FOG CHARACTERISTICS AND THE DEVELOPMENT OF A FORECASTING MODEL AT KAMUZU INTERNATIONAL AIRPORT

BY

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DECLARATION

This research project report is my original work and has not been submitted for a degree in any other University.

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DEDICATION

This project is dedicated to the entire members of my family for their endless support and encouragement throughout my education period: MY LATE DAD, beloved MUM, BROTHERS; SANKHANI, GLYN, ANDREW, MALANI and my sister: TIZA.

ACKNOWLEDGEMENTS

I would like to pass my sincere heartily felt gratitude to my supervisors Dr. C. Oludhe and Dr. R.E. Okoola for their never ending advice and assistance throughout the period of the project.

I would also like to thank the entire staff of the Department of Meteorology (University of Nairobi) for the knowledge acquired from them that has enabled me to complete the project.

I would also like to thank the Department of Climate Change and Meteorological Services (Malawi) for the data provision.

I would not forget to extend my special gratitude to GOD ALMIGHTY for his love, care, protection and guidance.

ABSTRACT

The prediction of fog occurrence, extent, duration and intensity remains elusive despite improvements in numerical guidance and modeling of the fog phenomenon. This is because of the dependency of fog on microphysical and meso-scale processes that act within the boundary layer and that, in turn, are forced by the prevailing synoptic regime. With the availability of new technologies and techniques to the operational forecaster already in use, fog prediction may be greatly improved by the development and application of a statistical model. A preliminary attempt at such a model is presented for the Kamuzu International Airport, Lilongwe, Malawi. This requires knowledge of winds, temperatures and moisture availability among others.

The data used is from 2009 to 2014 obtained from the Department of Climate Change and Meteorological Services (DCCMS) headquarters in Blantyre and consists of synoptic observations for Kamuzu International Airport. The data includes dry bulb (screen) temperature, dew point temperature, wind speed and direction.

Results indicate that most fog events at KIA were recorded under calm winds, wind speeds less than or equal to 2 m/s and South Easterly winds. Fog occurrence per month is highest in May, June and July which coincide with the winter season. Minimum temperatures and low dew point depression are favorable for fog formation, which are mainly observed around 0300UTC. The mean critical fog formation temperature is 10.94 degree Celsius.

The temperatures at fog onset have shown a significant correlation with both the corresponding dew point and screen temperatures at 2300 UTC. A multiple regression model that uses the screen temperatures at 2300 UTC (T_{23}) and dew point depressions at 2300 UTC (D_{23}) for the prediction of the critical temperature of fog onset is then developed. The model is validated using the F-test (F calculated (147) greater than F critical, (3.09)). The Hit Rate of the model is 83.33%.

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DCCMS: Department of Climate Change and Meteorological Services

JKIA: Jomo Kenyatta International Airport

KIA: Kamuzu International Airport

WMO: World Meteorological Organization.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Widespread fog causes problems of safety for air, sea and land traffic due to low visibility. In particular, when fog occurs over airfield runways, pilots and air traffic control personnel are concerned about the risk of aircraft operations. The impacts range from cancellation of flights, delays in flights, deviation of planes to alternate aerodromes to serious accidents caused in part by poor visibility. For instance, the Tenerife airport disaster (1977) fatal collision between two Boeing 747 where 583 fatalities where reported due to runway fog.

1.2 Fog

Fog is often defined as simply a cloud on the ground forming as a result of cooling or humidification process (Lutgens and Tarbuck, 1995). According to the WMO fog is defined as "A concentrated suspension of very small water droplets causing horizontal ground level visibility below 1000 meters (WMO, 1992: International Meteorological Vocabulary WMO No.182). Furthermore, the WMO reports ‘fog’ (with symbol FG) when the visibility is less than 1000 meters and ‘mist’ (with symbol BR) when the visibility is from 1000 meters to 9000 meters.

Reporting fog when visibility is less than 1000 meters is appropriate for aviation purposes. For the general public and motorists an upper limit of 200 m is more realistic. Severe disruption to transport occurs when the visibility falls below 50 m. These three are categorized as aviation fog, thick fog and dense fog. The thickest fogs tend to occur in industrial areas where there are many pollution particles (Condensation Nuclei) on which water droplets can grow.

Fog formation requires a variety of factors in different combinations. Essential to fog formation are sufficient moisture and the process of cooling and lifting, inclusive of mixing. In addition to these factors, fog occurrence also favors stable atmosphere. This stability may precede or occur after fog formation and often increases with the advent of fog. Even fog that is associated with strong winds as it is the case with some radiation fog occurs in relatively stable layers of the boundary layer. (Croft, 2003)

Weather records show that fog occurs as the surface temperature approaches the dew point temperature and the relative humidity is more than 75 percent. (Ruangjun and Exell, 2004)

Fog which is composed entirely or mainly of water droplets are generally classified according to the physical process which produces saturation or near-saturation of the air (www.metoffice.gov.uk/learning/fog.) The main types of fog include:

1.2.1 Radiation fog

Radiation fog usually occurs in the winter, aided by clear skies and calm conditions. The cooling of land overnight by thermal radiation cools the air close to the surface. This reduces the ability of the air to hold moisture, allowing condensation and fog to occur. Radiation fogs usually dissipate soon after sunrise as the ground warms. An exception to this can be in high elevation areas where the sun has little influence in heating the surface.

1.2.2 Valley fog

Valley fog forms where cold dense air settles into the lower parts of a valley condensing and forming fog. It is often the result of a temperature inversion with warmer air passing above the valley. Valley fog is confined by local topography and can last for several days in calm conditions during the winter.

1.2.3 Advection fog

Advection fog occurs when moist air passes over a cool surface and is cooled. A common example of this is when a warm front passes over an area with snow cover. It is also common at sea when moist tropical air moves over cooler waters. If the wind blows in the right direction then sea fog can become transported over coastal land areas.

1.2.4 Upslope fog

Upslope fog forms when light winds push moist air up a hill side or mountain side to a level where the air becomes saturated and condensation occurs. This type of fog usually forms a good distance from the peak of the hill or mountain and covers a large area.

1.2.5 Evaporation fog or mixing fog

This type of fog forms when sufficient water vapor is added to the air by evaporation and the moist air mixes with cooler, relatively drier air. The two common types are steam fog and frontal fog. Steam fog forms when cold air moves over warm water. The cool air mixes with the warm moist air above the water, the moist air cools until its humidity reaches 100% and fog forms. This type of fog takes on the appearance of wisps of smoke rising off the surface of the water.

