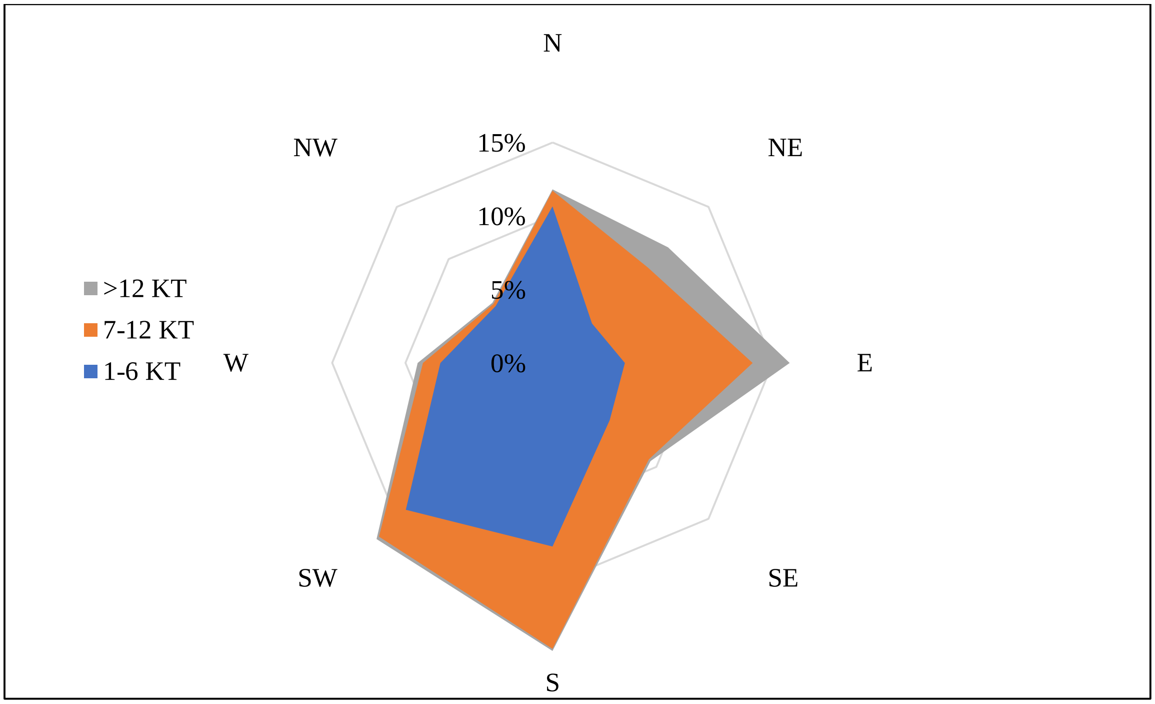

Figure 11: General Wind rose at JKIA

From figure 7, between 00Z and 06Z, the wind is coming from different directions mostly from South West followed by South and North and the most common wind speed is the light winds between 1 to 6 knots, there is no occurrence of strong winds during this period. Between 06Z and 12Z, the wind is dominantly coming from South and the most common wind speed is the moderate winds between 7 to 12 knots followed by light winds between 1 to 6 knots, there is some instances of strong wind occurrences as shown in figure 8 above.

Figure 9 shows that between 12Z and 18Z, the wind is dominantly coming from East and the most common wind speed is the moderate winds between 7 to 12 knots followed by strong winds above 12 knots, there is high frequency of strong wind occurrences during this period.

Between 18Z and 24Z, the wind is mostly coming from a variety of directions due to high frequency of light wind occurrences and also there is no instance of strong wind occurrence as shown in figure 10 above.

From figure 11 above, generally the wind is mostly coming from South followed by East and the most common wind speed is the moderate between (7-12kt) followed by Light winds between (1-6kt).

4.3 Accuracy of Wind speed forecasts

The wind speed forecast values and observed values were plotted on scatter plot to show the relationship between the forecasted and the observed values. The scatter plot was generated for forecasts and observations between 06 to 12Z and 12Z to 18Z since this is the range with many instances of strong winds as shown in part 4.1 above.

