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Aerosol optical depth patterns associated with urbanization and weather in Nairobi and Lamu

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Abstract

The massive increase in emissions of air pollution due to economic and industrial growth over the last century has made air pollution an environmental problem throughout the world. This study investigated the spatial-temporal characteristics of particulate air pollutants and its association with rainfall and wind variation over Nairobi and the upcoming Lamu city. The study utilized daily wind speed and direction, population data, land surface reflectivity, aerosol optical thickness and rainfall data. Wind rose plot view was used to analyze wind speed and direction. Time series and correlation analyses were done using R programming environment for statistical computing and graphics. Population and land surface reflectivity were used as indicators of urbanization. The dominant winds over Nairobi were found to be east-north-easterlies while southerlies and easterlies were found to be dominant over Lamu. Wind speed and direction does not seem to change significantly. Aerosol optical thickness and rainfall showed a significant correlation. In Lamu County high values of aerosol optical thickness were recorded over Witu division. In the neighborhood of Nairobi, South eastern parts had high concentration of aerosols. Seasonally, the (June July August) season had the highest values of aerosol optical thickness. These findings will be useful to researchers and ministries interested in environmental and air pollution matters concerning Nairobi and the Lapsett project.

Key words: urbanization, aerosol optical thickness, pollution, R programming

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1. INTRODUCTION

Industrial development is one of the major issues enshrined in the vision 2030 agenda of the Republic of Kenya. With the projected emergence of cities like the proposed Konza Techno City and Lamu by 2030, it is vital that we understand the interaction between urbanization and the environment. Nairobi is the most industrialized urban centre in Kenya and in East Africa in general. A total of 338 industries have registered with the Directorate of Occupational Health and Safety, excluding the EPZ industries on Mombasa road (Japan International Cooperation Agency - JICA, 2013). Emissions from industries contribute to smog and haze over the city.

According to (United Nations Populations Fund, 2014), human impact on the environment is a function of population size, per capita consumption and the environmental damage caused by the technology used to produce what is consumed. Urban areas are characterized by population density of equal to or greater than 1,000 people per square mile and greater than 30% constructed materials such as asphalt, concrete and buildings (United States Environmental Protection Agency, 2012).

Urban air pollution is recognized as major public health and environmental issue. Poor or deteriorating air quality results from high levels of energy consumption by industry, transport and domestic uses. Two sources of air pollutants ubiquitous in most urban areas are transportation and fuel combustion by stationary sources, including industrial heating. Vehicular emissions, seems to be dominant source of air pollutants especially in areas with high traffic densities & industrial (JICA, 2013). The most abundant components of urban air pollution in urban areas with high levels of vehicle traffic are airborne particulate matter, nitrogen dioxide, and ozone (D'Amato et al, 2010). The aerosol particles have strong influence on the climate system by reflecting, absorbing and scattering radiation, where reflection and scattering mostly predominates (Singh et al, 2005).

Due to the impending port project in Lamu, the Global Heritage Fund has listed Lamu Old Town as one of twelve sites "on the verge" of irreparable loss and damage. The main objective of this study was therefore to investigate the association of particulate air pollutants with rainfall and wind variation over Nairobi and Lamu.

Lamu County occupies the northern-most part of the Kenyan coast. It has a population of 101,539 people according to the 2009 census. It covers a total area of 6,167km^2. It lies within 600mm to 1000mm isohyets and has three rainfall zones. Nairobi lies between latitudes (1° 9' - 1° 28') south and longitudes

(36° 4' - 37° 10') East. It covers a total area of 684km^2 with a population of 3.1 million people (Kenya National Bureau of Statistics, 2010). Nairobi has a subtropical highland climate according to Koppen climate classification.

2. DATA AND METHODS

2.1 Data type and source

Three categories of datasets were used; directly observed data, satellite observed data and demographic data. Meteorological data include the daily wind speed and direction data for the period 2001 - 2012 for Wilson, JKIA, Dagoretti and Lamu stations. Monthly rainfall data for Wilson, JKIA, Dagoretti, Moi Air Base, Kabete and Lamu stations (Table 1) for a duration of 31 years (1983-2013). The data was sourced from the Kenya Meteorological Services. Decadal population census and population estimates were obtained from the Kenya National Bureau of Statistics. Land surface reflectivity data for the period 2005-2014 was extracted from OMI/Aura at a resolution of 0.25^{0}and at a wavelength of 342.5nm. Aerosol optical thickness data was used as an air pollution proxy. The data was also extracted from OMI/Aura. Several pixel points for Nairobi and Lamu were identified as shown in table 2. Aerosol optical thickness is a measure of radiation extinction at the encounter of aerosol particles in the atmosphere due to aerosol scattering and absorption.

The total optical depth (τTOT) is obtained using the following equation according to Beer-Lambert-Bouguer law (Holben et al): $V(\lambda) = V_O(\lambda)\ d\ exp\{-\tau[\lambda]TOT \times m\}$ .....(1)

Where V is the digital voltage measured at wavelength λ, Vo is the extra-terrestrial voltage, d is the ratio of the average to the actual Earth-Sun distance, τTOT is the total optical depth, and m is the optical air mass. The optical depth due to water vapour, Rayleigh scattering, and other wavelength-dependent trace gases must be subtracted from the total optical depth to obtain the aerosol component:

$\tau(\lambda) = \tau(\lambda_1) - \tau(\lambda_2) - \tau(\lambda_3) - \tau(\lambda_4) - \tau(\lambda_5) - \tau(\lambda_6) - \tau(\lambda_7)$……………….....……… (2)

λ_1 is the total optical depth, λ_2 is water, λ_3 is Rayleigh, λ_4 is ozone, λ_5 is nitrogen dioxide, λ_6 is carbon dioxide and λ_7 is methane.

