Original Research Article

TEMPORAL AND SPATIAL VARIABILITY OF TROPOSPHERIC OZONE IN NAIROBI CITY, KENYA

ABSTRACT

In both developed and developing nations urban air pollution is increasingly being recognized as a major public health and environmental issue. Poor or deteriorating air quality in many cities results from high levels of energy consumption by industries, transport and domestic use. The nature of air pollution is dependent on the source profile of the city and the presence of sunlight to promote production of secondary pollutants, such as ozone, through photochemical reactions. The study sought to analyze the surface ozone over Nairobi city, and identify the source of the surface ozone. Nairobi city is one of the fastest growing industrial and economic hubs in East Africa. Increased population which results in increased production and transport activities is therefore expected to increase the surface Ozone which is likely to cause a lot of negative effects to both fauna and flora beings. Surface ozone data for Nairobi was obtained from Kenya meteorological department ranging from 2011 to 2014; another set of data was collected from four sampling sites to determine the special variability and source of the surface ozone over Nairobi area. Analysis meteorological field from National Centre for Environmental Prediction -National Centre for Atmospheric Research (NCEP- NCAR) was used in running Hybrid Single Particle Lagrangian Integrated (HYSPLIT) model. From the analysis it was found out that June July August experiences the highest ozone levels as compared to the other months of the year in both lower and upper levels. This is due to incursion from the south according to the backward trajectories from the HYSPLIT model, which has been proven to have high ozone concentration during this season due to high biomass burning. On the other hand, the diurnal variation of ozone in the four site: Industrial area, Nakumatt Junction, Landhies road and Pangani Round about showed low amount in the early morning and at night hours, with the peak realized during the day. The peak in midday is due to the fact that surface ozone is produced by photochemical oxidation of precursor gases that are produced by motor vehicle and industries. The highest eight-hour mean was 20.2 ppb from Industrial area site, which is below the WHO mean of 51 ppb. Therefore, no much health effects are expected due to the exposure to ozone. This study recommended that there should be a continuous monitoring of ozone and other gases that are harmful to human health for better understanding and advice to the citizen.

Keywords: Temporal variability, Spatial Variability, Tropospheric Ozone, Surface Ozone, Nairobi City.

1. INTRODUCTION

Ozone (O_3) is one of the most important trace gases in the Earth's atmosphere. It is naturally present in our atmosphere and is a critical atmospheric trace species in the stratosphere and troposphere. Most O_3

resides in the stratosphere where it traps the Ultra Violet (UV) rays making it a greenhouse Gas (GHG). The region between 20 and 40 km, where most atmospheric O_3 is located, is commonly referred to as the ozone layer [1].Ozone is one of the most important chemical species involved in atmospheric chemistry, owing to its role in oxidizing many atmospheric trace species and its potential impact on the environment (chemical oxidation capacity, health, greenhouse effect and vegetation) [2, 3].

Great concern has always been attached to the elevated tropospheric ozone concentrations, particularly in densely populated urban and suburban areas. Photochemical ozone formation involving its chemical precursors and ozone transport from upwind air are the two major anthropogenic sources of ozone in rural and urban areas [4, 5]. Ozone at ground level, poses adverse impacts on plants and animal even at low concentration [6]. Unfortunately, ozone distributions within the troposphere are not sufficiently well researched and increasing trends in average tropospheric ozone concentrations remain a matter of discussion [7, 8, 9]. The budget, and therefore the trend of tropospheric ozone are highly dependent on precursor emissions into the atmosphere of carbonaceous and nitrogenous precursors [10, 11] occurring mainly in the boundary layer. Human activities contribute significantly to increased levels of certain precursors in relation to natural sources.

Over years, GHGs have increased. World Meteorological Organization (WMO), estimates that tropospheric O_3 has increased by 36% since 1750 [12]. CO_2 has grown by about 40% of its pre-industrial period; when its concentration was about 280 parts per million volume (ppmv) of dry air to a concentration of 389 ppmv by 2010 [13]. On the other hand, CH_4 has grown by about 150% to about 1780 parts per billion volumes (ppbv) of dry air. These increases have been as a result of increase in human activities; fossil-fuel combustion, cement manufacturing, transportation and deforestation. High smoke aerosol and enhanced tropospheric O_3 concentrations have been observed over the adjacent Atlantic Ocean [14, 15, 16, 17], where strong ozone-biomass burning links have been confirmed by airborne and ship-based measurements [18, 19, 20]. It is evident that the highest values of tropospheric ozone were over the Atlantic Ocean, adjacent to the heavy biomass burning areas of Africa and Brazil. Vertical O_3 measurements during SAFARI- 92/TRACE-A showed that this ozone enhancement over the mid-Atlantic occurred in an elevated mid-tropospheric layer, between 2 and 10 km altitude [15, 16].

Kenya Meteorological Department (KMD) monitors the concentration of house gases (GHG) at various sites in Kenya as one of its functions. The monitored GHGs include O_3, carbon dioxide (CO_2), carbon monoxide (CO), aerosols and particulate matter of different sizes. For almost six years, KMD only monitored vertical profiles and total column ozone using ozonesonde soundings and a Dobson spectrophotometer instrument. Since July 2012, KMD installed surface ozone analyzers specifically to measure ozone values at 10 m above the ground. In general, ozone has not been much recorded for a long period of time and with very few stations monitoring ozone, but it needs to be better understood since an increasing number of people around the world will be living in urban environments within the tropics, and there is possibility of increased negative health effects caused by increase surface ozone. This study therefore sought to (1) Investigate the spatial variation of surface Ozone over Nairobi city, (2) Investigate the temporal Surface Ozone distribution over Nairobi city and, (3) Identify the source regions of surface Ozone observed over Nairobi city.