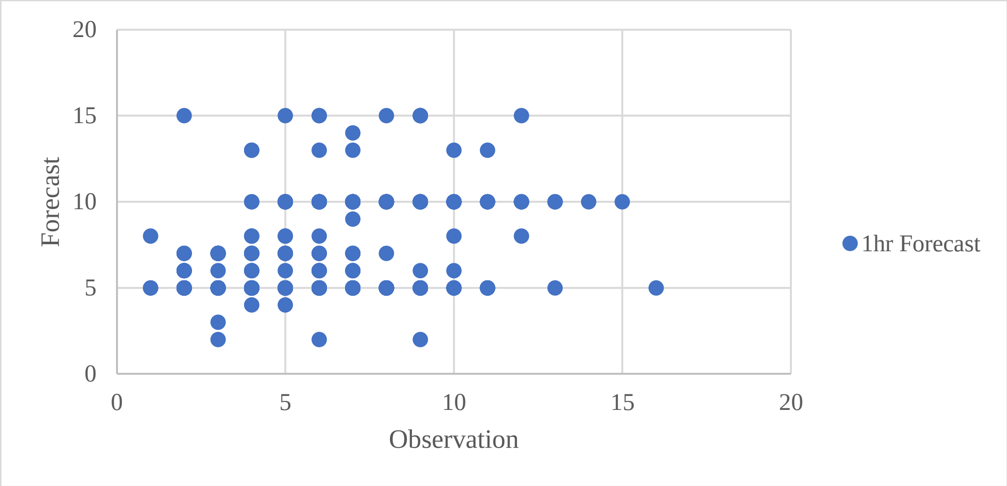

Figure 12: Scatter plot for 06Z at 1hr lead time

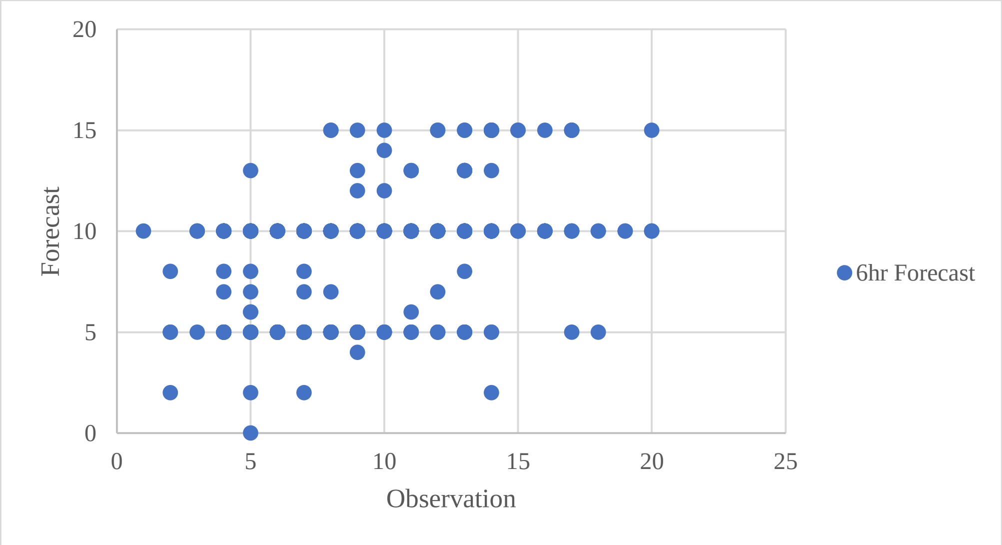

Figure 13: Scatter plot for 06Z at 6hr lead time

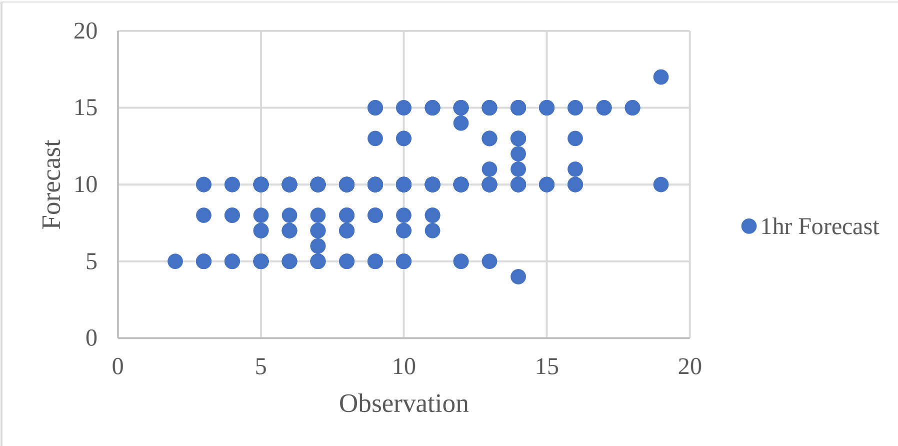

Figure 14: Scatter plot for 12Z at 1hr lead time

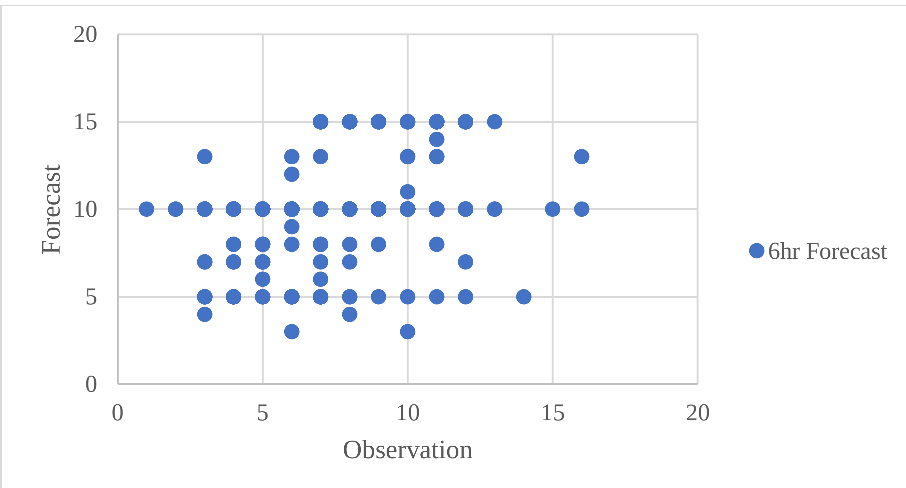

Figure 15: Scatter plot for 12Z at 6hr lead time

From figure 11 to figure 14, the scatter plots for 1hr lead time shows that most of the cases the wind speed was correctly forecasted as compared that for 6hr lead time, implying that at 1hr lead time the forecasts were correct compared to the forecasts at 6hr lead time.

While calculating the accuracy of wind speed forecasts, the observations and forecasts with a deviation of 5 knots were considered accurate. The accuracy calculations using the Root Mean Square Error was determined for 1hr and 6hr lead times respectively. The results are shown in the table 6 below.

Table 6: **Root mean Square Error**

Time (Z)	**Lead time**	**RMSE**
0600	One hour	2.607
0600	Six hour	2.808
1200	One hour	1.413
1200	Six hour	2.887

The RMSE for the One-hour lead time is low compared with the RMSE for the six-hour lead time. The wind speed forecasts should be utilized with urgency after being generated by the forecast since they are more accurate when compared with six hours later after being generated by the forecast. The wind speed forecast accuracy decreases with increase in lead time. The accuracy decrease could be due to abrupt occurrence of phenomena that effects the wind and lack of sufficient forecasting tools to forecast such phenomena.

4.4 Accuracy of wind direction forecasts

While calculating the accuracy, the wind direction is considered accurate if any one or more of the follows holds:

a) The observed wind direction deviates not more than 60 degrees from the forecast

b) the forecast and observed wind speeds are less than or equal to 6 kt, regardless of the observed wind direction.

The wind direction forecast values and observed values were compared and the percentage error was calculated for both one hour and Six-hour lead times at each interval. Table 7 below shows the percentage error values of each interval.

