Assessment of the forecasting skill of fog over Kigali International Airport (KIA)

By

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DECLARATION

Declaration by the candidate I declare to the best of my knowledge that this is my original work and has not been submitted for award of degree in any university or institution of higher learning or anywhere else.

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This work is dedicated to my family, especially to my brothers, SENYANAOdilon and SENYANA Lionel, and my sister SENYANAHéloïse, and it is written in memory of my parents and grand parents

ABSTRACT

This research work reviews forecasting for fog, in general, and particularly it focuses on methods used to forecast, accuracy of the forecast and occurrences of fog.

Performing time series and skills analysis help us to link the weather pattern and how the weather behaves in relation to fog. Although fog is hard to forecast but one can maximize the accuracy. Normally, forecast will be used by pilots and the personnel at the KIA (Kigali International Airport) but also by RTDA (Rwanda Transport Development Agency) and will be used to prevent people from accidents; and good decision making for air routes and nearby ground routes. For instance, for aviation industry, we require cloud bases and these are near the ground when fog has occurred and so we need to estimate how high "is the cloud base above the ground". In addition, forecasts are done in such a way that it can be reliable for the schedule and safety of the public (especially in aviation industry).

At the KIA; the crucial challenges faced the forecast of visibility and observation when the visibility is poor; especially during mornings can be less than 100m (fog). When it is foggy; pilots will not see (or not clear) the runway and so will choose to delay flights until fog clears, or to shift to a nearest airport or even worst to cancel the flight schedule (the flight plans are set according to information about weather and forecasts; by also taking into account what weather hazard is likely to happen).

The techniques used to forecast fog varies widely, and the KIA which is mostly affected by radiation fog; are using information about the cloud, temperature, humidity and wind by considering the season of the year; mostly they occur in the wettest season which is from March to May also known as MAM, and less occurrences of fog in the transition season of SOND (September to December) with the highest frequency in April, March and December due to enhancement in rainfall resulting in topography of the country (Kaligirwa, 2013).

By information on what was forecasted (about fog) and what really happened, we will determine whether we need to improve on our forecast and how to correct an error (from observation, through forecasting, to transmission and storing information)

Peer reviewed journals and papers; advised verification as effective on improvement forecasting, and so we are choosing this method to help improve forecast of fog at the KIA

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AFTN Aeronautical Fixed Telecommunications Network

ATS Air Traffic Services

BECMGBecoming (used in TAF code)

CSI Critical Success Index

DJF period of the year from December to February

E Event

ENSO El Niño-Southern Oscillation

F False alarm rate

FAR False Alarm Ratio

FCSTD Forecasted

FM From (used in TAF code)

GGggTime statement in weather reports

H Hit rate (probability of detection POD)

HKHanssen and Kuipers discriminant

hrHour

HSSHeidke Skill Score

ICAOInternational Civil Aviation Organization

ICPACIGAD Climate Prediction and Application Centre

IGADIntergovernmental Authority on Development (in East Africa)

IOD Indian Ocean Dipole

ITCZInter-Tropical Convergence Zone

JJAperiod of June to August, considered as the driest season of the year

JKIA Jomo Kenyatta International Airport

KIA Kigali International Airport

MAM period of March to May, considered as the wettest season of the year

METARMETeorological Aviation routine weather Report

OBS Observed

ONDOctober to December

PA Post Agreement

PC Percentage/Portion Correct

POD Probability of Detection (hit rate)

PGDPostgraduate Diploma

PSS Pierce's Skill Score

RMSE Root Mean Square Error

RTDA Rwanda Transport Development Agency

SONDSeptember to December

SPECISpecial weather report in METAR code

TAFTerminal Aerodrome Forecast

TEMPO Temporary (used in TAF code)

THSThreat Score

UTCUniversal Time Coordinated

VC Vicinity

VCFG Fog in Vicinity

VVVertical Visibility

WMOWorld Meteorological Organization

Z or **UTC**

CHAPTER ONE

1.0 Introduction

For Aviation Industry to be safe and reliable there must be favorable weather conditions. Kigali International Airport (KIA) is mainly affected by fog which is crucial for airplanes to take on/off; that's why forecasting include visibility forecasting in TAFs (Terminal Aerodrome Forecasts)

In this research the forecasts for visibility was verified against visibility observation. The lowest observed value was used to score against the lowest forecasted value. Fog (FG) was categorized into ranges of poor covering range below 1000m, if else, the visibility is above 1000m but below 4000m, this range is recognized as fog in vicinity (VCFG) and will be recognized as fog for easy of analysis.

Weather phenomena that can reduce visibility at KIA is fog (radiation mostly) which can lead to delays/ cancellation of flight plans or sometimes shift the flight route to a nearest airport.

Radiation fog occurs over a land area when radiation cooling reduces the air temperature to its dew point. Therefore a strict radiation fog is a night –time occurrence, but it may begin to form by evening twilight and often does not dissipate until after sunrise.

To forecast the visibility is a big challenge, so a forecaster on duty has to consult models of forecasting (which do not forecast fog at all) and combine the information for ensemble model and by considering various meteorological processes that can lead to Radiation Fog.

Verification of visibility forecast is determined by the observed data; and is verified by the quality control of the accuracy of the forecast (visibility) as shown in the rules and regulations of the appendix B of The ICAO annex 3 published in 2010

Verification of the forecast TAF regarding visibility changes, we consider the use of change groups like BECMG for transition within a time interval, FM for transition beginning at a specified time, TEMPO for temporary changes and PROB for changes expected with a certain probability usually a probability of 30% or 40% is employed in the TAF. The forecast is not for an isolated time but a range of time interval hence one cannot directly compare observed conditions at a single time with what was forecasted since there is more than one forecast state valid for many points of time in a TAF. This challenge calls for the use of blocks of time usually 6hours as for the KIA, fog will clear out (dissipation) before 0900 Kigali Local Time (UTC+02). Poor visibilityis a consideredextreme case wherethe worstobservedwithinthe time intervalis compared to theworstexpectedwithinthistime interval.Mahringer(2008) defines the operationalforecastimpactthat forecastedeffectis mostlikely to havea significant impact onthe flightoperationthus usesa very complexapproach toTEMPOverification.A forecast iscorrectasthe observed valueis within therangeopenby the “used change group”fromforecastsin this caseis given as arange of possible conditionswithin adefined time interval.

1.1 Concepts and Theoretical Framework

Assessment; is the process of documenting knowledge, skills, attitudes by gathering of information and analyzing them.

Analyzing; is to examine what was observed (Determining the weather pattern), studying the relationships between several variables or its behavior in the data.

Forecasting; the process of making predictions about the future based on past and present data and analysis of trends estimation.

Trends estimation; is a statistical analysis of data to extrapolate trends.

Skill; is the learned ability to carry out a task with pre-determined results.

Fog; is a complex atmospheric phenomenon. It is a visible mass consisting of cloud water droplets or ice crystals suspended in the air at or near the Earth's surface (condensation near the ground). Fog can be considered a type of low-lying cloud, and is heavily influenced by nearby bodies of water, topography, wind conditions, and even human activities. In turn, fog has affected many human activities, such as shipping and transport, warfare, and culture. It’s a reduce visibility to less than 1000meters due to condensation near the ground (often generated locally)

Fog forms in the lower boundary layer (ABL) approximately 0-100m from the ground hence very few Numerical Weather Prediction (NWP) models can simulate the detailed fog processes for operational forecasting application.

