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Analysis of Surface Ozone and Its Precursors with Relevance to Urban Air Pollution in Nairobi, Kenya

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Abstract: Ozone (O_3) is an important greenhouse gas and a key global air pollutant, potentially responsible for premature deaths, and the loss crop productivity. Nairobi city facing major challenge is ineffective public transport network with increasing emissions of air pollutants and poor air quality. This study focused on the current levels of surface O_3 over Nairobi taken from the continuous and mobile measurements and different surface O_3 precursors (NOx, NMHCs, and CO) from various selected locations around the city. Consistent diurnal and seasonal variations in surface O_3 concentrations were observed for the past four years. Day time O_3 levels peaks at mid-day hours, and the seasonal behavior highlighted bimodal peaks i.e., for the month of March (32 ±5 ppb hourly mean concentrations) and September with (36 ± 5 ppb hourly mean concentrations). Diurnal variations in O_3 were within the WHO limits (50 ppb for 8 hours). Mobile precursor measurements were found to be within the WHO limits apart from CO (0.05–0.12 ppm 24 hour). The study concludes that, surface O_3 over Nairobi is mostly contributed by vehicular source. This work recommends the extended surface O_3 monitoring networks in the city are suggested to create a larger data base. This may assist in evaluating the potential health and agriculture implications of surface O_3 anomalies, and development and implementation of policy to combat air pollution at local level.

Keywords: Air quality; pollution; ozone; Nairobi.

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1. Introduction

Role of tropospheric ozone (O_3) is significant in the chemical processes of Earth's atmosphere, moreover it is a critical global air pollutant and an important greenhouse gas (Derwent et al., 2018; IPCC, 2007; Tiwari and Agrawal, 2018; Wu and Xie, 2017). It is found most abundant in atmospheric smog (Mauzerall et al., 2001; Sullivan et al., 2018) and exists as a special form of oxygen allotrope, constituting of three oxygen atoms. Ozone is a very strong oxidizing agent weighing about 1.5 times heavier than air with a vapor density of 24 units and has its solubility in water greater than that of oxygen, at about 49% by volume at 0 °C (Naik, et al., 2016; Qin et al., 2018; Saez et al., 2018).

While O_3 is a harmful pollutant in the troposphere and near ground level where plants, animals and humans are exposed (Ainsworth et al., 2012: Farré-Armengol et al., 2016; Liu et al., 2018; Wang et al., 2017; Xiaodu, 2005). Contrarily, it is important in the stratosphere where it shields the Earth from intense UV radiation by absorption and thus accounting for a direct change in the atmospheric energy i.e. Radiative Forcing (RF) of 3.5 – 3.7 Wm^2 (Ainsworth et al., 2012; Benca et al., 2018; Bjorn and McKenzie. 2015; Forster et al., 2007; Reese, 2018). From pre-

industrial times, tropospheric O_3 concentrations have been observed to be on a continual increase, modeled O_3 distributions has been linked to wet deposition, although the influence has not been kinked well. Previous studies using a single CTM have suggested half reductions of the wet depositions by precursors leads to a 10 Tg (~3%) increase in the tropospheric O_3 burden and a smaller (~2%) increase in surface O_3 (Lin et al., 2017; Staehelin et al., 2017; Tiwari and Agrawal, 2018; Young et al., 2016). Elevated O_3 levels, particularly in urban areas, are detrimental and have been known to cause an estimated 5-16% global temperature change (Forster et al., 2007; Gerald et al., 2018; Neu et al., 2014; Pyrgou et al., 2018; Verstraeten et al., 2015), substantial decrease to plant health and productivity (Chuwah et al., 2015), as well as resulting in an estimated 0.7 million human deaths every year (Anenberg et al., 2010; WHO, 2010), in addition to between 7 and 8 million premature deaths every year (WHO 2012). Although studies showed non-significant variations in the O_3 levels within week (Wang et al., 2014), however due to variations in the traffic during working days and weekends in the Narobi city lead to huge variations in the O_3 levels within week. This background explains the interest of this study to analyze the seasonal distribution of surface O_3 and its precursors over Nairobi city

In polluted air masses of O_3 are formed by photochemical oxidation of its precursor pollutants, such as non-methane volatile organic compounds (NMVOCs) and carbon monoxide (CO) in the presence the oxides of nitrogen (NOx). Its concentrations have also been seen to correlate with various other toxic photochemical oxidants arising from similar sources, including the peroxyacyl nitrates, nitric acid and hydrogen peroxide (Li et al., 2017; Sadanaga et al., 2017; Waring and Wells. 2015; WHO 2006). The atmospheric environment around Nairobi has been for long lacking continuous monitoring atmospheric pollutants such as O_3. Only recently, from an initiative by the Kenya Meteorological Department and The National Environmental Management Authority (NEMA), a survey was conducted on a few sites in Industrial area and Athi River in 2015 of the ambient air around Kitengela Township by Shilenje et al (2015). The city has been growing very rapidly at a rate of over 4% per annum, with a population estimated at 3.1 million in 2009 by the Kenya National Bureau of Statistics, (2010), and projected to increase to 7.14 million by 2030 (Rajé et al., 2018). These presents challenges such as lack of a well-planned and effective public transportation system, existing industrial pollution near the city, poor solid waste disposal and burning among other challenges around the city that could potentially lead to increased rates of emissions to harmful and toxic levels.

The projected increases of O_3 concentrations for the East African region indicated by National Center for Atmospheric Research (NCAR) chemical forecast global output for 6-hour frequency are estimated at 10 ppb to 50 ppb annual mean surface concentration, and changes between the years 2000 and 2030 suggest that these conditions may well significantly worsen in the near future (Muhammad, 2011). Further, Liousseet al (2014) have stated that, Africa has significantly contributed to the total global emissions amounting to about 5% for SO2 and NOx, to 20% for OC, and 10% for CO, BC and NMHC which could potentially lead to the African contribution significantly increases for all species by 2030. This calls for more actions in terms of systematic monitoring and analysis as well as setting up regulations to prevent further increase in harmful levels of pollutants given that currently there are few reliable and regulated urban air pollution assessments and more specifically to surface O_3. Its effects in Nairobi and that urban air pollution is higher in low and middle-income countries compared to developed countries and mostly attributed to from vehicular emissions (Kinney et at., 2011).

This study focused on the analysis of surface O_3 from a continuous source measurement and from mobile measurements, and its precursors measured from several points around Nairobi city. We analyzed and presented the levels and the seasonal distributions from 2013 to 2016 to show the contributions by natural and man-made trace gas emissions as highlighted from concentrations of the mobile locations measurements of surface O_3 and its precursors.