1.2.6 Freezing fog

Freezing fog occurs when the water droplets that the fog is composed of are "super cooled". Super cooled water droplets remain in the liquid state until they come into contact with a surface upon which they can freeze. As a result, any object the freezing fog comes into contact with will become coated with ice.

1.3 Statement of the problem

The forecasting of fog occurrence, extent, duration and intensity remains difficult despite improvements in numerical guidance and modeling of the fog phenomenon. This is because of the dependency of fog on microphysical and meso-scale processes that act within the boundary layer and that, in turn, are forced by the prevailing synoptic regime.

At KIA, the forecasting of fog highly depends on climatology of the season (experience of forecaster on duty) and available global models hence developing a multiple regression model would assist in improving the accuracy of the forecast.

1.3 Objectives of the study

The overall objective is to study fog formation properties and forecast it at Kamuzu International Airport. In order to attain the overall objective of the study, the specific objectives are as follows:

a. To determine the relevant processes for the formation of fog and thus the characteristic features of fog occurrences
b. To determine the temporal variations of fog
c. To develop a statistical model for fog forecasting

1.4 Justification

Fog is a meteorological phenomenon that poses a great operational hazard to aircrafts. In Malawi, let alone Kamuzu International Airport, little research has been done on fog forecasting despite serious fog related aviation problems. For instance, persistence of fog in 2006 at Chileka International Airport caused flight delays and diversion of flights to Kamuzu International Airport. Furthermore, thick fog events from 7^{th} to 11^{th} June 2014 disrupted aircraft operations at KIA.

As such, there is need to develop a linear regression to complement the existing techniques of forecasting fog at KIA so that reliable warnings of low visibility due to fog can be issued to pilots.

The findings of this study should therefore be useful to both the meteorological office and the department of civil aviation at Kamuzu International Airport.

1.5 Study area

1.5.1 Geography of Malawi

Malawi covers an area of 118,484 square kilometers, is a land-locked country lying between latitudes 9°S and 17°S and longitudes 32°E and 36°E. Lake Malawi which is 571.5 km long and 470 m above sea level and covers two thirds of the length of the country in the east. It is also a part of the Great African Rift valley.

1.5.2 Climatology of Malawi

Malawi experiences a tropical type of climate with two seasons, namely the rainy season and the dry season. The rainy season is experienced from November of one year to April of the next year while the dry season is experienced from May to October. Summers are generally hot and wet while winters are cool and dry. According to Torrance (1972) the climate of Malawi depends on the ITCZ, the subtropical high pressure belt in the south between 25°S and 35°S, and its topography. It invades the country from the north on its southwards movement to its southern limit in February and then moves back to the north. During the rainy season the ITCZ may oscillate over the southern tropical areas in sympathy with pressure changes usually across South Africa.

The other main rain bearing system for Malawi weather during the rainy season is the Congo Air Boundary (CAB) which marks the confluence between the Indian Ocean southeast trades and recurved South Atlantic air that reaches Malawi as northwesterly air mass through the Democratic Republic of Congo. This system brings well-distributed rainfall over the country.

There are times when the country is affected by tropical cyclone originating from the Indian Ocean. Depending on its position over the Indian Ocean, a cyclone may result in having either a dry or a wet spell over Malawi.

The other weather features of significance are easterly and westerly waves, and temperate weather systems. The extra tropical waves are believed to be active during the start and end of the rainy season. During winter Malawi is influenced by a divergent southeasterly air mass driven by high pressure cells southeast of Africa. A strong high pressure cell over the eastern South African coast draws a cool moist easterly air mass into the country causing overcast conditions with drizzle over highlands and east facing escarpments near Lake Malawi, locally called "chiperoni". (Mwafulirwa , 1999)

1.5.3 Geography and Climatology of KIA

The registered location of KIA is latitude: -13.78, longitude: 33.78, at an elevation of 1230 meters. KIA is in the central region district of Lilongwe, which happens to be the capital city of

Malawi. Lilongwe features a humid subtropical climate that borders on subtropical highland climate with pleasantly warm summers and mild winters. Lilongwe has a short wet season that runs from December to March and a lengthy dry season that covers the remainder of the year, particularly June and July are cooler than the rest of the year.