At The Kigali International Airport, the coding of visibility for aviation purpose is provided in meters or kilometers. A weather observer is obliged to report fog (FG) when the obstruction to vision consist of water droplets and the visibility has been reduced to less than 1000m and when the visibility is between 1000 and 4000m, the observer reports in the vicinity fog as "VCFG" (ICAO Annex3, 2007).

In meteorology, **visibility** is a measure of the distance at which an object or light can be clearly discerned.

In ICAO Annex 3(2010), visibility is defined as the greatest distance at which a black object of suitable dimension situated near the ground, can be seen and recognized when observed against a bright background. Visibility is often reduced by air pollution and high humidity. Poor visibility affects road, air and marine transportation.

Kigali; with population of more than 1 million (2012), is the capital and largest city of Rwanda. It is situated near the geographic centre of the nation. The city has been the economic, cultural, and transport hub of Rwanda since it became capital at independence in 1962 (total area $730km^2$, density $1600/km^2$)

Kigali International Airport (KIA); sometimes referred to as **Kanombe International Airport**, is the primary airport serving Kigali, the capital of Rwanda. It is the main air gateway for all destinations in the country, and in addition serves as a transit airport for Goma and Bukavu in the eastern Democratic Republic of Congo.

1.1.1 Framework

(Results of Forecast Verification in TAF; Croatia *Mesometeorology Journal)*

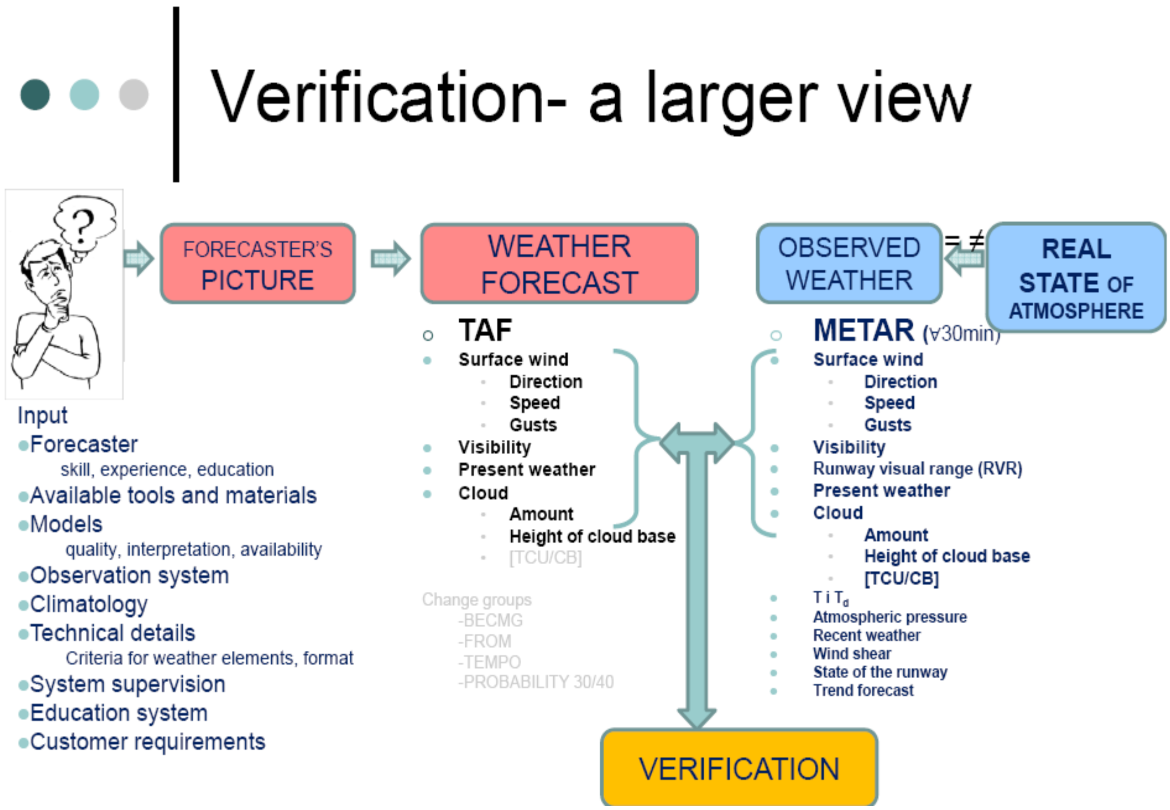


Figure 1: Framework for forecast verification

1.2 Statement of the Problem

Fog is the long persisting weather phenomenon that reduce the visibility to critical range (at extreme level; i.e. poor visibility)

Poor visibility as fog (below 1000m) is a hazard that can lead to some tough decisions like diverting, delaying and/or cancellation of flights and these will affect economy in many sectors (Aviation, Tourism, ...to list some)

Decision making will depend on the forecasts and abruptly taking a decision about missed event of fog occurrences

Information about fog is not easily available for digital use; however, one can retrieve the information from the observation book and keep them on a digital memory for future use.

This project aims to minimize the cost of aviation industry;time and accurately effective of transport when dealing with poor visibility at the Kigali International Airport.

From Weather Theory; we know that the atmosphere, by nature, contains moisture in the form of water vapor. The amount of moisture present in the atmosphere is dependent upon the temperature of the air. Every 20 °F increase in temperature doubles the amount of moisture the air can hold. Conversely, a decrease of 20 °F cuts the capacity in half.

High concentration in low level induce fog formation, however, water vapor is added into the atmosphere only by the processes of evaporation and sublimation that increase the upper level relative humidity.

Humidity refers to the amount of water vapor present in the atmosphere at a given time. Relative humidity is the actual amount of moisture in the air compared to the total amount of moisture the air could hold at that temperature.

The relationship between dew point and temperature defines the concept of relative humidity. The dew point, given in degrees centigrade (Celsius), is the temperature at which the air can hold no more moisture. When the temperature of the air is reduced to the dew point, the air is completely saturated and moisture begins to condense out of the air in the form of fog, dew, frost, clouds, rain, hail, or snow (here we are concerned by fog).

1.3 Research Objectives

1.3.1 Overall Objective

The primary objective of this project is to assess the accuracy of fog forecasting by carrying out the verification of the forecasts produced for Kigali International Airport against the observed to determine the accuracy and skill of fog forecasting.

1.3.2 Specific Objectives

i. Assess fog by time series
ii. AnalyzeTAFs (Terminal Aerodrome Forecasts)
iii. Determine accuracy of fog forecasting

1.4 Research Questions

a) What is the accuracy of fog forecast at Kigali International Airport?
b) What is the skill for fog forecasting at Kigali International Airport?

1.5 Hypothesis

Verification tells us how good is the forecast and also is a key to open gates for what methods has been left behind or method which can be dropped out if the forecast is misleading.

1.6 Justification of Study

Fog is the long persisting weather phenomenon that reduce the visibility to critical range (at extreme level; i.e. poor visibility)

Poor visibility as fog (below 1000m) is a hazard that can lead to some tough decisions like diverting, delaying and/or cancellation of flights and these will affect economy in many sectors (Aviation, Tourism, ...to list some)

Decision making will depend on the forecasts and abruptly taking a decision on missed event of fog occurrences

This study will be of assessing fog and its impacts at the KIA (Kigali International Airport) when forecasted; when not and also when precaution is taken while it's "a false alarm" (F)

Information about fog is not easily available for digital use; however, one can retrieve the information from the observation book and keep them on a digital memory for future use.

