Ongoma et al., 2014, 1:10
Journal of Environmental and Agricultural Sciences
ISSN: 2313-8629

Research Article **Open Access**

An investigation of the transport and dispersion of atmospheric pollutants over Nairobi City

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Abstract: Current rapid deterioration of air quality in most urban can be majorly attributed to ongoing urbanization. This study simulates air pollutant dispersal over Nairobi city using Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model, considering a case for emission of Total Suspended Particles (TSP) into the environment. The wind climatology was established using Wind Rose Plot (WRPlot) view. The predominant wind speed over the city is 4-6 knots and the wind direction is easterly. The forward trajectory of a pollutant released in the city is generally observed to flow to the western side of the city. The pollutant is observed to be dispersed beyond 100 km from the city reducing the concentration of the same in the city. The study recommends for a consultative planning process of the city that factors in the wind characteristics over the city; most industrial activities should be located to the extreme western side of the city to minimize concentration of pollutants over the city. The study further recommends research to be carried out for a longer period of time to ascertain the quality of rain water during the long rain season. This calls for accurate observation and monitoring of pollution levels over the city and other cities in the country.

Key words: City planning, environment, HYSPLIT, Nairobi, total suspended particles, urban pollution

Received: September 09, 2014; **Revised:** October10, 2014; **Accepted** November 20, 2014, Online November 30, 2014

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1. Introduction

The concentration and transport of pollutants varies on spatial and temporal scales depending on the sources of pollutants, the prevailing meteorological conditions and the topographical features in the surrounding (Li et al., 2014; Steffens et al., 2013; Habeebullah, 2013; Mayer, 1999). Wind, rainfall, air temperature and relative humidity are of high significance to transport and dispersion of pollutants from one locality to another. The effects of air pollution vary depending on the nature of the pollutant and the exposure to it. According to a report by UNEP/WHO (1992), most respiratory and eye diseases are closely linked to air pollution. The vulnerability of those exposed to the pollutants varies depending on a number of reasons, among them being exposure (Cassiani et al., 2013). WHO (2006) points out that the most vulnerable are the elderly and the young and those with lung and heart conditions.

Although some air pollutants get way into the atmosphere through natural occurrences such as volcanic eruptions and wind soil erosion, emissions associated with anthropogenic activities have become worrying in the recent past (Sharma and Kulshrestha, 2014; Wang et al., 2014; Tolis et al., 2014; Bandyopadhyay, 2010; Gurjar et al., 2008; Singh et al., 2006; Wahid, 2006; Viana et al., 2006; Reddy and Venkataraman, 2002). Anthropogenic activities are more in developed nations as compared to developing ones; they mainly concentrated in industrial zones and urban areas. Air pollutants, primarily particulate matter (PM), sulphuroxide (SO_x) and nitrogen oxide (NOx) compounds result in acid rain that can degrade ecosystem and manmade structures (Cheng et al., 2007).

Most of the air pollutants occur naturally in the atmosphere and are harmless at low concentrations. Rao (1991) reported that the pollutants become harmful when their concentrations are relatively high compared to the background value. According to Andreae (2001), the radiative effect of atmospheric aerosols is believed to be of the same magnitude as greenhouse gases. Similarly, other aerosol components such as black carbon (BC) are known to have a warming effect on global climate (Babu et al., 2002).

According to Schneider et al., (2009), approximately 50% of the global population currently resides in urban areas despite the fact that the urban areas constitute less than 1% of the Earth's land surface. Unfortunately, most developing countries especially in Africa don't have air quality monitoring systems in place despite having the very fast growing urban populations and industrialization. Nairobi city is an example of the cities that lack continuous and reliable air quality monitoring system; measurements of air pollution are done on need basis, especially for research. A study by UN on the management of air quality over Nairobi ranked the city's capacity as the poorest among 20 mainly developing country cities sampled (UNEP/WHO, 1996). A study by Mulaku and Kariuki (2001) showed that total suspended particulates (TSP) in Nairobi, is above World Health Organization (WHO) recommended pollutant concentration levels in most parts of the City. This is alarming for both short and long term forecasting and management of air pollutants in the atmosphere to help in the mitigation of effects associated with them, an observation made by Kolehmainen (2004).

Nairobi is the Kenya's capital located within latitude 1° 9' - 1° 28'S and longitude 36° 4' - 37° 10'E (Fig. 1). The city is approximately 684 km^2 in area and has a population of approximately 3.1 million people (KNBS, 2010; Mitullah, 2003). The City has various iconic features including Ngong Hills, Nairobi national park and indigenous Karura forest.

Emissions from vehicles are among the main sources of air pollution in Nairobi City just like in many other cites globally. A study in India by Gupta and Kumar (2006) showed that diesel engines have significant contribution to fine PM and chemicals that adversely affect human health, the same observations are made by Baltrenas (2014). Nairobi residents are equally endangered by the emissions from an open dumpsite located in Dandora; it occupies about 30 acres of land, 8 km away from the city centre. Commercial activities in the city are concentrated mainly within the city whereas most of the industrial activities are located to the southeast.

The predominant winds over the city are easterlies; they are associated with precipitation occasioned by moisture inflow into the country from the Indian Ocean (Opijah et al., 2007; Ongoma et al., 2013). Nairobi experiences just like most places over the entire country and the entire east Africa region at large receives bimodal rainfall regime with 'long rain' season in the months of March to May (MAM) and 'short rains' coming in October to December (OND) (Owiti and Zhu, 2012; Camberlin and Philippon, 2002; Opijah et al., 2007; Okoola, 1996). The other seasons are the cold season (JJA) and the hot season (DJF). The observed rainfall pattern is associated with the seasonal migration of Inter-Tropical Convergence Zone (ITCZ) owing to the movement of the over head sun (Asnani, 1993; Okoola, 1996).