Table 1: Meteorological stations and their respective locations

Station	Elevation	Longitude	Latitude
Dagoretti	1798	36.750	-1.300
Wilson	1676	36.820	-1.320
JKIA	1615	36.920	-1.320
Kabete Agromet	1914	36.750	-1.270
Moi Air Base	1637	36.867	-1.267
Lamu	6	40.900	-2.270

Table 2: Pixel points

Longitude	**Latitude**	**Location**
36.125	-1.625	South West of Nairobi
36.375	-1.375	West of Nairobi
36.625	-1.125	North West of Nairobi
37.125	-1.625	South East of Nairobi
36.875	-1.375	Nairobi
41.125	-1.875	Kiunga division, Lamu
40.375	-2.125	Witu division, Lamu
40.875	-1.875	Faza division, Lamu
40.875	-2.125	Lamu, Central division

A limitation in this study was that the satellite derived data was only available for short periods of time. Also, this study only considered particulate pollutants whereas other pollutants types such as gaseous pollutants also exist in cities.

2.2 Methods

In this study, time series analysis was employed. In R programming environment, the data was arranged in a time series manner then graphs plotted using the R functions for graphics. Wind roses were plotted using wrplot view. Wrplot is software that runs in windows to generate wind statistics and plots for a given meteorological station within a specified time span. A wind rose is a graph showing the direction, speed and frequency of wind in a particular area.

Correlation coefficients were computed to establish various relationships.

3. RESULTS AND DISCUSSIONS

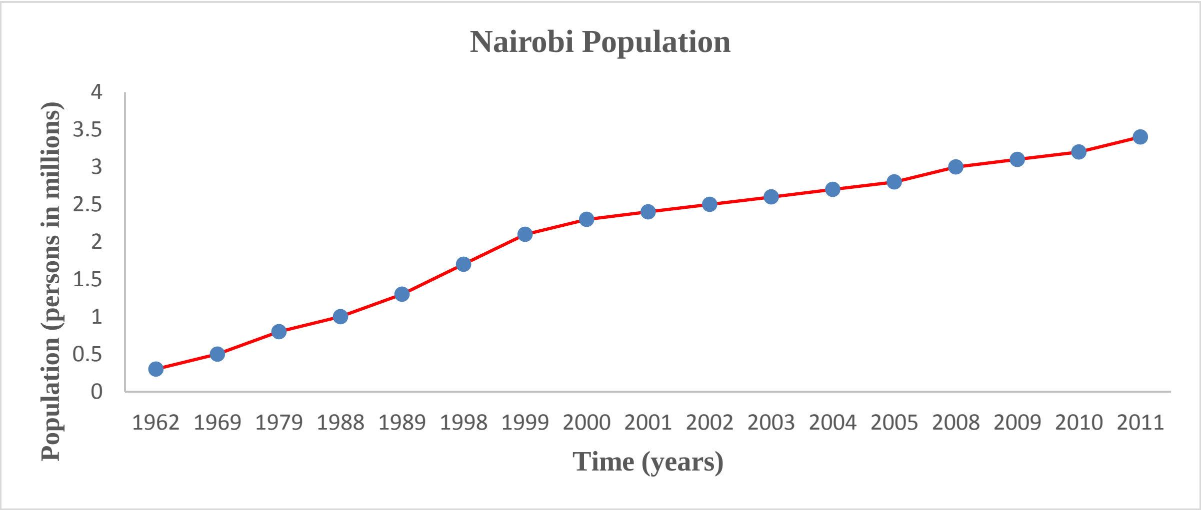

Figure 1: Graph showing Nairobi population census and population estimates from the year 1962 to 2011

The population of Nairobi has increased rapidly for the last half century as shown in figure 1. Population increase depicts urban growth which changes land use patterns.

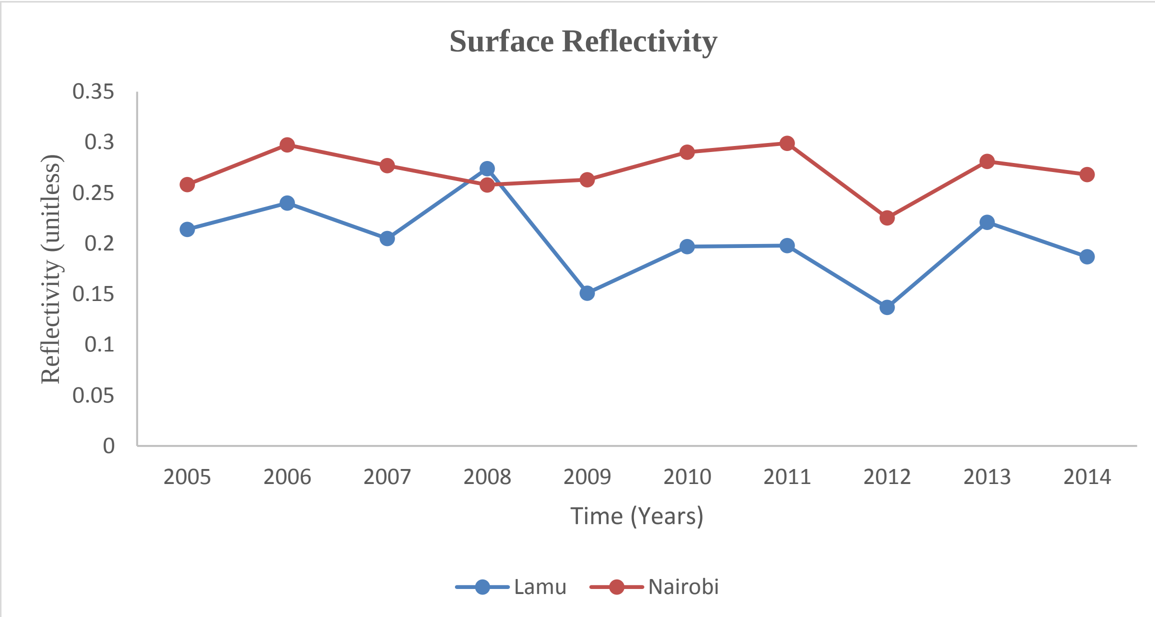

Figure 2: Graphs depicting Nairobi and Lamu land surface reflectivity from 2005 to 2014

The land surface reflectivity over Nairobi shows a decrease in the recent years (figure 2) which can be attributed to decrease in the albedo as a result of urban development. Over Lamu, land surface reflectivity depicts a decreasing trend for the period 2005-2014.