This project will help to minimize the cost of aviation industry, time and accurately effective of transport when dealing with poor visibility at the KIA

The International Civil Aviation Organization (ICAO) requires each aviation meteorological provider to be ISO certified and forecast verification is a crucial ingredient towards ISO certification (ICAO Annex 3, 2010). Muiruri (2006, 2011) and Mahringer (2008) recommended the assessment of the aviation forecast for accuracy.

Part of Quality management system (ICAO Annex 3) is forecasts Improvement

- Understand correct, miss, false alarm events
- Verification of special problems
- Fog (reduced visibility)

Because of safety concerns, fog occurrences are associated with disruptions in air traffic at airports and navigation in marine harbors.

Muiruri (2006) in his research on influence of fog on aircraft delays at Jomo Kenyatta International Airport (JKIA) used meteorological data and aircraft delays data and found that fog occurs between 2100 to 0700 UTC and it rarely occurred between 0800 and 2000 UTC. He found also that fog occurrence per month was highest in April, November and December. He further concluded that fog occurrence at JKIA reduces flight operations to the tune of US dollars 1.5 million annually!

Kaligirwa (2013) studied the visibility and concluded that fog formation is caused by radiation cooling results in radiation fog, early in the morning at the KIA.

1.7 Study Area

1.7.1 Location and Topography

KIA (Kigali International Airport) is located in Kigali (Capital City of Rwanda) which has many hills in the vicinity (VC) of the airport

Rwanda also known as “a Country of a thousand hills” is very humid and with favorable conditions for fog formation

Rwanda borders Uganda in the north, Tanzania in the east, Burundi in the south and Democratic Republic of Congo in the west of the country.

Figure 2: Map of Rwanda (showing the location of the KIA)

KIA is the only International Airport in Rwanda Located in North-East of Kigali City

KIA lies at latitude of 01˚ 58’S and longitude of 30˚ 08’E at about 1490.5 m (in the tropics) within the region known as “Great lakes region” and surrounded by “high mountains” and “volcanoes range” which are bit far from the airport

Kigali City sprawls across about four ridges; the top of the ridges have an average elevation of 1,600metres (5,250ft) while the valleys are around 1,300metres (4,270ft)

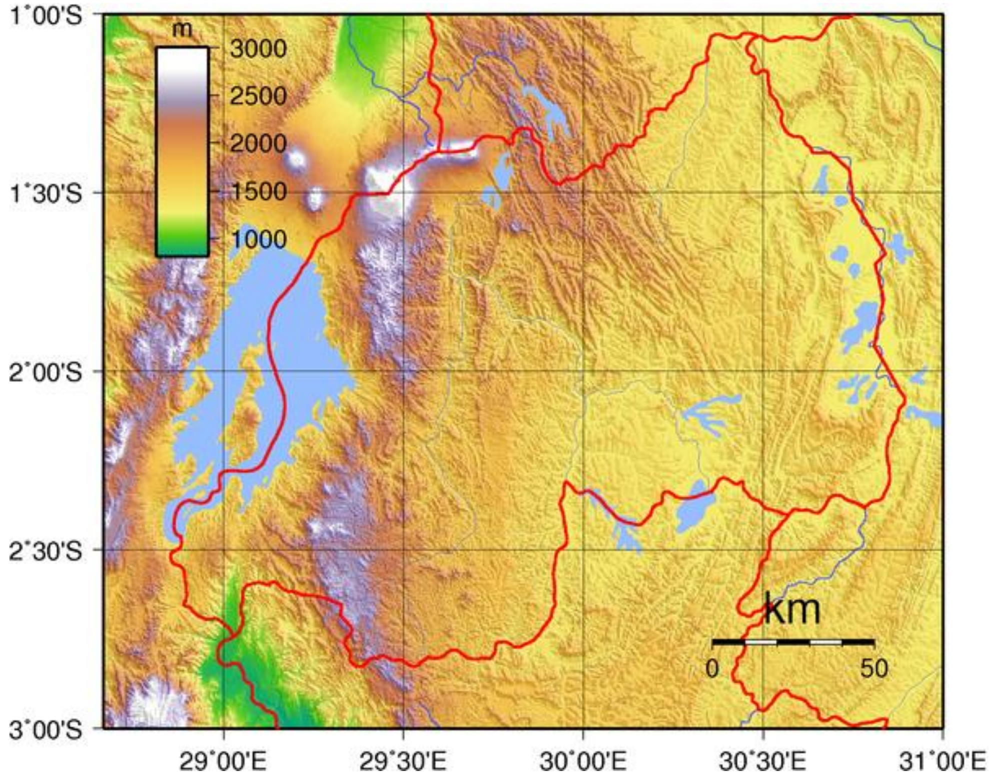


Figure 3: Topography of Rwanda

1.7.2 Climate

By Koppen Climate Classification, Kigali City is classified as "tropical savanna climate" typically with a pronounced dry season

Four seasons are experienced, two dry and a bimodal pattern of rainfall which is driven primarily by the progression of the Inter-Tropical Convergence Zone (ITCZ). The ITCZ is point where the northern and southern trade winds converge; it is characterized by a belt of low pressure and rainfall. The ITCZ migrates from southern to northern Tropics and back through the course of the calendar year; the 'long rains' occur over March to May (MAM) as the ITCZ moves north and the 'short rains' of October to December (OND, also can be taken from month of September) occur on its return south.

1.8 Rwanda Airports

1.8.1 Kigali International Airport

Kigali international Airport is the primary airport serving Rwanda. It is the main gateway for all destinations in the country. The airport is located in the suburb of Kanombe at the eastern edge of Kigali, approximately 12kilometers from the city centre.

Plains, hills and mountains are located in the east, the centre of the country with altitude varying between 900m and 1700m. Rwanda experiences a temperate climate as a result of its high elevation.

Four seasons are experienced, two dry and a bimodal pattern of rainfall which is driven primarily by the progression of the Inter-Tropical Convergence Zone (ITCZ). The ITCZ is point where the northern and southern trade winds converge; it is characterized by a belt of low pressure and rainfall.

The ITCZ migrates from southern to northern Tropics and back through the course of the calendar year; the 'long rains' occur over March, April and May (MAM) as the ITCZ moves north and the 'short rains' of October, November and December (OND) occur on its return south.

The ITCZ displays two branches: zonal and meridional arm. The meridional seems to be the dominant system over the country with westerly winds from Congo air mass. Rainfall amounts are affected by climate phenomena, such as the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). Warm ENSO events ('El Niños') and positive IOD events are associated with unusually wet conditions in the OND season, while the opposite cool phase of ENSO (La Niña) is associated with less OND rainfall.

Kigali International Airport is located in the centre of the country and experiences the same climate as its surrounding. The occurrence of fog is mainly observed during the rainy seasons; i.e. MAM and OND but also sometimes in January and February due to change in the rainy season

CHAPTER TWO

2.0 Literature Review

Visibility has been crucial to air traffic, and this may be reduced by particles (aerosols) blocking the sunlight. Kigali neither being in a desert nor even close to an active volcano, meet this problem of poor visibility at extreme by occurrences of fog and less by heavy rain.
Poor visibility occurs due to the presence of the suspended droplets and/or crystals that render an object undistinguishable to a distant observer.

On the other hand the obscurity could be caused by the scattering of the sun rays due to the presence of the droplets and/or crystals thus causing the blurring of the objects to the observer.

Atmospheric obscurity can be caused by the concentration of hygroscopic nuclei, small and large water droplets, fine sand, smoke and smog. The concentration of these particles tends to reduce the distance through which an observer can see and identify an object situated some distance away from the observer.