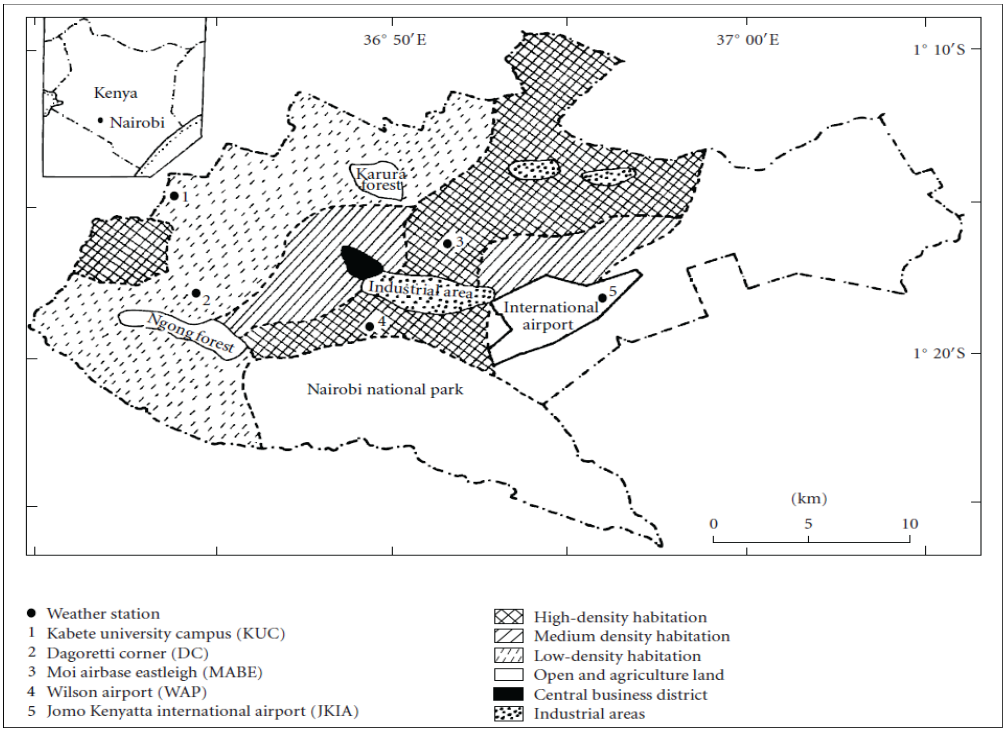

Fig 1 : Positions of weather stations and land use in Nairobi (Source: Makokha and Shisanya, 2010).

This paper simulates possible distribution of air pollutants in case of an accident and/or emission of pollutant from the city.

2. Methodology

The wind climatology was established using Wind Rose Plot (WRPlot) view, considering hourly average wind speed and direction over for 12 years; 2001-2012. The software is program that runs in windows to generate wind statistics and plots for a given meteorological station within a specified time span (Lakes Environmental, 2000). It has a frequency count that displays the number of occurrences of winds in tabular form in each of sixteen direction sectors and 6 wind speed classes for a given location and time period. It also has a frequency distribution tab which gives a table displaying the frequency of wind occurrences in each compass direction and six wind speed classes.

The daily wind roses, forward trajectories, and concentration and distribution of pollutants were done with the aid of Hybrid Single-Particle Lagrangian Trajectory (HYSPLIT) model, described in detail by Draxler and Rolph (2013).

HYSPLIT model is a computer-based air pollution modeling package used for modeling and can provide an accurate representation of air pollution levels. According to Draxler and Rolph (2013), the model computes both simple and complex air parcel trajectories and dispersion. The system also simulates pollutant deposition. In this case, hybrid between Lagrangian and Eulerian approaches is used. The calculation of the concentration of the pollutant is done on a fixed grid. The output results from the simulation results are complex contoured pattern for concentration of air pollutants.

Calculations are performed on archive meteorological data from the runs the Global Data Assimilation System (GDAS) operated by United States (US) National Centers for Environmental Prediction (NCEP). GDAS is run four times in a day; at 0000, 0600, 1200, and 1800 Universal Coordinated Time (UTC). The output of the model is mainly for the analysis time and 3, 6, and 9-hour forecasts. The NCEP post-processing converts the data from spectral coefficient form to 1 degree latitude-longitude (360 by 181) grids. The output of the model is in GRidded Information in Binary (GRIB) format. The data that is finally archived is in synoptic time order and does not have missing records. It is thus possible to position without any order to any location within a data file Wind circulation patterns determine the transport and dilution of air pollutants. Representative dates for each season were chosen corresponding wind frequency patterns computed using wind roses. Table 1 presents the four climate seasons over the city of Nairobi.

The pollutant concentrations are calculated on a fixed grid. Simulation output results are complex air concentration contour patterns. Calculations are performed on archive meteorological data from the runs the Global Data Assimilation System (GDAS) run by United States National Weather Service's National Centers for Environmental Prediction (NCEP). The GDAS is run 4 times a day, i.e., at 00, 06, 12, and 18 UTC. Model output is for the analysis time and 3, 6, and 9-hour forecasts. The NCEP post-processing of the GDAS converts the data from spectral coefficient form to 1 degree latitude-longitude (360 by 181) grids and from sigma levels to mandatory pressure levels. Model output is in GRIB format. The archive data file contains the data in synoptic time sequence, without any missing records. Therefore it is possible to position randomly to any point within a data file.

