Source apportionment and seasonal variation of $PM_{2.5}$ in a Sub-Sahara African city: Nairobi, Kenya

Samuel M. Gaita[1]*, Johan Boman[1], Michael J. Gatari[2], Jan B. C. Pettersson[1] and Sara Janhäll[3]

[1]Department of Chemistry and Molecular Biology, Atmospheric Science, University of Gothenburg, SE-412 96 Gothenburg, Sweden

[2]Institute of Nuclear Science and Technology, University of Nairobi, P.O. Box 30197, 00100 Nairobi, Kenya

[3]Swedish National Road and Transport Research Institute, P.O. Box 8072, SE-402 78 Gothenburg, Sweden

*Corresponding author. Tel.: +46 31 786 9075; E-mail: samuel.gaita@chem.gu.se.

Abstract

Sources of airborne particulate matter and their seasonal variation in urban areas in Sub-Sahara Africa are poorly understood due to lack of long-term measurement data. In view of this, filter samples of airborne particulate matter (particle diameter ≤ 2.5 µm, $PM_{2.5}$) were collected between May 2008 and April 2010 at two sites (urban background site and suburban site) within the Nairobi metropolitan area. A total of 780 samples were collected and analyzed for particulate mass, black carbon (BC) and thirteen trace elements. The average $PM_{2.5}$ concentration at the urban background site was 21 ± 9.5 µg m^{-3} whereas the concentration at the suburban site was 13 ± 7.3 µg m^{-3}. The daily $PM_{2.5}$ concentrations exceeded 25 µg m^{-3} (the World Health Organization 24 h guideline value) 29% of the days at the urban background site and 7% of the days at the suburban site. At both sites, BC, Fe, S and Cl accounted for approximately 80% of all detected elements. Positive matrix factorization analysis identified five source factors that contribute to $PM_{2.5}$ in Nairobi, namely; traffic, mineral dust, industrial, combustion and a mixed factor (composed of secondary aerosol and biomass burning components). Mineral dust and traffic factors were related to approximately 74% of $PM_{2.5}$. Identified source factors exhibited seasonal variation though traffic factor was prominently consistent throughout the sampling period. Weekly variations were observed in all factors with weekdays having higher concentrations than weekends. The results provide information that can be exploited for policy formulation and mitigation strategies to control air pollution in Sub-Sahara African cities.

KEYWORDS: $PM_{2.5}$, source profiles, urban air quality, Sub-Sahara Africa

1. Introduction

The air quality in major cities within Sub-Saharan Africa (SSA) is deteriorating due to several factors which include an increasing urban population, unregulated traffic activities, poorly maintained vehicles, inadequate regulations and air pollution control policies (Zachariadis et al., 2001; van Vliet and Kinney, 2007; UN, 2010). In order to draft environmental regulations to control air pollution, high-quality and long-term measurement data are required. However, such data are not readily available in the SSA region due to a lack of long-term air pollution monitoring (Petkova et al., 2013; UNEP, 2013). Most studies on aerosols in cities within SSA are limited and usually based on short-term measurements (Gatari et al., 2009; Mkoma et al., 2010; Odhiambo et al., 2010; Sawyer, 2010). As a result, there is poor understanding of long-term variations of airborne particulate matter (PM) and little is known about its sources, elemental constituents and seasonal variation.

Vehicular related emissions (both exhaust and non-exhaust) account for a large portion of urban air pollution in developing countries (van Vliet and Kinney, 2007; Kinney et al., 2011). A study conducted in Nairobi by Kinney et al. (2011) reported that concentration levels of $PM_{2.5}$ at street level, next to a city road, frequently exceeded the World Health Organization (WHO, 2000) 24 h guideline of 25 µg m^{-3}. This poses serious questions concerning health risks for people who frequent the city on a daily basis. Vehicular related emissions in the SSA region are exacerbated by the import of second-hand vehicles which for instance in Kenya can be up to eight years old (KEBS, 2013a). In addition, the road network in Nairobi is progressively improving and this has translated into increased motorized traffic activities with a large part of the increased traffic load coming from old and poorly maintained vehicles. This improving road network has led to severe congestion problems and air pollution exposure to the many pedestrians especially during morning and evening rush hours (Graeff, 2010). Recently, there has been a rapid increase (from 50 000 units in 2008 to 140 000 units in 2011) in importation and usage of motorcycles in urban and rural areas (KEBS, 2013b).

Mineral dust accounts for a significant portion of PM and originate from unpaved road surfaces as well as wind-blown dust during dry seasons (Boman et al., 2009; Reeves et al., 2010; Lindén et al., 2012). The natural background concentration of mineral dust in Africa is bound to be influenced by increasing episodes of droughts (WMO, 2013) as well as

increased anthropogenic activities which are related to economic growth. This will pose a challenge to formulation of strategies aimed at mitigating mineral dust effects on air quality. However, quantification of the contribution of mineral dust to urban PM will provide necessary information that can be used in drafting relevant air quality legislation.

On a regional level, emissions from biomass burning are also significant and dependent on season (wet or dry). Savannah fires account for a large percentage of carbonaceous aerosols detected in regional PM as has been reported from the extensive research campaigns carried out in southern African during the Southern African Regional Science Initiatives in 1992 and 2000 (SAFARI 1992 and SAFARI 2000) (Cahoon et al., 1992; Lindesay et al., 1996; Cachier et al., 1998; Andreae and Merlet, 2001; Formenti et al., 2003; Swap et al., 2003).

In Kenya, there is the Draft Air Quality Regulation which is referred to as "The Environmental Management and Coordination (Air Quality) Regulation, 2008" (NEMA, 2013). The said regulation does not set any air quality guidelines but instead proposes their formulation. It is interesting to note that the draft of air quality regulations in Kenya allows for burning of vegetation in the savannah grassland as part of cultural and traditional practices.

This paper presents results from a long-term measurement campaign initiated in 2008/2009 at two sites in the Nairobi metropolitan area. Samples were analyzed for their elemental content using X-ray fluorescence spectroscopy and the results were evaluated using positive matrix factorization (PMF). The results are compared with available data from previous short-term studies in Nairobi and their implications for urban air pollution mitigation strategies are discussed. The overall aim is to identify sources of $PM_{2.5}$ and evaluate their seasonal variations based on measured concentrations of $PM_{2.5}$, black carbon and 13 trace elements.

2. Materials and methods

2.1. Description of the study area

Nairobi city lies some 200 km south of the Equator and occupies an area of about 684 km^2. It has a population of about 3.2 million people with a daytime population of about 4 million (KOD, 2012). The larger Nairobi metropolitan area had a population of 6.1 million as of

2007 and it is expected to grow to over 12 million by 2030 (MoNMD, 2008). This increase in population has resulted in an increase in commercial, traffic and industrial activities, especially within the central business district. The peri-urban areas of the city continue to experience both controlled and uncontrolled development in buildings and infrastructure, especially mushrooming of informal settlements (Karanja and Makau, 2012). In these settlements, solid waste is usually burned in open air and a majority of the households use kerosene and biomass based fuels (charcoal, wood and vegetation) for domestic cooking (Egondi et al., 2013). The city's industrial area is located to the east and south-east and dominated by small and medium-sized industries which include food processing, power generation, chemical processing industries, battery manufacturing and scrap metal recycling.

2.2. Climate of the study area

Nairobi city experiences a moderate climate even though it is located along the equator. At a height of about 1795 m above the sea level, the city has a subtropical high climate according to the Köppen climate classification (Peel et al., 2007) 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) (Henne et al., 2008). 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 (KMD, 2013). Severe changes in this cycle usually result in droughts or flooding in the East African region (WMO, 2013). The average annual rainfall is approximately 900 mm but varies from less than 500 mm to more than 1500 mm between years. The average daily temperature varies from about 17 °C in July and August to 20 °C in March (KMD, 2013).

2.3. Sampling sites and $PM_{2.5}$ sampling procedure

Sampling of $PM_{2.5}$ was carried out at two sites within the Nairobi metropolitan area. The first site was at the University of Nairobi main campus (1.279° S, 36.817° E) (herein referred to as university and marked S1 in Fig. 1), which is within the city center. The second sampling site was established in a suburban area, within the compound of the United Nation Environmental Programme headquarter (1.234° S, 36.818° E) (herein referred to as UNEP and marked as S2 in Fig. 1) and about 5 km to the north of the university site.

Cyclone samplers (Casella, Bedford, UK) were used to collect fine particles ($PM_{2.5}$) on pre-weighed polycarbonate filters with 0.4 μm pore size (Whatman International Ltd., Maidstone, UK). Samples were collected for 24 h per sample at a flow rate of 3 L min^{-1}, except on weekends when samples were collected for 48 h per sample. At both the university and UNEP sites, sampling started at 10.00 a.m., local time (UTC + 3). At the university site, $PM_{2.5}$ samples were collected from 22nd May 2008 to 2nd April 2010. The cyclone sampler was mounted on the rooftop of the Engineering building at about 17 m above ground level (agl). This site being at an elevated location and close to the city center represents an urban background setting.

At the UNEP site, sampling was carried out from 16th April 2009 to 30th March 2010. The cyclone setup was placed on the rooftop of the administration block about 10 m agl. The site is located in a suburban area compared to the university site and it is surrounded by two local forests (Karura to the east and Gigiri to the south), and comprises office blocks and low-density residential houses.

A total of 780 valid samples were collected, of which 502 and 278 were from the university and UNEP sites, respectively. Loaded filters were analyzed for $PM_{2.5}$ mass concentration, black carbon (BC) and trace elements (from S to Pb). The $PM_{2.5}$ mass concentration was determined gravimetrically using a microbalance (Mettler Toledo model TM5). Empty and loaded filters were weighed after being conditioned at a relative humidity of 50 ± 10% and a temperature of 20 ± 2 °C for 24 h. The BC concentration was analyzed using a BC reflectometer (ESM Emberline, model FH62 1-N). The reflectometer measures the absorption and reflection properties of the sample-loaded filter, whereby the reflected light intensity at 650 nm is observed to non-linearly decrease as BC concentration increases on the filter (Gatari and Boman, 2003; Moosmüller et al., 2009).

Trace elements were determined using Energy Dispersive X-ray Fluorescence (EDXRF) spectroscopy. The spectrometer uses a Philips diffraction X-ray tube and a Mo secondary target. The secondary target consists of a 1 mm thick Mo plate of 99.99% purity. Fluoresced secondary X-rays propagate through two Ag collimators giving a relatively focused beam of near monochromatic X-rays for sample excitation. The spectrometer is laboratory built (University of Gothenburg, Sweden) in an optimized three axial geometry that gives good signal to noise ratios for the measured elements (Boman, 1991). It was operated at a voltage

of 50 kV and a current of 20 mA and spectral information was acquired for a live time of 1000 s. The spectra were analyzed using Analysis of X-ray spectra by Iterative Least-square fitting (AXIL) which is a subprogram of the Quantitative X-ray Analysis System (QXAS) software from International Atomic Energy Agency (Bernasconi et al., 2000). The subprogram assists in spectrum conversion and fitting. In this study, a calibration file was created using single element standards. The standards were run, fitted and evaluated for element's net peak area (P_A) and associated background area (B_A). The obtained P_A and B_A together with the known concentration (C_A) of the element were used to calculate the detection limit (DL_A; see Table 1) using the IUPAC equation below (van Grieken and Markowicz, 1993):

$$DL_A = 3 \times C_A \times \frac{\sqrt{B_A}}{P_A}$$

In order to correct for the positive artefacts from organic carbon (OC), measured concentration values from the field blanks were subtracted from the measured samples' concentration values (Watson et al., 2009).