Jet-carbon exhaust contributes greatly to the instances of poor visibility (Mcdonald, 1962), hence need for its investigation.

The abruptness related to the occurrence of low visibility makes its forecasting difficult and hence it is a threat to the aviation operations.

Fog can be defined as clouds forming very close to the ground that reduces visibility to less than a kilometer.

Although little has been done on fog forecasting at Kigali International airport, observational experience, suggests that fog is one of the major weather conditions responsible for adverse weather at this airport.

At Jomo Kenyatta International Airport (JKIA); Mwebesa (1981) shows that fog occurs between 2100Z and 0700Z with prevalence between 0200Z and 0500Z.

Studies have been made to understand more about visibility in the tropical region; Muiruri (2010) agrees that forecast accuracy is very vital for the pilot because it not only helps in the planning of the flight, but even to land or decision making. According Mahringer (2008) an unexpected visibility below the minimum threshold (1000meters) affects airport operations to a greater extent. Airport operations are affected by adverse weather conditions and therefore timely information about sudden climate change is necessary to ensure safety, efficiency and regularity of air transport.

In 2008; Mahringer also stated that "the most important parameter in the digital orientation is visibility". The size and particle concentration can lead to partial or total atmospheric darkness; these particles tend to reduce the distance through which an observer can see and identify an object located at a distance from the observer. On the other hand, the mist of darkness is caused by the dispersion of sunlight due to the presence of droplets resulting in deletion of the object to the observer.

Forecast verification is very important in operational forecasting. It helps create the accuracy, competence and the forecast value. Benedetti (2010) argues that effective verification regime can go a long way in improving forecasting skills and consistent use of the forecast for economic importance.

Visibility is very important for the pilot intends to land or take off from an aerodrome. The pilot is required to see track marks well enough to get into one of the tasks.

The decision to land or take off the pilot is not done by incorporating the views from the traffic controller who directs the driver to maneuver either before takeoff or after landing at an airport. From this point as it is important for the driver to be in a good situation for fair visibility, it is also very important for the traffic controller in the tower to be in better visibility position. With the advance in technology aerodynamic aircraft are now equipped with instruments to help the landing.

Goteman (2007) shows that even in these instances security depends entirely on the current visibility range on the complex of the track, in his work, he describes the use of Head Up Display (HUD) as an instrument for landing in low visibility.

Looking at the San Francisco International Airport Reynolds et al (2012) noted that poor visibility can reduce half of inbound traffic compared to normal days. The importance of visibility in air transport has seen the development of visible Enhancing tools like Kramer et al (2008) described for use by the driver in particular for landing in low visibility. He further explained that improving forecasting clearance low visibility can result in greatly reduced upon arrival delays and significantly contributing to the monetary savings for airlines.

Also looking at many studies done in the tropics; at the JKIA; According to Muiruri (2010) among the adverse weather phenomenon affecting airport operations at JKIA low visibility is ranked the highest. The same fact is supported by Mahringer (2008) he states that ‘the most important parameter in the numerical guidance is visibility and Oundo (2013) studied on visibility at The JKIA and come up with a clear understanding of the fog characteristic where most occurrence was observed in the period of MAM (March to May) other reduced visibility was heavy rain in the evenings; Kaligirwa (2013) noticed that at KIA; most occurrence of fog are between 0000UTC and 0600UTC with the highest occurrence at 0400UTC.

The problem with the fog lies in the technicality of its forecast as Roquelaure (2008) agrees with that prediction phenomenon that is on a mesoscale factor is very difficult, especially when it involves short-range forecasting; this includes fog forecasting. Fog is considered to support a large effect on the visibility in many parts of the world as Jenamani et al (2011) inferred. The challenges with reduced visibility are most encountered in fog forecasting. Gultepe (2009) states that, if the fog can be accurately and timely planned then the lost economic value due to sudden occurrence of fog in the form of delays and diversions will be reduced. Fog occurrence poses serious challenges to air operators. As Gultepe (2007) noted, the human and financial losses related to fog and low visibility is now comparable to losses of tornadoes and hurricanes! This brings the need to improve its forecasting and issuing early warning of its onset. The intensity of fog depends entirely on the amount of liquid water droplets contained in the clouds low level while the vertical and horizontal distribution of cloud water in the boundary layer of stratiform clouds defines intensity of fog formation (Tjernsrom, 1992). The injection of moisture in the cloud much closer to the ground can eventually result in the formation of very dense fog. The quiet location or low-speed winds reduced the mixing depth which forms mist.

Accurate prediction of visibility can help the pilot in flight planning and thus reduce the cost of fuel on delays and diversions to the airport. The sudden visibility changes have proven a challenge to accurately forecast low visibility. As Jacobs et al (2004) says various physical processes involved in fog forecasting as humidification are not available in numerical weather prediction models of the time, limiting the visibility estimation means. By testing the competence Mahringer (2008) concludes that it is wise to consider each variable at a time. The problem is to test the ability to assign a score to different groups change as BECMG, TEMPO and PROB used in the TAF; Mahringer also advises on the use of the highest value observed for the higher rating than the expected value and the value observed to mark worst prediction value. When building a system of major operational audit of the workload is devoted to particular data management issues on data quality (Casati et al, 2008). As Terradellas (2007) concluded the competence tests will help alleviate the inconvenience caused by poor visibility increasing accuracy and confidence placed on the forecast. The practice-based audit skills enhancement improves confidence of the forecast. As Mason (2008) shows the verification scores should be used to answer the question, what is the quality of forecasts and if we can be sure that forecast is not misleading.

In assessing the competence for rare events Stephenson (2008) recommends a simple three-parameter model for how Hit Rates (H) and bias depends on the base rate to disappear rare event by providing the extreme dependence score. The competency score is derived contingency table since most events are binary (true/false). forecast verification reinforces the trust placed on predicting and can also be used as a tool for improving forecasts of skills and Ebert (2008) shows that from the perspective of the forecasting fuzzy checking user provides information significant on the scales and intensities that forecasts must be trustworthy. The forecast depends entirely on the judgment of the forecaster of the situation leading to coverage stops and defines three properties related verification measures that are property of the forecasts in the form of probability distributions and non-deterministic distributions best meets expectations for a single forecast. Next is equity for a series of forecasts and finally measuring the consistency (Joliffe, 2008). The main objective of forecast verification is the ability to answer the questions “what is the forecast and what confidence is represented by a given forecast”. Mason (2008) answers the question of how a good and confidence is forecast by the use of confidence intervals and further shows that the p-value cannot be applied to similar objective. Checking allows deep insight into forecasting weaknesses and strengths with predictions focused on methods to improve the quality of forecasts of where management involvement is highly recommended as highlighted by Stern (2008), the participation of management will cascade development and implementation of new forecasting techniques and Plan attention succession. The quality of the forecast and fully depends on the quality of observational data. Verification of the forecast is largely affected by errors of observation by reducing the apparent competence of the forecast (Bowler, 2008), this can be corrected by applying fuzzy verification process (Ebert, 2008) that relaxes requirements for connections Exact between forecasts and observations using the spatial window or surrounding neighborhood forecasting and / or observed points. The problem of forecast verification point needs a wide network of observation stations remains a challenge. Because of the problem of insufficient observation stations in and around the KIA of the research will focus on the checkpoints (verification)

CHAPTER THREE

3.0 Data and Methodology

This chapter presents the data and methods used to achieve the overall objectives of this study. It uses the approach method similar to Austrocrontrol'sMahringer (2008)

3.1 Data Sources

The hourly surface observation and special reports (SPECI) from Kigali aerodrome station (Kigali aero) located at Kigali

International Airport (KIA) was obtained from Rwanda Meteorological Agency (Meteo Rwanda) and AFTN Gateway (the gateway sever that provides the Internet email/web conversion between the AFTNswitching device and the internet/intranet).