Table 1. Seasons and their duration over Nairobi city

Season	Months
Hot Season	December–January–February (DJF)
Long Rain	March –April–May (MAM)
Cold Season	June – July– August (JJA)
Short Rains	September – October–November (SON)

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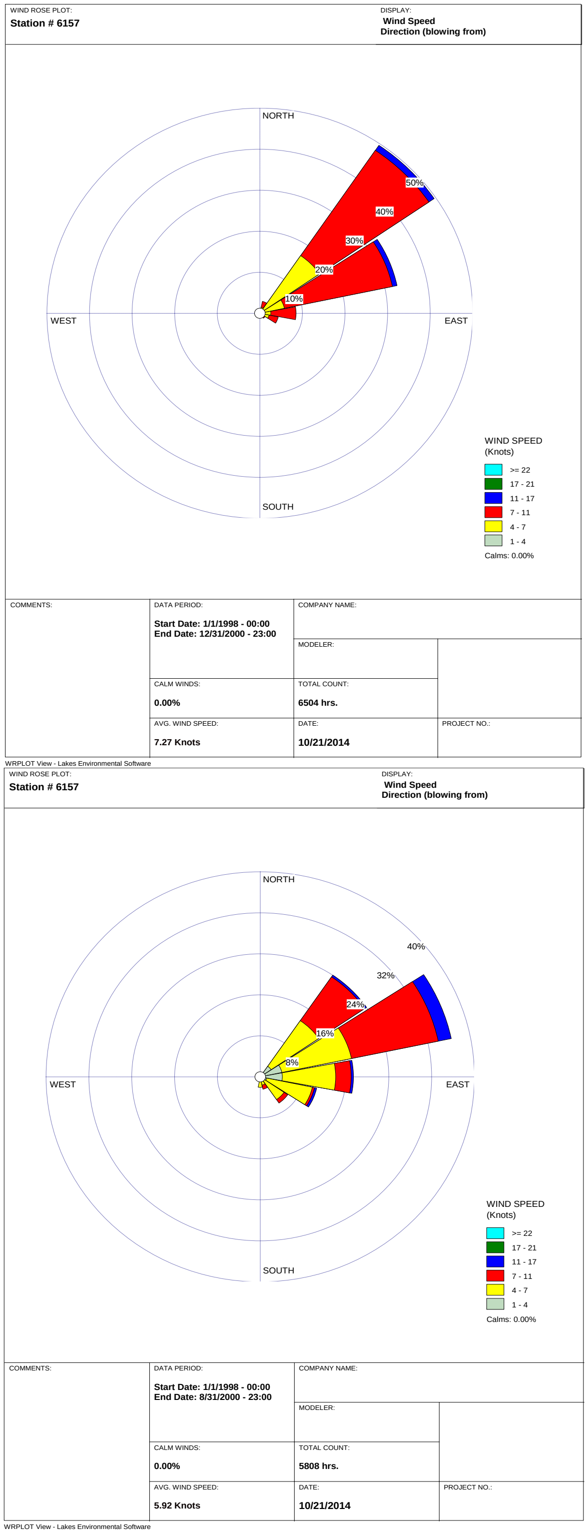
3. Results and Discussion

The predominant wind speed over the city is generally easterly; with the direction ranging from north easterly in DJF to south easterly in JJA (Fig. 2-3. The results are in agreement with previous studies (e.g. Opijah et al., 2007; Ongoma et al., 2013) which showed that easterlies are the dominant winds in January and November over Nairobi city.

(a)