2.4. Data treatment and analysis

$PM_{2.5}$, trace element and BC concentrations were further analyzed using positive matrix factorization (PMF) for purposes of source apportionment. PMF is a multivariate factor analysis method that decomposes a matrix of speciated sample data into factor contributions and profiles, which are then interpreted as to what source types they represent (Paatero, 1997). The EPA PMF 3.0 program from USEPA (Norris et al., 2008) was used for the analysis. Data below the detection limit (DL) were substituted with one-half of the respective DL and uncertainty was set to ± 5/6 times the DL (Polissar et al., 2001). During PMF analysis the number of factors was varied between three and nine factors. From the analysis output, only five factors were seen to give meaningful results for possible PM sources and are thus presented herein.

Meteorology data for this study were collected from Jomo Kenyatta International Airport (JKIA) that is approximately 13 km to the south-east of the university site (data was purchased from AccuWeather Enterprise Solutions, New York, USA). In addition, back-trajectories of air masses arriving at 100 m above the sampling sites were generated using

the HYSPLIT_4 model (Draxler and Hess, 1998). Daily back-trajectories were run for 72 h, clustered on a monthly basis and compared with monthly averages of measured hourly wind speeds and directions.

3. Results and discussion

3.1. Meteorology during the sampling period

Sampling period was characterized by periods of long rains (mid-March to May), short rains (October to November) and dry periods (from January to mid-March and from June to September) in 2008 and 2010. However, in 2009 there was a pronounced drought (from March to October) and as a result, lower than normal amount of rainfall was recorded during the long rains season (Zwaagstra et al., 2010; Williams and Funk, 2011).

Measured wind direction mainly oscillated between north and east (Fig. 2) for the entire sampling period. Average hourly wind speed for entire sampling period was 4 ms^{-1} and varied from 0 to 33 ms^{-1}. On a monthly basis, the wind direction was predominantly north-easterly during the period from October to March whereas during the months of April to September, the direction was mainly easterly and south-easterly. The average relative humidity was 67% and varied from 10 to 100%, while the average temperature was 20 °C and ranged from a minimum of 8 °C to a maximum of 32 °C.

Figure 3 shows clustered back trajectories for the sampling period and illustrates that air masses arriving in Nairobi area mainly originated from the south-easterly (52%) and easterly (48%) directions. From April to October, the air masses originated from the south-easterly direction (back trajectories numbered 2 and 3), whereas from November to March, the direction of origin was easterly and north-easterly (back trajectories 1 and 4). There was a discrepancy between calculated back trajectories and recorded wind direction in the months of September and October. This discrepancy between local wind directions and regional air mass movement indicates that the Nairobi PM is influenced by both local wind dynamics and regional air mass movement.

3.2. $PM_{2.5}$ mass and elemental concentrations

Results for $PM_{2.5,}$ BC and 13 trace elements concentrations from the university and UNEP sites are presented in Table 1 and Table 2. The statistics in Table 1 are from combined data sets from the two sites and depict a general picture of $PM_{2.5}$ and its constituents in the Nairobi metropolitan area. From all the filters collected, approximately 29% of the elemental contents were detected with the balance of 71% attributed to the contribution from organic matter, nitrates, aluminosilicates and oxides of both detected and undetected elements. BC has the highest average concentration and accounted for 15% of the $PM_{2.5}$ concentration whereas trace elements accounted for 14%. Average Fe concentration is the highest among the detected elements followed by S and Cl in that order. Average lead concentration is well below the WHO annual guideline concentration of 500 ng m^{-3} (WHO, 2000). This is probably due to the phasing out of leaded gasoline in 2006 in Kenya. Due to the high altitude of Nairobi a Tel-B mixture was being used (before 2006) as an anti-knock additive in the gasoline resulting in a Br/Pb ratio of 0.77 in particulate matter from fresh exhaust (Harrison and Sturges, 1983).

Table 2 shows the comparison of $PM_{2.5}$ and elemental concentrations at the university and UNEP sites for the common sampling period (16 April 2009 to 30 Mar 2010). At the university site, $PM_{2.5}$ concentration ranges from 3 to 53 µg m^{-3} with an overall mean of 21 µg m^{-3}. The average $PM_{2.5}$ concentration exceeds the annual WHO guideline limit of 10 µg m^{-3} by a factor of two. The 24 h WHO guideline was exceeded 29% of the total sampling days. Elemental composition of $PM_{2.5}$ at the university site is dominated by BC, Fe, S and Cl. Average BC concentration accounts for 19% of the of the total $PM_{2.5}$ concentration whereas Fe, S and Cl accounted for a total of 9%.

At the UNEP site $PM_{2.5}$ concentration ranges from 1.9 to 36 µg m^{-3} with an overall mean of 13 µg m^{-3}. The average $PM_{2.5}$ concentration is about 30% higher than the annual WHO guideline. At this site, the 24 h WHO guideline was exceeded 7% of the total sampling days. BC has the highest average concentration of the identified components and individually accounts for 11% of the total $PM_{2.5}$ concentration whereas all other elements account for 15%. The average concentration of S is the second highest followed by Cl, Fe and K in that order.

The average $PM_{2.5}$ concentration at the university site is about 50% higher than at the UNEP site. This observed difference points to inter site variation due to factors such the location of the measurement site, which in this case was that the UNEP site is located in a suburban area surrounded by forests (Fig. 1). The average BC concentration at the university site is more than twice the BC concentration at the UNEP site. Similarly, concentrations of Ca, Mn, Fe and Br show marked difference between the two sites. Albeit the close proximity of the sites to each other, the university site, an urban background site, is seen to be under greater influence from PM sources compared to the UNEP site. In addition, observed ranges and standard deviations of $PM_{2.5}$ and elements concentrations at the two sites indicate variability of the PM sources at both sites during the sampling period.

3.3. Seasonal variation of the $PM_{2.5}$, BC and some selected elements

Figure 4 shows the seasonal variation of $PM_{2.5}$ and some selected elements at the university site. Seasonal average concentration for $PM_{2.5}$ is highest during the cold and dry season in 2009 (25 μg m^{-3}) and lowest during the short rainy season (8.9 μg m^{-3}) in the same year. The high seasonal averages in 2009 especially during the long rainy season are linked to the then ongoing drought. WHO air quality guideline for a 24 h period was frequently exceeded during this drought period. High BC concentrations are observed during the cold and dry season in 2009 as well as during the latter part of the hot and dry season in 2009. The observed individual trends for the selected elements show marked variation. Zn concentrations display a variation that follows the erratic weather pattern reported in 2009. Pb concentration is prominent during 2009 indicating its relation to episodes of high $PM_{2.5}$ concentrations. Fe has a trend that is similar to that of $PM_{2.5}$ whereas both S and Cl display a similar trend to each other.

Figure 5 shows the seasonal variation of $PM_{2.5}$ and selected elements at the UNEP site. The general trend for the $PM_{2.5}$ concentration is that of variation from high concentrations in 2009 to lower concentrations in 2010. Similar trend was observed for Zn, Pb, S, Fe and BC. However Cl was observed to be somewhat consistent throughout the sampling period. The highest seasonal average concentration (19 μg m^{-3}) for $PM_{2.5}$ is measured during the cold and dry season in 2009 while the lowest seasonal average concentration is reported during the hot and dry season in 2010. This observation is supported by the high number of rainy

days manually recorded at that site during the said period compared to the other part of the sampling period.

Comparing the two sites, the observed seasonal variation is similar in 2009 but different in 2010. Observed trend for Pb concentrations at both sites shows similarity and it is intermittent probably due to decrease in airborne Pb as a result of banning the use of Pb in gasoline sold in Kenya. Observed trend of BC concentrations at both sites is equally similar pointing to common influence from possible local and regional sources. These observed differences in variations are attributed to differences in number and influences of possible PM sources, surrounding features such as forests at the UNEP site and differences in observed weather patterns at each site.

3.4. Weekly variation of $PM_{2.5}$, BC and some selected elements

Figure 6 shows the weekly variation of average concentrations of $PM_{2.5}$, BC, S, Cl, K, Fe, Zn and Pb calculated from the combined data of samples collected at the university and UNEP sites. In general, there is a common trend in all the indicated concentrations with weekdays (Monday to Friday) having higher concentration compared to the weekends (Saturdays and Sundays). This points to the influence of anthropogenic activities to airborne PM in Nairobi given that there is heightened human related activities during the weekdays and minimal activities during the weekends (Kinney et al., 2011). The concentrations of $PM_{2.5}$, BC, Cl, K and Fe do not display significant variations within the weekdays and this observation indicates consistency of their possible sources. The concentrations of S, Zn and Pb display variations within the weekdays indicating variability in their sources.

3.5. Positive matrix factorization analysis and source apportionment

Positive matrix factorization was applied to the combined data from the two sites to identify major $PM_{2.5}$ sources. The results from a five-factor solution are shown in Figures 7 to 11 and the individual factors are discussed hereinafter.

The first factor is attributed to both exhaust and non-exhaust traffic emissions (Fig. 7). The factor is characterized by a high contribution of BC, S, K, Fe and Zn and accounts for 39% of the $PM_{2.5}$. The factor shows a similar pattern as the elemental profile of $PM_{2.5}$ samples collected from a traffic polluted site in Connecticut, USA (Gent et al., 2009). The factor is

identified with exhaust traffic emissions due to the presence of S and BC (Zachariadis et al., 2001; Arku et al., 2008; Lestari and Mauliadi, 2009). The high S concentration comes from diesel sold in Kenya that contains 0.5% S and the visible black smoke from the exhaust pipes of many vehicles indicates incomplete combustion resulting in high emissions of BC. Furthermore, there are no regulations on vehicular emissions and a majority of the cars are imported as second-hand although there is an age-limit of 8 years. Non-exhaust traffic emissions such as re-suspension of road dust (Fe, K, Ca and traces of Pb) and tire abrasion (Zn) also contribute to this factor (Chueinta et al., 2000; Salma and Maenhaut, 2006; Pant and Harrison, 2013).

The second factor is attributed to mineral dust (Fig. 8). It is dominated by crustal elements (Fe, Ca, K and Ti) and has a pattern similar to that of elements from soil samples collected across SSA which were analyzed using Total X-ray Fluorescence technique (Towett et al., 2013). This factor highlights the contribution of local soil to $PM_{2.5}$ in Nairobi. The prolonged dry periods during the campaign contribute to the increased mineral dust loading to the sampled $PM_{2.5}$. The absence of S, Zn and Pb in this factor marks the difference between the origin of the mineral dust in this factor and the re-suspended road dust in the first factor hence justifying both dust components as separate entities.