2. Data and Methodology

2.1 Monitoring Sites

The research was conducted in Nairobi County, the capital city of Kenya1° 9'S, 1° 28'S and 36° 4'E, 37° 10'E, at an altitude of between 1,600 and 1,800 m above sea level. Its current population is about 4 million residents with an urban population growth rate increasing very fast and up to 60 % living in informal settlements around the city (Pascal and Mwende 2009).

Table 1. Instruments installed and parameters measured in the Mobile Air Pollution Monitoring Laboratory.

Instrument Model	Parameter Measured	Range (PPM)	LDL	Flow rate (LPM)	Measurement technique	Method
Ecotech Serinus 10	Surface ozone (O_3)	0-20	0.5 ppb	0.5	nondispersive UV photometer	FEM
Ecotech Serinus 30	Carbon Monoxide (CO)	0-20	200ppb	1	infrared photometric detection and gas filter correlation	FRM
Ecotech Serinus 44	Nitrogen Oxides (NO_X) and Ammonia (NH_3)	0-20	0.4ppb	0.5	gas-phase chemilluminescence detection	FRM

PPM, parts per million; LDL, Lower Detect6ion Limit, LPM, Liters Per Minute, FEM, Federal Equivalent Method, FRM, Federal Reference Method, UV, Ultra Violet Radiation.

The Nairobi city region has majorly low-level easterlies winds and is characterized by bimodal rainfall distribution, caused by the migratory Inter-Tropical Convergence Zone (ITCZ). The city experiences 'short' rains in October - December (OND) and the 'long' rains in March- May (MAM). The mean annual temperature is of 17 ^oC with the cold wet season being June to July (JJA), and late December to February (DJF) considered the warm period (Ng'ang'a, J.K., 1992).

The measurements from the Nairobi Regional Global Atmospheric Watch (GAW) station (ALT: 1795M ASL, Lat: 1.30 S, Lon: 36.75 E) was also considered because of the small number of working monitoring stations for surface O_3 in Nairobi and Kenya as a whole .The mobile air pollution laboratory sampled at 14 sites around Nairobi city including major urban roads (Ngong Road, Landhies Road, Outer Ring Road Roundabout, Mbagathi Road, City Mortuary Roundabout, Enterprise Road, Imara Daima Estate - residential area, and Valley Road, (Table 2). Surface O_3 was sampled both during the day and night in a few sites like Nakumatt Junction to show the consistency in the distribution and trend of surface O_3 at different times.

2.2. Methodology

Surface O_3 measurements data analyzed for four years (2013 to 2016) using surface O_3 analyzer model 49*i* at the Kenya Meteorological Department, Global Atmospheric Watch Division (GAW) and mobile measurements of surface O_3 from several sites around the city (Table 2) between November and December 2015.The instruments are under thorough routine maintenance, calibrations and quality assurance by the Swiss Meteorological (MeteoSwiss) and operated in Kenya by specially trained officers.

2.3. Monitoring Equipments

2.3.1. Surface Ozone Analyzer

Surface O_3 analyzer (Thermo scientific model 49i) is a stationary instrument mounted at the Global Atmospheric Watch operations room is a time shared dual cell Ultra Violet (UV) photometric ambient O_3 instrument capable of measuring ambient level O_3 concentration on a continuous, real time basis.

Fig. 1. Mobile Air Pollution Monitoring Laboratory used in this study

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Table 2: The geographical descriptions of the various sites monitored.

	Site	Elevation (ASL) m	Longitude	Latitude	Site Descriptions
1	Athi River GK Prison	1582	36.94635	-1.47387	Peri – urban site located downwind of major factories and to the West of Athi River and few kilometers from Kitengela town.
2	Assistant Commissioner's office	1574	36.95977	-1.47197	Peri – urban site located downwind of major factories and to the South of Athi River and a few kilometers from Kitengela town.
3	EPZ	1583	36.9764	-1.46587	Peri – urban site located downwind of major factories and to the East of Athi River
4	Nakumatt Junction	1750	36.76082	-1.2993	Urban road site. Located along Ngong road near the KMD headquarters which is 8 km south west of the Nairobi CBD.
5	City Mortuary Round about	1733	36.80382	-1.29802	Urban road site. Located on Ngong road, south west of the Nairobi CBD
6	Nakumatt Prestige	1747	36.78715	-1.29993	Urban road site. Located on Ngong road on the South West of the Nairobi CBD.
7	Nairobi NPC Church	1741	36.80535	-1.29255	Urban road site. Located on Valley road, Western side of the Nairobi CBD.
8	Nyayo Highrise Estate	1682	36.80717	-1.31398	Urban road site next to Mbagathi road, South Western side of the Nairobi CBD.
9	Muthurwa Market Near Machakos Bus Stage	1673	36.83518	-1.28683	Urban road site. Located near a busy bus terminus on Landhies road, Eastern side of the Nairobi CBD.
10	Pangani Round About	1675	36.83645	-1.27063	Urban road site. Located at an intersection, North Eastern side of the Nairobi CBD.
11	Outering Road roundabout	1632	36.87928	-1.26268	Urban road site. Located at a busy roundabout on the Eastern side of the Nairobi CBD.
12	Powerex Lubricant Limited	4983	36.86845	-1.32522	Urban industrial site. Located next to an industry on the South Eastern side of the Nairobi CBD.
13	Imara Daima Garden Flats	1645	36.87573	-1.32373	Urban site. Located in a residential estate next to an industry on the South Eastern side of the Nairobi CBD.
14	Chloride Exide	1648	36.86887	-1.32295	Urban industrial site. Located next to an industry on the South Eastern side of the Nairobi CBD.
15	Kenya Meteorological Department	1795	36.7570	-1.3022	Urban residential site. Located on the South Western side of the Nairobi CBD.

The instrument operates on the principle that O_3 molecules absorb Ultra Violet (UV) light at a wavelength of 254 nm and that the light absorbed is directly related to the O_3 concentration as defined by the Beer-Lambert Law in Equation 1:

$$I/Io = e^{-KLC} \quad [1]$$

Where:-K, molecular absorption coefficient, 308 cm-1 (at 0°C and 1 atmosphere); L, length of cell, 38 cm; C, O_3 concentration in parts per million (ppm); I, UV light intensity of sample with O_3 (sample gas); Io, UV light intensity of sample without O_3 (reference gas).