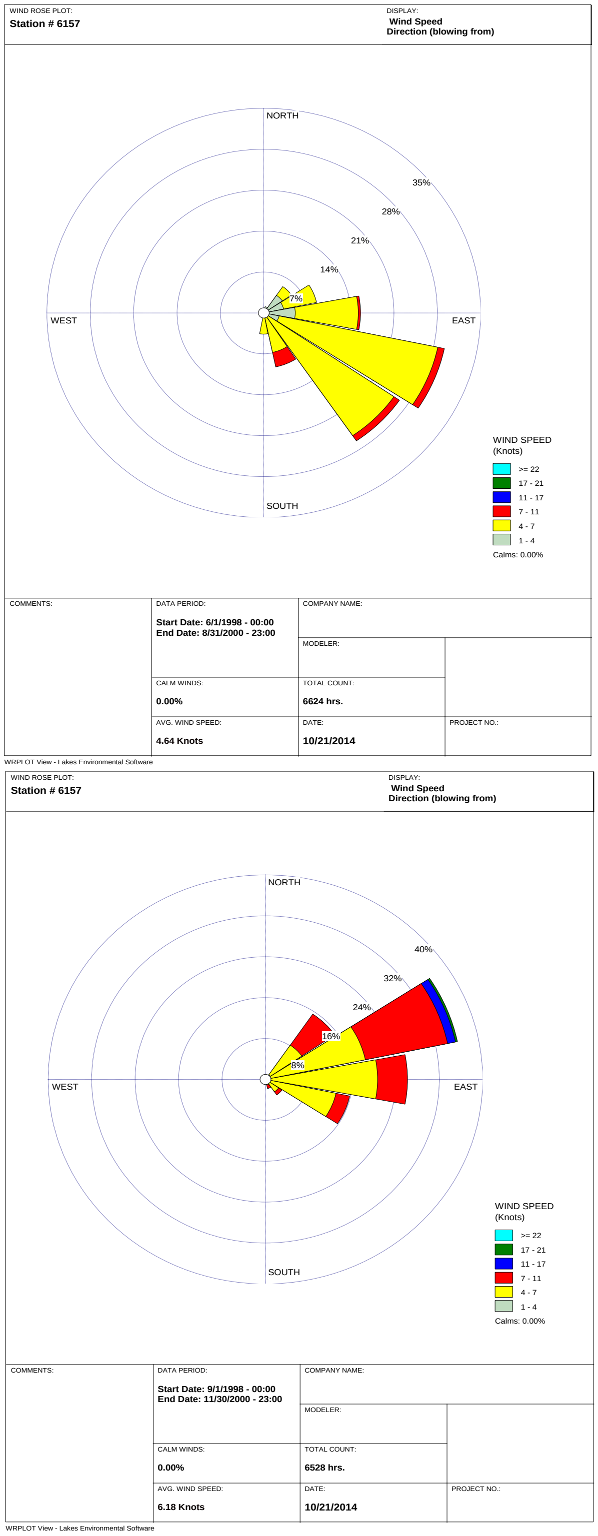


WIND ROSE PLOT: **Station # 6157**
DISPLAY: **Wind Speed Direction (blowing from)**
COMMENTS:
DATA PERIOD: **Start Date: 1/1/1998 - 00:00 End Date: 12/31/2000 - 23:00**
COMPANY NAME:
MODELER:
CALM WINDS: **0.00%**
TOTAL COUNT: **6504 hrs.**
AVG. WIND SPEED: **7.27 Knots**
DATE: **10/21/2014**
PROJECT NO.:

WIND ROSE PLOT: **Station # 6157**
DISPLAY: **Wind Speed Direction (blowing from)**
COMMENTS:
DATA PERIOD: **Start Date: 1/1/1998 - 00:00 End Date: 8/31/2000 - 23:00**
COMPANY NAME:
MODELER:
CALM WINDS: **0.00%**
TOTAL COUNT: **5808 hrs.**
AVG. WIND SPEED: **5.92 Knots**
DATE: **10/21/2014**
PROJECT NO.:

Fig 2: Frequency wind rose for (a) December-January-February (DJF) (b) March-April-May (MAM)

(b)



WIND ROSE PLOT: **Station # 6157**
DISPLAY: **Wind Speed Direction (blowing from)**
COMMENTS:
DATA PERIOD: **Start Date: 6/1/1998 - 00:00 End Date: 8/31/2000 - 23:00**
COMPANY NAME:
MODELER:
CALM WINDS: **0.00%**
TOTAL COUNT: **6624 hrs.**
AVG. WIND SPEED: **4.64 Knots**
DATE: **10/21/2014**
PROJECT NO.:

WIND ROSE PLOT: **Station # 6157**
DISPLAY: **Wind Speed Direction (blowing from)**
COMMENTS:
DATA PERIOD: **Start Date: 9/1/1998 - 00:00 End Date: 11/30/2000 - 23:00**
COMPANY NAME:
MODELER:
CALM WINDS: **0.00%**
TOTAL COUNT: **6528 hrs.**
AVG. WIND SPEED: **6.18 Knots**
DATE: **10/21/2014**
PROJECT NO.:

Fig 3: Frequency wind rose for (a) June-July- August (JJA) (b) September, October, November (SON) 2013

Table 2: Observed seasonal wind climatology over Nairobi

Season	Prevailing wind Direction (Frequency)	Prevailing wind Speed (knt)
Hot Season	East North East (ENE)	7-11
Long Rain	East North East (ENE)	7-11
Cold season	East South East (ESE)	4 - 7
Short Rains	East South East (ESE)	7 – 11

Table 2 presents the summary of the observed seasonal wind climatology. The wind speed over the city ranges from 4 – 11 knots.

Representative dates of each season used in this study were chosen as the 15th day of the second month of the season (Table 3), with each giving a good representation of the season (Figs. 4 -5).

Table 3: Representative dates for the seasons

Season	Representative Date
Hot Season	January 15, 2013
Long Rain	April 15, 2013
Cold season	July 15, 2013
Short Rains	October 15, 2013

The wind roses representing the four seasons within the period of January 2013 to December 2013 display the prevailing wind speed and direction during each of the seasons (Figs. 4-5). The results of Figs. 4 and 5 are summarized in Table 4.

Table 4: Seasonal representative wind speed and direction from HYSPLIT over Nairobi in 2013

Season	Prevailing wind Direction (Frequency)	Prevailing wind Speed (knt)
Hot Season	ENE	4 - 6
Long Rain	ENE	4 - 6
Cold season	ESE	4 - 6
Short Rains	ESE	7 - 10

The wind flow over the city throughout the year (Figs. 4-5) has an easterly component making easterlies to be dominant over the city in agreement with the climatology. The winds speed as well (Table 2) ranges from 4-10 knots, in agreement with the wind climatology (Table 2). Figs. 4 and 5 illustrate wind roses computed using gridded model data for Nairobi within the meteorological model domain.

It may be observed from the four wind roses that the pollutant introduced into the atmosphere over the city will be transported and dispersed to the southwest and northwest of the town. The wind speed over the city is 4-11 knots. However, most studies indicate that urbanization is likely to reduce wind speed over the cities (e.g. Ongoma et al., 2013; Shepherd, 2005). This poses a threat on the future of the air quality over the city.