The third factor is attributed to a mixture of biomass burning, secondary aerosol particles and aged sea salt (Fig. 9). This mixed factor accounts 13% of the mass concentration. Presence of Cl and S points to marine influence as shown by observed back trajectories (Fig. 3) that originate from the Indian Ocean as discussed in the meteorology section. This implies that marine aerosols reaching Nairobi, to some extent, undergo partial replacement of Cl by S during the long-range travel from the Indian Ocean. Sea salt particles have been reported to lose Cl due to reaction with acidic compounds, sulfuric acid in this case, to form sulfate aerosol particles (Pio and Lopes, 1998; Nyanganyura et al., 2007). The S component originates from diesel and heavy fuel oil consumption within the Nairobi region. However, the inclusion of sea salt as part of the mixed factor is not strong enough as this study did not measure Na which is a better indicator of sea salt than Cl given that the latter can be lost from the particle phase during atmospheric transport (Andreae and Crutzen, 1997; Oum et al., 1998). The contribution from biomass burning is indicated by presence of K, Zn and Rb. Biomass burning is a common phenomenon in the savannah plains that are located to the

southern part of the Equator as reported during the SAFARI campaigns (Lindesay et al., 1996; Formenti et al., 2003).

The fourth factor is attributed to combustion processes and accounts for 6% of the mass concentration. It is characterized by BC, S, K, Zn and Pb (Fig. 10) and shows similarity with a combustion factor from a study in Skopje, Macedonia (Kovacevik et al., 2011), which was associated with biomass and fossil fuel combustion. The combustion activities that are likely to contribute to $PM_{2.5}$ in Nairobi include use of heavy fuel oil in industries and in thermoelectric power generation (BC and S), solid waste burning (BC, Zn and Pb), domestic charcoal/wood fires/biomass burning (BC, K and Br) in the low income households and slums which account for over 80% of settlements in Nairobi metropolitan area (Karanja and Makau, 2012; Egondi et al., 2013).

The fifth factor is attributed to industrial emissions and accounts for 7% of the mass concentration. It is characterized by presence of Zn, Fe, Cl and K (Fig. 11). It is identified with emissions from smelting industries that depend on scrap metals as raw materials (Querol et al., 2007). These smelting industries are located on the eastern and south-eastern part of the city, which coincide with the general wind and air mass flow directions (Fig. 2 and 3). Contribution of Pb in this factor is below 1% but high concentrations of up to 427 ± 124 μg m^{-3} have been reported from a recycling plant at an industrial area (Were et al., 2012).

Figure 12 summarizes the percentage contribution of the identified $PM_{2.5}$ source factors. It is evident that traffic and mineral dust account for approximately 74% of $PM_{2.5}$ in Nairobi. This observation points to the significance of anthropogenic influence on air quality given that traffic is human-related whereas mineral dust component originates from both natural and human-related activities.

3.6. Seasonal variation

Figures 13 and 14 show the seasonal variation of the PMF factors at the university site and the UNEP site, respectively. The seasons are demarcated based on the description of the Nairobi climate by Kenya Meteorological department (KMD, 2013).

3.6.1. University site

Traffic and mineral dust factors dominate at the university site (Fig. 13) and are generally inherent during the entire sampling period. It is important to note that the dip observed during the short rainy season in 2009 was partly due to high uncertainty as a result of majority of the filters collected at that time exhibiting concentrations below the detection limit. The mineral dust factor is prominent due to the then ongoing drought and its seasonal percentage contribution in 2009 ranges from 33% to 55%. The drought effect is evident in that during the long rainy season in 2009, no significant change in mineral dust contribution (with seasonal percentage contribution of 33%) is noted when compared with the cool and dry season in the same year (seasonal percentage contribution, 40%). A low amount of rainfall (223 mm) was recorded compared to the normally expected amount (450 mm).

The traffic factor is almost consistent throughout the sampling period except during the short rainy season of 2009. During this period the seasonal percentage contribution was 11% compared to other seasons, which had a range of between 35% and 69%. The factor's contribution is seen to dominate in the beginning of 2010, with percentage contribution of 49% during the hot and dry season. Further statistical analysis of data in relation to the traffic factor shows that the average ratio of Pb to $PM_{2.5}$ during the hot and dry season in 2009 deviates from the average ratio of Pb to $PM_{2.5}$ (0.0014) obtained for all seasons. Percentagewise, it is 25% higher than the average ratio. In addition, the average Br/Pb ratio in this season is 0.64 compared to a ratio of 0.77 reported from fresh vehicular exhaust by Harrison and Sturges (1983). This indicates that part of the Br from gasoline emissions was present in the vapor phase, as also reported from the city of Butare, Rwanda, by Maenhaut and Akilimali (1987). In addition, during this season the wind blows mainly from north-eastern direction (same direction as the Thika highway and the Globe roundabout which is the entry point of vehicles from central and northern Kenya). Furthermore, contribution from tire abrasion was also a possibility (Salma and Maenhaut, 2006) given that many on road vehicles rely on second-hand tires.

The mixed factor though not prominent, is consistent throughout the sampling period but slightly pronounced during the short rainy season in 2009 with a seasonal contribution of 26%. During this season wind direction is usually easterly to north-easterly and therefore vehicular emission from the city center contributes S to this factor due to the S emissions

from vehicles, as described in the sections above. In addition, marine influence from Indian Ocean, as indicated by presence of Cl, is evident as shown in Figure 8, that back trajectories of air mass arriving in Nairobi principally originate from Indian Ocean.

The combustion factor was not consistent through the sampling period, but was prominent from the hot and dry season in 2009 with a seasonal percentage contribution of 6% and 8% during the long rainy season of the same year. Thereafter the factor's percentage contribution drops to 4% for the remaining seasons. This observed trend in combustion factor is an indication of the complexity of combustion sources in Nairobi such as unregulated burning of solid waste, extensive domestic use of kerosene and use of biomass based fuels (firewood and charcoal) in slum areas for energy generation (Salma and Maenhaut, 2006; Reinard et al., 2007).

The industrial factor showed a seasonal variation in that seasonal percentage contribution was highest (10% in each season) during the cool and dry seasons in 2008 and 2009. The percentage contribution was also high during the long rainy season in 2009 (8%) but was significantly low (2 to 4%) during the short rainy as well as all the hot and dry seasons. This observation highlighted contribution of metallurgical industries since local winds and regional air masses were generally easterly to south-easterly during the seasons with high percentage contributions. Thus emissions from the said industries were transported to the site, which were located in the same (mainly south-easterly) direction relative to the sampling site.

3.6.2. UNEP site

Figure 14 shows the trend in source factors at the UNEP site. Contribution of the factors is highest during the cool and dry season in 2009 and is dominated by the mineral dust, traffic and industrial factors. The contribution decreases towards the beginning of 2010. Wind direction during the cool and dry season is generally southerly to easterly that is the same direction as the city center and industrial area in relation to this site. During the hot and dry season in 2010, contribution from the mineral dust factor is minimal (percentage contribution, 22%). This coincided with the observation that the UNEP site recorded 19 rainy days during that season. This observation highlights the erratic nature of rainfall

pattern in Kenya during the sampling period (WMO, 2013) and its influence on the airborne particulate matter levels.

The traffic factor is consistently distributed throughout the sampling period but prominent during the long rainy season in 2009 with a seasonal percentage contribution of 40%. This is identified as resulting from re-suspension of road dust from the neighboring motorways. As was the case at the university site, calculated $Pb/PM_{2.5}$ ratio shows seasonal variation. However the $Pb/PM_{2.5}$ ratio is slightly higher (about 28%) than at the university site indicating significance of the road dust compared to other sources at the UNEP site. At the UNEP site the Br/Pb ratio is 0.43. Even though use of leaded gasoline was banned in 2006 by the Kenya government, it is expected that the Pb concentration in the soil dust will last for long period and somewhat be constant as reported from other world cities (Xu et al., 2012; Datko-Williams et al., 2014). In absolute concentration values, the university site had higher concentration (23 ± 16 ng m^{-3}) compared to the UNEP site (17 ± 14 ng m^{-3}). More so, since the university site is close to the city center, it is influenced heavily by PM sources as characterized by the reported 50% higher $PM_{2.5}$ concentration than the concentration reported at the UNEP site.

The mixed factor is prevalent during the hot and dry season in 2010 with a seasonal percentage contribution of 45%. During this season the wind direction is usually north-easterly and thus S component from diesel related emissions are transported from Thika highway towards UNEP site and its environs. In addition, back trajectories during this period are dominantly easterly and thus travelled over the city center, industrial and populated regions of the Nairobi metropolitan area.

The industrial factor shows gradual decrease from the beginning of the sampling period towards the end the period. The seasonal percentage contributions show gradual decline from 14% to 12% to 8% and finally to 0%. Comparing with a similar period at the university site, the observed trend is similar. Therefore, the explanation for this observation is the same as that given for the university site.

Lastly, the combustion factor is consistent throughout the sampling period but shows minimal contribution to $PM_{2.5}$ at this site. It does not show any seasonal variability and thus indicates to be dependent on contribution from regional sources. This observation is attributed to the fact that the site is in a suburban area where combustion activities such as

solid waste burning, domestic cooking using biomass among others are not common practice since the area is in uptown and has essential services such as waste collection.

3.7. Weekly trend of PMF factors

Figure 15 shows classification of PMF factors by days of the week. Considering individual factors, the mineral dust factor shows the least difference between weekdays and weekends. This observation points to the fact that contribution of dust particles to airborne $PM_{2.5}$ is influenced by both anthropogenic activities and natural phenomena. During the sampling period there was heightened activities in road infrastructure and given the working pattern in Kenya (working on weekdays and resting on weekends), road construction related activities such as quarrying of road materials was limited to weekdays (Kinney et al., 2011).

Weekly trend observed for the industrial factor is similar to the weekly working pattern in Kenya as explained previously. A majority of metallurgy industries in Kenya still use the open-hearth furnaces inherited from the colonial periods (early 20^{th} century).

The mixed factor was about 50% lower on weekends compared to weekdays and this implied that the factor was greatly influenced by anthropogenic activities compared to natural activities. This observation is supported by the fact that activities related to S emissions (consumption of high sulfur content diesel) reduce to a minimum during weekends.

All the five factors have lower concentrations on weekends compared to weekdays. This trend is similar to observed human activities in the city center on a typical week whereby weekdays are usually busy with both human and traffic activities compared to weekends (Kinney et al., 2011). Therefore it can be observed that all factors are impacted by anthropogenic activities.

3.8. Comparison of $PM_{2.5}$ with other studies

Since there were no other long-term studies of $PM_{2.5}$ and their elemental content in urban areas of Sub-Sahara Africa to compare with, $PM_{2.5}$, elements and BC concentrations from this study were compared with concentrations from a selection of available short-term studies (Table 3).

$PM_{2.5}$ concentration at the university site in the month of July 2009 was comparable to the $PM_{2.5}$ concentration reported by Gatari et al. (2009) from a study conducted at an industrial background site in Nairobi during July 2001. However in the month of July 2008, the $PM_{2.5}$ concentration was 30% lower. The agreement between the $PM_{2.5}$ concentrations in July 2001 and July 2009 and the difference compared to July 2008 illustrates the influence of drought on PM concentration since there was a severe drought in July 2001 as was the case in 2009. The abundance of PM in the air in July 2001 can be seen in the higher concentrations of many elements in the study by Gatari et al. (2009) compared to the average concentrations at the university site in this study. A clear exception is the concentration of Pb, which was more than three times higher in 2001 compared to this study. This demonstrates the effect of banning Pb from the gasoline in 2006.