The land surface reflectivity for Nairobi is generally higher than that for Lamu due to differences in surface material because of the fact that Nairobi is more urbanized than Lamu.

3.1 Seasonal wind speed

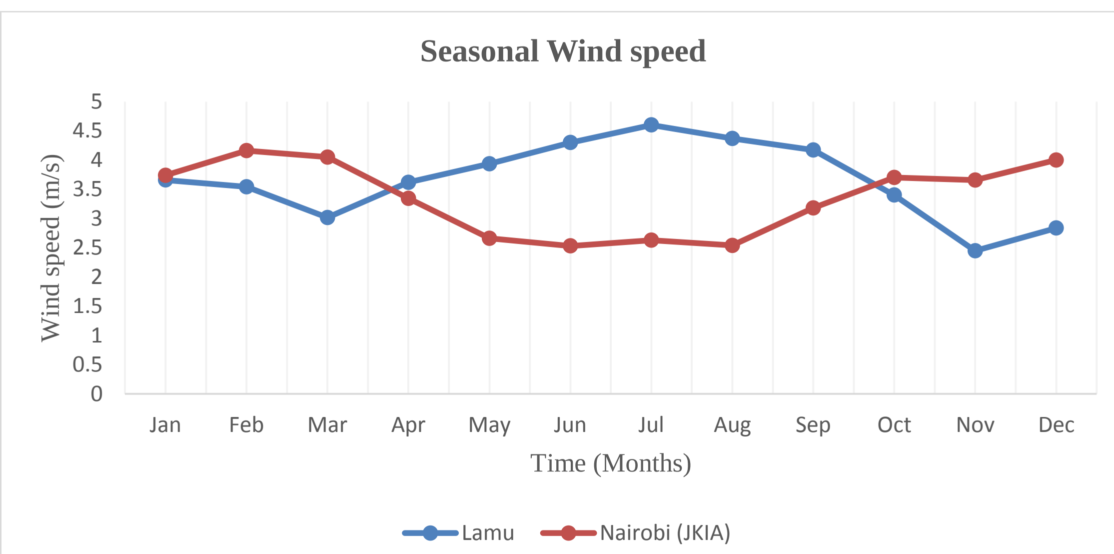

Figure 3: Graphs showing Seasonal wind speed for Lamu and Nairobi represented by JKIA

The monthly wind speed over Nairobi generally depicts two seasons as illustrated in figure 3. The September to April season is characterized by higher wind speed with a maximum occurring in the month of February. The season with relatively lowest wind speed over Nairobi is the May to August season. The May to September season has the highest wind speed over Lamu as shown in figure 3. October to April has the lowest wind speed. The month of July experiences the highest wind speed while November has the least.

3.2 Seasonal wind direction and speed by wind frequencies

From figure 4(a) the January-February winds are mainly north easterlies. During this season, the general wind orientation over Nairobi and East Africa in general is north easterly and this is due to the ITCZ position which is usually to the southern parts of the African continent.

(a) **(b)**

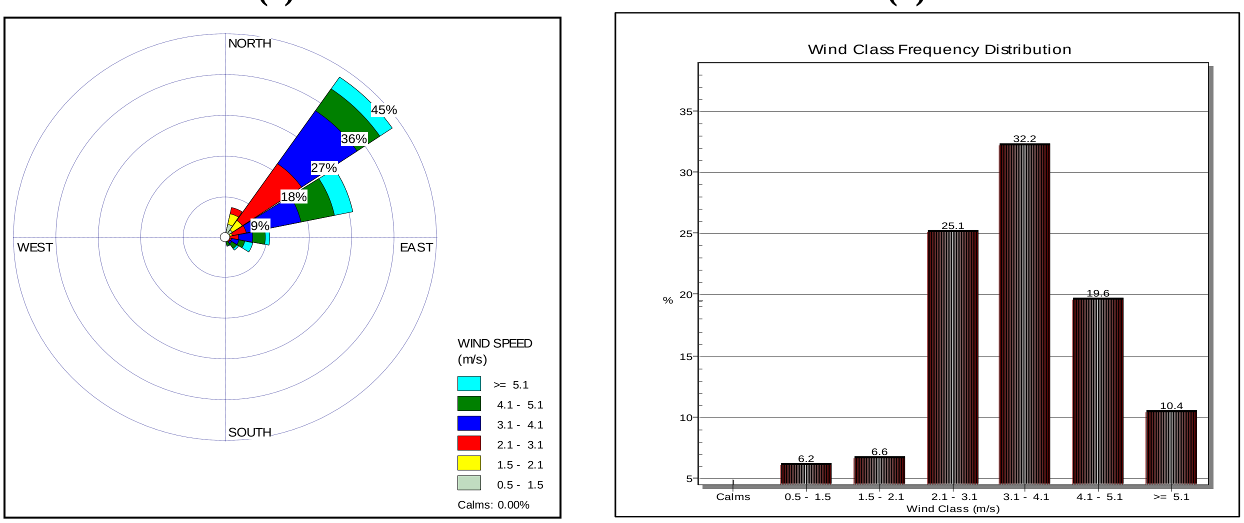

Figure 4: Nairobi wind rose (a) and wind class frequency (b) for January-February