Table 7: Percentage error

Time	Lead time	Percentage Error
0000Z	One Hour	2%
	Six Hour	8%
0600Z	One Hour	4%
	Six Hour	16%
1200Z	One Hour	8%
	Six Hour	17%
1800Z	One Hour	8%
	Six Hour	6%

From table 7, One-hour lead time forecasts shows more accuracy as compared to the Six hour lead time except the interval between 1800Z and 2400Z, this is because the wind is becoming light as the lead time increases during this period which increases the accuracy since the direction is considered accurate if the speed is less than 6knots.

4.5 Contingency table analysis for the wind speed

By considering wind speed forecast categories mentioned in section 3.3, a 3-category contingency table was generated for one hour and six-hour lead time. The contingency tables were first categorized considering the time at which the forecasts were produced for example 0000-0600, 0600-1200, 1200-1800 and 1800-0000, and later a general contingency table was built for one-hour and six- The accuracy at 1hr and 6hr lead times was calculated by using Root Mean Square The accuracy at 1hr and 6hr lead times was calculated by using Root Mean Squarehour lead time incorporating the above time intervals.

4.5.1 Contingency tables analysis for 1200Z to 1800Z forecasts

The contingency table for forecasts generated at 1200Z, were developed both for One hour and six-hour lead times as shown in table 8 and 9 below:

Table 8: 1hr lead time

		OBSERVED			
		Strong	**Moderate**	**Light**	**Total**
FORECASTED	**Strong**	38	20	0	58
	Moderate	33	166	61	260
	Light	2	20	25	47
	Total	73	206	86	365

Table 9: 6hr lead time

		OBSERVED			
		Strong	**Moderate**	**Light**	**Total**
FORECASTED	**Strong**	5	46	3	54
	Moderate	12	188	73	273
	Light	0	21	17	38
	Total	17	255	93	365

From the tables 8 and 9, the 1hr lead time shows higher number of correct forecasts for strong winds as compared to forecasts at 6hr lead time. From the two tables skill scores were calculated for the two lead times as shown in the table and graphed as shown below.

Table 10: Skill scores for 12Z-18Z forecasts

	1hr Lead time	6hr Lead time
P.C	0.627	0.575
FAR	0.00	0.044
HSS	0.305	0.044
HK	0.452	-0.035

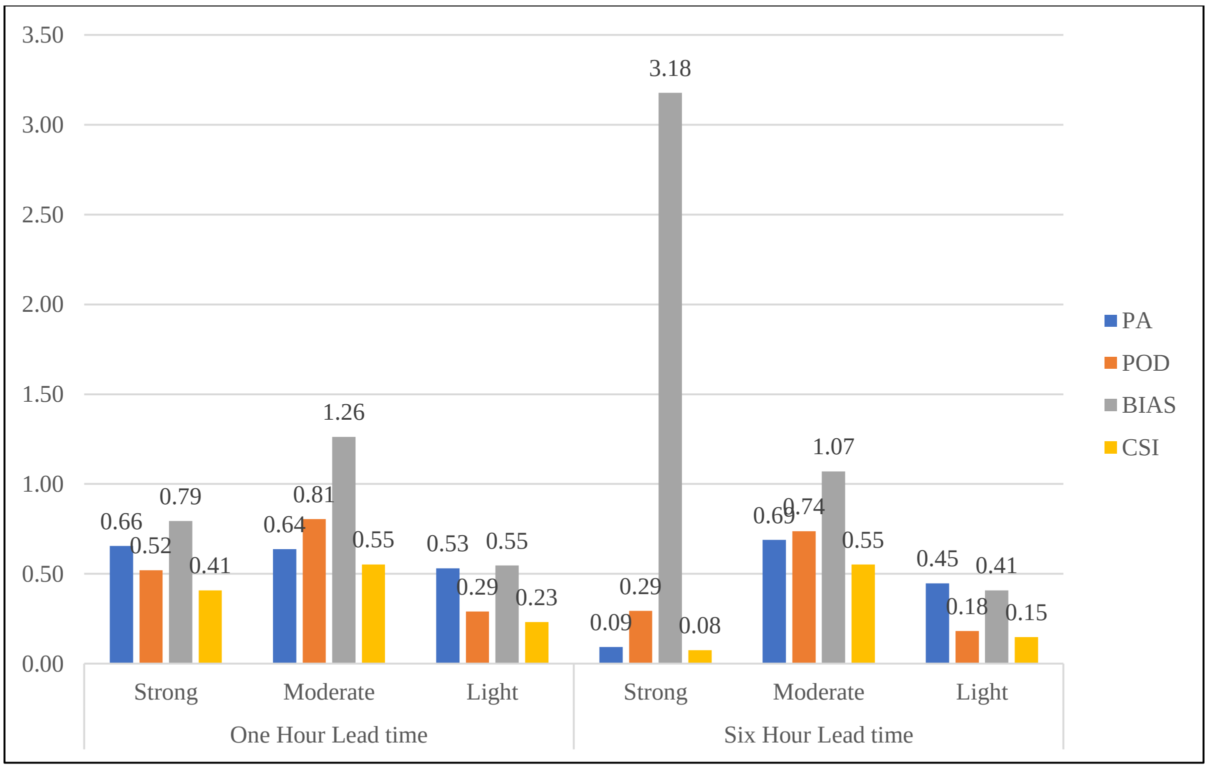

Figure 16: Forecast skill scores for 12Z to 18Z

From Figure 15 above, generally the skill scores are high for 1hr lead time as opposed to the 6hr lead time. The skill scores of strong winds were higher for 1hr lead time as compared to 6hr lead time. In all cases the probability of detection for the moderate wind is very high due to high frequency of occurrences of moderate winds during this period. The Strong winds are over-forecasted at 6hr lead time since the bias of strong winds is high on 6hr lead time.