The sample was drawn and subsequently split into two gas streams, either through an O_3 scrubber to become the reference gas (Io) then to the reference solenoid valve. The sample gas (I) flows directly to the sample solenoid valve. The solenoid valves alternate the streams between cells A and B every 10 seconds. UV light intensities of each cell are measured by detectors A and B. The Model 49*i* calculates the O_3 concentration for each cell and outputs the average concentration to the front panel display, the analog outputs, and also makes the data

available over the serial or Ethernet connection (Wang et al., 2015).

2.3.1. The Mobile Air Pollution Laboratory

Various gas analyzers measuring concentrations of various atmospheric pollutants and aerosols are installed in a Mobile Air Monitoring Laboratory (MAML; Fig.1; Table 1) (Papapostolou et al., 2017), which moves to the site of interest. The analyzers generate and store data with a one-minute time resolution. The measured data were visually inspected and erroneous data were flagged as invalid

3. Results and Discussion

After the O_3 measurement and data collection from the various O_3 analyzers, the data was organized from the 5 minutes time resolution to hourly average consequently to daily and monthly average (Fig. 2) over Nairobi for the period January 2013 to December 2016.

3.1. Continuous Surface Ozone Measurement

Ozone formation is usually favored in the presence of high temperatures (Seinfeld and Pandis, 2016), and thus maximum diurnal O_3 concentrations are usually recorded at mid-day times. Ozone concentrations showed an increase in morning hours, a peak at mid-day and then a drop in the late afternoons (Fig. 2). This observation has been seen to be true for all the months of the years considered in this study (2013 to 2016). Generally, the months of March and most prominently September showed the highest peaks than the rest of the months of the year (Fig. 3). Surface O_3 concentrations gradually increases from 7:00 h with values of between 5 – 12 ppb (± 5 ppb), get to a maximum at values between 25 – 42 ppb (± 5 ppb) at around midday, then starts dropping toward the evenings at 17:00 h with values ranging 9 – 18 (± 5 ppb), (Fig. 2).

The monthly average variation results to the seasonal cycle trend for surface ozone over the year (Fig. 3). The general behavior for annual hourly average surface ozone concentrations was observed to be high in the first three months of the year then get low during the mid-year in May and then starts to increase from June through July and August to a maximum in September (Fig. 4).

Surface ozone concentrations are usually temperature driven (Simon et al., 2014). This is because ozone formation is chemically favored under strong sunlight and high temperature conditions (Kinney, 2018; Munir, et al., 2014; Wang et al., 2017).

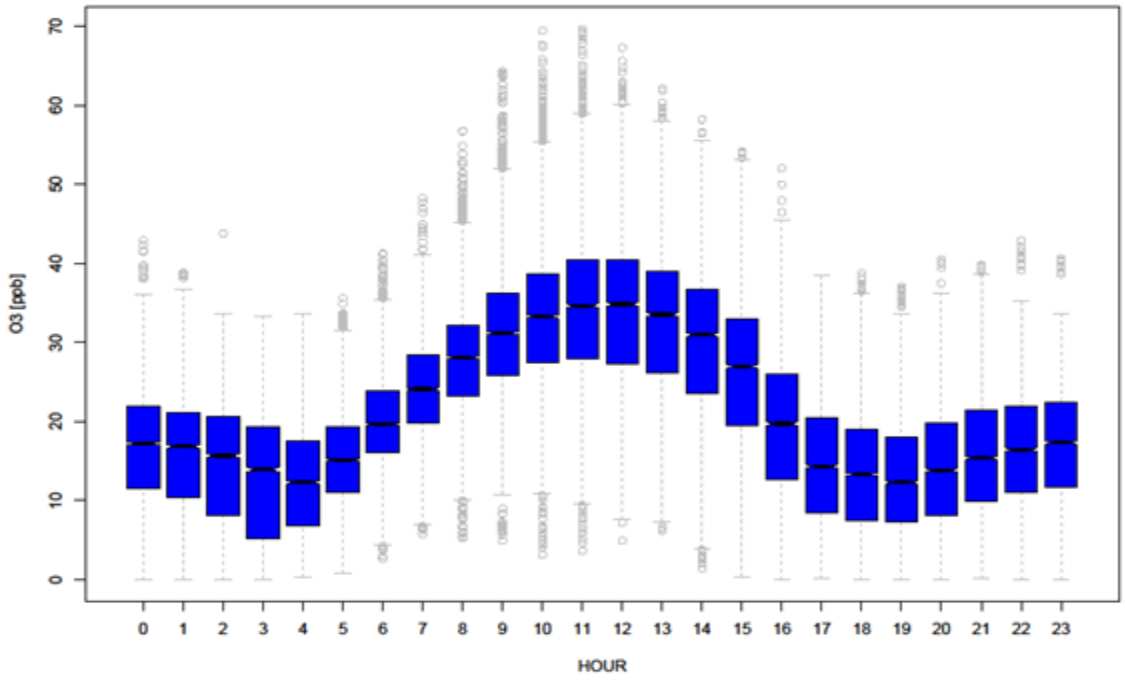

Fig. 2. Hourly mean distribution (hourly) of diurnal surface ozone for years 2013 to 2016 at the GAW, Nairobi. The upper whiskers shows the highest concentrations (7-12ppb) and the lower whiskers shows the lowest concentrations (- 7 to 12 ppbv).

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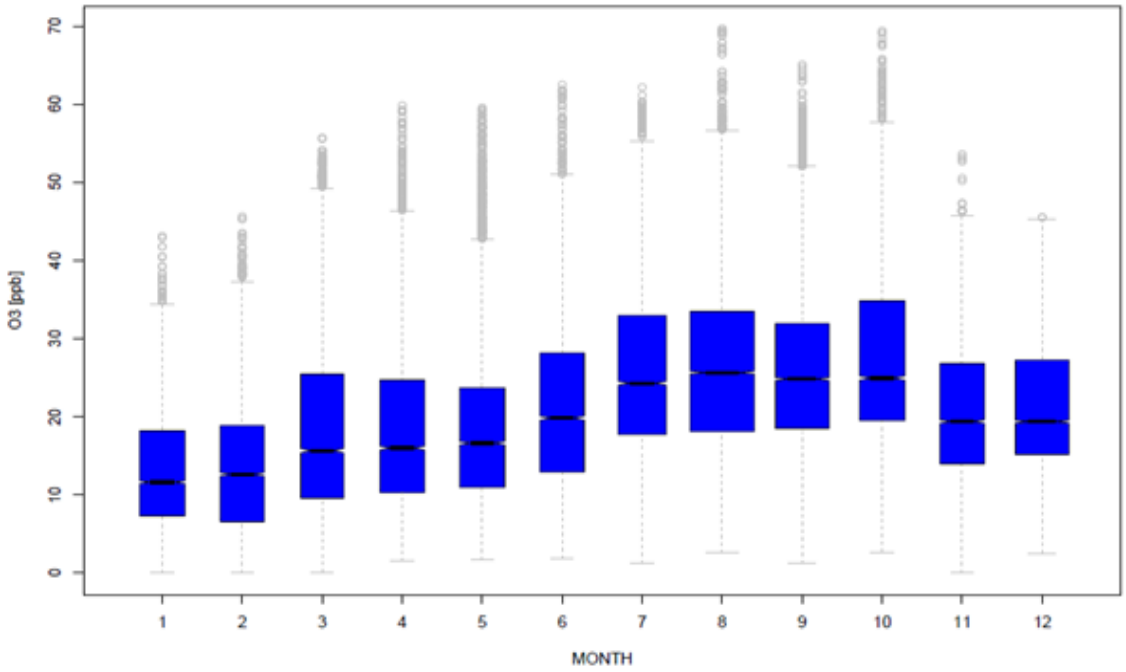