Data include:

- Forecasts (both 00 and 06UTC) and Observations from the KIA
- Period 2013-2014
- Contingency table for correlation and skill score were used for skill analysis

  Percent or Portion Correct (PC)

  Probability of Detection (POD)

  Bias

  Post Agreement (PA)

  False Alarm Ratio (FAR)

  Heidke Skill Score (HSS)

  Hanssen and Kuipers discriminant (HK)

  Critical Success Index/ THreat Score (CSI/THS)

Extracted information on visibility from METARs (METeorological Aerodrome Reports) and TAFs (Terminal Aerodrome Reports) at The KIA are assessed for poor visibility (fog) forecast; these weather forecasts and observations are done at the KIA and are issued for aviation purpose. TAF is forecast used for aviation operation; The TAF comprises of forecast for wind speed, wind direction, visibility (our based data), weather phenomena, cloud amount and height of the cloud base; TAF cover thirty hours and is updated after every six hours. The data verified was for a period of two years beginning with January 2013 to December 2014

3.2 Data Quality Control

Data quality is very critical for inference testing. Meteorological data errors arise from the point of observation, through transmission to archiving. With the implementation of quality management in all meteorological aviation weather providers the quality of the data is guaranteed due to examination for completeness and consistency before transmission and storage for future use (ICAO Annex3).

3.3 Determination of Accuracy of Forecast

To determine the accuracy of forecast the forecasted value for visibility was checked alongside the observed value; scatter plots for observations and forecasts were generated. The accuracy of the considered forecast lead times was then calculated using the Root mean Square Error. The Root Mean Square Error formula is given as follow:

$$\boldsymbol{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{n}(F_i - O_i)^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where; ***N***; is the number of times (observations and forecasts)

F_i; is the forecasted at iteration corresponding to the observed O_i

O_i; is the observed at time i

The Time Series Analysis will show the trend of Fog as weather pattern for poor visibility.

3.4 Skill Analysis

The visibility (vis) was categorized into the following ranges:

a. FG (Fog): Vis ≤1000m
b. VCFG (Fog in vicinity): 1000m < Vis ≤ 3000
c. Fair: Vis ≥ 4000

The ranges are defined based on the thresholds related to flight operation. The poor category in terms of visibility represents fog; conditions that reduced visibility to less than one kilometer.
Presence of the value of visibility in the range indicated by poor can lead to diversions, detention, delays and/or cancellations of flights, thus affecting the timing and cost of the flight. The category with clear (fair enough) visibility does not lead to disruption of the schedule. The contingency table can be used to draw conclusions about the quality of the forecasts verification

algorithm. It is the best way to assess the type of errors being made by the forecaster. A perfect forecast would produce only the results and correct negative events only. The accuracy of visibility from TAFs was tested alongside the observed visibility values of METARs/SPECI and based on the ranges described above a contingency table-3 category created as shown next.

		OBS			
		FG	**VCFG**	**FAIR**	**TOTAL**
FCSTD	**FG**	*a*	*b*	*c*	***M***
	VCFG	*d*	*e*	*f*	***N***
	FAIR	*g*	*h*	*i*	***O***
	TOTAL	***J***	***K***	***L***	***T***

Table 1: Contingency table

Where;

a, e, i are correct forecasts

M is the total number of forecasted "fog"

N is the total of forecasted "fog in vicinity"

O is the total number of forecasted "fair visibility"

J is the total number of observed "fog"

K is the total number of observed "fog in vicinity"

L is the total number of observed "fair visibility"

T is the overall total number

A contingency table (also referred to as cross tabulation or crosstab) is a type of table in a matrix format that displays the (multivariate) frequency distribution of the variables. They are heavily used in survey research, business intelligence, engineering and scientific research. They provide a basic picture of the interrelation between two variables and can help find interactions between them. The term "*contingency table"* was first used by Karl Pearson in "On the Theory of Contingency and Its Relation to Association and Normal Correlation"

Oundo (2013) defines a contingency table; as essentially a display format used in the analysis of relationship between two or more categorical variable sand determining the forecasting skill by calculating various skill scores. Tartaglione (2010) describes a contingency table as a better way to test the skill especially in weather forecasting. The forecasting technique depends entirely on the distribution of observation stations and the validation of data Roebber (2009) noted a good distribution of the observation network is needed in forecast verification. In this study, the forecasts were verified with a delay of zero and six. From the contingency table, the skill score will be calculated as follow:

a) **Percentage Correct (PC)**; showsa fractionof the forecastwhich is correct.It ranges from0-1;with1beingthe perfect score.This scorecan bemisleading because itis heavily influenced bycommon category,usuallyno wayin the case ofrare events.It is determinedby the formula below

$$PC\ (\%) = \frac{a+e+i}{T} * 100 \quad \ldots\ldots\ldots\ldots \quad (2)$$

b) **Probability of detection/ Hit Rate (POD/H);** shows the fractionofobservedevents that "yes"wereproperlyplanned.Thescore ranges from0-1,with a score of1beingperfect score. It is sensitiveto blowsbut ignoresfalse alarm(F)making itgood forrare events. The POD for fog is determinedby the formula below

$$POD = \frac{a}{J} \quad \ldots\ldots\ldots\ldots \quad (3)$$

c) **Bias**; the frequency of events "yes forecasts" compare to the observed frequency of "events of yes". The score ranges from 0 to ∞, with a perfect score being 1. The BIAS>1 and BIAS<1 indicates over-forecasting and underestimation, respectively. BIAS measurement report frequency forecasting events of the frequency of observed events. The Skills score does not measure how the prediction matches the observations instead they only measure the relative frequencies. The score of competency of forecasting of fog can be calculated using the formula below

$$Bias = \frac{M}{J} \quad \ldots\ldots\ldots\ldots \quad (4)$$

d) **Post Agreement (PA)**; skill is the ratio of the number of correct forecasts made to the number of forecasts done for each category. For fog forecasting, the formula is given by the formula below

$$PA = \frac{a}{M} \quad \ldots\ldots \quad (5)$$

e) **False Alarm Ratio (FAR)**; shows the percentage of predicted events to that didn't happen in reality. FAR Skills score between 0-1 with a perfect score being 0. The score skill is susceptible to false alarms (F), but ignores other probable situation. It is also very sensitive to the climatological frequency of the event. FAR skill score can be determined by applying the formula below

$$FAR = 1 - (PA) \quad \ldots\ldots \quad (6)$$

f) **Heidke Skill Score (HSS)**; skill score indicating the accuracy of the forecast compared to chance. HSS skills scores range from -∞ to 1, with a perfect score being 1. Skills score measures the fraction of correct predictions after the elimination of these forecasts which would be due purely to correct random chance. The HSS score Skills can be determined by applying the formula below

$$HSS = \frac{a+e+i-\frac{JM+KN+LO}{T}}{T-\frac{JM+KN+LO}{T}} \quad \ldots\ldots \quad (7)$$

g) **Pierces skill score/ Hanssen and Kuipers discriminant (HK)**; skill score showing how well the forecast separate the yes events from the no events. The score ranges from -1 to +1, with the perfect score being 1. The score does not depend on climatological event frequency. For rare events the score is unduly weighted hence more useful for more frequent events. This skill score is determined by formula below

$$HK = \frac{a}{J} - \frac{b+c}{K+L} \quad \ldots\ldots \quad (8)$$

h) **Critical Success Index /THreat Score (CSI/THS)**; skill score showing how the forecast yes events corresponded to the observed yes events. The score ranges from 0-1, with the perfect score being 1. The score measures the fraction of observed and/or forecast events that were correctly forecasted. The score is sensitive to hits and penalizes both misses and false alarms. The score of fog forecasting can be determined by the formula below

$$CSI\ (THS) = \frac{a}{J+M-a} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

CHAPTER FOUR

4.0 Results and Discussions

This chapter presents and discusses the results obtained from the methods described in chapter three to achieve the objectives of this study.