4.5.2 Contingency tables analysis for 18Z-24Z, 00Z to 06Z and 06Z to 12Z forecasts

4.5.2.1 Contingency tables analysis for 18Z-24Z

Table 11: 1hr lead time

		OBSERVED			
		Strong	**Moderate**	**Light**	**Total**
FORECASTED	**Strong**	2	9	0	11
	Moderate	2	88	41	131
	Light	4	99	120	223
	Total	8	196	161	365

Table 12: 6hr lead time

		OBSERVED			
		Strong	**Moderate**	**Light**	**Total**
FORECASTED	**Strong**	0	1	3	4
	Moderate	0	15	40	55
	Light	1	67	238	306
	Total	1	83	281	365

From the tables 11 and 12, there were a few instances of strong winds with 1hr lead time showing hits while at 6hr lead time the same was missed. Six-hour lead time is showing a very high FAR as compared to one-hour lead time.

4.5.2.2 Contingency tables analysis for 00Z-06Z

Table 13: 1hr lead time

		OBSERVED			
		Strong	**Moderate**	**Light**	**Total**
FORECASTED	**Strong**	0	0	0	0
	Moderate	0	18	7	25
	Light	0	71	269	340
	Total	0	89	276	365

Table 14: 6hr lead time

		OBSERVED			
		Strong	**Moderate**	**Light**	**Total**
FORECASTED	**Strong**	0	0	1	1
	Moderate	1	16	13	30
	Light	2	80	252	334
	Total	3	96	266	365

From table 13 and 14, there is no instances of strong wind occurrences at 1hr lead time, while at 6hr lead time there is few instances of strong wind occurrences which we have missed therefore, at 1hr lead time we have correctly forecasted the strong winds as compared to 6hr lead time.

4.5.2.3 Contingency tables analysis for 06Z-126Z

Table 15: 1hr lead time

		OBSERVED			
		Strong	**Moderate**	**Light**	**Total**
FORECASTED	**Strong**	0	10	8	18
	Moderate	5	63	70	138
	Light	2	60	147	209
	Total	7	133	225	365

Table 16: 6hr lead time

		OBSERVED			
		Strong	**Moderate**	**Light**	**Total**
FORECASTED	**Strong**	18	14	1	33
	Moderate	37	106	73	216
	Light	6	56	54	116
	Total	61	176	128	365

From table 15 and 16, there is high frequency of strong wind occurrences at six hour lead time as compared to one hour lead time with the 1hr lead time forecasts showing higher percentage correct compared to the Six hour lead time.

4.5.2.4 Percentage Correct for 18-24Z, 00-06Z and 06-12Z

Table 17: Percentage correct for 18-24Z, 00-06Z and 06-12Z

Time	1hr lead time	6hr lead time
1800-2400	0.575	0.693
0000-0600	0.786	0.734
0600-1200	0.575	0.556

Although the scores are higher both for One hour and Six hour lead time, One hour lead time shower a higher percentage correct as compared to the six hour lead time except the interval between 18Z and 24Z and this is due to that the wind speed is decreasing with the lead time during this period.

4.5.3 General Contingency table Analysis

A contingency table for the general forecasts were developed for both One hour and six-hour lead times as shown in the table 18 and 19

Table 18: 1hr lead time

		OBSERVED			
		Strong	**Moderate**	**Light**	**Total**
FORECASTED	**Strong**	40	39	8	87
	Moderate	40	335	179	554
	Light	8	250	561	819
	Total	88	624	748	365

Table 19: 6hr lead time

		OBSERVED			
		Strong	**Moderate**	**Light**	**Total**
	Strong	23	61	8	92
	Moderate	50	325	199	574
FORECASTED	**Light**	9	224	561	794
	Total	82	610	768	365

From table 18 and 19, 1hr lead time shows higher number of correct forecasts for strong winds as compared to forecasts at 6hr lead time. The instances of strong winds were in most instances correctly forecasted at 1hour lead time than at 6hr lead time. From the generalized contingency tables, the following skill scores were calculated for the two lead times as shown in the table and graph shown below.

Table 20: Skill scores from the generalized contingency table

	1hr Lead time	**6hr Lead time**
P.C	0.641	0.622
FAR	0.540	0.750
HSS	0.344	0.308
HK	0.420	0.230

From Table 20 above, the skill scores are high for the 1hr lead time as opposed to the 6hr lead time. 1hr lead time shows low FAR as opposed to 6hr lead time which is high. There were more correct forecasts at 1hour lead time than the 6hr lead time hence the higher score for P.C, HSS and HK and lower score for FAR.