The African cities listed in Table 3 have similar characteristics to Nairobi and are reported to have their air quality influenced largely by mineral dust, combustion activities and vehicular emissions. $PM_{2.5}$ concentration from this study was half of that reported from measurements in 2006 and 2007 at a semi-rural area of Accra city, Ghana (Aboh et al., 2009). The main difference is probably the influence of the dust filled Harmattan winds blowing from the Saharan desert to Accra. The same can be seen in a comparison between this study and the study in 2007 in Ouagadougou, Burkina Faso (Boman et al., 2009). In another study in Accra the Harmattan wind conditions were not present during the sampling and the $PM_{2.5}$ concentration in this study are similar to the $PM_{2.5}$ concentration reported from a 3 week study conducted in 2006 at a low income residential area in Accra city, Ghana (Arku et al., 2008). The proximity to the desert is also reflected in the high $PM_{2.5}$ concentration in a nine month study conducted between September 2010 and May 2011 at Cairo city center (Boman et al., 2013).

In comparison with a two weeks' study (not in Table 3) conducted at street level in Nairobi by Kinney et al. (2011), the average $PM_{2.5}$ concentration from the university site was 50% lower. In addition, average $PM_{2.5}$ concentration at the university site was a factor of 15 lower than average $PM_{2.5}$ concentration reported from a one week measurement campaign carried out along one of the major roads in Nairobi (Thika Road) by van Vliet and Kinney (2007). Observations from these two comparisons point to the discrepancy between background $PM_{2.5}$ concentrations and those from curb side concentrations in Nairobi city.

The elemental composition of $PM_{2.5}$ from the semi-rural area of Accra city had large concentrations of S, K and Fe as was the case with the composition of $PM_{2.5}$ in Nairobi in both this study and the study by Gatari et al. (2009) in 2001 pointing to a similarity in the sources of particles. A noticeable difference between this study and the ones by Gatari et al. (2009), Aboh et al. (2009) and Arku et al. (2008) is the higher concentration of Fe in the $PM_{2.5}$ particles at the university site in this study. This might partly be due to a difference between mineral dust compositions in the two cities but differences in measurement periods also play a role. The elemental concentrations at the low income area in Accra (Arku et al., 2008) are comparable to the concentrations at the UNEP site in this study, illustrating the importance of the distance between the measurement site and major pollution sources, like city center and busy roads.

In comparison to Cairo city, the elemental concentrations from this study were about 3 times lower than the concentrations reported from the nine month study conducted between September 2010 and May 2011 at a city center site (Boman et al., 2013). $PM_{2.5}$ in Cairo city had a large contribution from Ca, Cl and S. Since the city is within the Sahara region, its air quality is likely to be influenced by a mineral dust contribution from the desert. The higher concentrations of S and Cl in Cairo might be due to its location close to the Mediterranean Sea. The Pb concentration in Cairo is comparable to the Pb concentration in Nairobi in 2001, and thus higher than in this study. Egypt is one of the few countries in Africa where leaded gasoline is still allowed and the comparison points to the importance of banning leaded gasoline to decrease the health burden of the city inhabitants.

4. Conclusions

This study has shown that traffic related emissions (both exhaust and non-exhaust) and mineral dust (both natural and anthropogenic) have significant contribution to $PM_{2.5}$ in Nairobi city. It can also be concluded that policies such as banning of Pb in gasoline have shown positive effect on reducing Pb concentration in $PM_{2.5}$ and hence reducing the risk of Pb toxicity to the urban inhabitants. Similarly a reduction of sulfur from the diesel fuel could lead to an improved air quality situation in Nairobi. More so, prevailing weather and climate patterns have been found to play a significant role by influencing the concentration and composition of airborne PM as is the case in other cities in SSA. As shown from wind direction and air mass back trajectories analysis, industrial emissions should be firmly

controlled, as the industrial area in Nairobi is located in the upwind direction. Since this study points at factors contributing to the air quality situation in Nairobi the outcome of this study can be used as a background for further policy actions. Contribution of $PM_{2.5}$ from traffic factor can be controlled by inclusion of emission checks as part of annual vehicle inspection and this would significantly reduce air pollution in the city. On the other hand, natural background concentrations of mineral dust as well as prevailing weather conditions would give guidance when formulating any policy aimed at air pollution mitigation. In conclusion, the study has shown that enactment and adherence to air pollution regulations on identified source factors can significantly reduce air pollution levels in cities within SSA.

Acknowledgements

This work was supported by the Swedish Research Council, Swedish International Development Agency (SIDA). International Science Programme, Uppsala University, supports the host institute (Institute of Nuclear Science & Technology) of the study in Nairobi, Kenya. The presented research is a contribution to the Swedish strategic research area ModElling the regional and Global Earth system, MERGE.

References

Aboh, I. J. K., Henriksson, D., Laursen, J., Lundin, M., Ofosu, F. G., Pind, N., Selin Lindgren, E., and Wahnström, T.: Identification of aerosol particle sources in semi-rural area of Kwabenya, near Accra, Ghana, by EDXRF techniques, X-Ray Spectrom., 38, 348-353, 10.1002/xrs.1172, 2009.

Andreae, M. O., and Crutzen, P. J.: Atmospheric Aerosols: Biogeochemical Sources and Role in Atmospheric Chemistry, Science, 276, 1052-1058, 10.1126/science.276.5315.1052, 1997.

Andreae, M. O., and Merlet, P.: Emission of trace gases and aerosols from biomass burning, Global Biogeochem. Cy., 15, 955-966, 10.1029/2000GB001382, 2001.

Arku, R. E., Vallarino, J., Dionisio, K. L., Willis, R., Choi, H., Wilson, J. G., Hemphill, C., Agyei-Mensah, S., Spengler, J. D., and Ezzati, M.: Characterizing air pollution in two low-income neighborhoods in Accra, Ghana, Sci. Total Environ., 402, 217-231, http://dx.doi.org/10.1016/j.scitotenv.2008.04.042, 2008.

Bernasconi, G., Tajani, A., and Kregsamer, P.: Manual for QXAS/AXIL Version 3.5, IAEA, Vienna, 2000.

Boman, J.: Sample area dependence in quantitative EDXRF analysis, X-Ray Spectrom., 20, 321-324, 10.1002/xrs.1300200613, 1991.

Boman, J., Lindén, J., Thorsson, S., Holmer, B., and Eliasson, I.: A tentative study of urban and suburban fine particles (PM2.5) collected in Ouagadougou, Burkina Faso, X-Ray Spectrom., 38, 354-362, 10.1002/xrs.1173, 2009.

Boman, J., Shaltout, A. A., Abozied, A. a. M., and Hassan, S. K.: On the elemental composition of PM2.5 in central Cairo, Egypt, X-Ray Spectrom., 42, 276-283, 10.1002/xrs.2464, 2013.

Cachier, H., Ruellan, S., Liousse, C., Gaudichet, A., Masclet, P., and Lacaux, J.: Biomass burning aerosols in tropical Africa, J. Aerosol Sci., 29, Supplement 1, S23-S24, http://dx.doi.org/10.1016/S0021-8502(98)00088-3, 1998.

1 Cahoon, D. R., Stocks, B. J., Levine, J. S., Cofer, W. R., and O'Neill, K. P.: Seasonal
2 distribution of African savanna fires, Nature, 359, 812-815, 1992.

3 Chueinta, W., Hopke, P. K., and Paatero, P.: Investigation of sources of atmospheric aerosol
4 at urban and suburban residential areas in Thailand by positive matrix factorization, Atmos.
5 Environ., 34, 3319-3329, http://dx.doi.org/10.1016/S1352-2310(99)00433-1, 2000.

6 CSUD: 2005 Nairobi Land Use & Roads Network, Center for Sustainable Urban
7 Development, Columbia University, New York, 2010.

8 Datko-Williams, L., Wilkie, A., and Richmond-Bryant, J.: Analysis of U.S. soil lead (Pb)
9 studies from 1970 to 2012, Sci. Total Environ., 468–469, 854-863,
10 http://dx.doi.org/10.1016/j.scitotenv.2013.08.089, 2014.

11 Draxler, R. R., and Hess, G. D.: An overview of the HYSPLIT_4 modeling system of
12 trajectories, dispersion, and deposition., Aust. Meteorol. Mag., 47, 295-308, 1998.

13 Egondi, T., Kyobutungi, C., Ng, N., Muindi, K., Oti, S., Vijver, S., Ettarh, R., and Rocklöv,
14 J.: Community Perceptions of Air Pollution and Related Health Risks in Nairobi Slums, Int.
15 J. Environ. Res. Publ. Health, 10, 4851-4868, 2013.

16 Formenti, P., Elbert, W., Maenhaut, W., Haywood, J., Osborne, S., and Andreae, M. O.:
17 Inorganic and carbonaceous aerosols during the Southern African Regional Science
18 Initiative (SAFARI 2000) experiment: Chemical characteristics, physical properties, and
19 emission data for smoke from African biomass burning, J. Geophys. Res.-Atm., 108, 8488,
20 10.1029/2002JD002408, 2003.

21 Gatari, M. J., and Boman, J.: Black carbon and total carbon measurements at urban and rural
22 sites in Kenya, East Africa, Atmos. Environ., 37, 1149-1154,
23 http://dx.doi.org/10.1016/S1352-2310(02)01001-4, 2003.

24 Gatari, M. J., Boman, J., and Wagner, A.: Characterization of aerosol particles at an
25 industrial background site in Nairobi, Kenya, X-Ray Spectrom., 38, 37-44,
26 10.1002/xrs.1097, 2009.

27 Gent, J. F., Koutrakis, P., Belanger, K., Triche, E., Holford, T. R., Bracken, M. B., and
28 Leaderer, B. P.: Symptoms and medication use in children with asthma and traffic-related

sources of fine particle pollution, Environ. Health Persp., 117, 1168-1174, 10.1289/ehp.0800335, 2009.

Graeff, J.: The Organization and Future of the Matatu Industry in Nairobi, Kenya, Manuscript submitted for publication, 2010.

Harrison, R. M., and Sturges, W. T.: The measurement and interpretation of Br/Pb ratios in airborne particles, Atmos. Environ., 17, 311-328, http://dx.doi.org/10.1016/0004-6981(83)90048-3, 1983.

Henne, S., Junkermann, W., Kariuki, J. M., Aseyo, J., and Klausen, J.: Mount Kenya Global Atmospheric Watch Station (MKN): Installation and Meteorology Characterization, J. Appl. Meteorol. Clim., 47, 2946-2962, 2008.

Karanja, I. W., and Makau, J.: An inventory of slums in Nairobi, UN Office for the Coordination of Humanitarian Affairs, Nairobi, 2012.

KEBS: Regulations on Vehicle Importation, Kenya National Bureau of Statistics, Nairobi, 2013a.

KEBS: Registered Vehicles: 2001-2009, Kenya National Bureau of Statistics, Nairobi, 2013b.

Kinney, P. L., Gichuru, M. G., Volavka-Close, N., Ngo, N., Ndiba, P. K., Law, A., Gachanja, A., Gaita, S. M., Chillrud, S. N., and Sclar, E.: Traffic impacts on PM2.5 air quality in Nairobi, Kenya, Environ. Sci. Policy, 14, 369-378, http://dx.doi.org/10.1016/j.envsci.2011.02.005, 2011.