2. METHODOLOGY

2.1. Study area

The study was carried out in Nairobi (Figure 1). Nairobi is the capital city of Kenya and lies 200 km south of the Equator. It is located at approximately 1°9' S, 1°28'S and 36°4'E, 37°10'E. It occupies an area of about 696km^{2}and the altitude varies between 1,600 and 1,850 meters above Mean Sea Level (AMSL) [21]. The western part of Nairobi is on high ground (approximately 1700–1800 AMSL) with rugged topography while the eastern side is generally low (approximately 1600 AMSL) and flat [22]. Key physical features include the Nairobi National Park, Ngong hills, Mathare River and the indigenous Karura forest in the north side.

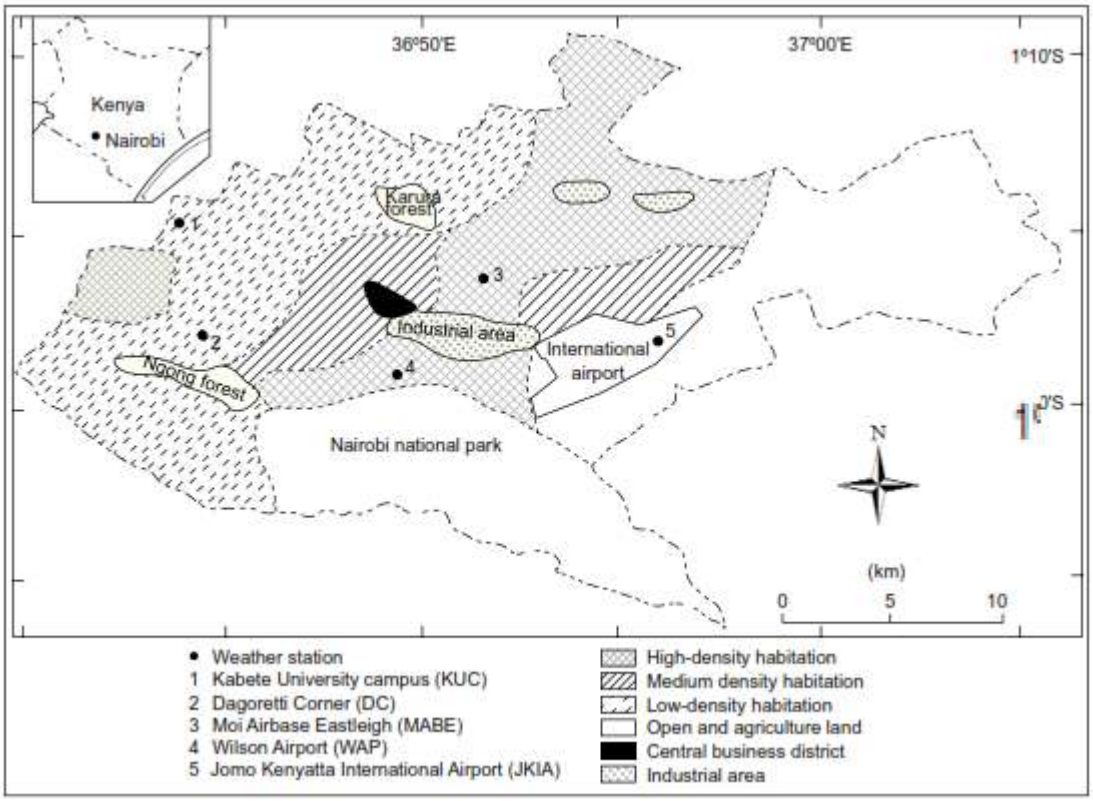


Figure 1: Map of Nairobi and its environs showing the study area. (Source: Makokha and Shihanya, 2010*)*

2.2 Climate of the study area

Nairobi experiences a moderate climate even though it is located along the Equator. At a height of about 1795 m above sea level, the city has a subtropical high climate according to the Köppen climate classification [23], as opposed to the expected tropical climate. The regional climate of East Africa is influenced by the seasonal displacement of the Inter-tropical Convergence Zone (ITCZ). The north–south–north annual shift of the ITCZ is driven by the apparent annual motion of the Sun and results in monsoon trade winds, which give rise to well-defined wet and dry seasons [24]. Severe changes in this cycle usually result in droughts or flooding in the East African region [12]. The average annual rainfall is

900 mm but varies from less than 500 mm to more than 1500 mm between years. The average daily temperature varies from 17° C in July and August to 20 °C in March [25].

2.3 Data collection

Data used in this study was partially collected from KMD while other sets of data were gathered from four sampling sites for data collection. The sites were designed to be at busy intersections or roundabouts (Ngong road, Landhies road and Pangani Roundabout) and a site in Industrial Area (Table.1).The four stations represented different locations with different intensity of human activities. The selection was done after a feasibility assessment that mapped out busy and potential monitoring sites considering witnessed traffic jams, possible elevated emissions and assessing the general prevailing meteorological conditions that influences pollution levels. The sampling was done in the month of December 2015 for ten days, 24 hours a day in each site. The data was collected every one minute using EcotechSerinus 10 gas analyzer for Ozone from Kenya Meteorological Department (KMD) and the meteorological parameters were measured by an automated weather observing stations.

Observed ozone data at KMD headquarter was also used. This data included; daily total column Ozone, measured by Dobson Spectrophotometer for a period of five years from 2011 to 2014. These were the years with complete data; weekly vertical Ozone profiles measured by Ozonesonde flights for the same period and Meteorological data (Rainfall and Temperature) for Dagoreti station for the same period of five years.