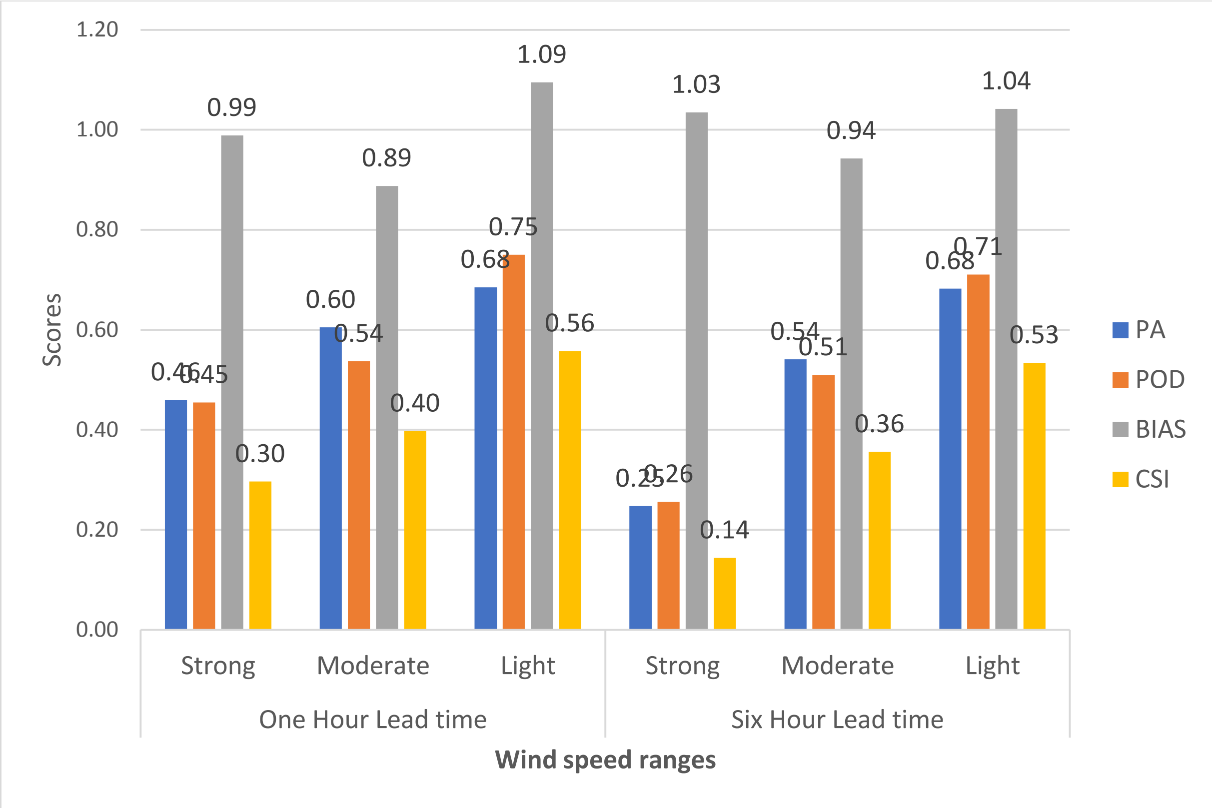

Figure 17: General Forecast skill scores

From the figure 16 above, the skill scores like P.C, HSS, HK, PA, POD and CSI related to 1hr lead time are higher as compared to the same for 6hr lead time. The FAR at 1hr lead time is lower as compared to that for 6hr lead time. The scores related to instances of strong winds are lower as opposed to those with light or moderate winds, this is an indication that the forecasters are challenged when it comes to forecasting stronger winds as opposed to forecasting Moderate and Light winds.

It is easier to forecast light winds through persistence evidenced by high scores for light winds. The number of correct forecasts at 1hr lead time is higher as compared to the same at 6hr lead time.

4.6 Contingency table analysis for the wind direction

The wind direction was divided into the four cardinal directions: north, south, east, and west. by considering these wind directions discussed above, a 4- category contingency table was developed for One hour and six-hour lead time. The contingency tables were first categorized depending on the time of the day at which the forecasts were generated i.e 0000-0600, 0600-1200, 1200-1800 and 1800-0600, and later a general contingency table was constructed for one hour and six hour lead time incorporating the above time intervals.

4.6.1 Wind direction contingency table analysis for 1200Z to 1800Z

The contingency table for forecasts generated at 1200Z, were developed both for One hour and six-hour lead times as shown in the tables 21 and 22 below.

Table 21: 1hr lead time

		OBSERVED				
		North	**East**	**South**	**West**	**TOTAL**
	North	4	15	1	0	20
	East	21	188	19	1	229
FORECASTED	**South**	1	30	68	6	105
	West	0	1	4	6	11
	TOTAL	26	234	92	13	365

Table 22: 6hr lead time

		OBSERVED				
		North	**East**	**South**	**West**	**TOTAL**
	North	6	10	1	1	18
	East	39	179	12	2	232
FORECASTED	**South**	5	58	34	3	100
	West	4	6	2	3	15
	TOTAL	54	253	49	9	365

From table 21 and table 22, the number of correct forecasts for one-hour lead time is higher than the number of correct forecasts at six-hour lead time. The direction of dominance (East) during this time is correctly forecasted at 1hour lead time as compared to the 6hour lead time. The skill scores of the above two tables are shown in the table and the graph below.

Table 23: Skill scores for 12Z-18Z forecasts

	1hr Lead time	**6hr Lead time**
P.C	0.73	0.61
FAR	0.18	0.23
HSS	0.48	0.23
HK	0.49	0.23