KMD: Nairobi climate, Kenya Meteorological Department, Nairobi, 2013.

KOD: Rural and Urban Population Census: 2009, Kenya Open Data, Nairobi, 2012.

Kovacevik, B., Wagner, A., Boman, J., Laursen, J., and Pettersson, J. B. C.: Elemental composition of fine particulate matter (PM2.5) in Skopje, FYR of Macedonia, X-Ray Spectrom., 40, 280-288, 10.1002/xrs.1337, 2011.

Lestari, P., and Mauliadi, Y. D.: Source apportionment of particulate matter at urban mixed site in Indonesia using PMF, Atmos. Environ., 43, 1760-1770, http://dx.doi.org/10.1016/j.atmosenv.2008.12.044, 2009.

Lindén, J., Boman, J., Holmer, B., Thorsson, S., and Eliasson, I.: Intra-urban air pollution in a rapidly growing Sahelian city, Environ. Int., 40, 51-62, http://dx.doi.org/10.1016/j.envint.2011.11.005, 2012.

Lindesay, J. A., Andreae, M. O., Goldammer, J. G., Harris, G., Annegarn, H. J., Garstang, M., Scholes, R. J., and van Wilgen, B. W.: International geosphere-biosphere programme/international global atmospheric chemistry SAFARI-92 field experiment: Background and overview, J. Geophys. Res.-Atm., 101, 23521-23530, 10.1029/96JD01512, 1996.

Maenhaut, W., and Akilimali, K.: Study of the atmospheric aerosol composition in equatorial Africa using PIXE as analytical technique, Nucl. Instrum. Meth. B, 22, 254-258, http://dx.doi.org/10.1016/0168-583X(87)90338-7, 1987.

Mkoma, S. L., Chi, X., and Maenhaut, W.: Characteristics of carbonaceous aerosols in ambient PM10 and PM2.5 particles in Dar es Salaam, Tanzania, Sci. Total Environ., 408, 1308-1314, http://dx.doi.org/10.1016/j.scitotenv.2009.10.054, 2010.

MoNMD: A World Class African Metropolis – Building a Safe, Secure and Prosperous Metropolitan., Ministry of Nairobi Metropolitan Development, Nairobi, 2008.

Moosmüller, H., Chakrabarty, R. K., and Arnott, W. P.: Aerosol light absorption and its measurement: A review, J. Quant. Spectrosc. Ra., 110, 844-878, http://dx.doi.org/10.1016/j.jqsrt.2009.02.035, 2009.

NEMA: Draft Air Quality Regulation, 2008, National Environment Management Authority - Kenya, Nairobi, 2013.

Norris, G., Vedantham, R., Wade, K., Brown, S., Prouty, J., and Foley, C.: EPA Positive Matrix Factorization (PMF) 3.0 Fundamentals & User Guide, U.S. Environmental Protection Agency, Washington D.C., 2008.

Nyanganyura, D., Maenhaut, W., Mathuthu, M., Makarau, A., and Meixner, F. X.: The chemical composition of tropospheric aerosols and their contributing sources to a continental background site in northern Zimbabwe from 1994 to 2000, Atmos. Environ., 41, 2644-2659, http://dx.doi.org/10.1016/j.atmosenv.2006.11.015, 2007.

Odhiambo, G. O., Kinyua, A. M., Gatebe, C. K., and Awange, J.: Motor vehicles air pollution in Nairobi, Kenya., Res. J. Environ. Earth Sci., 2, 178-187, 2010.

Oum, K. W., Lakin, M. J., DeHaan, D. O., Brauers, T., and Finlayson-Pitts, B. J.: Formation of Molecular Chlorine from the Photolysis of Ozone and Aqueous Sea-Salt Particles, Science, 279, 74-76, 10.1126/science.279.5347.74, 1998.

Paatero, P.: Least squares formulation of robust non-negative factor analysis, Chemometr. Intell. Lab., 37, 23-35, http://dx.doi.org/10.1016/S0169-7439(96)00044-5, 1997.

Pant, P., and Harrison, R. M.: Estimation of the contribution of road traffic emissions to particulate matter concentrations from field measurements: A review, Atmos. Environ., 77, 78-97, http://dx.doi.org/10.1016/j.atmosenv.2013.04.028, 2013.

Peel, M. C., Finlayson, B. L., and McMahon, T. A.: Updated world map of the Köppen-Geiger climate classification, Hydrol. Earth Syst. Sc., 11, 1633-1644, 10.5194/hess-11-1633-2007, 2007.

Petkova, E., Jack, D., Volavka-Close, N., and Kinney, P.: Particulate matter pollution in African cities, Air Qual Atmos Health, 10.1007/s11869-013-0199-6, 1-12, 10.1007/s11869-013-0199-6, 2013.

Pio, C. A., and Lopes, D. A.: Chlorine loss from marine aerosol in a coastal atmosphere, J. Geophys. Res.-Atm., 103, 25263-25272, 10.1029/98JD02088, 1998.

Polissar, A. V., Hopke, P. K., and Poirot, R. L.: Atmospheric Aerosol over Vermont: Chemical Composition and Sources, Environ. Sci. Policy, 35, 4604-4621, 10.1021/es0105865, 2001.

Querol, X., Viana, M., Alastuey, A., Amato, F., Moreno, T., Castillo, S., Pey, J., de la Rosa, J., Sánchez de la Campa, A., Artíñano, B., Salvador, P., García Dos Santos, S., Fernández-Patier, R., Moreno-Grau, S., Negral, L., Minguillón, M. C., Monfort, E., Gil, J. I., Inza, A.,

Ortega, L. A., Santamaría, J. M., and Zabalza, J.: Source origin of trace elements in PM from regional background, urban and industrial sites of Spain, Atmospheric Environment, 41, 7219-7231, http://dx.doi.org/10.1016/j.atmosenv.2007.05.022, 2007.

Reeves, C. E., Formenti, P., Afif, C., Ancellet, G., Attié, J. L., Bechara, J., Borbon, A., Cairo, F., Coe, H., Crumeyrolle, S., Fierli, F., Flamant, C., Gomes, L., Hamburger, T., Jambert, C., Law, K. S., Mari, C., Jones, R. L., Matsuki, A., Mead, M. I., Methven, J., Mills, G. P., Minikin, A., Murphy, J. G., Nielsen, J. K., Oram, D. E., Parker, D. J., Richter, A., Schlager, H., Schwarzenboeck, A., and Thouret, V.: Chemical and aerosol characterisation of the troposphere over West Africa during the monsoon period as part of AMMA, Atmos. Chem. Phys., 10, 7575-7601, 10.5194/acp-10-7575-2010, 2010.

Reinard, M. S., Adou, K., Martini, J. M., and Johnston, M. V.: Source characterization and identification by real-time single particle mass spectrometry, Atmos. Environ., 41, 9397-9409, http://dx.doi.org/10.1016/j.atmosenv.2007.09.001, 2007.

Salma, I., and Maenhaut, W.: Changes in elemental composition and mass of atmospheric aerosol pollution between 1996 and 2002 in a Central European city, Environ. Pollut., 143, 479-488, http://dx.doi.org/10.1016/j.envpol.2005.11.042, 2006.

Sawyer, R. F.: Vehicle emissions: progress and challenges, J. Expo. Sci. Env. Epid., 20, 487-488, 10.1038/jes.2010.44, 2010.

Swap, R. J., Annegarn, H. J., Suttles, J. T., King, M. D., Platnick, S., Privette, J. L., and Scholes, R. J.: Africa burning: A thematic analysis of the Southern African Regional Science Initiative (SAFARI 2000), J. Geophys. Res.-Atmos., 108, 8465, 10.1029/2003JD003747, 2003.

Towett, E. K., Shepherd, K. D., and Cadisch, G.: Quantification of total element concentrations in soils using total X-ray fluorescence spectroscopy (TXRF), Sci. Total Environ., 463–464, 374-388, http://dx.doi.org/10.1016/j.scitotenv.2013.05.068, 2013.

UN, D. o. E. a. S. A.: World Urbanization Prospects: The 2009 Revision, United Nations, New York, 2010.

UNEP: Eastern Africa Regional Framework Agreement on Air Pollution (Nairobi Agreement – 2008), United Nations Environmental Programme, Nairobi, 2013.

van Grieken, R. E., and Markowicz, A. A.: Handbook of X-ray Spectrometry, Marcel Dekker, New York 1993.

van Vliet, E. D. S., and Kinney, P. L.: Impacts of roadway emissions on urban particulate matter concentrations in Sub-Saharan Africa: new evidence from Nairobi, Kenya., Environ. Res. Lett., 2, 045028 (045025pp), 2007.

Watson, J. G., Chow, J. C., Chen, L. W. A., and Frank, N. H.: Methods to Assess Carbonaceous Aerosol Sampling Artifacts for IMPROVE and Other Long-Term Networks, J. Air Waste Manag. Assoc., 59, 898-911, 10.3155/1047-3289.59.8.898, 2009.

Were, F. H., Kamau, G. N., Shiundu, P. M., Wafula, G. A., and Moturi, C. M.: Air and Blood Lead Levels in Lead Acid Battery Recycling and Manufacturing Plants in Kenya, J. Occup. Environ. Hyg. , 9, 340-344, 10.1080/15459624.2012.673458, 2012.

WHO: Air quality guidelines for Europe, World Health Organization, Copenhagen, 2000.

Williams, A. P., and Funk, C.: A westward extension of the warm pool leads to a westward extension of the Walker circulation, drying eastern Africa, Clim. Dyn., 37, 2417-2435, 10.1007/s00382-010-0984-y, 2011.

WMO: The Global Climate 2001-2010: A decade of climate extremes, World Meteorological Organization, Geneva, 61, 2013.

Xu, H. M., Cao, J. J., Ho, K. F., Ding, H., Han, Y. M., Wang, G. H., Chow, J. C., Watson, J. G., Khol, S. D., Qiang, J., and Li, W. T.: Lead concentrations in fine particulate matter after the phasing out of leaded gasoline in Xi'an, China, Atmos. Environ., 46, 217-224, http://dx.doi.org/10.1016/j.atmosenv.2011.09.078, 2012.

Zachariadis, T., Ntziachristos, L., and Samaras, Z.: The effect of age and technological change on motor vehicle emissions, Transport Res. D.-Tr. E., 6, 221-227, 2001.

Zwaagstra, L., Sharif, Z., Wambile, A., de Leeuw, J., Said, M. Y., Johnson, N., Njuki, J., Ericksen, P., and Herrero, M.: An assessment of the response to the 2008-2009 drought in Kenya, Nairobi, Kenya, 108, 2010.

Table 1. Summary of the results from all filter samples for the collection period 22 May 2008 to 30 March 2010 at two sites in Nairobi, Kenya which include: detection limits, range, mean concentrations (ng m^{-3}), standard deviations (SD) and percentage composition (%$PM_{2.5}$) for detected trace elements, BC and $PM_{2.5}$. N is the number of valid samples.