In addition, back trajectories of air masses arriving at 100m above the sampling sites were generated using the HYSPLIT_4 model [26]. Daily and back trajectories were run for 72h, clustered on a monthly basis and compared with monthly averages of measured hourly wind speeds and directions.

Table 1: Location of the monitoring sites

Road	Site	Latitude	Longitude	Elevation (M)
Ngong Road	Nakumatt Junction	S. 01°17. 958’	E. 036° 45. 649’	1790
Landhies Road	Muthurwa Market near Machakos bus stage	S. 01°17. 210’	E. 036°501’	1673
Juja road	Pangani round about	S. 01°16. 238’	E. 036°50. 187’	1637
Industrial Area	Met Station (TX)	S. 01°18’	E. 036° 36’	1626

2.4 Data analysis

The collected data was analyzed using a number of methods. Time series analysis was used to analyze the temporal variation of surface Ozone. The time series analysis involves a graphical plot of the element of interest against time. The graphical representation shows the spread of the data over time. Any gaps of missing data become apparent; unless a smoothing function is applied. Seasonal cycles may also be deduced in the plotted data. The Ozone data from KMD was subjected to time series analysis and as a result seasonal, monthly and diurnal graphs were reanalyzed.

GraDS was used to analyze zonal wind and trajectories while HYSPLIT model was used to determine the source region. A trajectory is a calculated transport pathway of an infinitely small air parcel. Trajectories provide a useful tool for understanding the three dimensionnal transport of airborne material in the atmosphere [27]. Backward trajectories are particularly useful in tracing aerosols and trace gases back in time and space to ascertain their origins. On the other hand, forward trajectories provide a guide on the locations where pollutants are likely to be deposited. Thus, trajectories corresponding to individual transport events provide an indication of the mean motion of an advected air parcel.

Different models for air trajectories can be used depending on the availability of input data. Each model requires gridded fields of meteorological variables at regular temporal intervals, and for this research HYSPLIT ((Hybrid Single-Particle Lagrangian Integrated Trajectory) Model was used from National Centre for Environmental Prediction -National Centre for Atmospheric Research. The HYSPLIT model is a complete system for computing single air parcel trajectories to complex dispersion and deposition simulations. The HYSPLIT model computes the advection of a single pollutant particle, or simply its trajectory. The model was run interactively on the Web through the READY system on NOAA's site http://ready.arl.noaa.gov/.

The data sets used are the monthly reanalysis fields available from the National Centre for Environmental Prediction- National Centre for Atmospheric Research (NCEP- NCAR) global re-analyses. The start or end of the trajectories was determined from the time series plots of the surface ozone concentrations for Nairobi. A sudden sustained rise or fall in the ozone concentration could be indicative of changed air source characteristics or path. For a rise or fall in the ozone concentration, the timing is supposed to coincide with the start (of a backwards trajectory to indicate the path and source region of airflow. Forward air trajectories merely indicate the outflow from the station and in this case will be Nairobi.

3. RESULTS AND DISCUSSION

3.1 Trend analysis for tropospheric zone columns

The tropospheric ozone columns (TOCs) measured by ozonesonde at the KMD station was averaged for a period of three years. The ozonesonde profiles were integrated from the ground to the 200 hPa pressure level and then the monthly mean were calculated: there were between 2 to 6 ozonesonde

measurement ascents each month as shown in Table 2. The Monthly average values of the TOC is also shown in Table 3.

Table 2: Monthly ascents

	2011	2012	2013	2014
Jan	4	4	5	3
Feb	4	5	4	4
Mar	5	4	4	4
Apr	4	4	4	5
May	2	4	5	3
Jun	4	5	5	4
Jul	4	4	5	5
Aug	5	6	3	4
Sep	3	5	4	4
Oct	4	4	5	5
Nov	5	4	6	3
Dec	4	4	2	5
Total	1. 8	53	42	46

Table 3: Monthly averaged ozonesonde measured data, based on three years of data (2011-2014)

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual mean**	**Std.dev**	**COV %**
Ozone (ppb)	17.2	17.9	17.3	16.3	16.9	19.6	22.9	21.5	22.5	19.4	17.6	16.3	18.8	2.4	12.6