(a) **(b)**

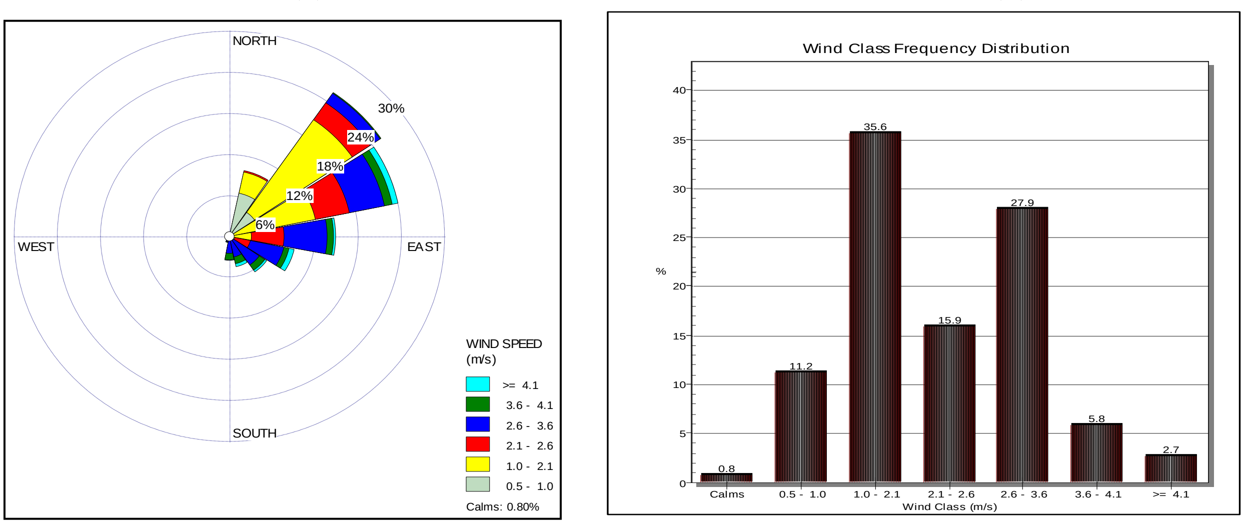

Figure 5: Nairobi wind rose (a) and wind class frequency (b) for March-April-May (MAM)

The most frequent wind speed is between 2.1-4.1 m/s at 58.8% as shown in figure 4(b). The relatively high wind speed during this season can be attributed to the strong solar insolation especially during the month of February which results to steep pressure gradients. Figure 5 shows that the MAM season is mainly dominated by north easterly winds coupled with easterly winds blowing at a relatively lower speed compared to the January-February season. The highest wind class frequency is 1.0-3.6 m/s at 79.4%. This is the wet season over Nairobi and most parts of East Africa and it is accompanied by little solar activities due to cloudiness. There is therefore minimum differential heating and small pressure gradients thus resulting to the observed decrease in wind speed. The winds during the June-July-August-September (JJAS) (figure 6) season are observed to be mainly North easterlies. About 57.3% of the wind was observed to blow at a speed less than 3.6 m/s. The general wind flow during the October-November-December (OND) season was observed to be east-north-easterly (figure 7). The class with the highest wind frequency was 2.1-4.1 at 55%.

(a) **(b)**

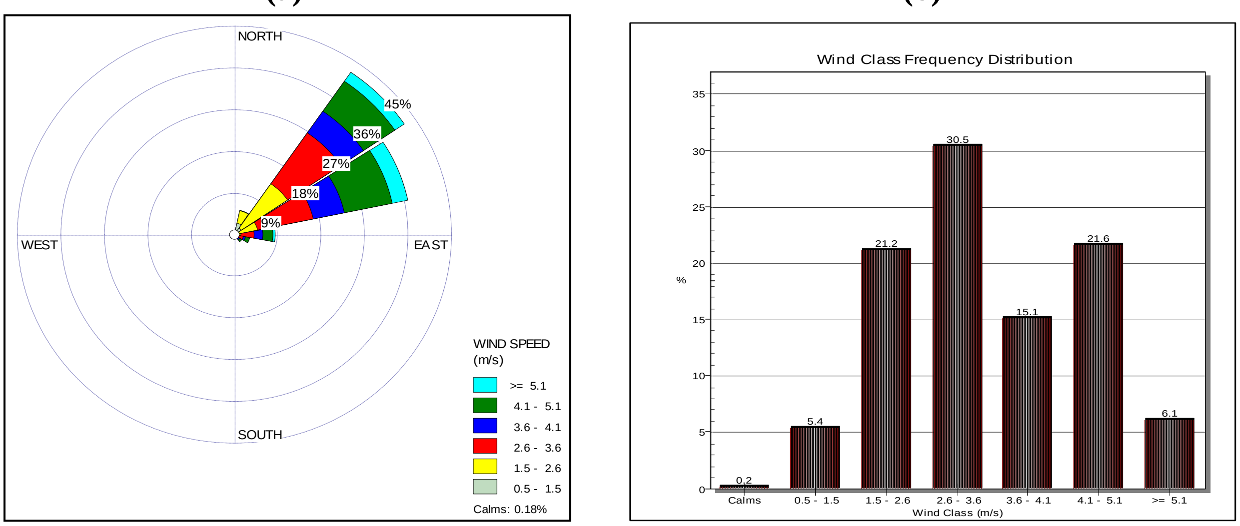

Figure 6: Nairobi wind rose (a) and wind class frequency (b) for JJAS

The predominant winds over Nairobi city were found to be east-north-easterlies. This conforms to other studies carried elsewhere (Opijah et al., 2000, nganga et al., 2005 and Ongoma et al., 2014). Normally, wind direction does not vary significantly because of the quasi-stationary nature of the systems controlling wind circulation. Other local factors such as rural-urban winds and meso scale systems could have contributed to the observed variation in wind speed and direction.