4.1 Temporal Distribution of Visibility Observations

The temporal variability of visibility observed at Kigali International Airport (KIA) was plotted on graphs as shown below

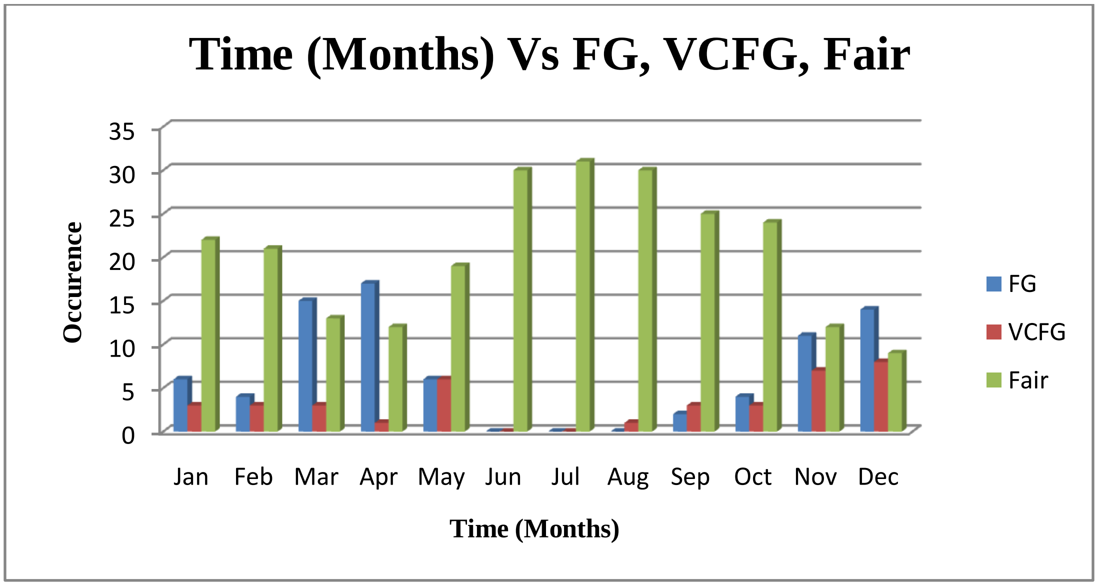


Figure 4: Mean visibility observations during the year 2013 and 2014 at the KIA

During the month of June to September, fog is almost nil, this period corresponds to the long dry season in Rwanda, where there is no moisture to favour fog formation. The highest frequency occurrences were found in April followed by March and December. Fog occurrences were found during January and February months due to possibility of enhancement in rainfall.

4.1.1 Time Series Analysis

A time series is a collection of observation taken at specified times, usually at equal time intervals. In this study time series analysis were used to study fog frequencies.

4.1.1.1 Fog Frequency Analysis

Fog frequency analysis was done to determine the variation of fog at Kigali International Airport. This was done as follows:

i. Mean hourly frequencies to determine the time with the highest occurrence
ii. Mean monthly to determine the month with the highest occurrence
iii. The variation of fog with visibility

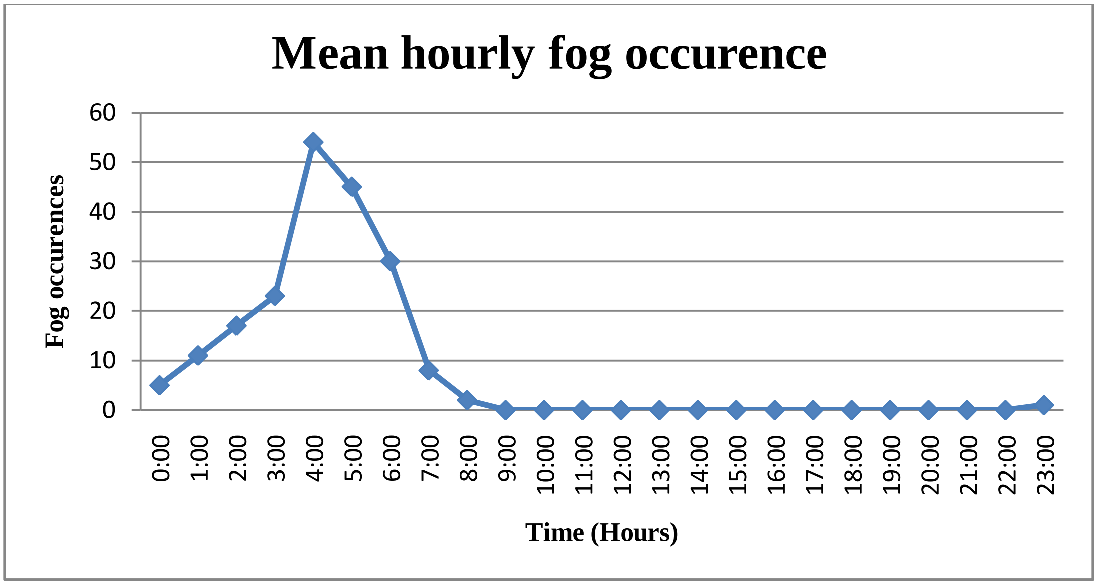


Figure 5: Mean hourly observation of fog occurrence within the same period

From graphs the high frequency of poor visibility (fog and/or fog in vicinity) occurrence was observed between 00Z and 06Z. The high frequency is attributed to fog occurrence at the airport. The poor visibility is frequently observed during the period of MAM (March to May) and the transition period of SOND (September to December) densely from October to December (OND). This time series was used to determine the behavior of weather parameters some few hours before fog onset, and during fog dispersion. This helped us to choose what type of blocks we can use (1800Z to 0000Z and 0000Z to 0600Z) where there is occurrence of low visibility.

4.2 Accuracy of Visibility Forecasts

The visibility forecast values and observed values were plotted on a scatter plot to show the relationship between the forecasted and the observed values. The scatter plot was generated for forecasts and observations between 0000Z and 0600Z since this is the range with many occurrences of poor visibility as shown above in part 4.1

This is a tool used to find out if a given forecast made is a good forecast or a bad forecast. It is done by computing a number of skill score such as Percent Correct (PC); Probability Of Detection (POD); Bias; Post Agreement (PA); False Alarm Ratio (FAR); Heidke Skill Score (HSS); Hanssen and Kuipers discriminant (HK); and Critical Success Index/ THreat Score (CSI/THS) from the Contingency table.