Table 4: Seasonal variation of Ozone

	MAM	JJAS	OND	JF
Mean Ozone (PPb)	16.8	21.6	17.8	17.6

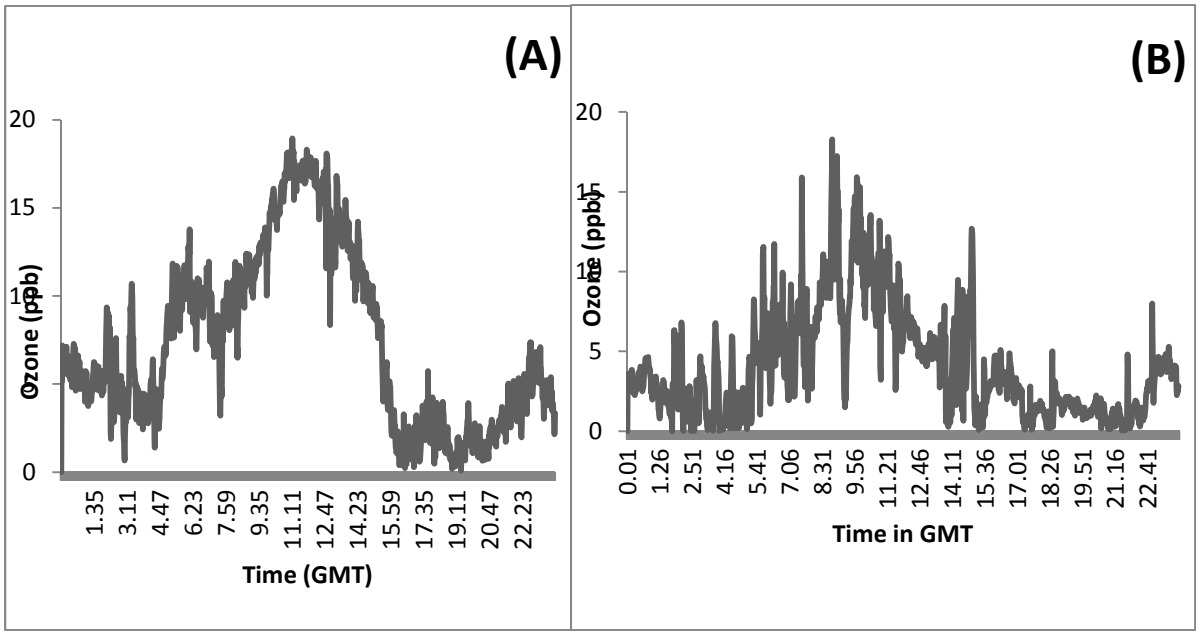
Table 3 and 4 shows the mean monthly variation of surface ozone over Nairobi. It shows that, the ozone was lowest in the months of March to May (MAM) and November to January. Also the standard deviation and coefficient of variation is quite low, which means, the monthly variability is quite low. The seasonal

variation in the surface ozone column is explained by the migration of the ITCZ over Kenya, when it passes twice a year, between March-May and October-December [28]. These are the two wet seasons over the study area. In both seasons, the tropospheric ozone columns are fairly low, due to convection of humid and ozone poor air. The increase in the tropospheric ozone values during the cold season (July-September) over Nairobi can be explained by incursion of ozone from the Southern Africa especially from Zambia which has high biomass burning during these seasons [29].

3.2 Trend analysis for the surface Ozone

Figure 2 depicts the diurnal variation of ozone from the four sampling sites. It generally shows low amount in the early morning and at night with high amount of ozone during the day. This can be due to the presences of precursor gases that are produced during the morning traffic hours which in presence of electromagnetic energy from the sun react in the atmosphere leading to ozone formation. Also at the Industrial area site, the peak of surface ozone is earlier as compared to other site. This is because of the availability of the precursor gases from the night industrial activity, while the other sites have their sources mainly from motor vehicle traffic, and during the night most of these roads have low or no traffic.

The 8 hour mean (8 to 17 hrs) of surface ozone at the four sites show that, industrial area had relatively high mean ozone concentration (20.2 ppb) compared to other sites that had 10 ppb and less concentration (Table 5). This may mean the precursor gases at the industrial site are higher than in other sites considered in the study. This may be attributed to emissions from industrial activity in industrial area, while in other sites the emissions are mainly from motor vehicle traffic.



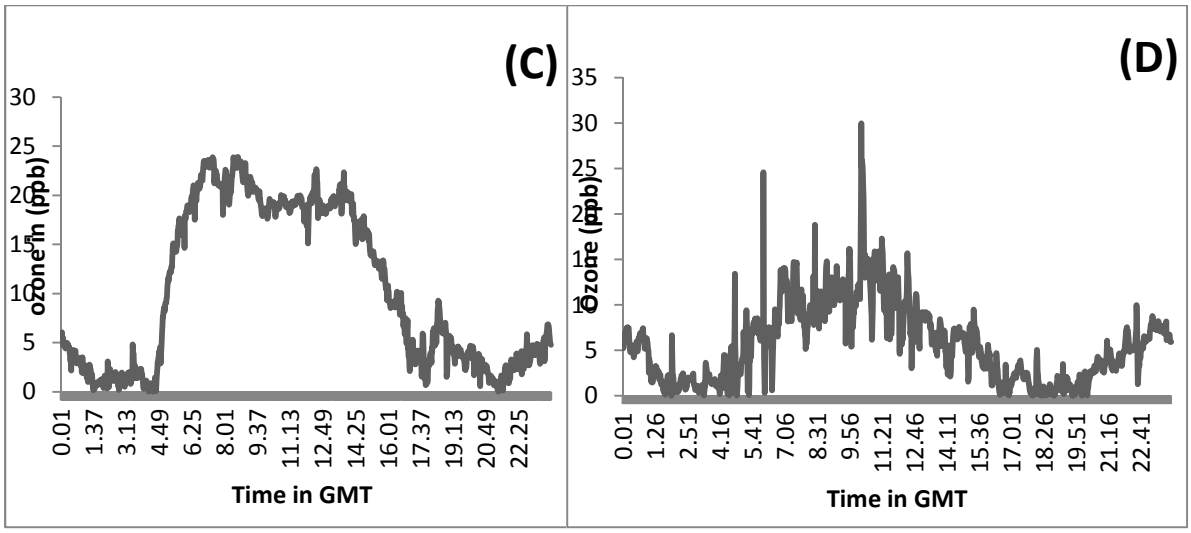


Figure 2: Diurnal variation of Ozone concentration at; (A) NakumattJunction, (B) Landhies, (C) Industrial Area and (D) Pangani.