Fig. 3. Monthly mean distribution of surface ozone over Nairobi (2013 to 2016). The WHO threshold of surface ozone is 50 ppb for 8 h mean.

The seasonal cycle and the inter-annual variation of surface ozone is mainly due to the low hourly average surface ozone observed in April, May and June could be attributed to low temperatures usually experienced during this season also accompanied by the rainy periods in Nairobi (Ng'anga et al., 1992). Rainy seasons usually presents upper limits cloud covers that decrease the presence of UVB, which in turn decrease the temperature levels and increase the humidity leading to low ozone formation from photochemical reactions. Moreover, rainfall cleans the atmosphere and thus removes pollutants such as nitrogen oxides (NO_X), the precursor of ozone (Marathe and Murthy 2015). Further, dry hot periods are usually experienced between December and February, subsequently in August and September usually have broad summer maximum distribution with conditions favoring ozone formation from atmospheric pollutants.

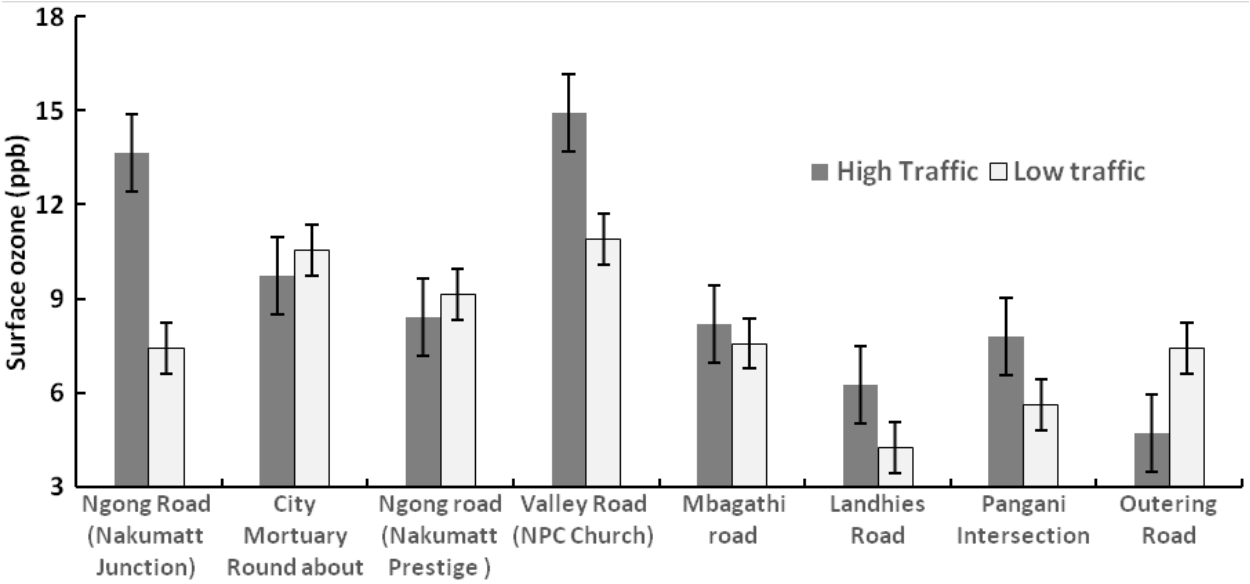

Fig. 4. The mean day time surface ozone values for the various road sites of Nairobi city.

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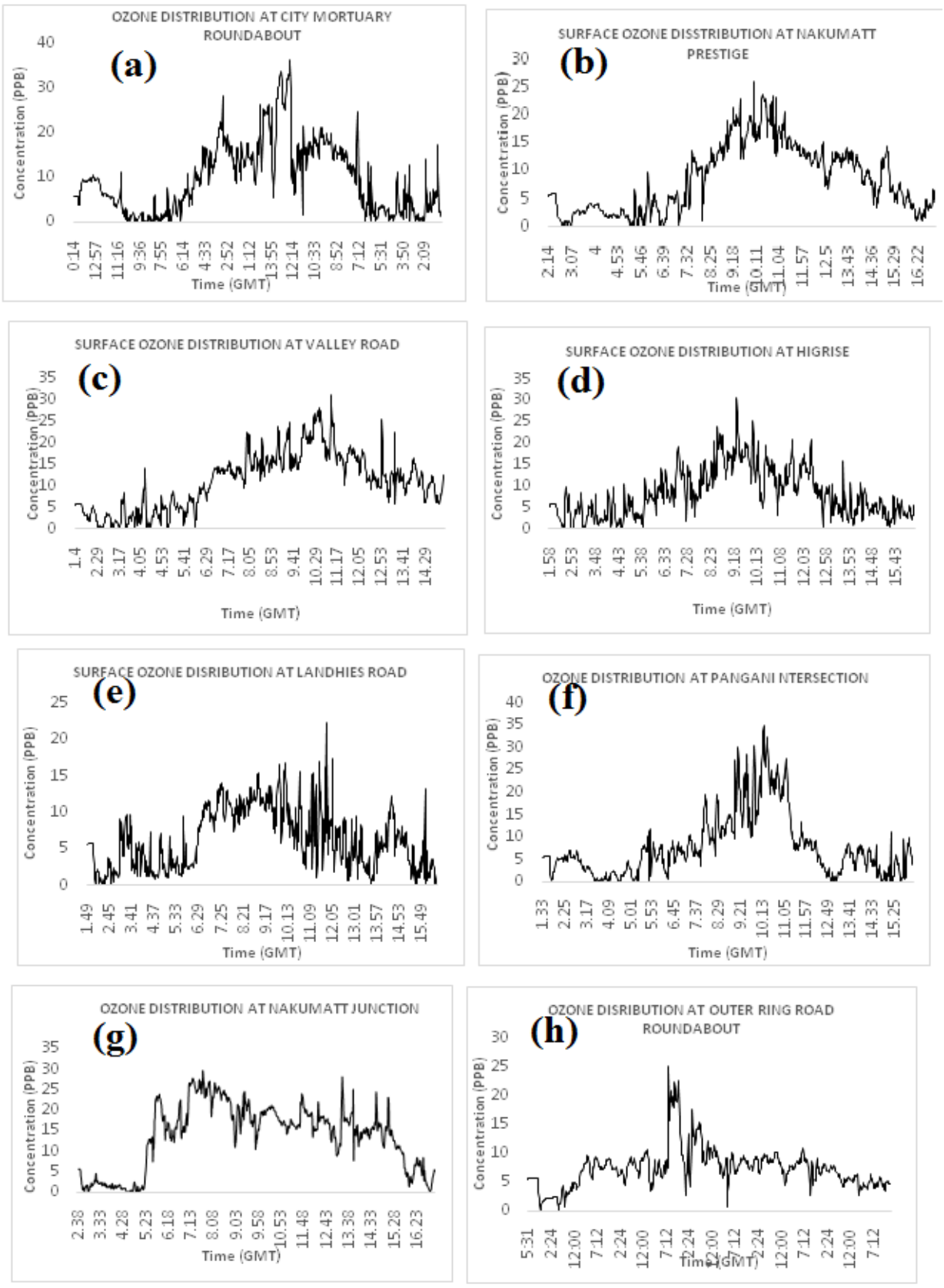