(a) **(b)**

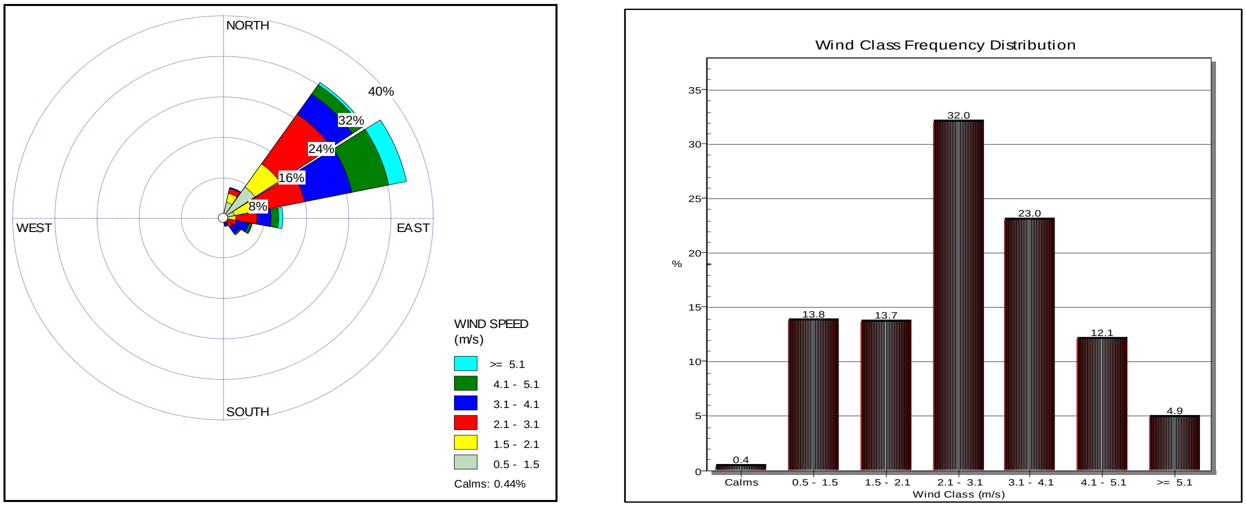

Figure 7: Nairobi wind rose (a) and wind class frequency (b) for OND

(a) **(b)**

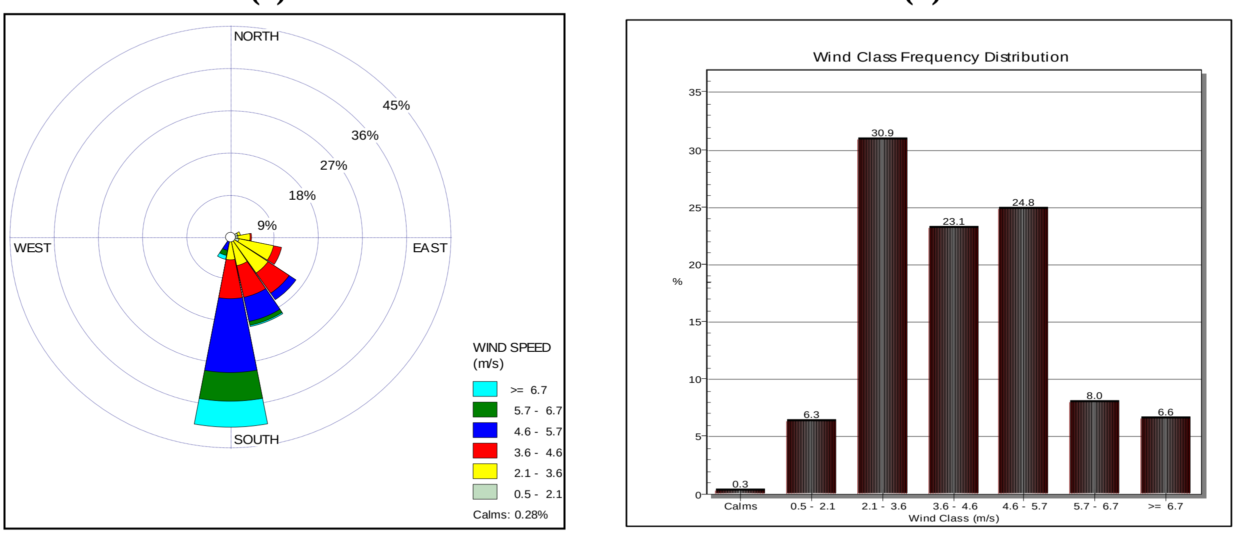

Figure 8: Lamu wind rose (a) and wind class frequency (b) for April, May & June

The wettest season in Lamu is the April-May-June (AMJ) season. During this season, the predominant winds are Southerlies while the dominant wind speed is 2.1-5.7 m/s at 86.8% (figure 8). It is approaching winter in the Southern hemisphere during this season and the monsoon winds are beginning to take place. From figure 9 the winds during the short rains season (OND) are mainly easterlies and the most frequent wind speed is 1.5-3.1 m/s at 50.3%. For the dry season January-February-May (JFM) the most observed winds are also easterlies with the most frequent wind speed being 1.5-4.1m/s at 68.4% as shown in figure 10. The seasonal variation of wind direction over Lamu is high compared to Nairobi.

(a) (b)