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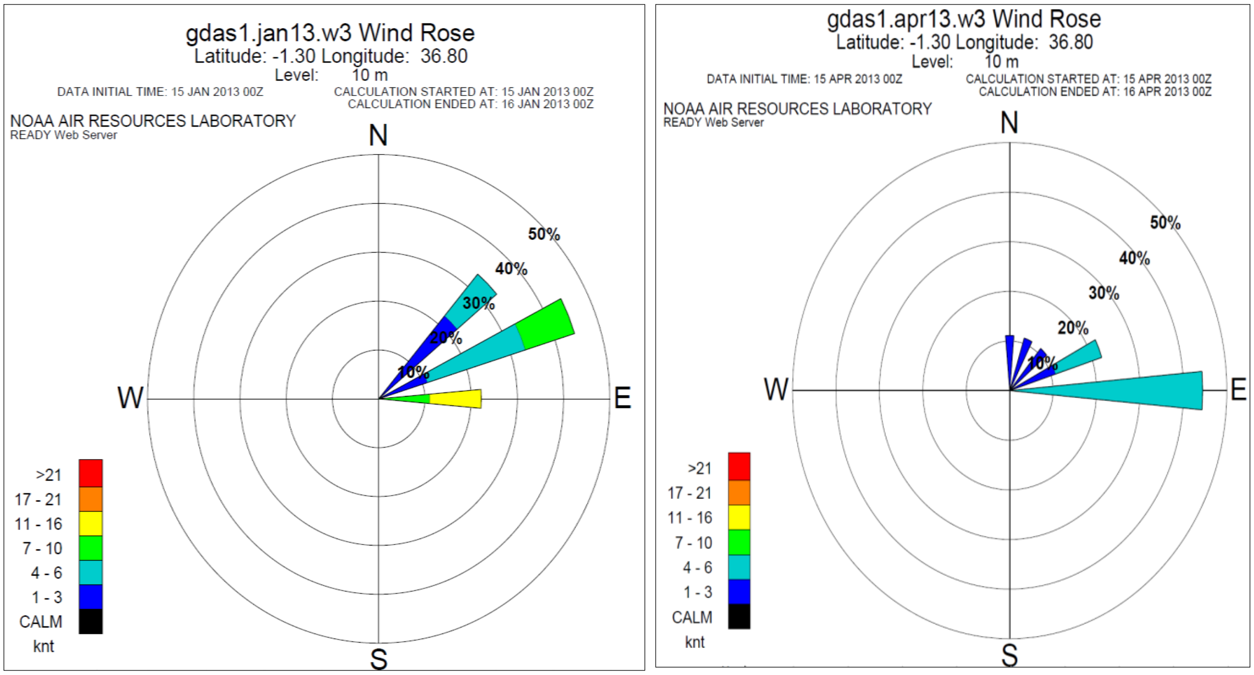
Forward trajectories for the respective seasons are presented in Figs. 6 and 7. The transfer of pollutants emitted over the city is generally observed to be to the western side of the city except for the cold season during which the flow from the city is towards the north east.

Simulation of pollutant concentration and dispersal was done considering a case of TSP. The background pollution levels were assumed to be high with respect to the recommended mean value by WHO. The mean value of 90 µg/m^3 recommended by WHO is exceeded by more than a factor of 2. The pollutant release quantity was 180 µg/m^3 starting at 00:00 UTC for duration of 1 hour. Pollutant averaging/integration period was 1 hour. The dry deposition rate was 0 cm/s while the release height was 10 m. The pollutant is observed to be transported beyond 100 m throughout the year. Figs. 8 and 9 display the pollutant dispersal while Table 5 presents a summary of the results.