Table 5: Ozone 8 hour mean values

Site	Ozone 8 Hour Mean (ppb)
Nakumatt Junction	10.3
Landhies	7.8
Pangani	10.1
Industrial Area	20.2

3.3 Analysis of Vertical profile of Ozone

Figure 3 shows temperature and ozone flight data. The analysis, (Figure 3 a), shows a decreasing temperature trend within the troposphere up to 110mb (16.3km) level where it becomes constant up to 88 mb (17.6 km) level. ^{O}

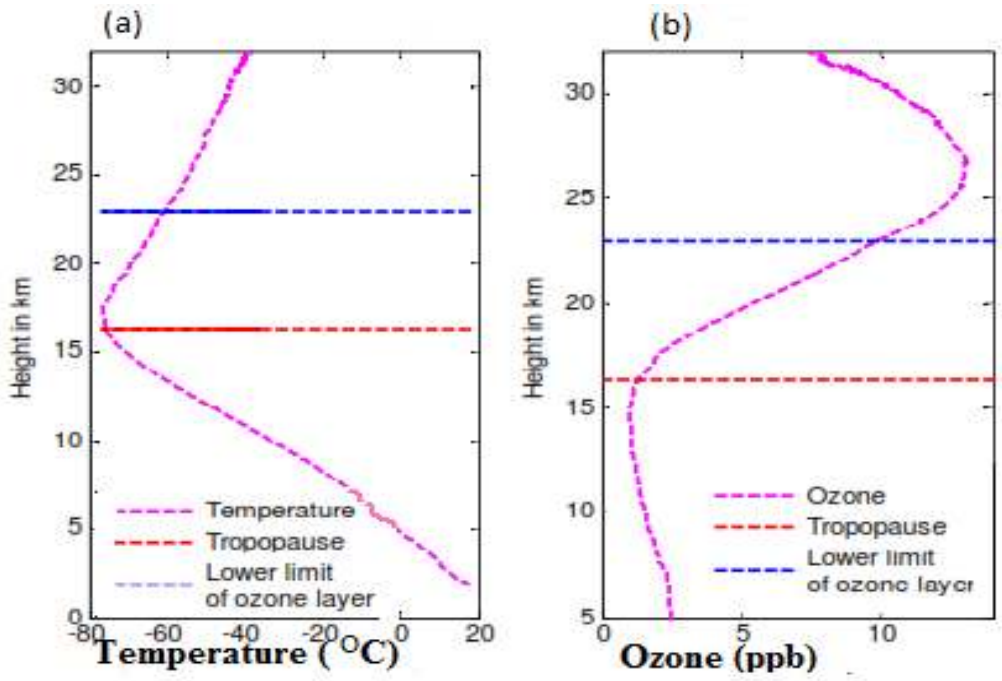


Figure 3: Mean Vertical variation; (a) temperature, (b) Ozone over Nairobi 2011 to 2014

Figure 3 shows temperature decreasing trend within the troposphere up to 16.3 km. The average flight data is in agreement with observations made by [30]. On the average level of tropical tropopause being located at close 16.3 km level with a height ranging from 12 - 19 km. The observed layer between 16.3 km level and 17.6 km level represents the tropopause. Although, [31] found out that the average depth of the troposphere is approximately 11km within the tropics, this study reveals, on average, over Nairobi it extends to about 16 km. Figure 4. further shows temperature increases within the lower stratosphere. The ozone concentration showed small values, with negative trend upwards within the troposphere, up until the tropopause (Figure. 3b). Within the tropopause, there was a gentle increase in the ozone concentration and a sharp increase in the lower stratosphere, peaking in the mid stratosphere. The maximum ozone concentration value of 13.04 ppb is found at a height of about 27km high. The ozone layer, with the highest concentration of ozone, is within about 23 – 30 km. The ozone layer is therefore, about 23km and covers a depth of about 7km, located in the mid stratosphere over Nairobi. This study agree with Sauvage et al. (2005) who noted that tropospheric ozone does not, exceed 20 - 40 ppb on average.

The ozone mean concentration values were decomposed into 3 months interval to correspond with different weather seasons over Kenya and Nairobi in particular and are presented in figure 4.