Fig. 5. The daily mean surface ozone distributions at the various road sites

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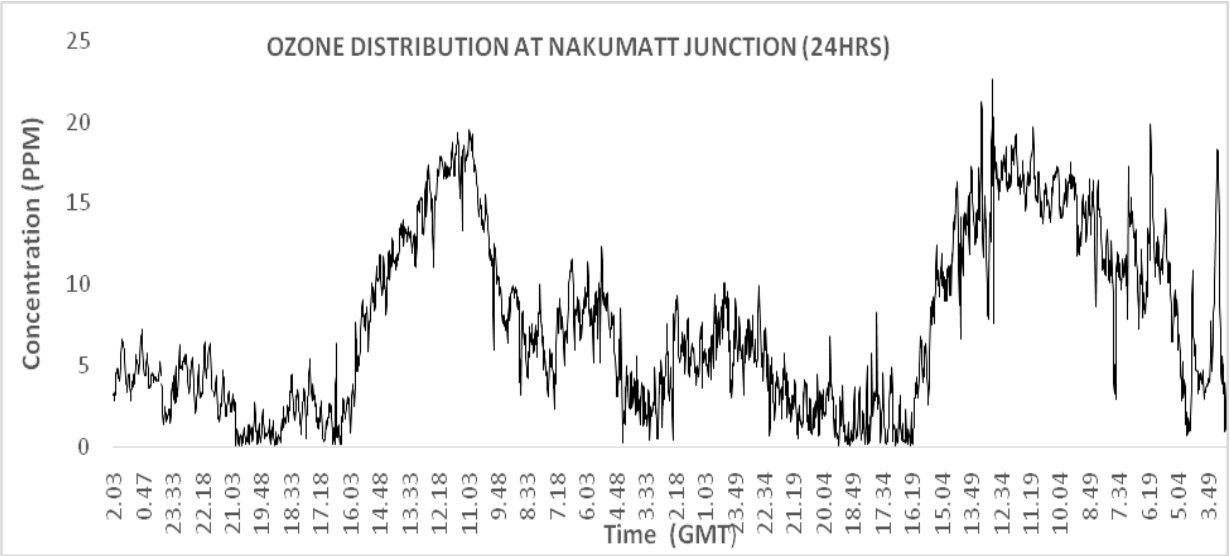

Fig. 6. Mean ozone distribution at Nakumatt Junction measured for 24 hours.

3.2 Mobile sites surface ozone measurements

Ozone measurements were performed using Ecotech Serinus 10 analyzer (Table 1). A total of 14 sites were sampled that included near industrial facilities, along known busy roads and roundabouts to a few residential estates. Mean day time surface ozone levels for the various road sites measured around Nairobi City (Fig. 4). Generally, most sites had day time mean ozone concentrations above 4 ppb and below 20 ppb, ± 5 ppb as seen from the error bands. Most high traffic days (Monday to Friday), were seen to have higher ozone concentration as compared to low traffic days (measured on Sundays on every site) apart from Nakumatt Prestige, City Mortuary roundabout and Kariobangi roundabout. Later mentioned sites had almost same kevels because of the ever consistent flow of traffic during both weekdays and weekends. The distributions for the road sites were also seen to be consistent for all the road sites (Fig. 5).

Three industrial sites were located in Athi River Township, about 20km Southeast of Nairobi County. This area is a designated industrial zone having many large-scale commercial activities ranging among others from manufacturing, steelworks, cement production, incinerators, salt production, industrial services, long haul transport and quarrying, however, the other three sites were just within a residential estate (Imara Daima) in Nairobi's industrial area (Fig. 5). All the six sites had minimum average ozone concentration of 11 ppb and a maximum of 18.5 ppb. Similar to continuous surface ozone measurements by the stationary analyzer at the GAW site laboratory, the mobile locations surface ozone levels exhibited the same pattern. All of the mobile sites had low morning levels followed by a gradual increase, reached high noon peaks and again decreased gradually to low evening concentrations in agreement as depicted at Nakumatt junction, Landhies road, Pangani intersection and industrial area (Kimayu et al., 2017).

Table 3: The various surface ozone precursors in Nairobi with their respective tolerance limits.

Pollutant	Time Weighted average	Industrial Areas	Residential, Rural & other areas	Controlled areas
Carbon monoxide (CO)	8 h	5.0 ng/m^3	2.0 ng/m^3	1.0 ng/m^3
Methane (CH_4)	24 h	5000 ppb	*	**
Non-Methane Hydrocarbons (NMHC)	Instant peak	700 ppb	*	**
Nitrogen Oxides (NO_X)	Annual Av.	80 g/m^3	60 g/m^3	15 g/m^3
Ozone (O_3)	1 h	200 µg/m^3	120 ppb	
	8 h	100 µg/m^3	50ppb	

* For residential premises in designated industrial areas, the above standards do not apply.
**For industrial premises in designated residential areas, standards for residential areas shall apply.