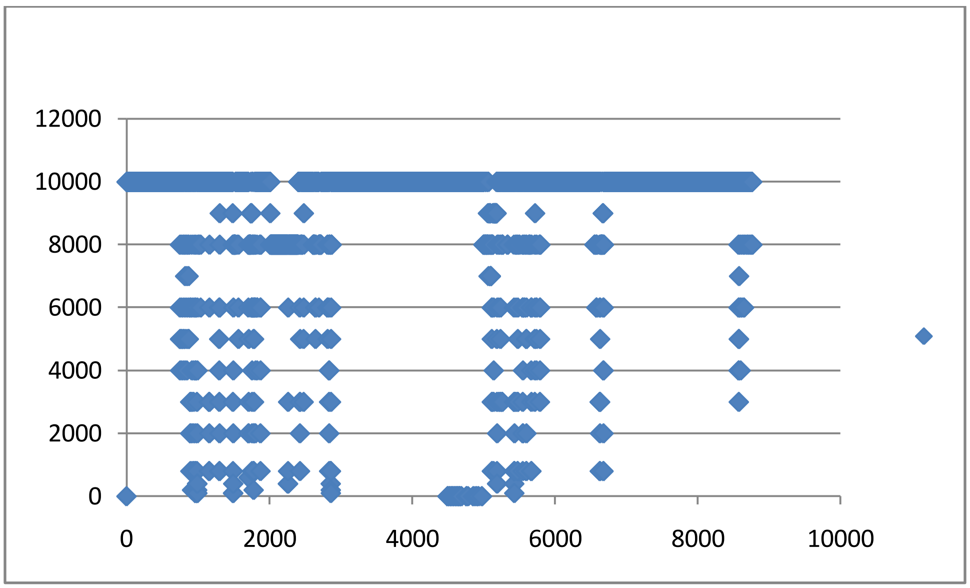


Figure 6: Scatter plot

From the scatter plots the higher margins represents the visibility of ten kilometers (this is because wherever there is 9999 value which means 10kilometers and above, was considered as 10kilometers for easy of analysis) and it is easy to forecast clear visibility than obscurity.

While calculating the accuracy of visibility forecasts, the observations and forecasts with visibility above were considered as favourable, since this kind of Vertical Visibility (VV) is fair enough for aviation industry. Only days with specific observed value coinciding with specific forecasted value were considered in this case. The accuracy of the calculations using the Root

Mean Square Error (RMSE) was determined for 0hr and 6hr lead times respectively. The results are as shown in the table below using equation 1

		RMSE
LEAD TIME	**0hr**	0.4811515
	6hr	0.6291982

Table 2: RMSE

The RMSE for a zero hour lead time is very low compared to the RMSE for a six hour lead time. From the results the visibility forecasts should be used just immediately after being produced by the forecast since they are more accurate as compared to the same forecast six hours after being produced by the forecast. From the results the visibility forecast accuracy deteriorates with increase in lead time. The accuracy deterioration could be due to the abrupt occurrence of fog interfering with visibility and lack of adequate forecasting tools to forecast such phenomena way to in advance. We'll use BIAS to know if the method is for overestimating or underestimating.

4.3 Contingency Tables

By considering visibility forecast range discussed in methodology, a 3- category contingency table was developed for 00 and 06hr lead time. The contingency tables were first categorized depending on the time of the day at which the forecasts were generated, and later a 'general contingency table"was constructed for 00 and 06hr lead time incorporating the above time intervals.

4.3.1 Contingency Table Analysis

The contingency table for forecasts generated at 0000Z were developed both for zero hour and six hour lead times as shown in the tables below:

		OBS			
		FG	**VCFG**	**FAIR**	**TOTAL**
FCSTD	**FG**	*81*	*26*	*1*	***108***
	VCFG	*7*	*38*	*7*	***52***
	FAIR	*7*	*26*	*537*	***570***
	TOTAL	***95***	***90***	***545***	***730***

Table 3: 0hr lead time

		OBS			
		FG	**VCFG**	**FAIR**	**TOTAL**
FCSTD	**FG**	*35*	*39*	*4*	***78***
	VCFG	*17*	*12*	*52*	***81***
	FAIR	*43*	*39*	*489*	***571***
	TOTAL	***95***	***90***	***545***	***730***

Table 4: 6hr lead time

The 0hr lead time blocks show higher number of correct forecasts for fog 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 next; by using equation 2 to equation 9 we have:

	0hr	6hr
PC	89.86%	73.42%
POD	0.852631579	0.368421053
Bias	1.136842105	0.821052632
PA	0.852631579	0.368421053
FAR	0.147368421	0.631578947
HSS	0.739424051	0.315861936
HK	0.70659164	0.382767028
CSI/THS	0.663934426	0.253623188

Table 5: Skill scores

From the results above, generally the scores are very high for 0hr lead time block as compared to the 6hr. The skill scores within the range of fog were higher for 0hr lead times as compared to 6hr lead time. By the table itself, we observe that the skill scores for fair enough are very high since there is no technicality involved in forecasting clear visibility. In all the cases the portion correct is very high due to high frequency of occurrence of clear weather. And less Bias since the season of fog is well pronounced; this can mislead when based on the fact that fog is likely and forget to check if all factors for fog formation are present; and so avoiding actuation of a large FAR.

The distancing to no Bias for both lead times is close, but 0hr over-forecasting while 6hr lead time is under-estimating; but if we separate the “yes events” from the “no events”, 0hr has a perfect score. This also is confirmed by the HSS of the 0hr, which ensures great accuracy compared to 6hr.

4.3.2 Generalized Contingency Table Analysis

		OBS			
		FG	**VCFG**	**FAIR**	**TOTAL**
FCSTD	**FG**	*123*	*34*	*2*	***159***
	VCFG	*7*	*88*	*30*	***125***
	FAIR	*28*	*27*	*1121*	***1176***
	TOTAL	***158***	***149***	***1153***	***1460***

Table 6: 0hr lead time

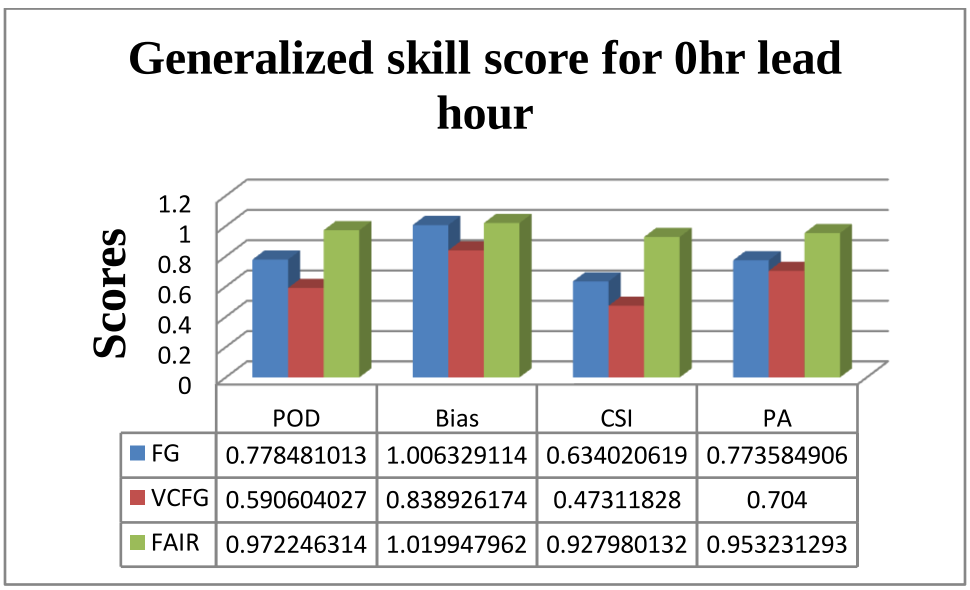
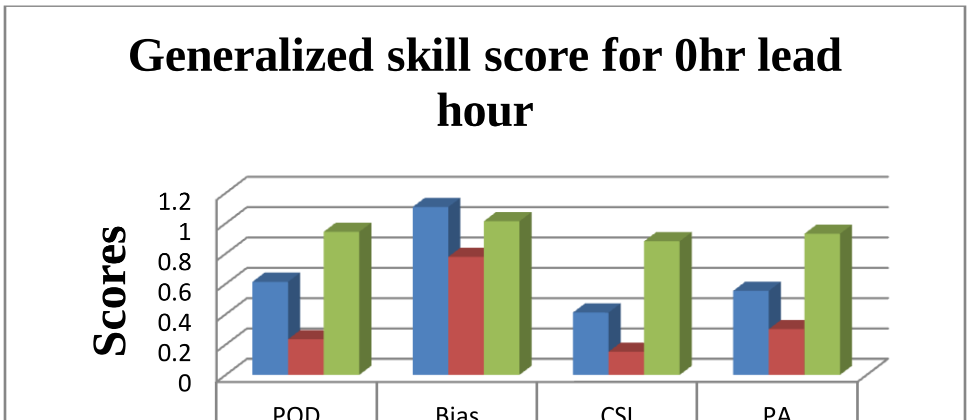