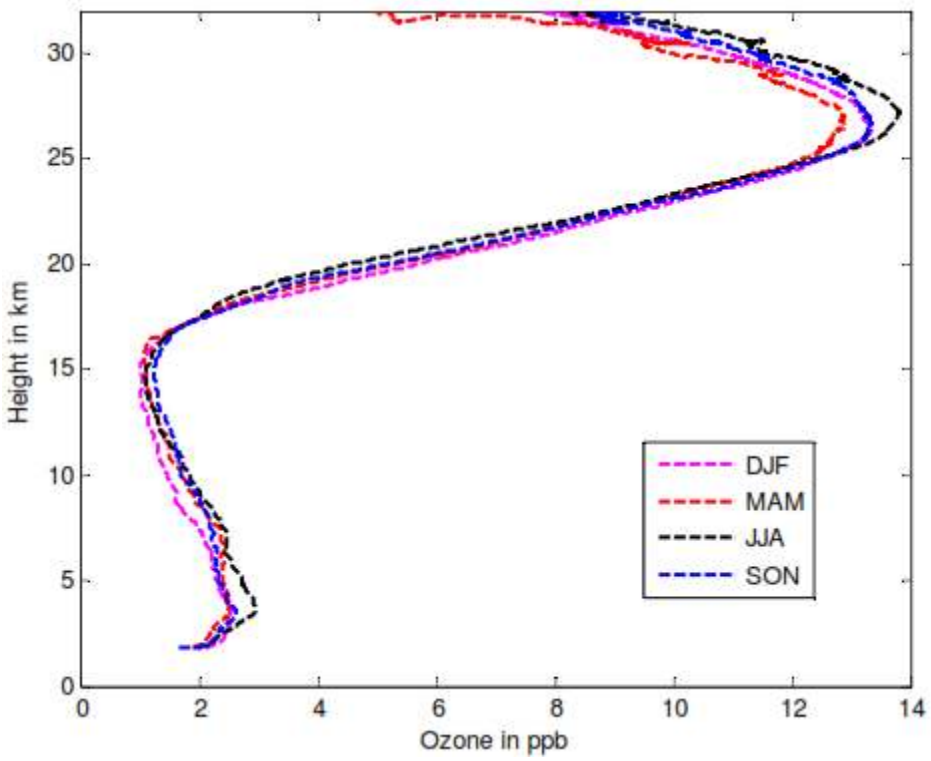


Figure 4: Mean Vertical seasonal variation of Ozone over Nairobi, 2011 to 2014

Generally, the June, July and August (JJA) season experienced the highest ozone concentration in both the low and upper levels as compared to the other seasons. This is partly in agreement with [33]; who reported that there exist a significant positive correlation between O_3 concentrations, solar radiation and temperature. However, there was an exception at the tropopause where higher values of ozone are reported during September, October and November.

3.4 Analysis of Wind system over Nairobi

Figure 5 shows the mean zonal wind distribution over Nairobi. Easterlies are predominant in the lower troposphere, up to about 500mb, westerlies in the mid troposphere and again, easterlies in upper troposphere, extending into the lower stratosphere, commonly known ‘steering winds’ in this region.

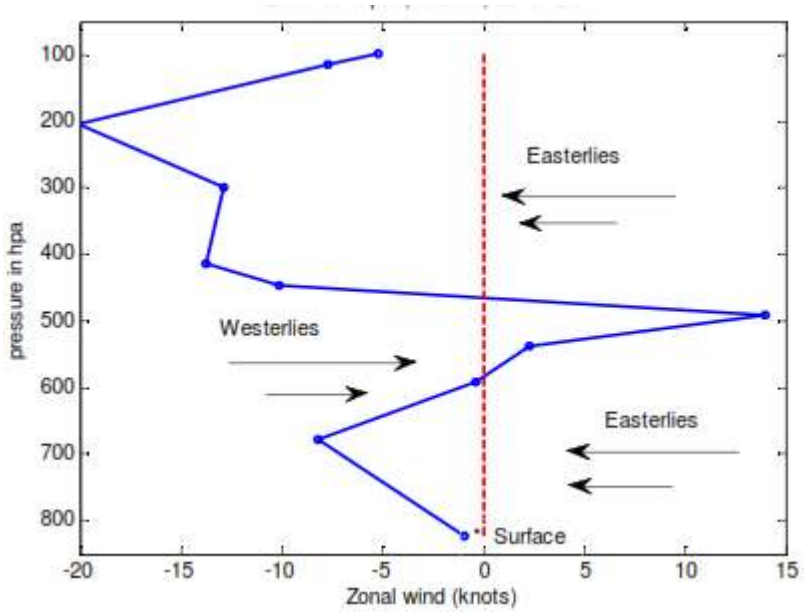


Figure 5: Profile of Zonal wind Component for Nairobi, 2011 to 2014

This is because of their effect of 'steering' or advecting weather systems such as convective cells or moisture in and out the region of east Africa. The observed predominant easterlies in the lower troposphere were observed by other studies [34, 35]. Ozone is depleted by dry and wet deposition on the ground and long-term transport. Figure 6 displays mean seasonal wind speed, direction at 850mb pressure level (boundary layer) over East Africa. Meteorological conditions at pressure level 850mb are used to consider lower atmospheric conditions rather than surface conditions normally 2-10m above the ground.