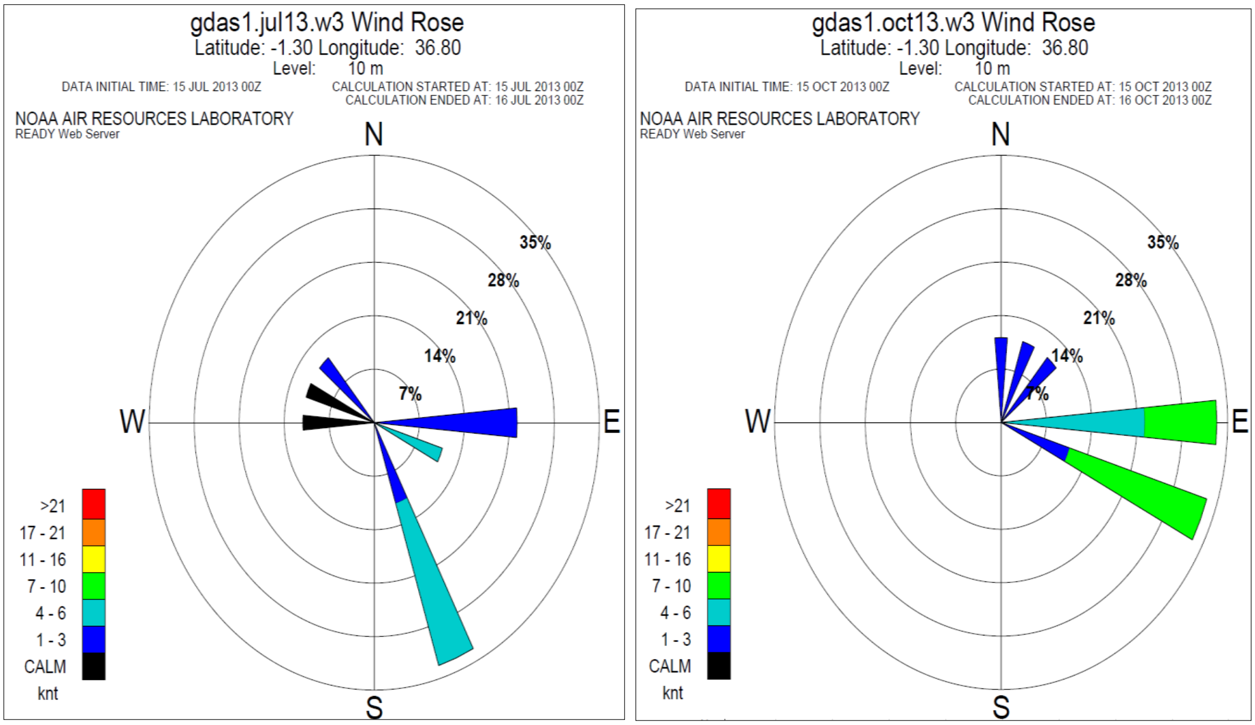
The pollutant is observed to be transported beyond 100 m throughout the year. In consistence with the trajectories during the cold season (Fig.7a), the dispersal of pollutants is observed to be in the north eastern direction (Fig. 9a). The dispersal is observed to be furthest during the DJF and JJA seasons and least during the MAM and SON seasons (Fig. 8 -9). This may be attributed to strong monsoon winds that blow over the country during the DJF and JJA (Omeny et al., 2008; Kalapureddy, 2007; Okoola, 1999).