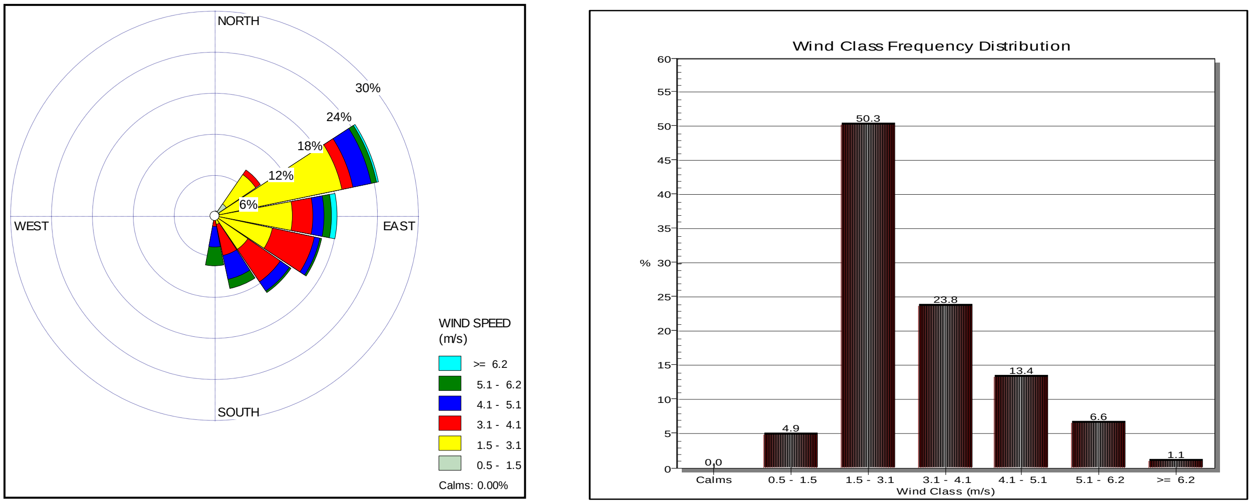

Figure 9: Lamu wind rose (a) and wind class frequency (b) for OND

(a) (b)

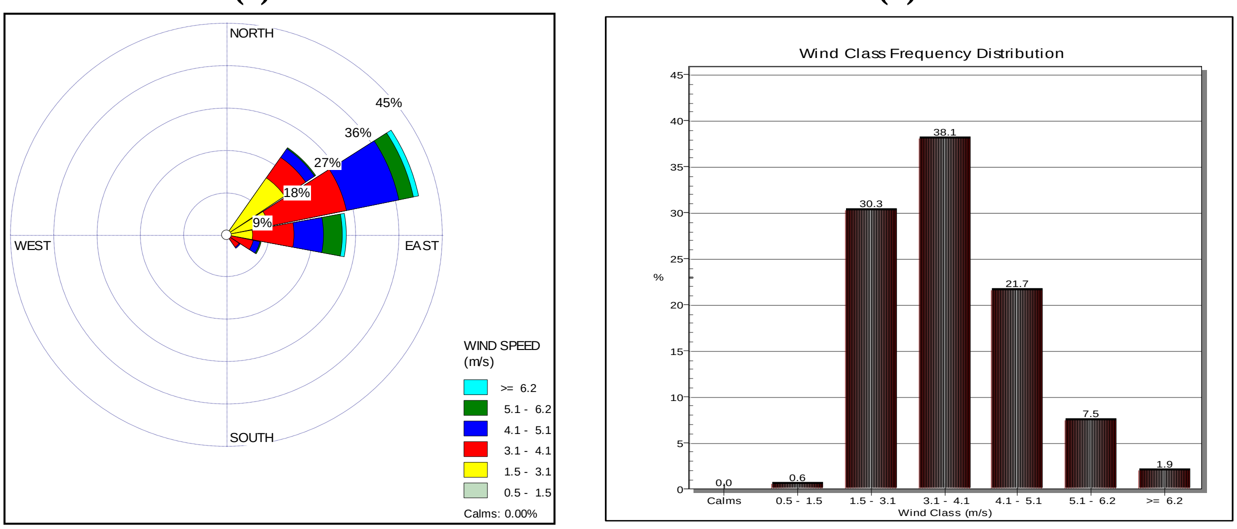

Figure 10: Lamu wind rose (a) and wind class frequency (b) for JFM

3.3 Seasonal variation of rainfall

The two distinct rain seasons over Nairobi are MAM and OND as shown in figure 11. April, May and June are the wettest months over Lamu as shown in Figure 11. There is only one wet season. For the rest of the year, most of the rainfall received is below 80mm.

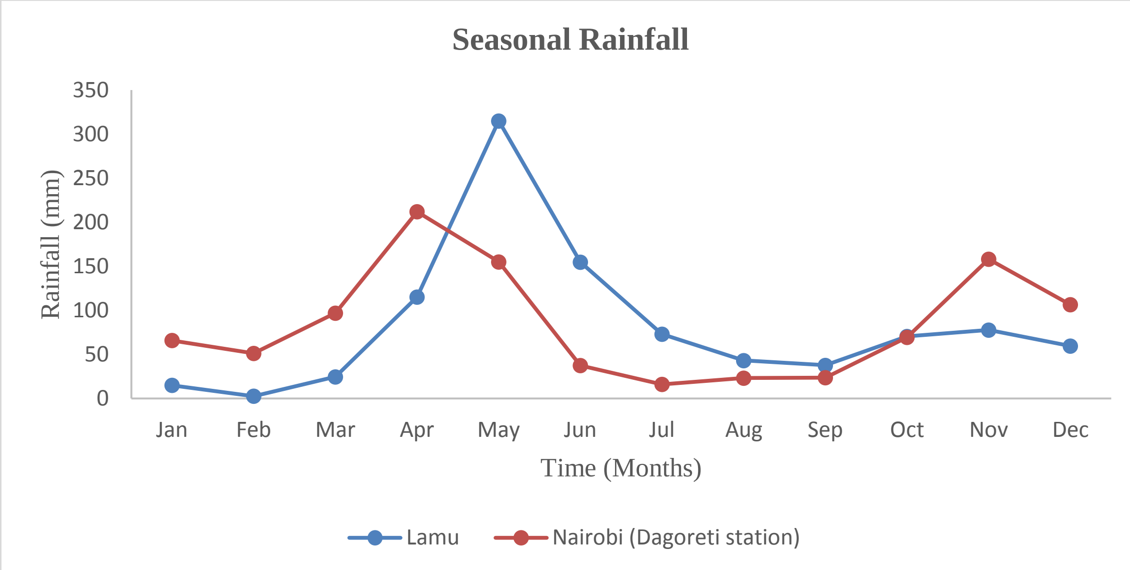

Figure 11: Graphs showing seasonal rainfall for Lamu and Nairobi (Dagoretti station)

3.4 Seasonal variation of Aerosols

From figure 12, the JJA season has the highest values of aerosol optical thickness. This coincides with the season having the lowest wind speed over Nairobi and the least rainfall amount. September to April season has the least values of aerosol optical thickness. This season coincides with the season with the highest wind speed over Nairobi. The months of January and February though dry with minimum rain wash and rain out activities have the least aerosols concentration. This is mainly because of the high wind speed during these months.