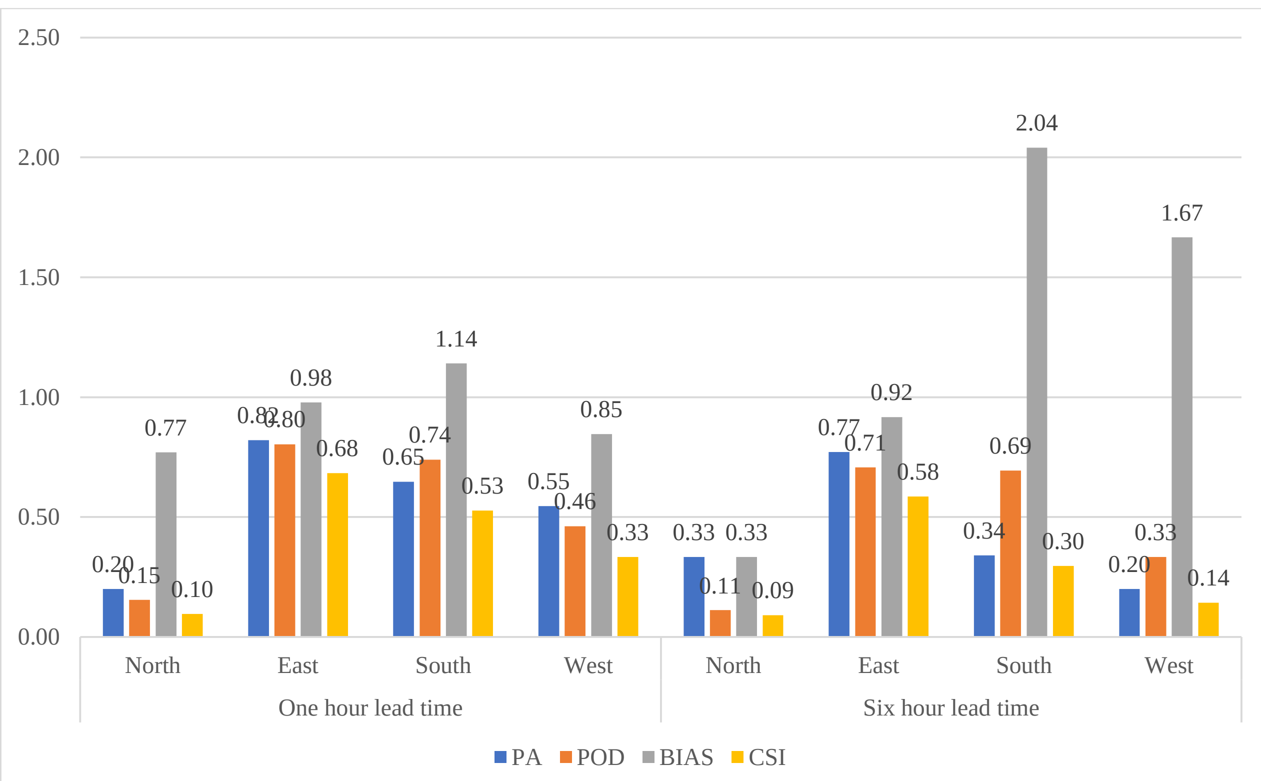

Figure 18: Forecast skill scores between 12Z and 18Z

From figure 17, generally the skill scores of the dominant wind direction (East) are high, although one-hour lead time shows higher skill scores than the six-hour lead time. The skill scores of the directions north and west are low due to less occurrences of wind blowing from that directions during this period.

4.6.2 Wind direction contingency table analysis for 18Z-24Z, 00Z-06Z and 06Z-12Z

In this section, the contingency table analysis for 18Z-24Z, 00Z-06Z and 06Z-12Z forecasts were presented considering one hour and six hour lead times.

4.6.2.1 Contingency table analysis for 18Z-24Z

Table 24: 1hr lead time

		OBSERVED				
		North	**East**	**South**	**West**	**TOTAL**
FORECASTED	**North**	57	68	4	2	131
	East	19	108	16	1	144
	South	7	18	38	3	66
	West	1	12	8	3	24
	TOTAL	84	206	66	9	365

Table 25: 6hr lead time

		OBSERVED				
		North	**East**	**South**	**West**	**TOTAL**
FORECASTED	**North**	106	47	12	17	182
	East	38	20	16	11	85
	South	8	6	25	18	57
	West	11	4	12	14	41
	TOTAL	163	77	65	60	365

From the tables 24 and 25, one-hour lead time shows more hits as compared to Six-hour lead time, thus higher percentage correct and HSS as shown in table 26 below.

Table 26: Percentage correct and HSS for 1800 to 2400Z

	1hr Lead time	**6hr Lead time**
P.C	0.564	0.452
HSS	0.340	0.196

4.6.2.2 Contingency table analysis for 00Z-06Z

Table 27: 1hr lead time

		OBSERVED				
		North	**East**	**South**	**West**	**TOTAL**
FORECASTED	**North**	113	48	12	9	182
	East	20	32	6	7	65
	South	10	7	46	19	82
	West	4	1	7	24	36
	TOTAL	147	88	71	59	365

Table 28: 6hr lead time

		OBSERVED				
		North	**East**	**South**	**West**	**TOTAL**
FORECASTED	**North**	72	61	13	16	162
	East	15	23	14	3	55
	South	9	16	63	24	112
	West	3	4	16	13	36
	TOTAL	99	104	106	56	365

Table 29: Skill scores for 00Z to 06Z

	1hr Lead time	6hr Lead time
P.C	0.589	0.468
HSS	0.410	0.274
HK	0.525	0.405

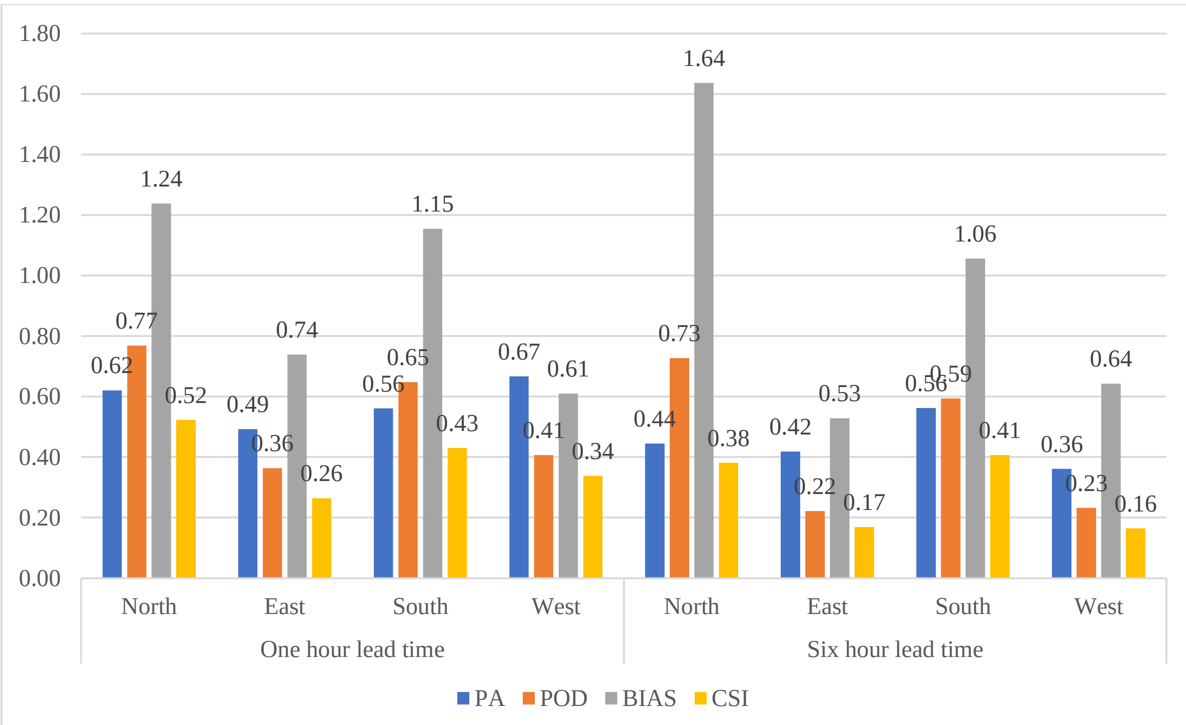

Figure 19:Forecast skill scores between 00Z and 06Z

One-hour lead time shows higher skill scores as compared to the six-hour lead time. The P.C, HSS, POD, HK, CSI and POD are all high at one-hour lead time as compared to the six-hour lead time as shown in Table 29 and Figure 18 above