Elements	Detection limit (ng m^{-3})	Mean (ng m^{-3})	SD (ng m^{-3})	%$PM_{2.5}$	Range (ng m^{-3})	N
S	250	640	340	3.6	250-3800	459
Cl	110	480	200	2.7	110-1800	723
K	50	310	150	1.7	51-840	719
Ca	30	310	250	1.7	30-2700	713
Ti	14	54	25	0.3	14-180	570
Mn	9.5	41	23	0.2	10-190	722
Fe	10	530	350	2.9	11-1800	780
Ni	0.8	4	2	0.0	1-17	478
Cu	0.7	11	6	0.1	2-82	773
Zn	6.6	91	100	0.5	7-760	780
Br	2.5	12	21	0.1	3-340	667
Rb	0.5	2	1	0.0	1-5	383
Pb	1.5	22	18	0.1	2-160	525
BC	6	2700	1800	15	74-9900	767
$PM_{2.5}$	1000	18000	8600		1900-53000	780

Table 2. Summary of the results from the University and the UNEP site for the time period from 16 April 2009 to 30 Mar 2010: range, mean concentrations and standard deviations (SD) for detected trace elements, BC (in ng m^{-3}) and $PM_{2.5}$ (in µg m^{-3}). N is the number of valid samples.

	University			UNEP		
Elements	Range (ng m^{-3})	Mean (SD) (ng m^{-3})	N	Range (ng m^{-3})	Mean (ng m^{-3})	N
S	250 – 1600	660 (240)	132	250 – 1700	620 (280)	184
Cl	110 – 1300	520 (200)	253	110 – 1600	430 (170)	259
K	60 – 840	340 (160)	265	50 – 760	270 (160)	239
Ca	40 – 2700	340 (270)	268	30 – 1300	200 (150)	228
Ti	21 – 180	62 (27)	241	14 – 110	40 (18)	156
Mn	11 – 120	53 (23)	267	10 – 90	28 (14)	236
Fe	33 – 1700	730 (340)	270	11 – 1200	320 (240)	278
Ni	2 – 10	4 (1)	153	1 – 17	4 (2)	191
Cu	2 – 80	12 (7)	269	2 – 55	9 (4)	275
Zn	9 – 760	120 (120)	270	7 – 640	76 (97)	272
Br	3 – 340	16 (30)	240	3 – 70	7 (5)	215
Rb	1 – 5	3 (1)	160	1 – 5	2 (1)	123
Pb	2 – 80	23 (16)	202	2 – 79	17 (14)	186
BC	40 – 9500	3900 (800)	270	70 – 5700	1500 (1000)	267
$PM_{2.5}$ (µg m^{-3})	3 - 53	21 (9.5)	270	1.9 - 36	13 (7.3)	278

Table 3. $PM_{2.5}$, BC, and trace element concentrations from this study (Nairobi) compared with concentration from other cities in Africa. Concentrations are in ng m^{-3}. Values enclosed in brackets are the standard deviations.

	This study		Gatari et al. (2009)	Aboh et al. (2009)	Boman et al. (2009)	Arku et al. (2008)	Boman et al. (2013)
Site/ Elements	University (urban background)	UNEP (suburban)	Industrial background, Nairobi	Semi-rural area, Accra	City center, Ouagadougou	Low income area, Accra	Urban center, Cairo
S	660 (240)	620 (280)	1300 (400)	462 (290)	- -	909 (267)	1200 (870)
Cl	520 (200)	430 (170)	- -	123 (133)	960 (290)	706 (423)	2200 (2200)
K	340 (160)	270 (160)	730 (220)	377 (325)	670 (210)	694 (188)	470 (260)
Ca	370 (270)	200 (150)	70 (34)	144 (322)	1400 (570)	57 (22)	2900 (3200)
Ti	62 (27)	40 (18)	8.7 (4.4)	37.5 (64.8)	240 (81)	6 (3)	100 (89)
Mn	53 (23)	28 (14)	12 (3.9)	7.6 (11.4)	61 (25)	6 (2)	24 (20)
Fe	730 (340)	320 (240)	130 (43)	289 (504)	3000 (1400)	69 (27)	1000 (1000)
Ni	4 (1)	4 (2)	2.6 (1.1)	3.2 (2.8)	- -	- -	6.8 (1.7)
Cu	12 (7)	9 (4)	3.5 (2.2)	4.1 (3.9)	19 (6.4)	9 (15)	16 (9.8)
Zn	120 (120)	76 (97)	100 (69)	6.5 (5.7)	45 (35)	32 (13)	200 (180)
Br	16 (30)	7 (5)	36 (18)	5.9 (3.5)	7.3 (2.7)	30 (16)	21 (15)
Rb	3 (1)	2 (1)	1.56 (0.5)	1.4 (1.4)	4.2 (1.9)	2 (1)	4.4 -
Pb	23 (16)	17 (1)	76 (30)	2.5 (1.7)	8.8 (4.2)	18 (25)	86 (180)
BC	3900 (800)	1500 (1000)	4800 (1800)	1900 (1100)	4900 (1700)	- -	3700 (2100)
$PM_{2.5}$	21000 (950)	13000 (7300)	30000 (9400)	40800 (54400)	86000 (42000)	22700 (5700)	51000 (39000)

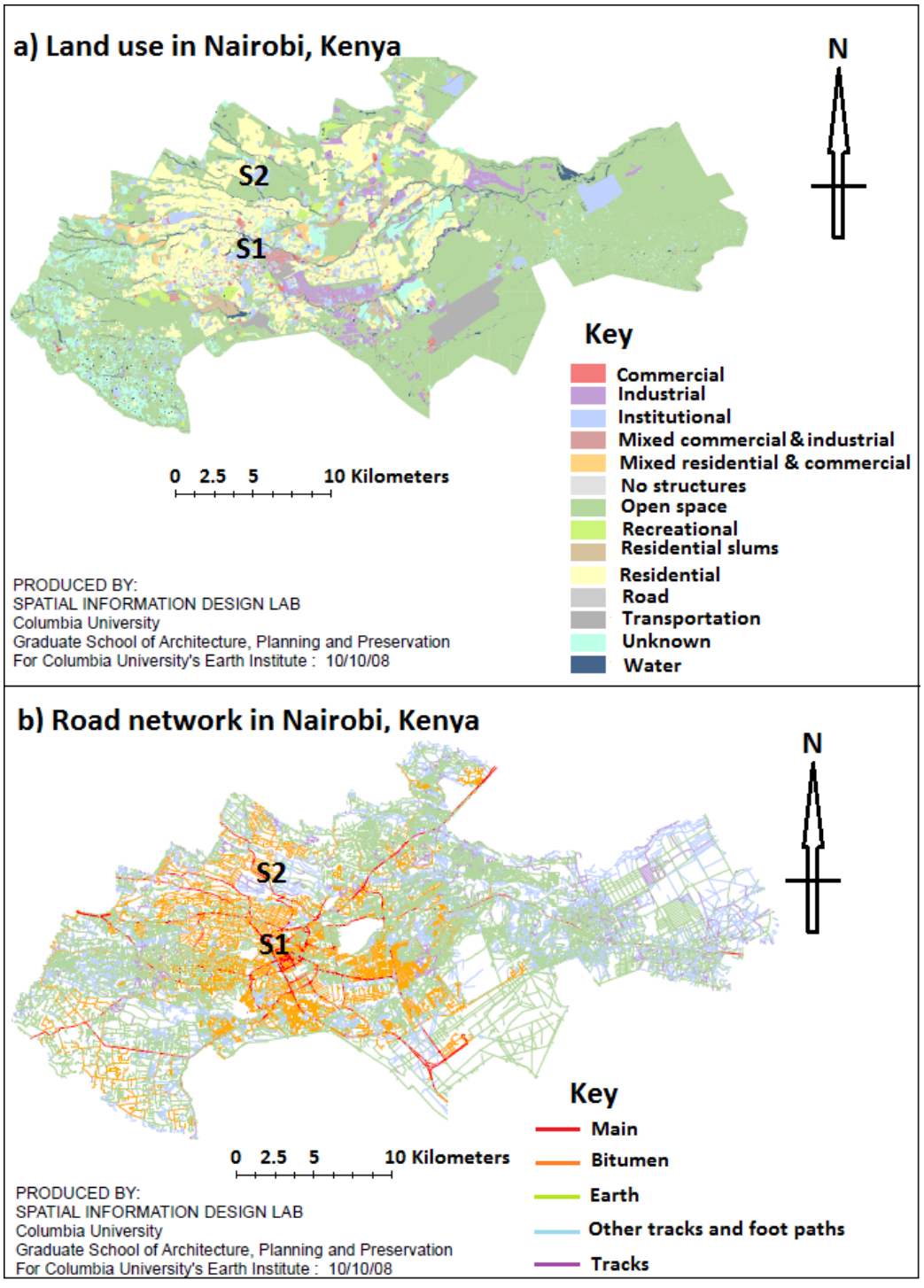

Fig. 1. GIS map of the Nairobi metropolitan area showing land use pattern (a) and transportation network (b). Original maps were modified to include sampling sites as shown on both maps; University of Nairobi (S1) and United Nations Environmental Programme (UNEP) headquarters (S2). Original maps were downloaded from the Center for Sustainable Urban Development's Nairobi GIS maps and database website (CSUD, 2010)).

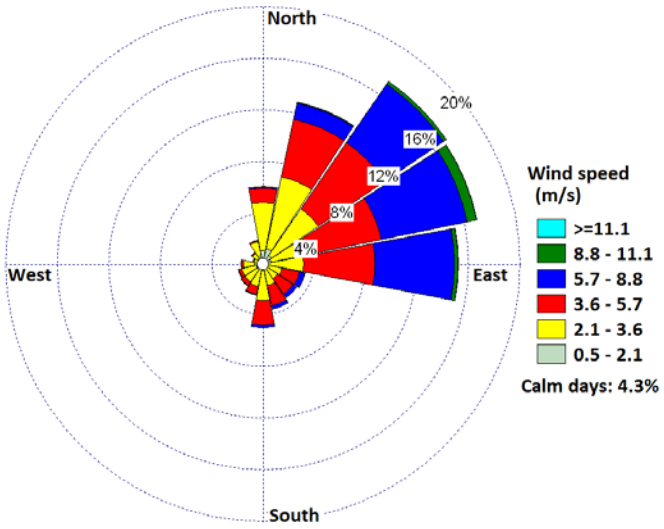

Fig. 2. Wind speed and direction during the sampling period i.e. from 22 May 2008 to 30 March 2010. The wind data was measured at Jomo Kenyatta International Airport (JKIA), Nairobi, which was approximately 12 km south-east of the city center.