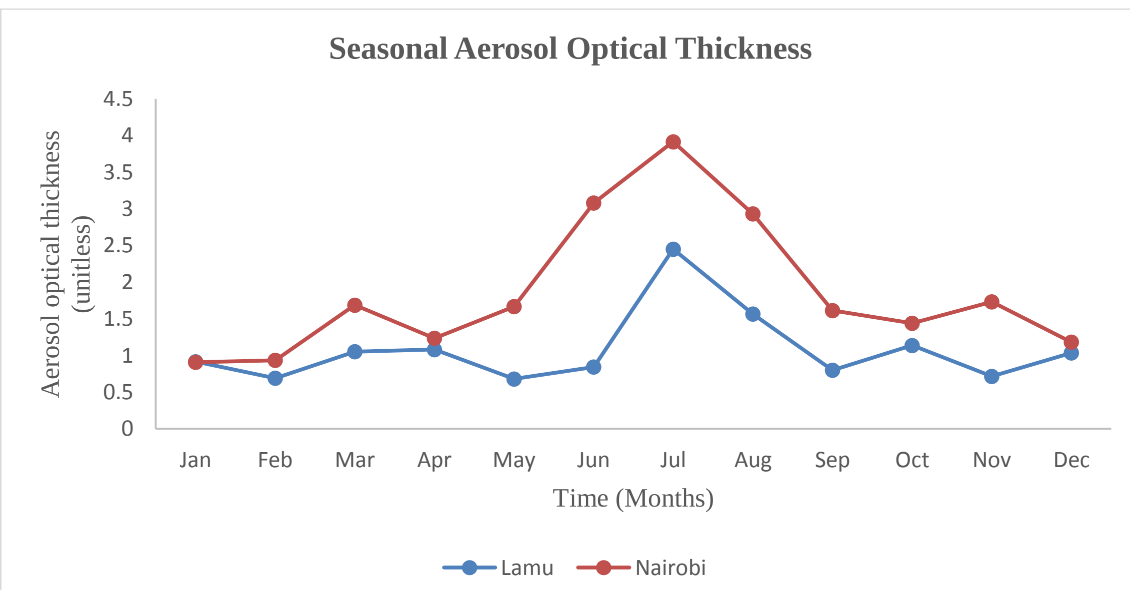

Figure 12: A depiction of monthly averaged values of aerosol optical thickness over Lamu and Nairobi

MAM has moderate aerosols despise the least wind speed experienced. The high amount of rainfall received during this season serves to clean the atmosphere. All the pixel points in the neighbourhood of Nairobi metropolis were found to have aerosol optical thickness less than that over city. South Eastern parts of Nairobi recorded considerably high values.

The months of July and August have the highest values of aerosol optical thickness over Lamu with a peak occurring in July (figure 12). September to June have the least aerosol values. Sea sprays significantly influence aerosols over Lamu and the coastal areas in general. Sea sprays refers to aerosol particles that are formed directly from the ocean, mostly by injection into the atmosphere by bursting bubbles at the air-sea interface.

It is worth noting that the highest values of aerosol optical thickness over Lamu occur during periods of high wind speed. The months of July and August were found to have high wind speed in Lamu. This is contrary to the case in Nairobi where the least values of aerosol optical thickness occurred during the season with high wind speed

3.5 Trend testing

This was done using the Welch two sample t-test at 95% confidence interval

Table 4: Welch t-test table for aerosol optical thickness trend for Nairobi and Lamu

Pixel point	**t-value**	**Lower tail**	**Upper tail**	**Inference**
Nairobi	-1.3998	-0.6865892	0.1733323	**Reject**
SW Nairobi	0.3872	-0.3353644	0.4641574	**Accept**
W of Nairobi	-0.4847	-0.2905662	0.1934524	**Reject**
NW of Nairobi	-1.4337	-0.6943441	0.1682099	**Reject**
SE of Nairobi	-0.3249	-0.4181527	0.3185052	**Accept**
Lamu	-3.1682	-0.31848749	-0.04061871	**Reject**
Kiunga	-1.1536	-0.3001729	0.1018412	**Reject**
Witu	-0.839	-0.3443604	0.1636725	**Reject**
Faza	-2.1629	-0.42346980	0.01460461	**Reject**

Most of the areas sampled indicate that there was a significant change in the mean of aerosol optical thickness for the period 2005-2014. With the exception of South West and South East of Nairobi, the rest of the areas portray an increasing trend in the aerosol optical thickness. The null hypothesis holds for South West and South East of Nairobi.

3.6 Association between Rainfall and Air pollution

This was done using monthly data for equal time periods i.e., from 2005 to 2013 for both rainfall and aerosol optical thickness. From figures13 and 14, aerosol optical thickness values decrease with increasing rainfall. The correlation coefficient between rainfall and aerosols over JKIA was found to be -0.1883164 while that for Lamu was -0.1146165 implying a negative relationship. Other factors such as the type of particles, size of particles, wind direction and speed and hygroscopic nature of the aerosols also play a role in the spatial-temporal distribution of aerosols.