4.6.2.3 Contingency table analysis for 06Z-12Z

Table 30: 1hr lead time

OBSERVED

		North	East	South	West	TOTAL
	North	27	23	2	2	54
	East	63	81	21	6	171
FORECAST	**South**	6	11	81	19	117
	West	1	2	12	8	23
	TOTAL	97	117	116	35	365

Table 31: 6hr lead time

OBSERVED

		North	East	South	West	TOTAL
	North	5	13	3	1	22
	East	30	150	26	5	211
FORECAST	**South**	7	33	75	3	118
	West	1	1	8	4	14
	TOTAL	43	197	112	13	365

From table 30 and table 31, the correct forecasts for the dominant wind direction (South) are high at one-hour lead time as compared to the six-hour lead time hence higher CSI, HK, PA, and POD at 1hour lead time than the 6hr lead time as shown in figure 18 below.

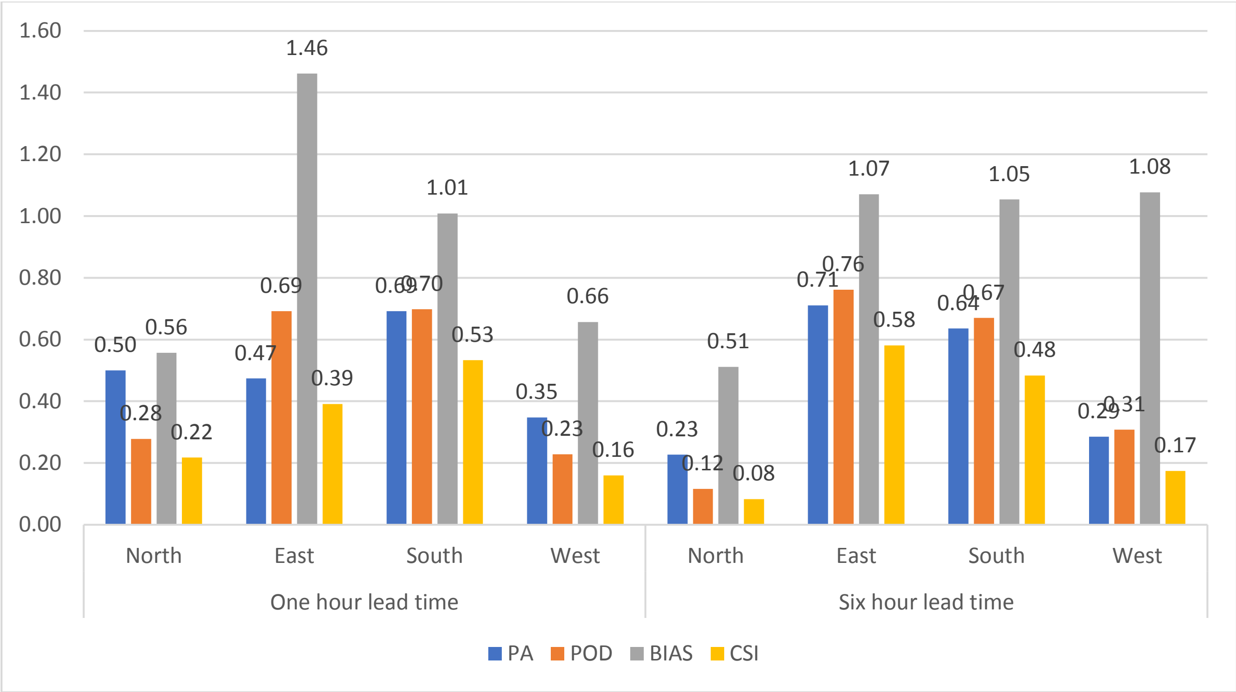

Figure 20:Forecast skill between 06Z and 12Z

From Figure 18, the direction of dominance which is south at this time interval is correctly forecasted at 1hr lead time as compared to Six-hour lead time.

4.6.3 General wind direction contingency table analysis

Table 32: General one-hour contingency table

		OBSERVED				
		North	**East**	**South**	**West**	**TOTAL**
	North	201	154	19	13	387
	East	123	409	62	15	609
FORECASTED	**South**	24	66	233	47	370
	West	6	16	31	41	94
	TOTAL	354	645	345	116	1460

Table 33: General six-hour contingency table

		OBSERVED				
		North	**East**	**South**	**West**	**TOTAL**
	North	189	131	29	35	384
	East	122	372	68	21	583
FORECASTED	**South**	29	113	197	48	387
	West	19	15	38	34	106
	TOTAL	359	631	332	138	1460

From table 32 and 33 above, One hour lead time shows more correct forecasts as compared to the six hour lead time, the skill scores of the above two tables are shown in the table and the graph below.

Table 34: General skill scores

	1hr Lead time	**6hr Lead time**
P.C	0.61	0.54
FAR	0.37	0.49
HSS	0.43	0.34
HK	0.55	0.42

Table 34 above shows that the P.C, FAR, HSS and the HK are all better at one hour lead time as opposed to six hour lead time.