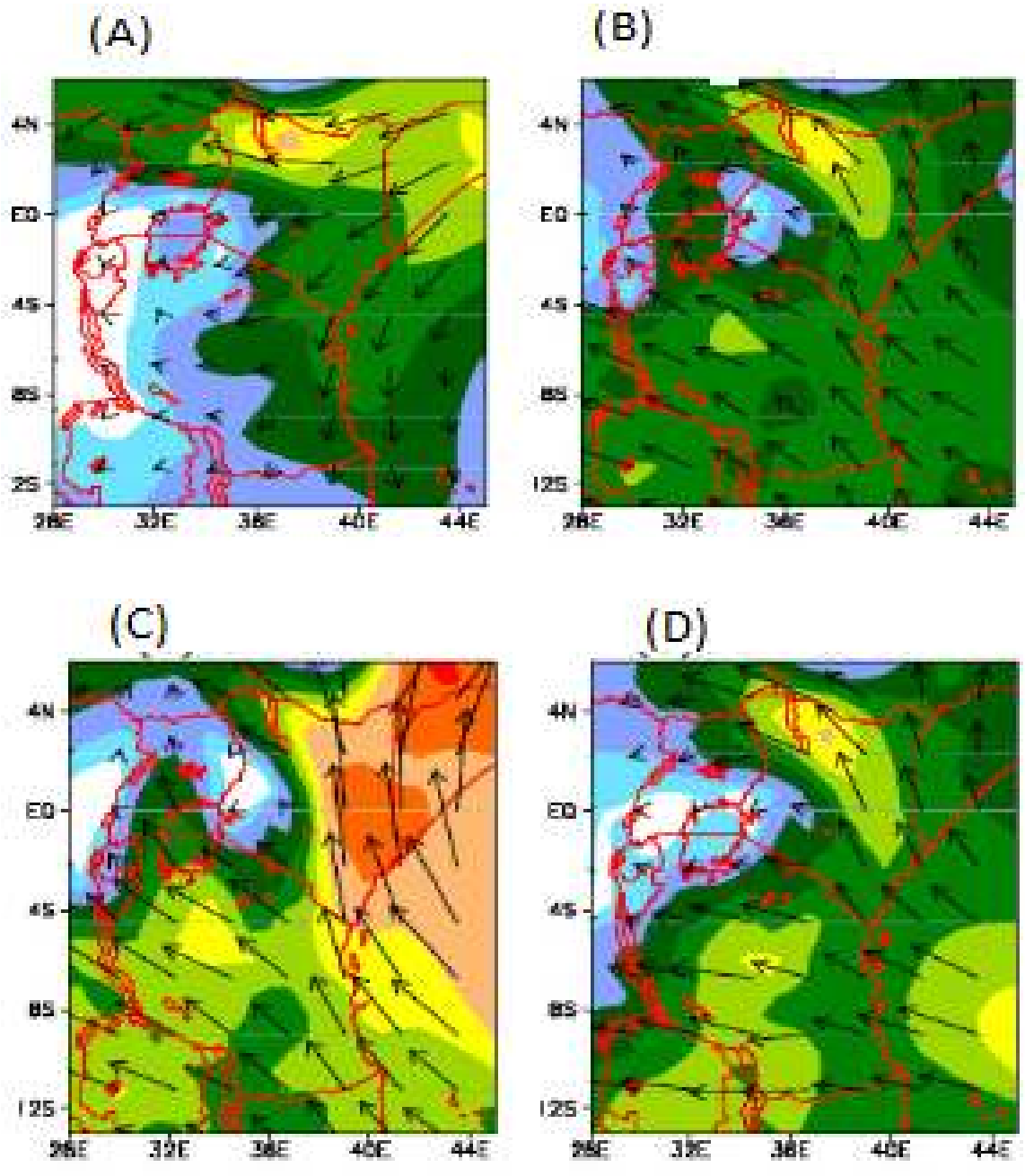


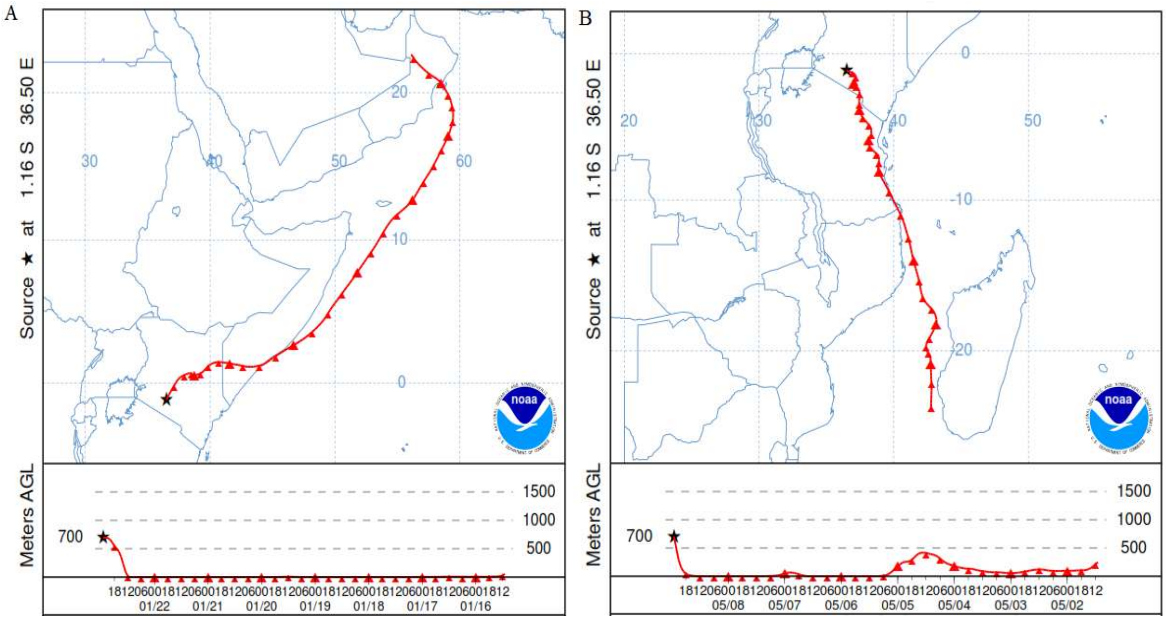
Figure 6: The mean seasonal wind speed (m/s) and direction (a) December, January and February (DJF) (b) March, April and May (MAM) (c) June, July and August(JJA) (d) September, October and November (SON)

During the March, April and May (MAM) period, there is predominantly easterly flow (6) from Indian Ocean contributing to high moisture content over east Africa. High moisture content implies presence of a humid atmosphere that is negatively correlated with ozone; similar observation was made by other studies [36, 37]. The winds penetrate into Nairobi during MAM, JJA and DJF but the wind vectors

reverses to dry north easterly flow during DJF. A comparison of wind speeds during different seasons shows that weak north-easterlies are observed during DJF as compared to other seasons that generally experience strong easterlies (Figure 6a). The observed high concentration of ozone especially in the upper levels during DJF (Figure 4) can partly be explained by the observed weak winds. This is supported by observations made earlier by [38] in a study on motor vehicles air pollution in Nairobi.