This implies that the concentration of pollutants in the atmosphere during the two rainy seasons is likely to be higher than what is observed in dry and cold seasons. However, wet deposition due to the precipitation occurring during rain seasons is likely to reduce atmospheric pollutants from atmosphere in the locality (Kaskaoutis et al., 2010).



(a) (b)

Fig. 4: Frequency Wind Rose for (a) January 15, 2013, (b) April 15, 2013



(a) (b)

Fig. 5: Frequency Wind Rose for (a) July 15, 2010, (b) October 15, 2010

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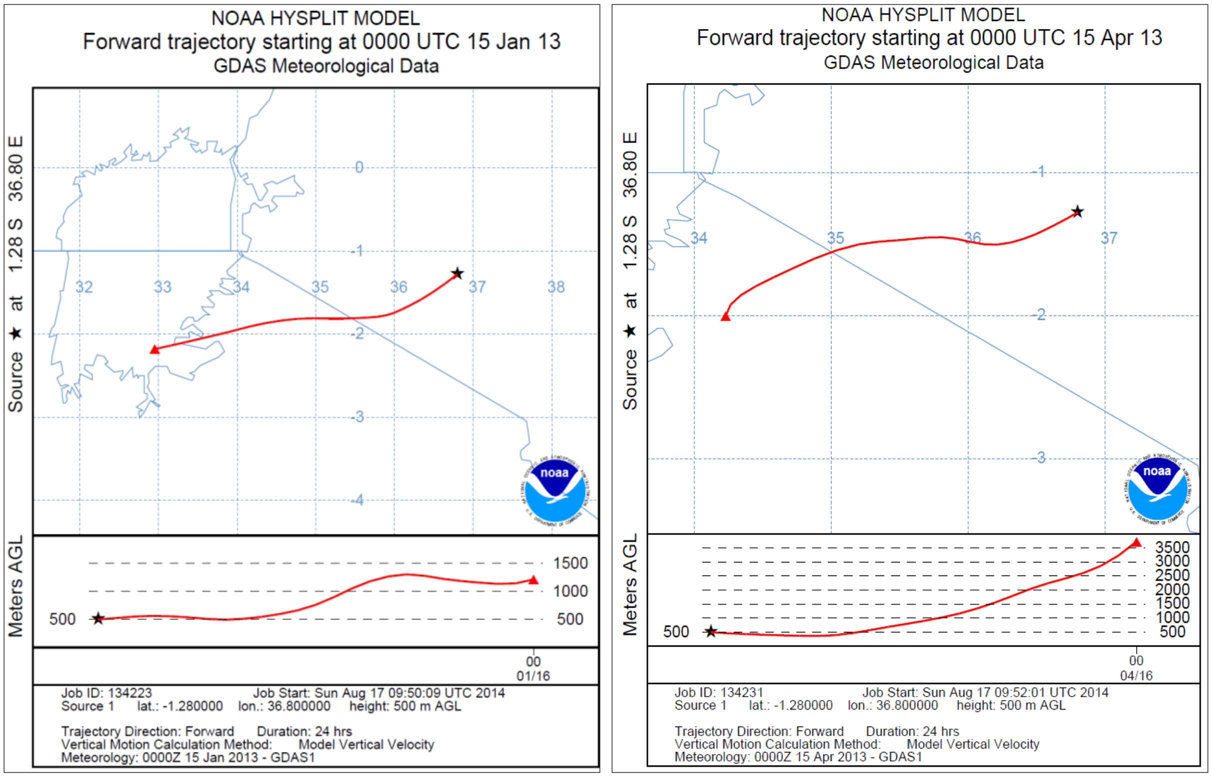
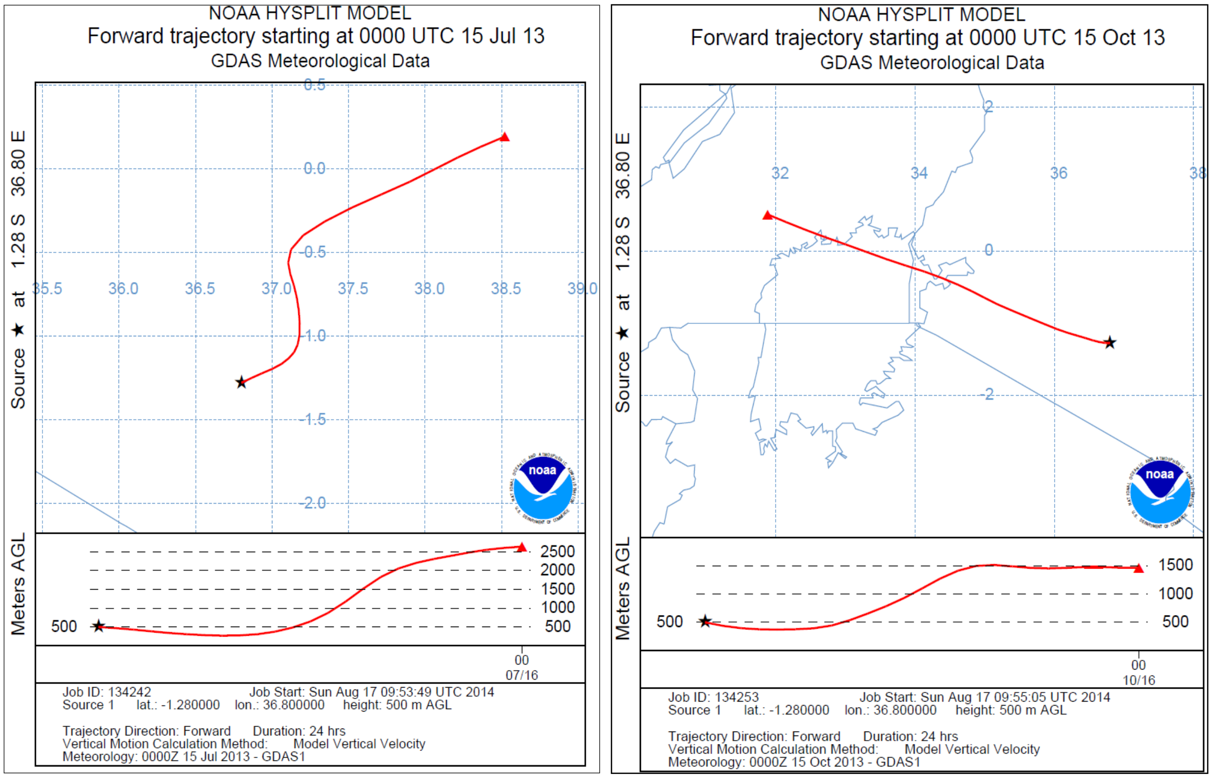