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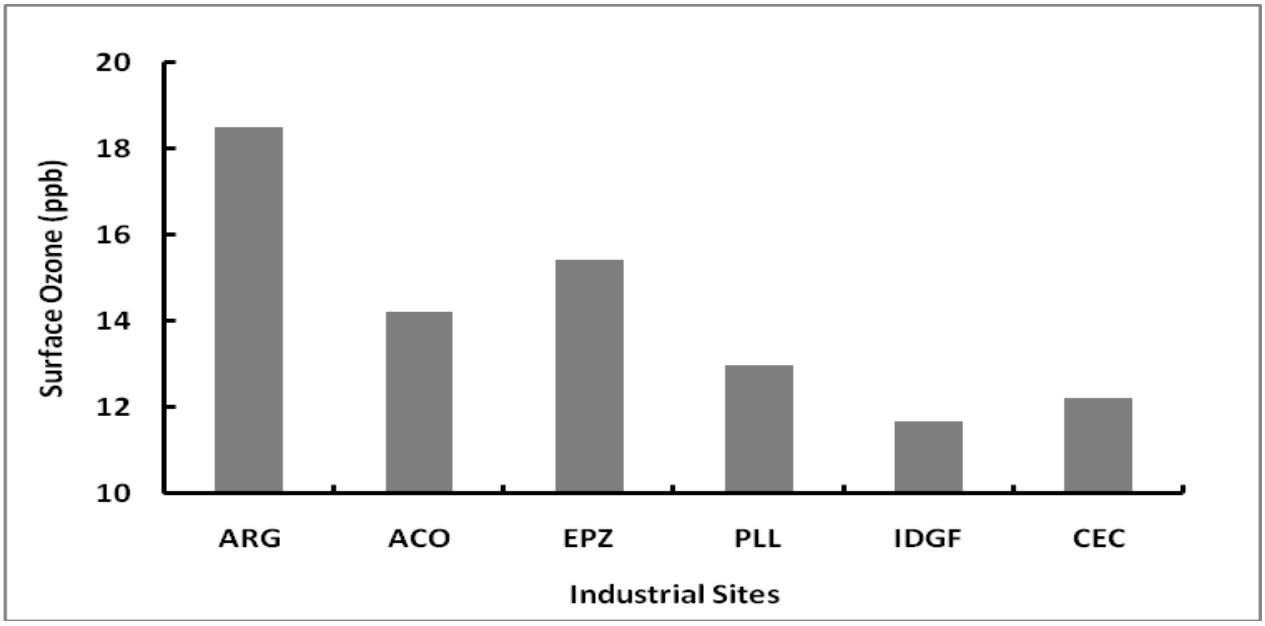

Fig. 7. Diurnal mean surface ozone values for the various sites near industries. ARG, Arthi River GK Prison; ACO, Assistant Commissioner's Office; EPZ, Export Processing Zone; PLL, Poweres Lubricant Limited; IDGF, Imara Daima Garden Flats; CEC, Chloride Exide Co.

The daytime increase and the peaks in surface ozone concentration in Nairobi City is typical of all urban air pollution scenarios (Shilenje et al., 2015). This is basically as a result of the precursor gases photo-oxidation (CO, CH_4, and NMHCs) in the presence of sufficient NOx (Fig. 8). Surface ozone concentrations in Nairobi City were found to be within the limits stipulated for property boundary, domestic or industrial threshold levels as stated in the Environmental Management Co-ordination (Air Quality) Regulations 2014 (Fig.5, Fig. 6).

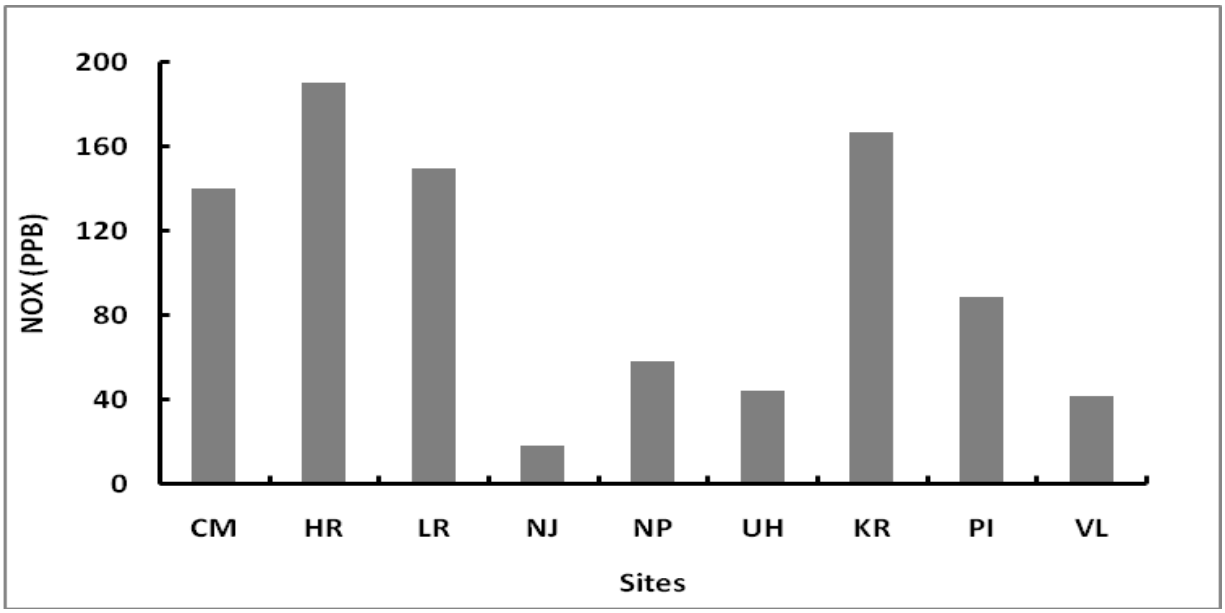

Fig. 8. NOx levels measured at different sites. CM, City Mortuary; HR, Highrise; LR, Landies Road; NJ, Nakumatt Junction; NP, Nakumatt Prestige; UP, Upper Hill; KR, Kariobangi Roundabout (Outer Ring); PI, Pangani Inersection, Valley Road.