3.5 Analysis of Source region for TOCs

The origin of ozone in Nairobi was analyzed using HYSPLIT backward trajectories. It was run in different months when we have high and low ozone concentrations. Each HYSPLIT backward trajectory was calculated for 180 hours with Global data assimilation system (GDAS) meteorological datasets. A starting time of 00:00 UTC was set to simulate the trajectories from the selected starting location (Nairobi). Figures 7 (a-d) demonstrate the typical trajectory of the backward trajectory of Nairobi for the months of January, May, July and November, respectively. Therefore, the source region of Nairobi tropospheric ozone will definitely be defined by the source of wind system. The transport corridors or plumes arriving over Kenya are clearly bounded and well defined (Figure 7). North-easterly and south-easterly transport from the north-western and south-western Indian Ocean corresponds to their seasonal monsoon airflow counterparts. Anticyclonic Sahara transport is a prominent feature and westerly transport mode is evident [35]. Through backtrack trajectory (Figure 7), the source of the ozone during the July to September is from the Southern Africa countries. This finding concurs with [17, 29]. They found out that Lusaka had the highest concentration of tropospheric ozone at 100ppbv at 2 – 5 km stable layer. This was due to biomass burning in Zambia during this period.



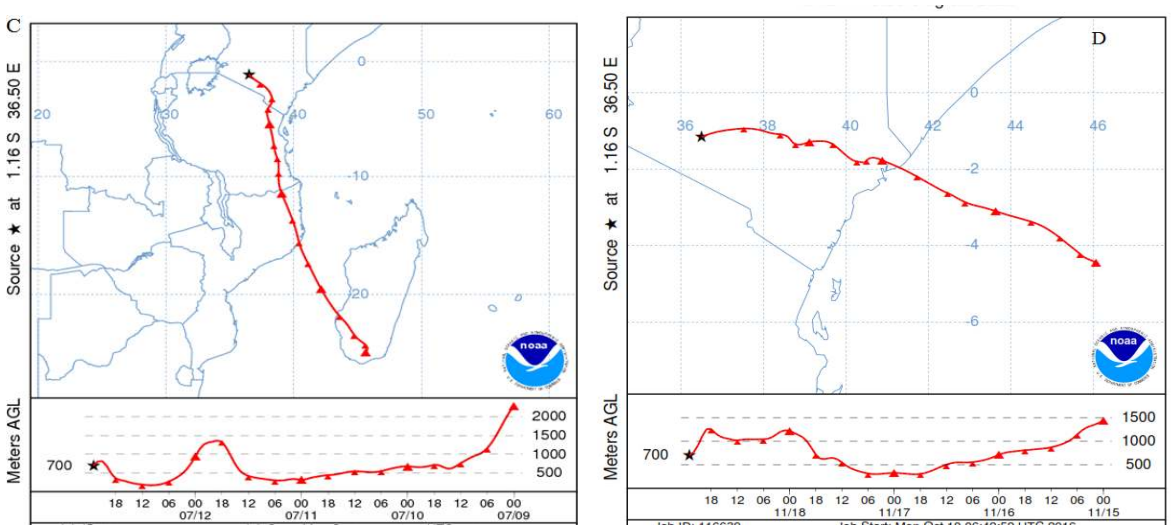


Figure 7: Mean backward trajectories ending at Nairobi. The ending point height is 700m, for (A) January (B) May (C) July (D) November

5. CONCLUSION

The main objective of this study was to assess spatial and temporal variation and identify the source regions of surface Ozone over Nairobi city. To achieve it, the following specific objectives were formulated to investigate: the spatial variation of surface ozone, the temporal variation and the find out the source region of the observed surface ozone. On the investigation of the spatial surface ozone, sampling was done at four sites within Nairobi, it was found out that the diurnal variation of Ozone in Nakumatt Junction, Landhies road and Pangani Roundabout showed low amount in the early morning and at night with the peak being realized during the day. This was due to the fact that surface ozone is produced by photochemical oxidation of CO, CH_4 and non-methane volatile organic carbons (VOCs) in the presence of NOx and UV light and these component are present due to the motor vehicle activities. However, the eight hour means for the three sites were below WHO mean of 51 ppb. In Industrial Area, the same low amount of ozone were realized in early morning and at night with high amount observed throughout the day. The high values of ozone show that there is high concentration of ozone precursors in this site which is caused by industrial activities throughout the day. The eight-hour mean was 20.2 ppb which is below the WHO mean of 51 ppb. However, this is the highest recorded amount of ozone in the four sites.

On the Temporal variability, it was found that June to August season experiences the highest ozone levels as compared to the other seasons in both lower and upper levels. This is due to incursion from the south according to the backward trajectories, which has been proven to have high ozone concentration during this season due to biomass burning. The vertical profile of ozone shows that approximately 80% of ozone is found in the stratosphere. And finally on the Source region, the analysis done by running the backward trajectory using the HYSPLIT model found out the during the peak Season of ozone, the source region is southern Africa which has high Biomass burning during these season, then is transported to Nairobi.

SUGGESTION FOR FURTHER STUDIES

Kenya seeks to be industrialized by the year 2030, at a time when world over, policymakers and the general public are concerned with the degradation of air quality, especially in urban centres. From this study it has been found that, area around industry had a high amount of ozone concentration with the peak of this ozone concentration being throughout the day time, which increases the outdoor pollution. Therefore, the government has to come up with adequate strategies of tackling air pollution, which has direct health impacts upon the increasing population. Therefore, concerted efforts have to be made to find a sustainable balance between industry, human health and environmental protection. The study recommends that; (1) Further monitoring of air pollution to be conducted along major roads in Nairobi and other major cities, especially the precursor gases to map the spatial ozone and other air pollutant concentration, (2) Further analysis on the impact of air pollution on health need to be conducted, (3) Develop an atlas of air pollution levels in major cities in Kenya and, (3) Enhancement of ad hoc air pollution monitoring in different counties in order to profile pollution levels within the country.

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