(a) (b)

Fig. 6: Trajectories for (a) January 15, 2013, (b) April 15, 2013



(a) (b)

Fig. 7: Trajectories for (a) July 15, 2013, (b) October 15, 2013

Table 5: Simulations of Pollutant Dispersal and Concentration

Season	Centre line concentration (in mg/m^3) at the ground level downwind at different distances					
	10 km	20km	30km	40km	50 km	60km
Hot Season	1x10^{-13}	1x10^{-13}	1x10^{-13}	1x10^{-13}	1x10^{-14}	1x10^{-13}
Long Rain	1x10^{-13}	1x10^{-13}	1x10^{-13}	1x10^{-14}	1x10^{-14}	1x10^{-14}
Cold season	1x10^{-14}	1x10^{-14}	1x10^{-14}	1x10^{-14}	1x10^{-14}	1x10^{-16}
Short Rains	1x10^{-13}	1x10^{-13}	1x10^{-14}	1x10^{-14}	1x10^{-14}	1x10^{-14}

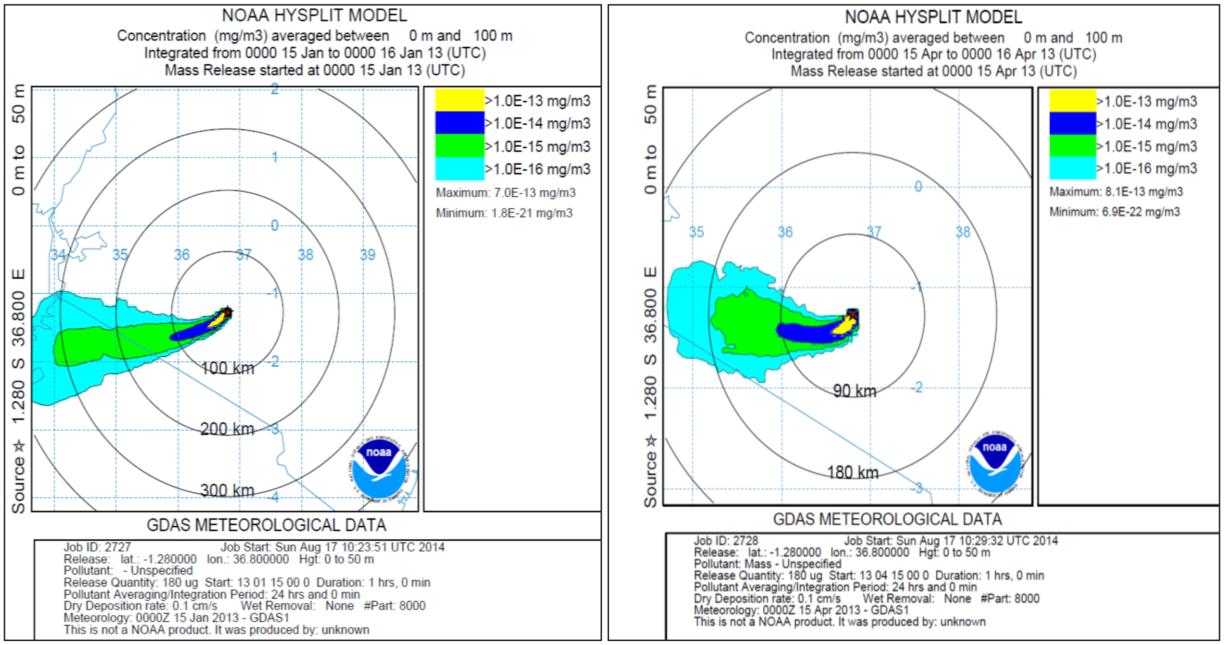


Fig. 8: Pollutant concentration (a) January 15 2013, (b) April 15 2013

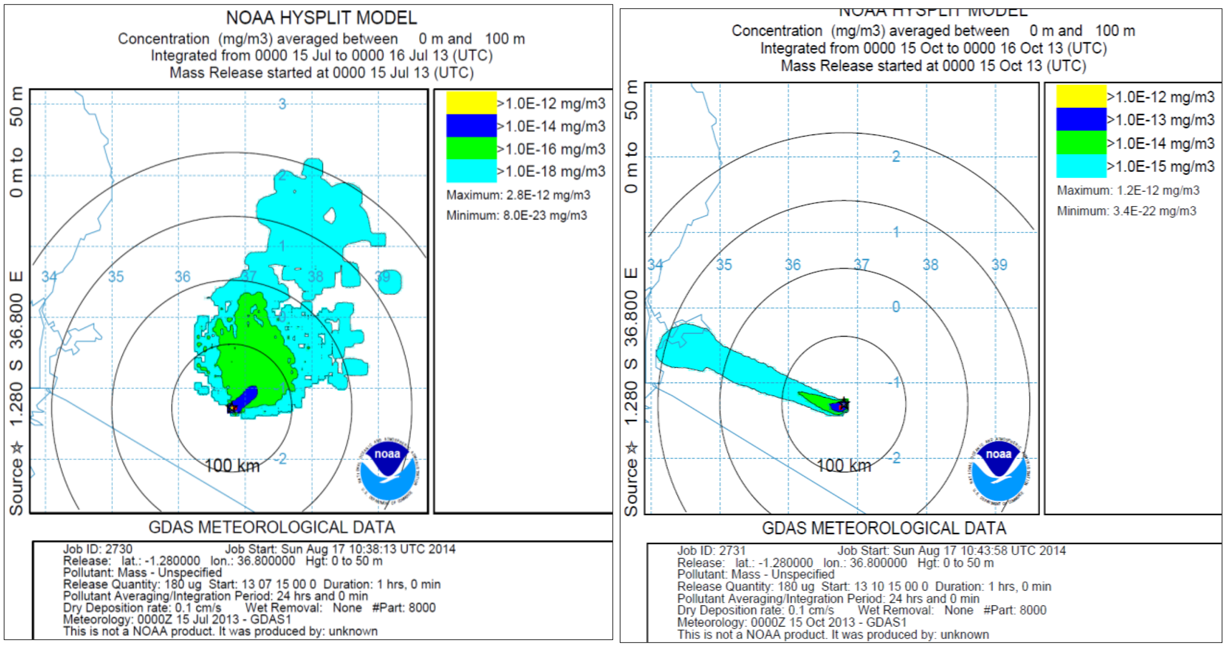


Fig. 9: Pollutant concentration (a) 15 July, 2013, (b) 15 October, 2013

4. Conclusion

The prevailing winds in Nairobi city are mainly easterlies implying that the pollutants will mainly be transported to the southwest and northwest of the town. The forward trajectories generally show an easterly flow of pollutants emitted within the city throughout the year. The pollutants are dispersed beyond 100 km within one hour with the least dispersion occurring during the long rain season. However, the interactions between different spatial and temporal scales play a major role in determining the flow structure over the urban canopy in densely built environment. The intense surface in-homogeneities equally generate intense temporal in-homogeneities calling for specific space and time monitoring of flow and pollutant concentration. The study thus recommends for a consultative planning process of the city that accounts for the observed wind characteristics over the city. For instance, most industrial activities should be located to the extreme western side of the city to minimize concentration of pollutants over the city. The study further recommends that more research especially for a longer period of time be carried out to ascertain the pollutant concentration and quality of rain water during the long rain season. This calls for accurate observation and monitoring of pollution levels over the city and other cities in the country.

Acknowledgement

The Authors express their sincere thanks to our host institutions for continuous encouragement and support. Special thanks to Kenya Meteorological Department and NCEP for the provision of data used in the study.

Competing Interests

Authors declare that there is no potential conflict of interest.

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Cite this article as: Ongoma et al., 2014. **An investigation of the transport and dispersion of atmospheric pollutants over Nairobi City**. *Journal of Environmental and Agricultural Sciences*. 1:10.