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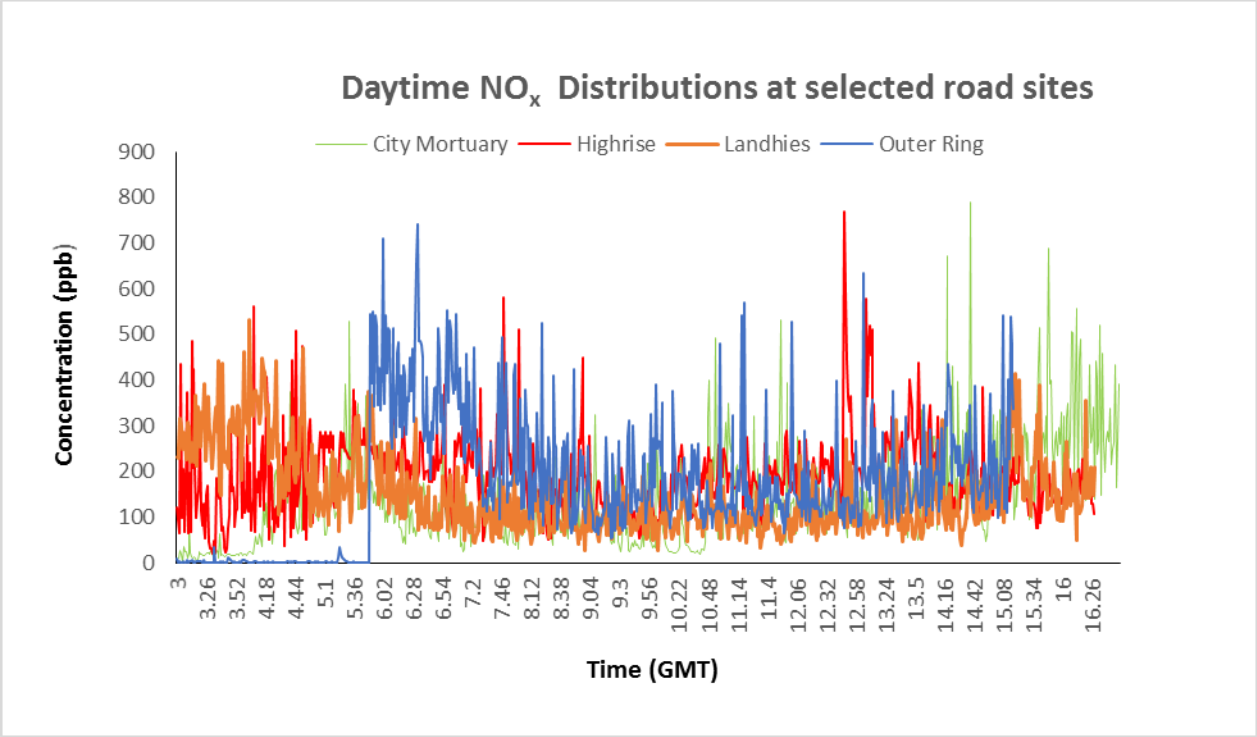

Fig. 9. Mean NOx Distribution at City Mortuary roundabout, Nyayo Highrise, Landhies road and Outer ring Roundabout.

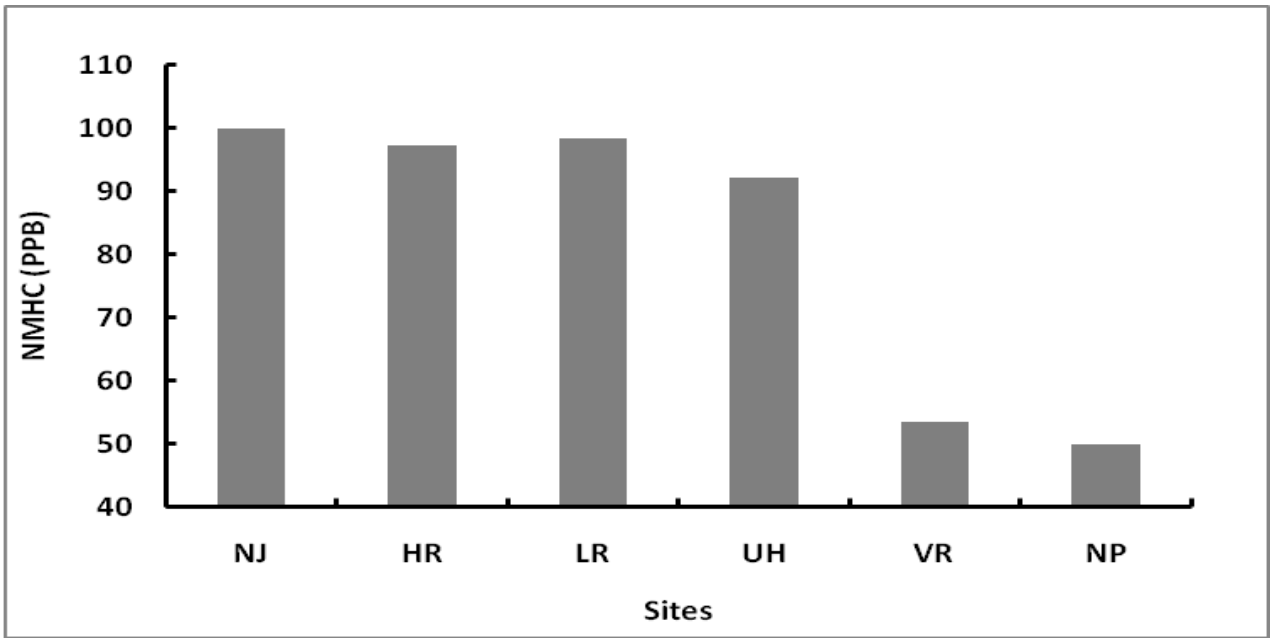

Fig.10. Mean NMHCs levels from the mobile sites. HR, Highrise; LR, Landies Road; NJ, Nakumatt Junction; NP, Nakumatt Prestige; VR, Valley Road.