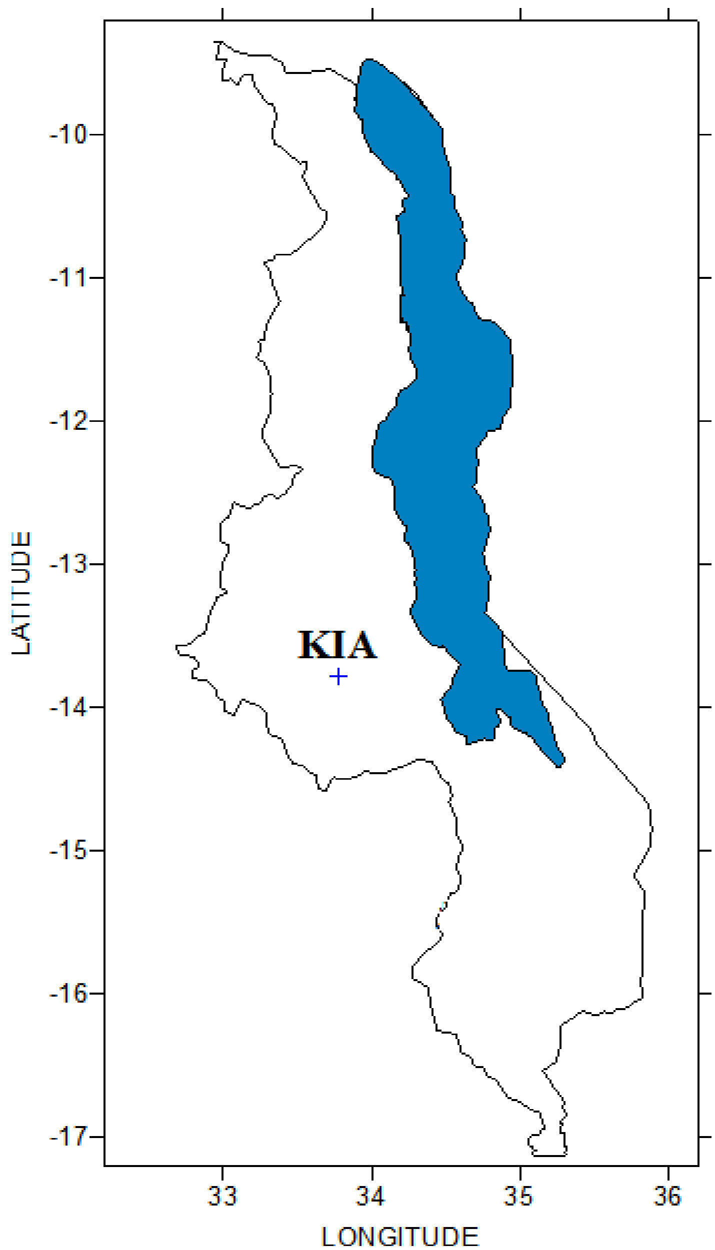

Figure 1: ***Map of Malawi showing the location of Kamuzu International Airport***

Figure 2: ***Map of Central Malawi showing the location of Kamuzu International Airport***

Source: **www.google.com/search?q=map+of+kamuzu+international+airport**

CHAPTER TWO

2.0 LITERATURE REVIEW

A complete understanding of the processes and interactions influencing boundary layer phenomena such as fog remains difficult. However, advances in understanding fog physics have been made over the years through field experiments and modeling studies. (Tardif, 2004)

To forecast fog more precisely, in terms of fog occurrence, extent, intensity, and duration, operational meteorologists must understand and diagnose the thermodynamics, kinematics, and microphysics of the fog process (Croft, 2003).These are predominantly radiative processes as lifting mechanisms are essentially cooling process as well. It is assumed that a combination of these processes, moisture availability and its effectiveness results in fog formation. Therefore, as numerical models have so far been inadequate in this regard, it is important that an operational forecaster develop and use a conceptual fog forecast model. The successful use of such a model will depend on the forecaster’s ability to assimilate the appropriate tools and techniques available in real time.

Mwebesa (1980), studied fog occurrence at JKIA for five years, from 1971 to 1975 to see what relative humidity, dry bulb temperature and wind direction and speed were when fog occurred. The occurrences were also examined to determine the frequencies by hour and per month. Fog seemed to have preferred temperatures (12-16 degree centigrade) and relative humidity (98-100%).

Muiruri (2006) studied the influence of fog on delays at JKIA for the period 2000 to 2005. His results indicated that fog occurrence at JKIA is between 2100 to 0700 UTC and was rare between 0800 and 2100 UTC. Fog occurrence per month is highest in April, November and December, which coincides with the rainfall seasons. Results also revealed that low dew point depressions are favorable for fog formation.

Ruangjun, S. and Exell, R.(2004) developed a method for predicting visibility over Donmuang airport at 0700 am in winter from surface meteorological observations at 0100am and 0500am using multiple linear regression. They used data from the Thai Meteorological Departments weather station at Bangkok International Airport for the months of December, January and

February. For each month two models were developed: one consisting of all available surface observations and the other one omitting the insignificant observations. The forecast consist of the probabilities of fog, poor visibility and good visibility.

Slemmer (2004) did a study to investigate dense fog at the Salt Lake City International Airport (SLC) and its impacts on aviation. The 30-year dense fog climatology showed the highest occurrence of dense fog to be during the winter when there is a minimum of solar radiation. Dense fog typically formed during the early morning hours when temperatures are on average at their daily minimum. There is an average of 58 hourly occurrences of dense fog per winter. Several winters have had very little dense fog while the winter of 1977-78 had no dense fog reports at all. Dense fog occurrences are most likely when the surface temperature is in the 20 F, the dew point depression is 3 degrees or lower, the wind is 6 knots or less, and the altimeter is 29.90 in Hg or higher. In his study dense fog most frequently occurs with a southeast or northwest wind, although a northwest wind is preferred. Prolonged dense fog events usually do not exceed 12 consecutive hours in duration, typically beginning in the evening hours and lasting through the morning. In one rare event, dense fog lasted 28 consecutive hours.

CHAPTER THREE

3.0 DATA AND METHODOLOGY

3.1Data

The data used in this research is from 2009 to 2013. The data was obtained from Malawi Department of Climate Change and Meteorological Services headquarters, Blantyre. It consists of synoptic observations from Kamuzu International Airport. For the fog formation temperature the data used are hourly temperatures between 0300 UTC and 0600 UTC for any particular foggy day. The dew point and air temperatures are recorded at 2300 UTC.

3.2Data quality control

3.2.1 Estimation of missing data

No missing data is estimated using the various methods.

3.2.2 Homogeneity of the data.

The data homogeneity is checked using the single mass curve. Cumulative values (both air temperature and dew point) of the observations are plotted against time.

3.2Methodology

The following methods are used in this study.

3.2.1Time series analysis

The time series analysis will be used to study the relationship between fog and other parameters as follows;

- Annual fog frequencies

- Monthly fog frequencies
- Fog occurrence in relation to dew point depression, temperature, relative humidity and wind speed

3.2.2Correlation Analysis

In this study, the correlation analysis is used to get the relationship between temperature at 2300 UTC (T23), dew point at 2300 UTC (D23) and the corresponding temperature of fog formation (T_f) for a particular foggy day. The coefficient of correlation 'r' will be measured to show the strength of the relationship between the variables.

3.2.3Multivariate regression analysis

The contribution of each parameter to the model will be determined using the multiple regression analysis. The relationship between each parameter to fog formation temperature may be written as;

$$Y = \beta_O + \sum_{x=1}^{k} \beta_{iX_i} + \mathrm{e} \quad \text{...} \quad (1)$$

Where 'e' is the error term and 'β_i' is the multiple regression constants.

3.2.4 Least squares technique

This will be used to estimate the regression constants under five major steps;

Hypothesize the form of the model i.e., choose the independent variables by going through the correlation matrix refer to equation 1.