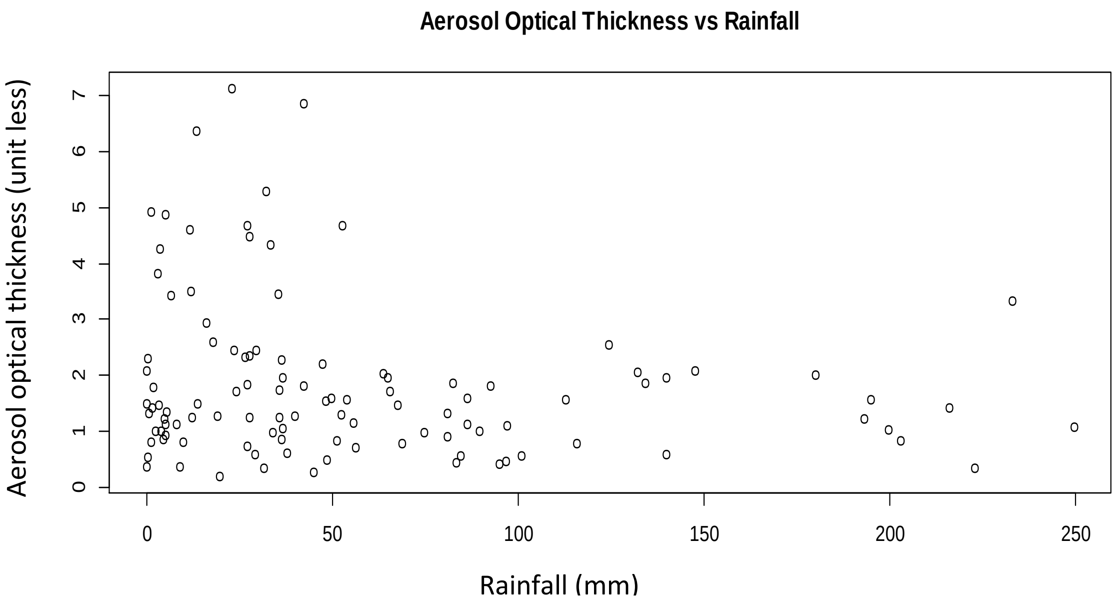

Figure 13: Scatter plot for Aerosol optical thickness vs Rainfall for Nairobi (JKIA station)

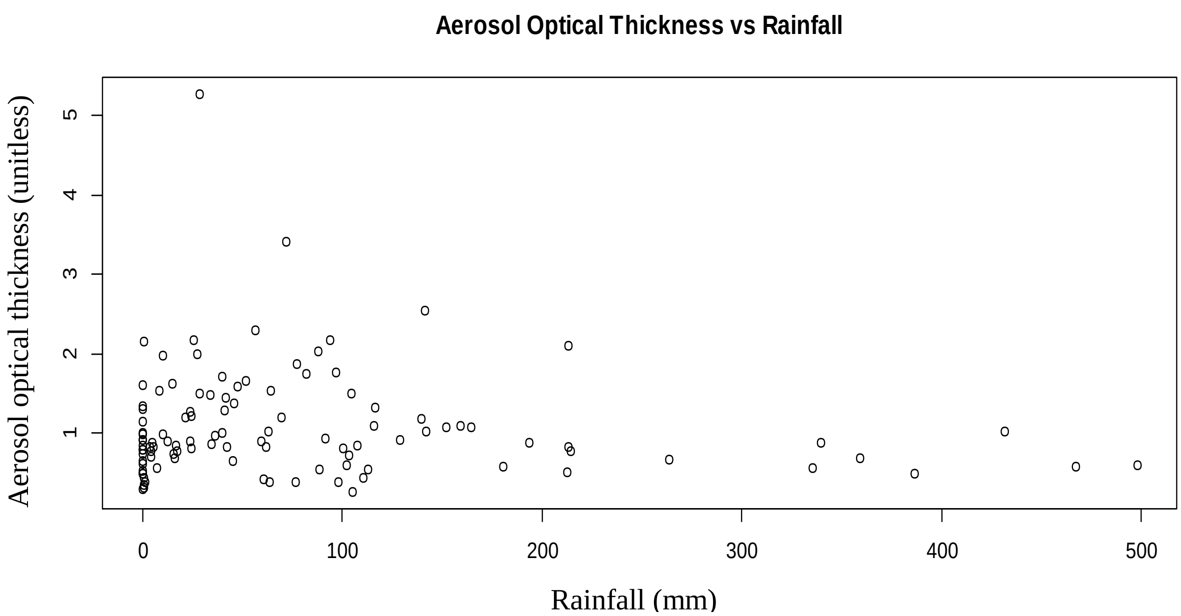

Figure 14: Scatter plot for Aerosol optical thickness vs Rainfall for Lamu

4. Conclusion

This study utilized a total of 20 stations and 5 dataset. Air pollution exhibited seasonality with high pollution levels during the JJA season mainly due to low wind speeds and little rainfall during this season. January and February had the least values of aerosol optical thickness thus low pollution levels due to high wind speed during these months while MAM and OND had moderate. Rainfall and air pollution portrayed a negative relationship which was found to be significant. The typical range of wind speed over Nairobi was found to be 2.1-4.1m/s. Compared to its surrounding, the pollution levels in Nairobi due to aerosols were high. This is as a result of urbanization in Nairobi. South Eastern parts of the city were found to have high values of aerosol optical thickness compared to other surrounding areas.

Pollution levels over Lamu were lower compared to Nairobi with high values of aerosol optical thickness being recorded over Witu division to the south west. Seasonally, the months of July and August were found to have high pollution levels despite experiencing the highest wind speeds. Rainfall over Lamu has only one peak during the AMJ season. Rainfall did not portray a significant relationship with air pollution since wind speed is the main factor affecting air pollution over the coast. The most frequent winds were South easterlies and easterlies. The wind speed is relatively higher compared to Nairobi implying faster dispersion and dilution of pollutants in the down wind direction. The typical range of wind speed was 2.1-5.1 m/s. Variation of wind direction is more pronounced possibly due to land-sea breeze. These findings form a benchmark for the maintenance of low aerosol pollution levels in Lamu as the city grows.

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