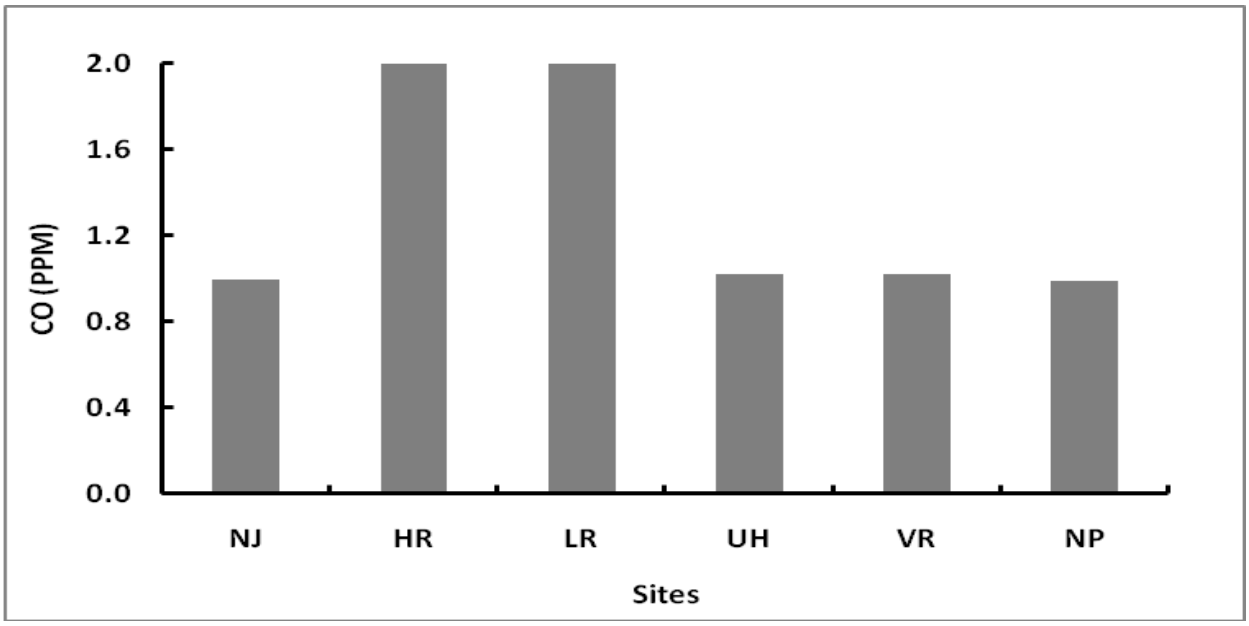

Fig. 11. Mean CO levels from the mobile sites.

3.3. Precursor Measurements

Ozone creation and destruction reactions is widely contributed to by NOx molecules in the troposphere and consequently, the response of ambient ozone levels to changes in VOC or NOx emissions is dependent on their relative concentrations and the intensity of insolation, which were seen to be high at around most noon times in Nairobi (Table 3). In cases where either the VOC/NOx ratio is low accompanied with low insolation, the effects of NOx on ozone lead to destruction and vice versa. High ambient NOx concentrations due to high emissions densities such as urban vehicular emissions which is majorly common in early mornings and evenings in Nairobi, leads to limited VOCs conditions and thus locally suppressed ozone concentrations relative to surrounding areas (Simon et al., 2014).

3.3.1. Nitrogen oxides (NOx)

NOx values were higher at Nyayo Highrise area and Kariobangi Roundabout than the rest of the mobile sites. Nakumatt Junction had the lowest NOx concentrations (Fig. 8, Fig.9).

3.3.2. Non-Methane Hydrocarbons (NMHCs)

The mobile site measurements for NMHCs (Fig. 10) highlighted that NMHC concentrations were more prominent at Nakumatt Junction with amounts (reaching 100 ppb), Nyayo Highrise (97.2 ppb), followed closely by Landhies road at Muthurwa bus terminus (98.4 ppb). Nakumatt Prestige however showed the least amounts of NMHC (50 ppb).

3.3.3. Carbon Monoxide (CO)

CO levels from the measured sites presented in the Fig. 11, showed that site of Nyayo Highrise remained the most dominant site, followed closely by Landhies road at Muthurwa bus terminus. High levels of NOx, CO, and MNHC were prominent during the morning and late evening hours at Nairobi city. These are rush hour times common for massive vehicular movement traversing the city from homes to work places and vice versa and major traffic snarl ups at many points around the city that result to the increase in the precursor gasses emissions. The situation is far aggravated by the combinations of the emissions and boundary layer processes. In these times and also due to unfavorable meteorological conditions, pollutant particles causes the reduction of the solar radiation at the surface to such a low level making the boundary layer static stability to become stable and consequently dropping down because of the increase in turbulence decay.

The pollutants-boundary layer feedback in the city due to congestion acts as a credible explanation for the existence of most severe haze episodes usually witnesses and loaded with pollutants. Pollutants from vehicular emissions and other sources are the possible contributors of surface ozone and the cause of critical levels air pollution and further to even poorer air quality (Agudelo-Castañeda et al., 2016; Wang et al., 2017; Zawacki et al., 2018; Zhao et al., 2018).

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4. Conclusion

Surface ozone measurements results were extracted for the years 2013 to 2016. Daytime ozone levels reach peak mainly at mid-day hours, and the seasonal levels showed bimodal trends. Annual two prominent peaks of ozone concentration were observed in March and September. The month of March in the four years had high peaks with hourly mean concentrations 32 ±- 5 ppb, subsequently decreasing trend towards April. Similar trend was prominent the second peak i.e., during September which reached highest ozone concentrations of 36 ± 5 ppb at midday (1 pm local time). The final phase of the seasonal distribution is then realized to start decreasing from October with maximum hourly averages of 29.51 ± 5 ppb towards November and finally December with values of 18 +/- 5 ppb where again it starts to peak and the cycle continues. Minimum values of surface ozone concentrations (2013-2016) were experienced in the months of May June and December, recording maximum hourly surface ozone values lower than 23.58 ppb. Due to variations in traffic levels mobile sites around the city showed marked diurnal variation in surface ozone levels from 4.28 ppb (Muthurwa market) to 14.9 ppb (Valley road). Surface ozone precursor concentrations were found to be quite lower than the threshold levels apart from CO (0.05–0.12 ppm) and Black Carbon (1000 ŋg/m^3) (24 h). Even at these levels, both contributed ssubstantially to the ozone formation in Nairobi as well as the background concentrations responsible for the air pollution. NOx was seen as the most prevalent precursor for ozone over Nairobi. In all the mobile sites measured, NOx was highest at Nyayo Highrise estate on Mbagathi road (190.23 ppb) followed closely by Kariobangi roundabout on Outer Ring road (166.68 ppb). NMHC levels were also remained quite low and reached maximum value of 100 ppb.

List of abbreviations: ASL, Above Sea Level; CO, Carbon Monoxide; CTM, Chemical Transport Model; GAW, Global Atmospheric Watch; IPCC, Intergovernmental Panel on Climate Change; ITCZ, Inter-Tropical Convergence Zone; KMD, Kenya Meteorological Department; MAML, Mobile Air Monitoring Laboratory; MNHC, Non-Methane Hydro Carbons; NCAR, National Centre for Atmospheric Research; NEMA, National Environment Management Authority; NMVOC, Non-Methane Volatile Organic Compounds; NO_X, Nitrogen Oxides; SHADOZ, Southern Hemisphere Additional Ozonesondes; UNEP, United Nations Environmental Programme; VOCs, Volatile Organic Compunds; WHO, World Health Organization; WMO, World Meteorological Organization.

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