Specifying the PDF of error term

$$S^2 = {}^{SSE}/_{n-(k+1)} \quad \text{...} \quad (2)$$

Where SSE = $\sum_{i=1}^{k}(y_i - \widehat{y_i})^2$

Checking for the adequacy of the model to find a statistic that measures how well the linear regression model fits the given data;

$$R^2 = 1 - \frac{SSE}{SS_{YY}} \qquad (3)$$

Using the model to estimate the mean values of 'y' or predict the particular values of y for a given value of x_i

3.2.5 Tests of Significance

The test statistic used is the t-test given by

$$t = r\sqrt{\frac{(n-2)}{(1-r^2)}} \qquad (4)$$

Where:

r = correlation coefficient

n = number of data points

The F-test is also used and is given by

$$F = \frac{R^2/K}{(1-R^2)/(n-(K+1)} \qquad (5)$$

Where:

K= number of parameters

n= number of data points

3.2.6 Contingency Table ratios

$$\text{Hit Rate (\% Correct)} = \frac{Number\ of\ hits}{number\ of\ Events} \times 100\ \% \qquad (6)$$

Gives a percent of events for which the forecast category is equal to observed category.

$$\text{Post AGreement (PAG)} = \frac{Number\ of\ correct\ forecast\ in\ each\ category}{number\ of\ observved\ in\ each\ category} \qquad (7)$$

The Post Agreement Ratio gives the fraction of forecasts which were correct.

False Alarm Ratio (FAR) = 1- PAG………………………………………………………… (8)

3.2.7 Computer Software

The Computer Software used in this study are Surfer, Excel and Word

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Homogeneity test of air temperature and dew point temperature.

Figure 2 is a plot of cumulative values for air temperature and dew point temperature against time at KIA for foggy days from 2009 to 2013.

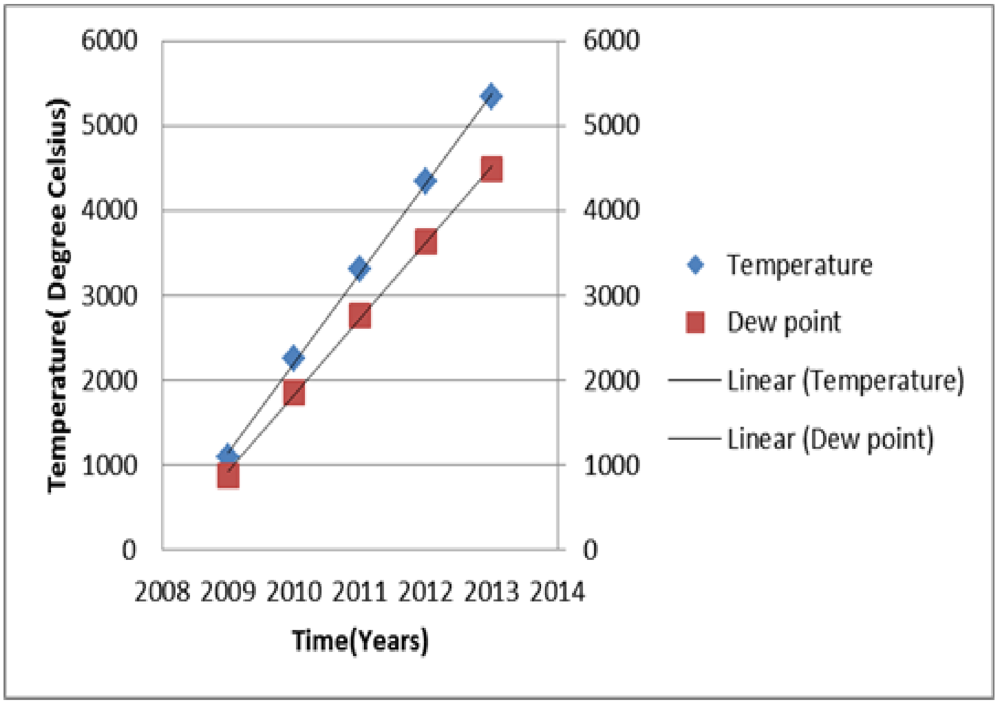

Figure 3: ***Single mass curves for air temperature and dew point at KIA on foggy days (2009-2013).***

The homogeneity test was done using the single mass curve for both parameters (air temperature and dew point temperature) where the cumulative values for the parameters were plotted against time in years. The data sets were homogeneous as seen from the graph.

4.2 Fog properties and trends.

Of the fog types discussed in section1.2, KIA experiences more of radiation fog during winter months (May, June, and July) and evaporation or mixing fog during rainy season like in February.

From surface observation data, weather conditions are analyzed to get fog trend and properties.

4.1.1 Fog occurrence in relation to wind speed.

The occurrence of fog in relation to wind speed at KIA for the period 2009-2013 is presented in figure 3 below.

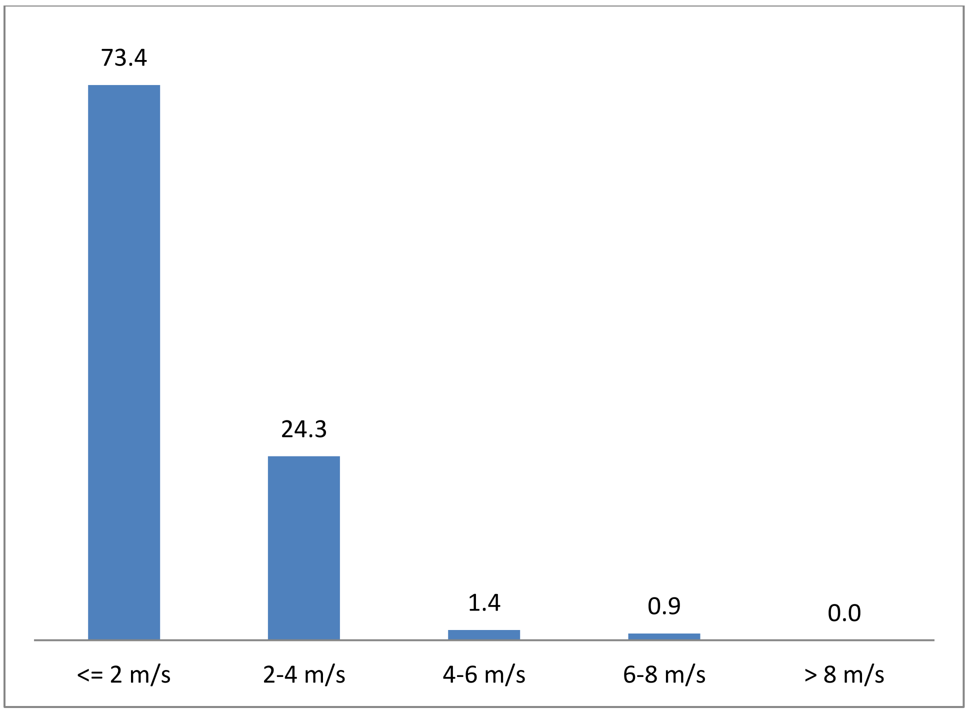

Figure 4: ***Frequency distribution of fog events (%) in relation to wind speed at KIA (2009-2013).***

Figure 3 shows that most fog cases were observed in conditions with wind speed less than or equal to 2 m/s, covering a total of 73% of reported fog cases for the period under study with fog events with wind speed in excess of 3 m/s covering the remaining 27%.