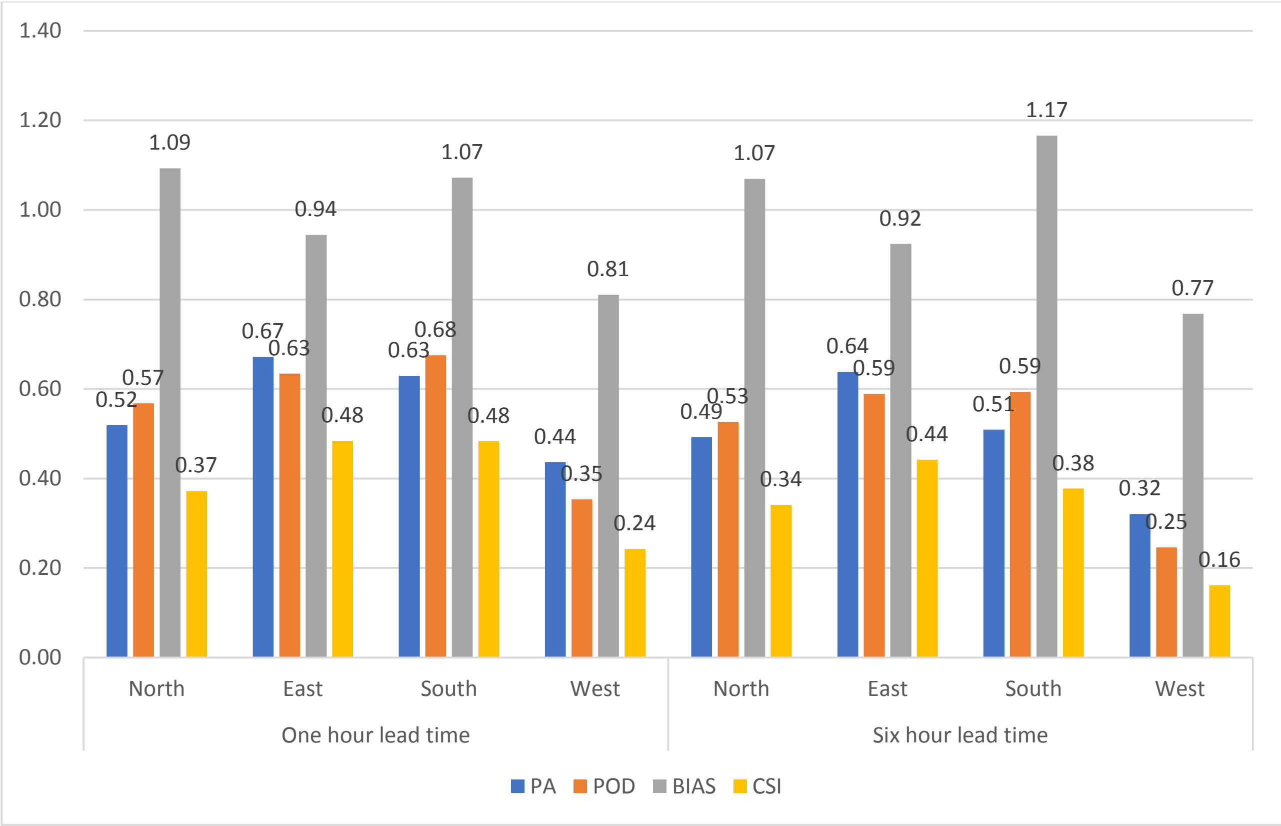

Figure 21: General Forecast Skill scores

From figure 20, one-hour lead time have higher skill scores as compared to the six-hour lead time, Generally the skill scores of the wind direction are high except the direction of west which is lower due to less occurrences of wind blowing from that direction as it can be seen in section 4.2.

The wind direction forecasts are generally better at 1hr lead time than the 6hr lead time which means that the forecast is deteriorating as the lead time increases.

CHAPTER FIVE: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.0 Summary, Conclusions and Recommendations

This chapter presents the summary of the study, conclusions of the study and recommendations.

5.1 Summary of the study

The main objective of this study was to verify the wind speed and direction forecasts generated at JKIA, so as to determine the accuracy and the skill of the forecast. The data for the study was gathered from METARs and TAFs produced at Jomo Kenyatta International Airport for a period beginning from March 2018 till February 2019. Wind speed was organized into three categories light, moderate and strong wind. The forecast and the observed values were then compared to determine the accuracy by utilizing scatter plot and Root Mean Square Error technique for 1hr and 6hr lead times. Wind speed forecasts were checked alongside the wind speed observations considering One-Hour and Six-Hour lead times.

A 3-category contingency table was produced for each lead time and evaluated for skill scores. Both accuracy and skill for wind speed forecasts were found to be high at 1hr lead time rather than 6hr lead time. Similarly, the wind direction was sorted into four cardinal directions north, east, south and west. The forecast and the observed values were then compared to determine the accuracy by utilizing Percentage Error technique for both 1hr and 6hr lead times. Wind direction forecasts were also checked with the wind direction observations to determine the accuracy regarding 1hr and 6hr lead times. A 4-category contingency table was created for each lead time and examined for skill scores. Both the accuracy and the skill for wind direction was also found to be high at 1hr lead time rather than 6hr lead time except the timeframe between 18Z and 24Z which the wind is becoming calm as the lead time increases which leads the 6hr lead time forecasts to be more accurate than the 1hr lead time because of low wind speed at that time interval.

5.2 Conclusion of the study

For wind direction verification, significant deviations among observations and the forecasts are inspected. Forecast errors are considered significant when the wind speed attains 7 kts and the deviation is more than 60^0. if the observed wind speed is more or equivalent than the predefined speed threshold, all the forecast errors valid for that specific hour are measured. If the observed mean wind speed is less than the speed threshold, the forecast wind direction is regarded as accurate since any direction deviation is operationally insignificant.

5.3 Recommendations

In this study, verification of surface wind forecast was done by employing TAFs, METARs, and SPECIs although METARs containing 10 min mean wind direction and speed observations often don't mirror the total behavior of wind in a time interval. For this reason, an analysis of continuous sensor data is recommended, which requires data that is typically not obtainable.

This study focused uniquely on verifying the wind speed and direction forecasts though every one of the parameters contained in the TAF should be verified individually to establish the accuracy and skill of the forecast. Verification of the Take-off and landing forecasts is recommended to determine the accuracy and skill for each forecast since this will go far in judgmental decision making in the aviation operations.

The accuracy and skill at 1hr lead time are high hence suggested for use in flight planning, but it drops for the six-hour lead time. To conquer the drop the management should consider the improvement of the equipment for observing and forecasting the wind at the airport. The forecasters should be considered for training in long-time wind speed and direction forecasts in order to enhance the accuracy and skill for Six-Hour lead time.

The verification results should be revealed to the customers and response obtained from the customers will contribute to determine the value of aviation weather forecasts to the customers.

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