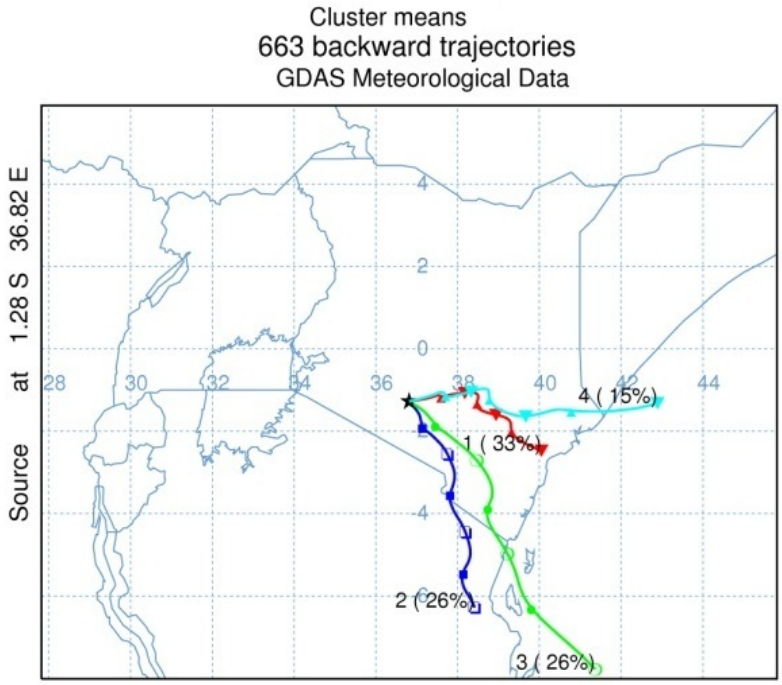

Fig. 3. Clustered 72 h back trajectories ending in Nairobi at 100 m height above the ground for the period, 22 May 2008 to 30 March 2010. Calculated back trajectories originate principally from south-east (trajectories 2 and 3) and east (trajectories 1 and 4).

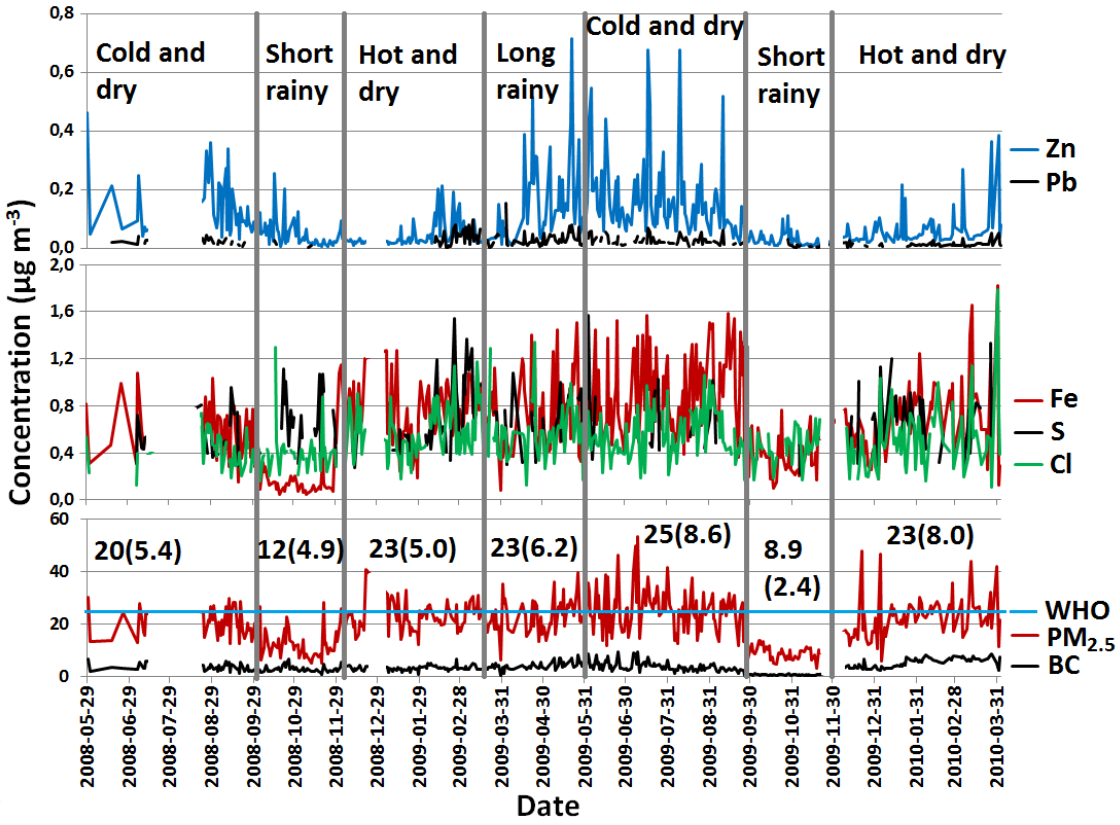

Fig. 4. Seasonal variation of $PM_{2.5}$ and some elements sampled at the university site. Included in the figure are the seasonal averages and standard deviations (enclosed in brackets) as well as the World Health Organization air quality guideline for a 24 h period.

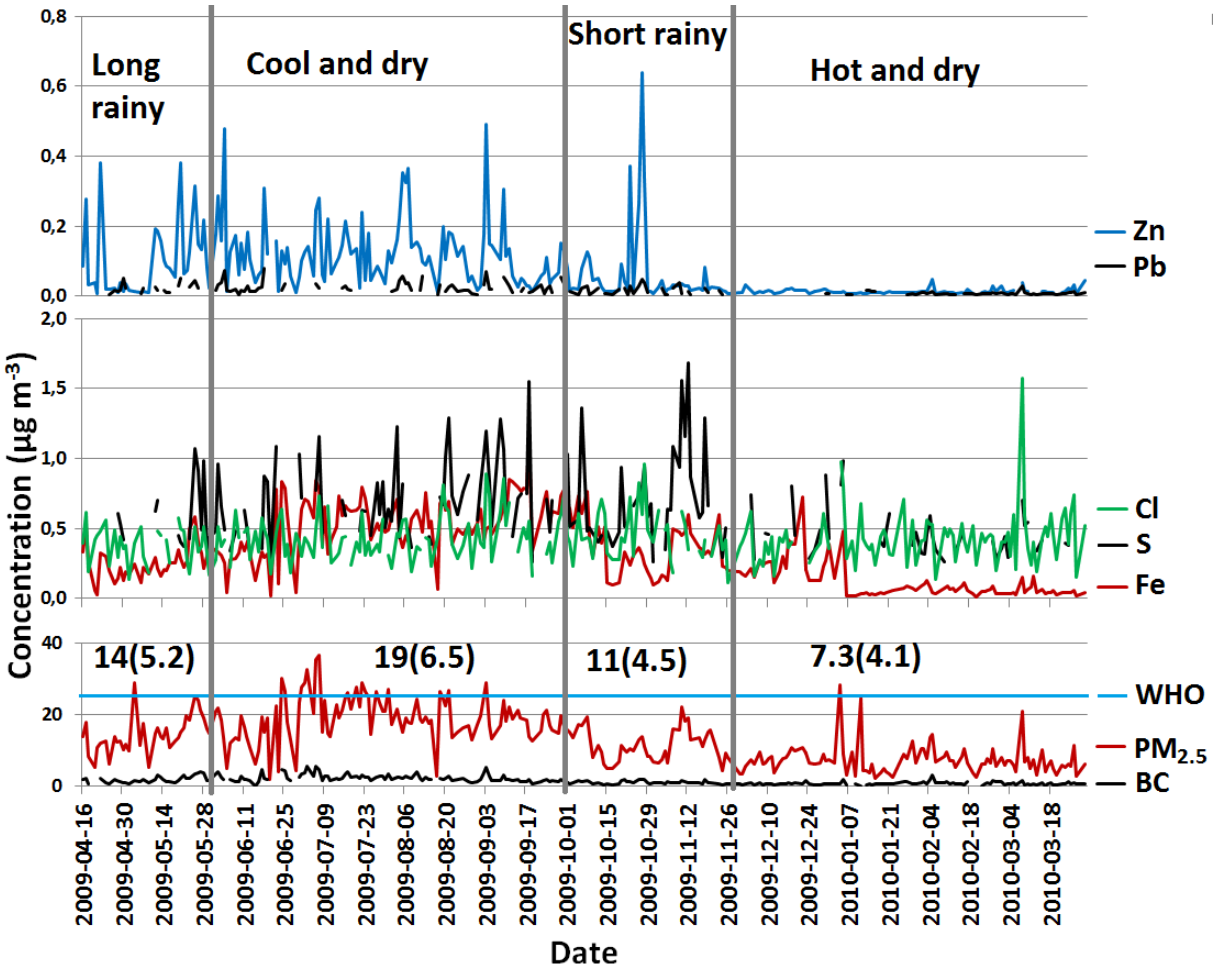

Fig. 5. Seasonal variation of $PM_{2.5}$ and some elements sampled at the UNEP site. Included in the figure are the seasonal averages and standard deviations (enclosed in brackets) as well as the World Health Organization air quality guideline for a 24 h period.

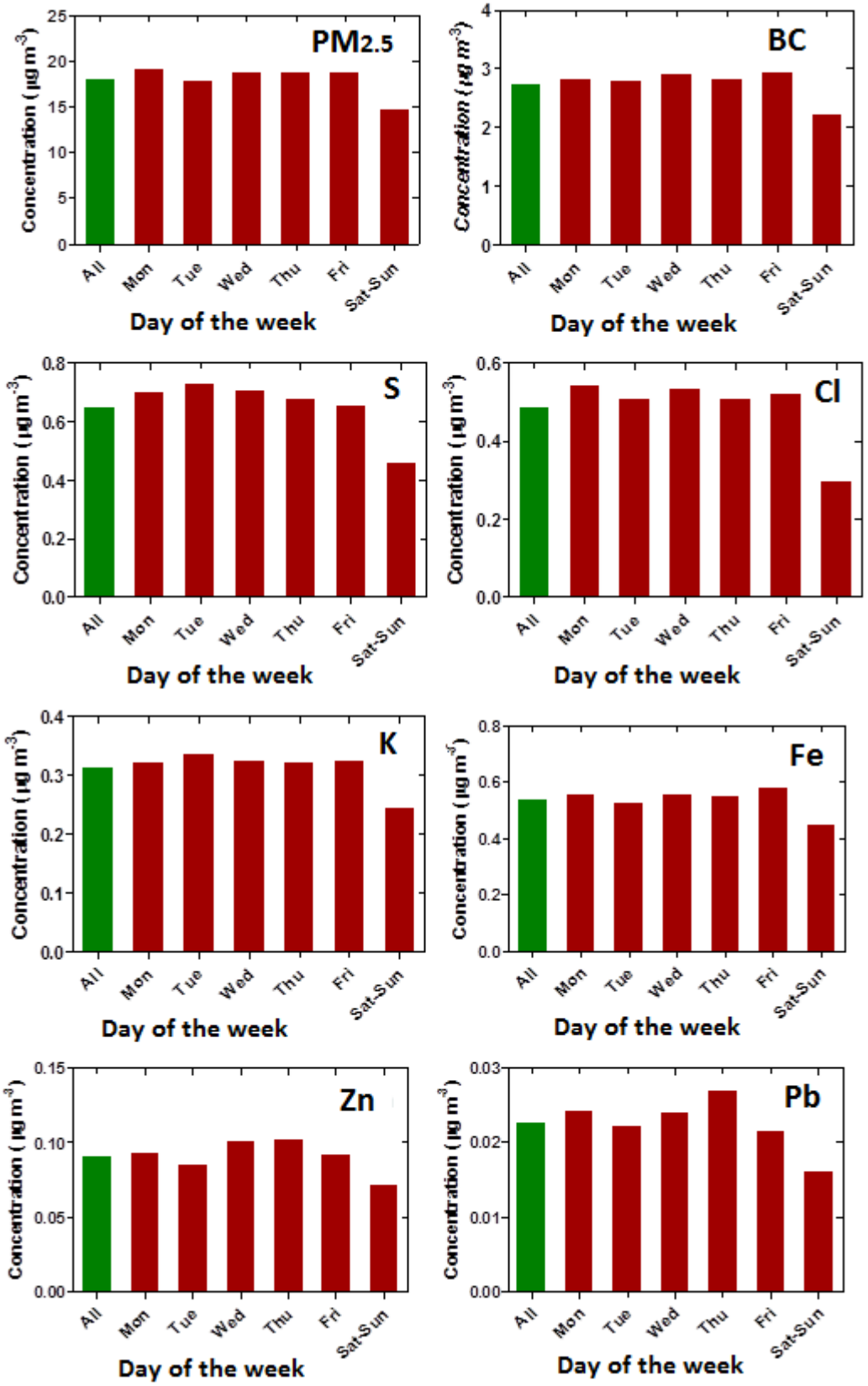

Fig. 6. Weekly variation of $PM_{2.5}$ and some selected elements showing the trend based on calculated averages from respective days of the week.