4.1.2 Fog occurrence in relation to wind direction.

Fog occurrences in relation to wind direction at KIA from 2009 to 2013 are shown in figure 4 below.

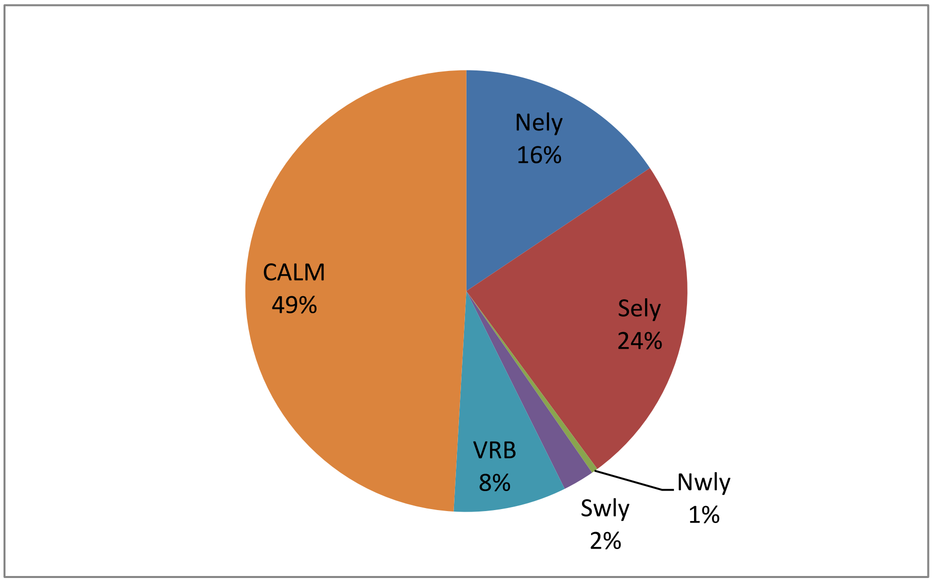

Figure 5: ***Pie chart of fog frequency (%) in relation to wind direction at KIA (2009-2013)***.

Most fog events occurred under calm conditions covering a total of 49%. The South Easterly airflow comes second with 24% largely due to the strengthening of the Mascarene high, Southern Hemisphere winter, inducing a cool moist airflow over Malawi thereby acting as a source of moisture.16% of the events are reported under North Easterly air flow, variable winds and North Westerly winds having a combined total of 9%.

4.1.3 Fog occurrence in relation to dew point depression

Fog occurrences in relation to dew point depression at KIA for the period 2009 to 2013 are shown in figure 5.

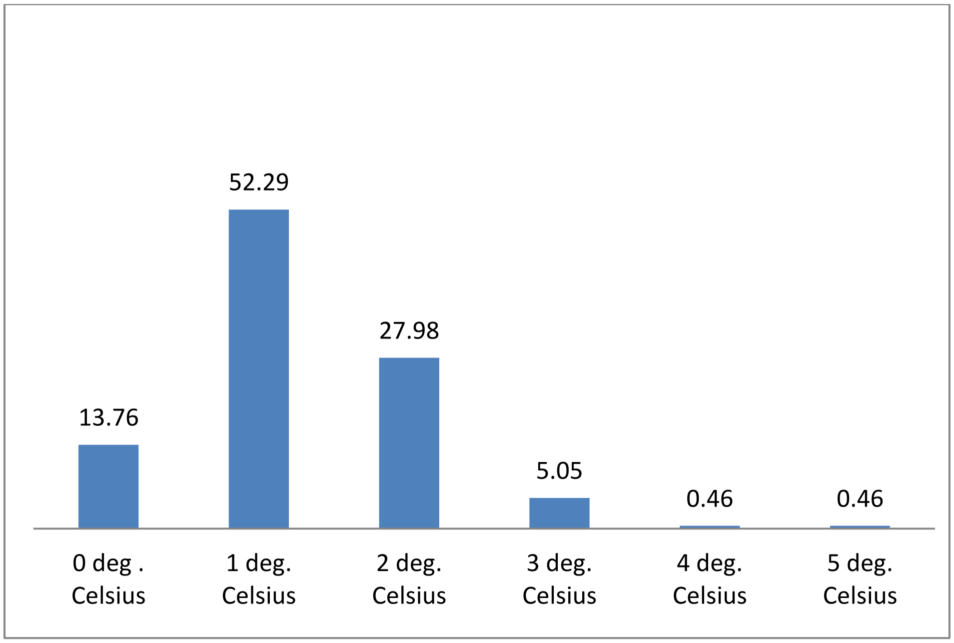

Figure 6: ***Fog occurrence (%) in relation to dew point depression at KIA (2009-2013).***

From figure 5, most fog occurrences were reported when the dew point depression was 1 degree Celsius (52%). The second highest percent was recorded at 2 degree Celsius (28%) followed by dew point of zero degree Celsius (14%). Dew point of at least 3 degree Celsius accounted for a combined less than 7%. Studies from other countries have shown a great pattern of more fog occurring when dew point depression is less than 2.5 degree Celsius, for instance Kenya at JKIA (Muiruri, 2006)

4.1.4 Fog occurrence in relation to air temperature and dew point temperature.

Figure 6 shows fog occurrence at KIA in relation to air temperature and dew point from 2009 to 2013.