Figure 7: Generalized skill score for 0hr lead hour

		OBS			
		FG	VCFG	FAIR	TOTAL
FCSTD	FG	*97*	*75*	*3*	***175***
	VCFG	*19*	*35*	*62*	***116***
	FAIR	*42*	*39*	*1088*	***1169***
	TOTAL	***158***	***149***	***1153***	***1460***

Table 7: 6 hr lead time



	POD	Bias	CSI	PA
FG	0.613924051	1.107594937	0.411016949	0.554285714
VCFG	0.234899329	0.77852349	0.152173913	0.301724138
FAIR	0.943625325	1.013876843	0.881685575	0.930710009

Figure 8: Generalized skill score for 6hr lead hour

From the tables the number of correct forecasts at 0hr lead time is higher as compared to the same at 6hr lead time. The instances of poor visibility were in most instances correctly forecasted at 0hr lead time than at 6hr lead time. From the generalized contingency tables the following skill score were calculated and represented in the table Next:

	0hr	6hr
PC	91.23%	83.56%
POD	0.778481013	0.613924051
Bias	1.006329114	1.107594937
PA	0.778481013	0.613924051
FAR	0.221518987	0.386075949
HSS	0.744673293	0.525723157
HK	0.745913883	0.493585325
CSI/THS	0.634020619	0.411016949

Table 8: Skill scores from generalized contingency table

From the table the skill score are very high for the 0hr lead time blocks as compared to the 6hr lead time. 6hr lead times; shows high values for FAR which in indeed a big serious and can be quoted as misleading. There were more correct forecasts at 0hr lead time than at 6hr lead time hence the higher score for P.C, POD, PA, HSS, HK and CSI with less FAR.

The scores related to "fog events" are lower as opposed to those with "fair enough"; this is an indication that the forecasters are challenged when it comes to forecasting visibility interference (fog) as opposed to forecasting clear visibility instances. It is easier to forecast clear visibility through persistence evidenced by high scores for clear visibility forecasts.

CHAPTER FIVE

5.0 Summary, Conclusion and Recommendations

This chapter presents a summary of the study, the main findings and recommendations
Note: for further study were also suggested.

5.1 Summary of the Study

The main objective of this study was to verify the visibility forecasts generated at Kigali International Airport (KIA), so as to ascertain accuracy and forecasting skill. The data for the study was obtained from METARs/SPECI and TAFs generated at Kigali International Airport for a period running from January 2013 to end of 2014. Visibility was categorized into three ranges foggy (fog), fog in vicinity and fair enough visibility ranges. The forecast and observed values were compared to determine the accuracy by using scatter plot and the root mean square error method for 0hr and 6hr lead times. Visibility forecasts were checked alongside visibility observations considering 0hr and 6hr lead times. A 3-category contingency table was developed for each lead time and analyzed for skill scores. Both the accuracy and skill for visibility forecast was found to be high for 0hr lead time blocks as opposed to 6hr lead time.

The result has shown that fog occurs highly during rain seasons, MAM and OND and few occurrences in January and February due to enhancement in rainfall. The occurrence of fog in rain seasons is due to availability of moisture. During June to August (JJA), there was no fog occurrence due to lack of moisture, these months consist the long dry season in Rwanda.

5.2 Conclusion of the Study

The result of the study has shown the following:

- Fog (FG) at Kigali international Airport occurs mostly during rain seasons, MAM and OND, high occurrence in April, March and December respectively.
- Fog reduces mostly the visibility range at 100-200meters and 700-800meters.
- Diurnally, fog occurs between 2300 and 0600UTC with the highest occurrence at 0400UTC, due to radiation cooling and advection
- Verification has been initiated
- Overall frequency of hours with ~ 6.312%

- Better scores when forecast FG period is shorter
- Less bias due to pronounced seasons; daily weather pattern and local features

The result has shown few occurrences in January and February due to enhancement in rainfall. The occurrence of fog in rain seasons is due to availability of moisture. During JJA (June to August); there was no fog occurrence due to lack of moisture, these months consist the long dry season in Rwanda.

Visibility forecasts contained in the TAF contains a range of forecasts rather than a single state. This is particularly achieved by the use of change groups as TEMPO and BECMG. These change groups are not considered in the verification exercise in this study. To determine the accuracy of 0hr and 6hr report times, METARs matching the forecast period have been verified alongside the forecast for visibility and RMSE estimates determined for coinciding with the observed values could be determined. Visibility was divided into three threshold ranges, and a 3-class emergency general picture from which the skills of scores were calculated. From the analysis of both the precision and skill scores were higher when 0hr lead times was considered, but with 6hr lead times for the accuracy and skill had dropped drastically. From the analysis of the forecast visibility should be used immediately after production and changes and updates of the forecast should be considered with the greatest urgency for flight operations. ICAO requires each TAF should be updated after every six hours and covers a 30-hours period; TAF amendments are to be issued promptly whenever necessary, this need is demonstrated by the results because the precision and skill drops dramatically after a long duration like the 6-hours block.

5.3 Recommendations

This study concentrated only on verification of fog forecasting; however; TAF is a bulletin/ row format that consists of groups; location identifier , time of forecast origin group, valid period and routine issuances, wind group, visibility group (includes information on fog if expected), significant weather group, cloud and vertical obscuration group, non-convective group, forecast change indicator. All the parameters covered in the TAF should be verified separately to determine accuracy and skill of the forecast. Verification of the Take-off and landing forecasts is recommended to establish the accuracy and skill for each forecast since this will go a long way in judgmental decision making in the aviation operations. The accuracy and skill at 0hr lead time blocks is very high thus recommended for use in flight planning, but it drastically falls for the 6hr lead time. The forecasters should be considered for training in long range poor visibility forecasting so as to improve the accuracy and the skills. The verification results should be presented to customers and feedback obtained from the customers. This will assist in determine the value of aviation weather forecasts to the customers.

The Kigali International Airport; as any other meteorological cite; should keep observations and forecasts on a digital memory for easy retrieve of information and facilitation of research project on improve of the skills.

Rwanda Meteorological Agency should start keeping hourly observational data in the data bank to facilitate research in aviation meteorology

Radiosonde station is needed in order to improve fog forecasting model by combining upper air and surface observational data.

Forecasters on duty should be very sensitive to the climatological frequency of the event such as fog for it is not a rare event but cannot be forecasted by random chances (to minimize the FAR).

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