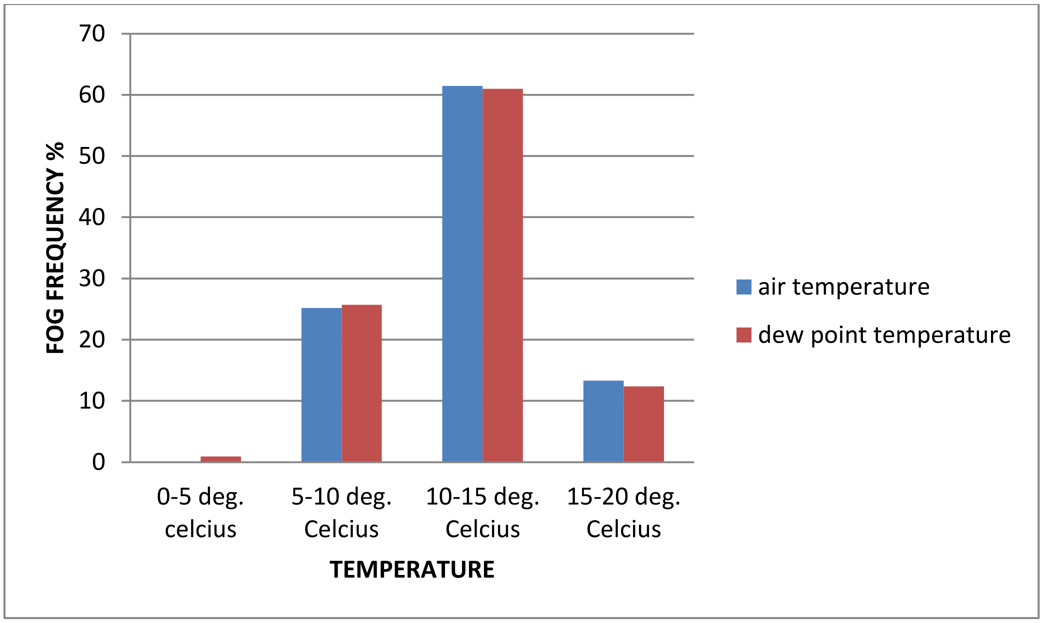

Figure 7: ***Fog occurrence relative to air temperature and dew point temperature at KIA for the period 2009-2013***

Figure 6 shows that fog events were highest when the air temperature and dew point temperature were both in the range 10-15 degree Celsius.

4.1.5 Variation of air temperature and dew point temperature between 1200 UTC and 0700UTC

Figure 7 is averaged the variation of dew point and air temperature at KIA between 1200 UTC and 0700 UTC for the period 2009 to 2013

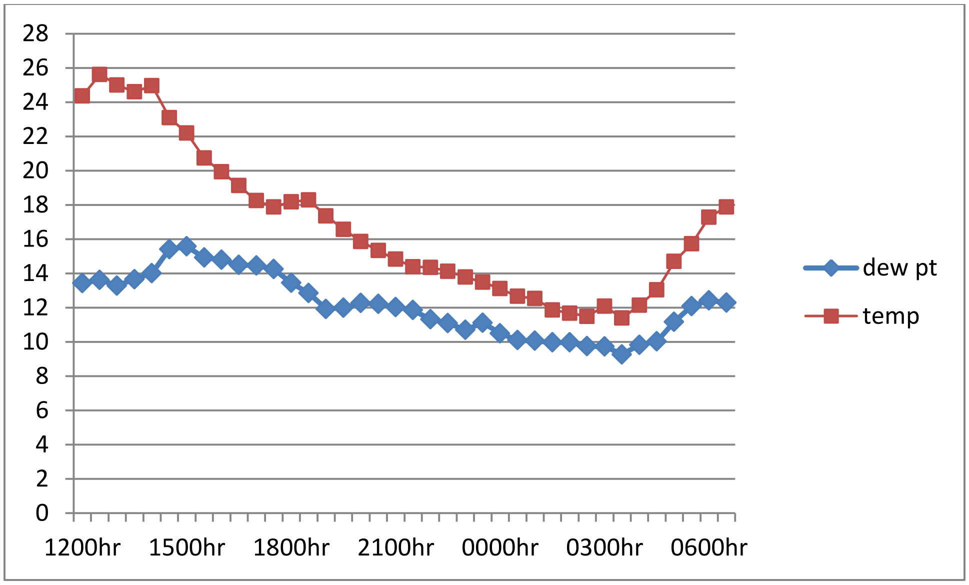

Figure 8: ***Variation of air temperature and dew point temperature at KIA (2009-2013)***

The results in figure 7 supports the results obtained in figure 5. The result in figures 5 shows that most fog events are reported when dew point depression is 1 degree Celsius which corresponds to region on figure 7 where the dew point and air temp plots are close to each other, around 0300 UTC. This is the time of day where temperature values are lowest.

4.1.6 Mean monthly fog occurrence.

Figure 8 shows the mean monthly fog occurrences at KIA from 2009 to 2013.

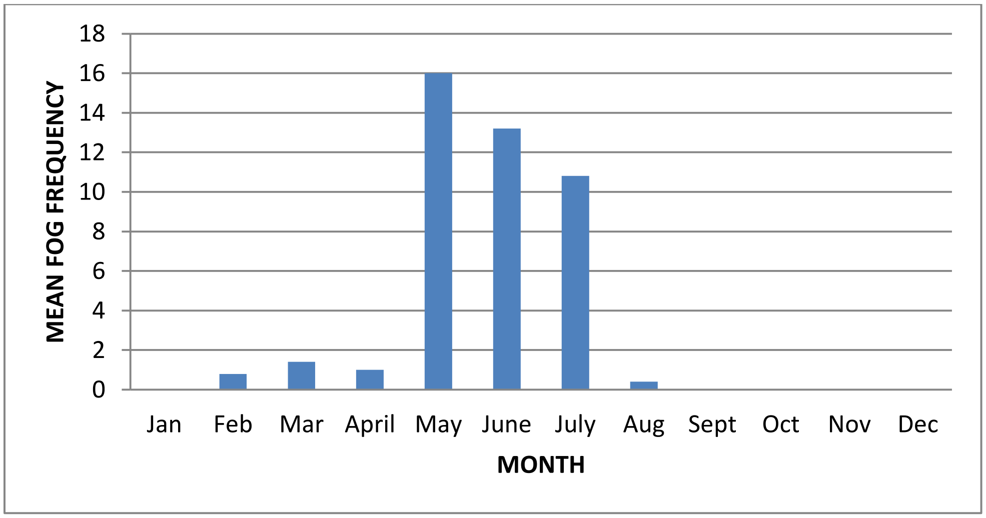

Figure 9: ***Mean monthly fog frequency at KIA (2009-2013)***

The mean monthly fog occurrences for the entire study period (2009- 2013) showed that most fog events occurred in winter, with May having highest mean frequency followed by June.

4.1.6 Fog occurrence over the study time.

Figure 9 is a time series plot of total annual fog events at KIA for the period 2009 to 2013.

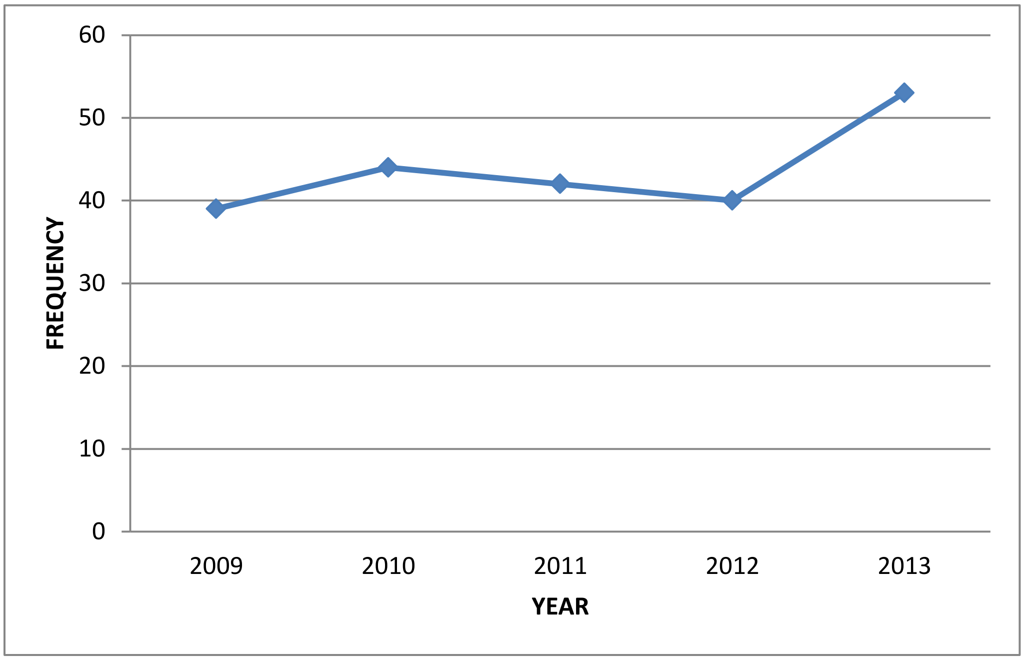

Figure 10: ***Annual fog totals for KIA for 2009 to 2013.***

The figure shows that 2013 was the foggiest year seconded by 2010.

4.2 STATISTICAL ANALYSIS

Both correlation and regression analysis was performed on the acquired data. For the purpose of performing statistical analysis, the following was done;

- Only fog days that show a persistent decrease in both temperature and dew point are used
- Only fog periods that occur after 0300UTC are used in developing the model. This allows sufficient radiation cooling to take place.

- For fog periods that persists for more than an hour, only conditions at the onset of the fog are taken into account so as to eliminate noise in the data.
- However foggy days that show non foggy conditions in between foggy conditions are not used.

The following were obtained:

4.2.1 Correlation Analysis and t-test results.

Correlation analysis done for the three parameters; fog formation temperature (T_f), air temperature at 2300 UTC (T_{23}) and dew point temperature at 2300 UTC (D_{23}) yielded the following results. The t statistic is for a two tail test.

Table 1: Correlation Analysis results for fog formation temperature, dew point and air temperature at 2300 UTC

Parameters	r	r squared	t statistic	t critical	p-value
Fog temp, air temp23	0.78	0.6	-13.12	-1.98	3.36E-25
Fog temp,dew pt23	0.82	0.67	15.26	1.98	2.97E-30
Air temp23, dew pt23	0.81	0.66	26.24	1.98	1.89E-52

The significance of the results in table 1 is tabulated below:

Table 2: significance of correlation analysis results of the three parameters.

Correlation	Significance
Fog temp, air temp23	Significant
Fog temp, dew pt23	Significant

Air temp23, dewpt23	Significant

4.2.2 Regression Analysis results.

Table 3 shows regression analysis results for the three parameters:

T_{23}, D_{23} and T_f.

Table 3: Regression analysis results

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.841412928
R Square	0.707975715
Adjusted R Square	0.703188431
Standard Error	1.211804625
Observations	125

As has been indicated from correlation analysis, air temperature (T_{23}), the corresponding dew point (D_{23}) and the temperature at which fog occurred on that particular fog day (T_f) show significant correlations. A multiple regression run for the three parameters give the results shown above. A total of 125 fog days are used in the development of the model.

The coefficient of determination (R square) measures how well the multiple linear regression model fits a given set of data. Thus from the regression statistics 70% of the variation of T_f are explained by the least squares prediction. Multiple R gives the correlation between an expected value of (E{T}) and a particular value of T_f. The error term refers to the estimated standard deviation of the error term.

4.2.3 Multiple Regression Coefficients.

Table 4: Regression Coefficients.

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	1.849	0.865	2.138	0.034502	0.137	3.560	0.137	3.560
T23	0.398	0.102	3.908	0.000153	0.196	0.599	0.196	0.599
D23	0.462	0.070	6.602	1.11E-09	0.323	0.600	0.323	0.600

Column 'standard error' gives the estimated standard deviation of the least square estimates. Column 't-stat' gives the computed t-statistics for H_O: at least one of the $\beta_{i's}$ is equal to zero and H_1:at least one of the $\beta_{i's}$ is not equal to zero. The column 'p-value' is for a two sided test. "P Critical two tail" gives the cut off value, so that the probability of an observed t-statistics larger in absolute value than "P Critical two-tail" is Alpha.

A summary of the above output is that the fitted line (model) that may be used in the forecasting of fog is given by:

$$\mathbf{T_f = 0.398T_{23} + 0.462\ D_{23} + 1.849} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

In equation 5, T_f is the critical temperature at which fog forms, T_{23} represents dry bulb temperature at 2300 UTC and D_{23} represents dew point temperature at 2300 UTC. T_f is predicted using T_{23} and D_{23}.

4.2.4 Test of statistical significance of the regression coefficients

The coefficient of T_{23} has an estimated standard error of 0.1017, t-statistics of 3.908 and a p-value of 0.00015. It is therefore statistically significant at α =0.05.

The coefficient of D_{23} has an estimated standard error of 0.0699, t-statistic of 6.6022 and a p-value of 1.1E-09. It is therefore statistically significant at α =0.05.

4.2.5 The F-test results

The results of the F-test are given in table 5 below:

Table 5: F-test results

ANOVA

	Df	*SS*	*MS*	*F*	*Significance F*
Regression	2	434.334605	217.1673	147.887	2.45786E-33
Residual	122	179.153395	1.4684704		
Total	124	613.488			

Large F indicates a large SS; that is, much of the variation in T_f is explained by the regression model. Therefore, if F is large, the model is considered valid and hence the null hypothesis should be rejected. In this study, clearly F calculated is greater than F critical (147> 3.09) at α =0.05. Therefore, H_O: at least one of the $\beta_{i's}$ is rejected in favor of the H_1:at least one of the $\beta_{i's}$ is not equal to zero, thus the model is valid.

4.2.6 Goodness of fit

A measure of the fit of the model,

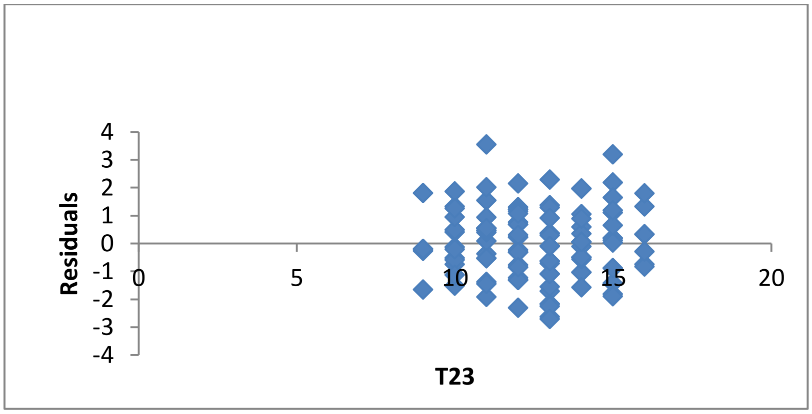

Figure 11a: Residual plot for T_{23}

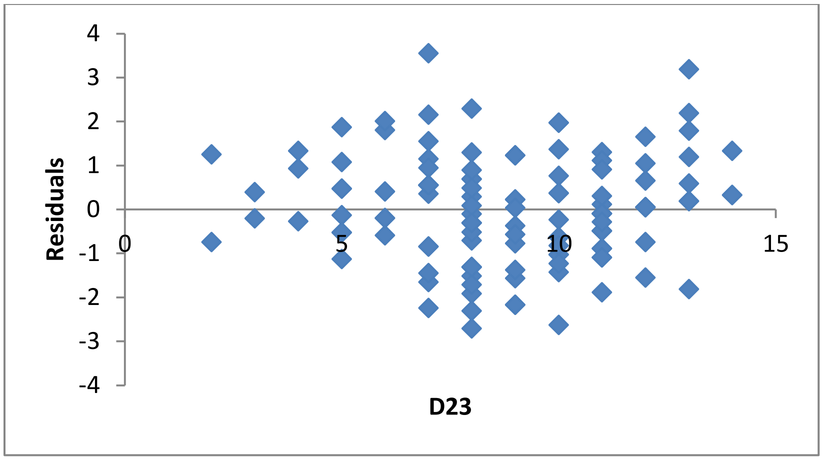

Figure 10b: **Residual plot for D_{23}**

Figures 10a and 10b show a random pattern of the residuals along the horizontal axes hence the multiple linear regression model is appropriate for the data.

4.2.7 Validation of model

A total of 42 fog days in 2014 were used. A contingency table was constructed after observed anomalies and predicted anomalies (from model predicted values) were calculated based on the mean critical fog formation temperature of 10.94 degree Celsius (2009-2013),

Table 6: Contingency Table

		FORECAST			
		BN	NN	AN	Total
OBSERVED	BN	14	0	0	14
	NN	2	11	1	14
	AN	0	4	10	14
	Total	16	15	11	42

Categories:

BN represents Below Normal category

NN represents Near Normal category

AN represents Above Normal category

The following ratios are obtained using data in Table 6:

Hit Rate (% Correct) = 83.33%

This shows that the model correctly forecasted 83.33% of all the fog events.

Table 7 Post Agreement ratios

Post Agreement	
Forecast for BN	0.875
Forecast for NN	0.733
Forecast for AN	0.909

The results in Table 7 show that the model correctly forecasted most events with AN category being the highest.

From the PAG ratios, the False Alarm Ratio is obtained as in equation 9. The False Alarm ratios for category are summarized in Table 8:

Table 8: False Alarm Ratio

False Alarm Ratio	
Forecast for BN	0.125
Forecast for NN	0.267
Forecast for AN	0.091

CHAPTER FIVE

5.1 Summary

Surface observations were used to develop the fog climatology. Fog typically formed during the early morning hours when temperatures are on average at their daily minimum. Several months have had very little fog occurrences and fog occurrence per month is highest in May, June and July coinciding with the winter season in Malawi. Fog occurrences are most likely when both the surface temperature and dew point temperature are in the range 10°C to 15°C, and the wind speed is less than or equal to2 m/s. The dominant airflow for most fog events is the South East flow. The mean critical fog formation temperature was calculated as 10.94 degree Celsius.

The temperatures at fog occurrence (T_f) showed a significant correlation with temperatures (T_{23}) and dew point (D_{23}) at 2300 UTC. This resulted into the development of a fog forecasting model that uses D_{23} and T_{23} to forecast the critical temperature (T_f).

5.2 Conclusions

From the results of the study it is concluded that fog form at a certain critical temperature (T_f). This temperature has a significant correlation with both dry bulb temperatures and dew point temperatures at 2300 UTC. This implies that T_{23} and D_{23} can be used in the forecasting of fog occurrences as long as the moisture condition of the atmosphere is met.

5.3 Recommendations for further work

I wish to recommend the following activities for further work:

- A similar study should be carried out for the same area extending more than 10 years and probably include other predictors for example minimum temperature
- Further research on fog occurrence when dew point depression is not supporting fog formation, for instance the influence of concentration of Condensation Nuclei of fog
- Autoregressive model should be created that would enable step by step monitoring of the conditions before fog onset.

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