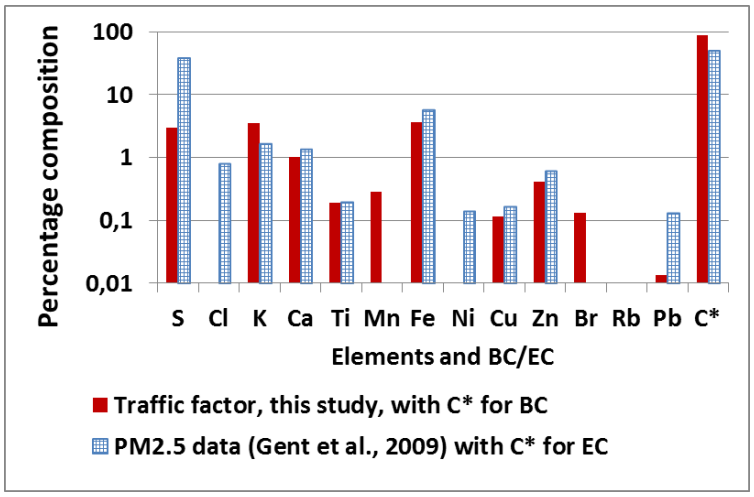

Fig. 7. Traffic factor from PMF analysis of $PM_{2.5}$ from this study compared with $PM_{2.5}$ from a traffic polluted site in Connecticut, USA (Gent et al., 2009).

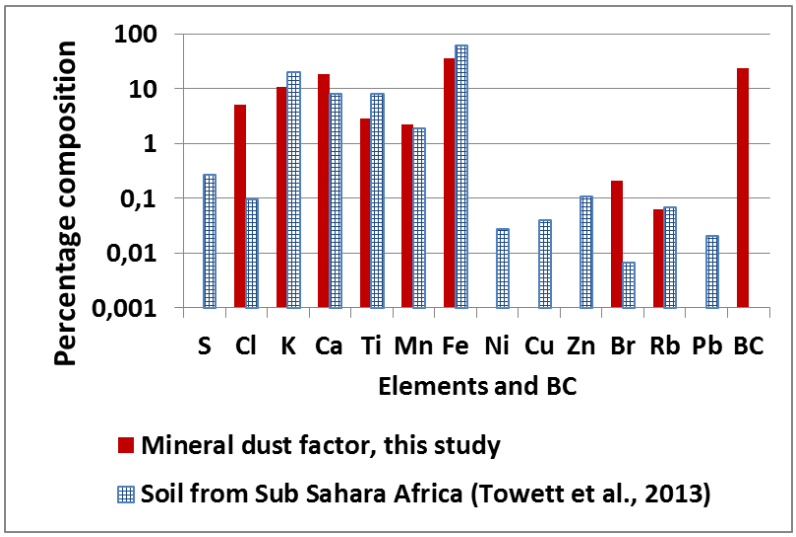

Fig. 8. Mineral dust factor from the PMF analysis of $PM_{2.5}$ from this study compared with elements from soil samples from SSA countries (Towett et al., 2013).

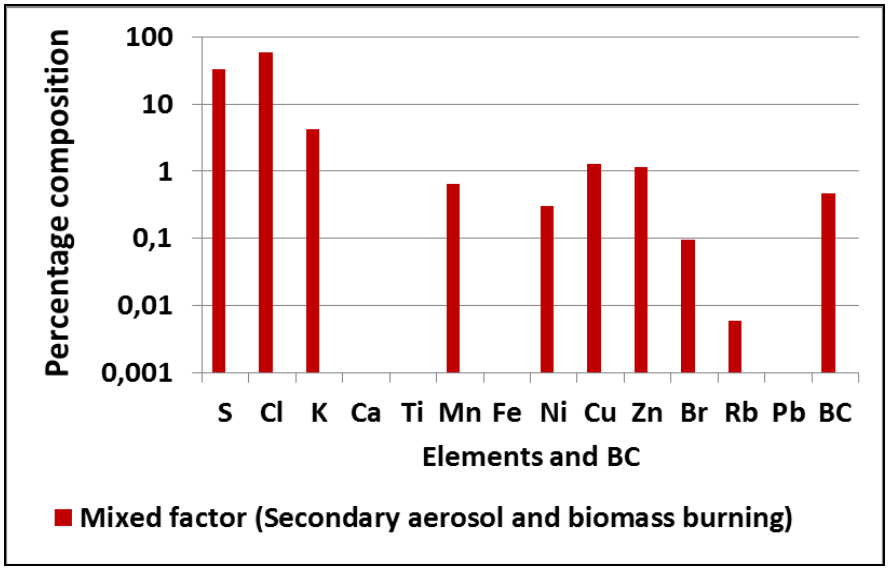

Fig. 9. Mixed factor (secondary aerosol and biomass burning) from the analysis of sampled $PM_{2.5}$ marked by high concentration of S and Cl as well as substantial concentration of K.

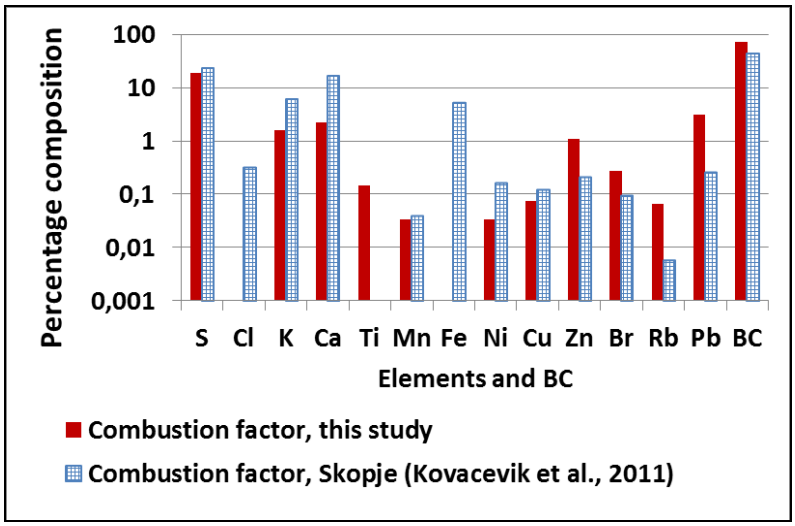

Fig. 10. Combustion factor from the PMF analysis of $PM_{2.5}$ from this study compared with combustion factor from Skopje, Macedonia (Kovacevik et al., 2011).

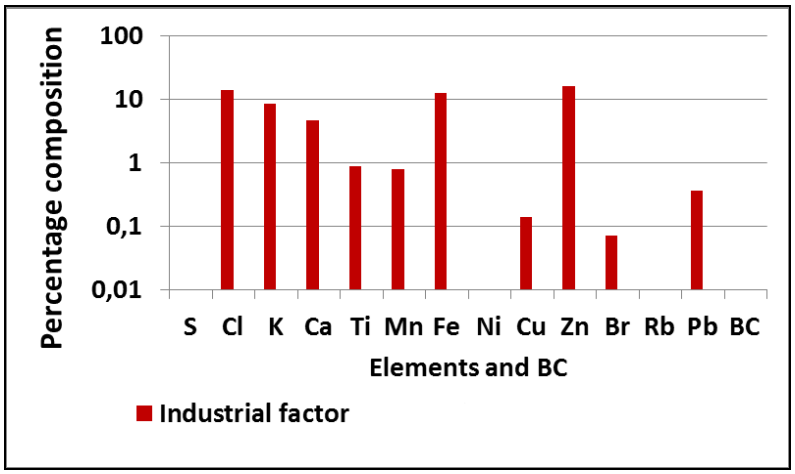

Fig. 11. Industrial factor from analysis of sampled $PM_{2.5}$ showing the contribution of metallurgy industries (Fe and Zn) to aerosol in Nairobi.

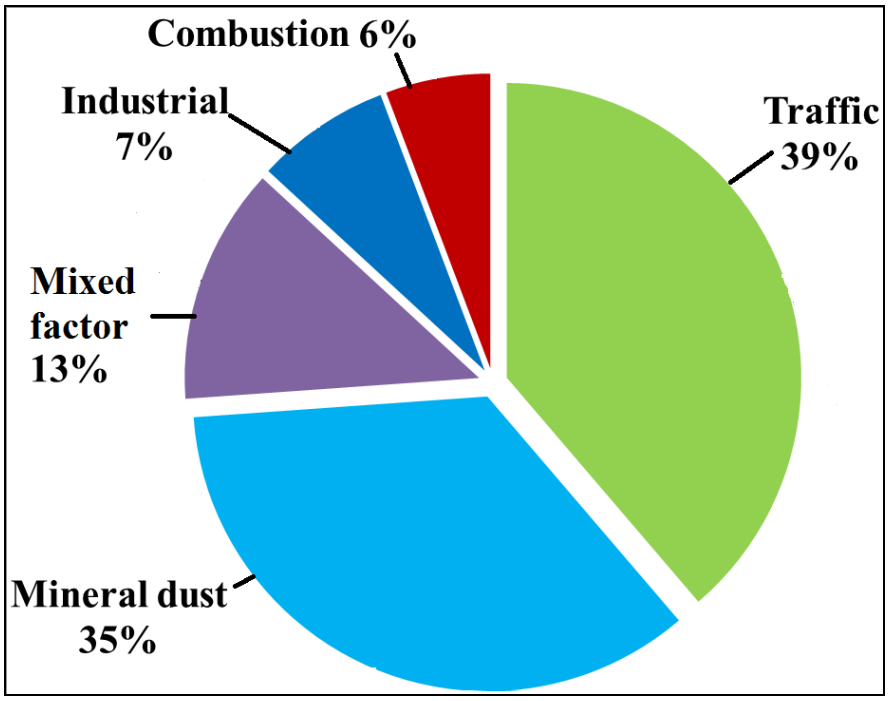

Fig. 12. Percentage contribution of source factors from PMF analysis to $PM_{2.5}$ collected in Nairobi, Kenya. Traffic and mineral dust factors have major contribution to airborne particulate pollutants.

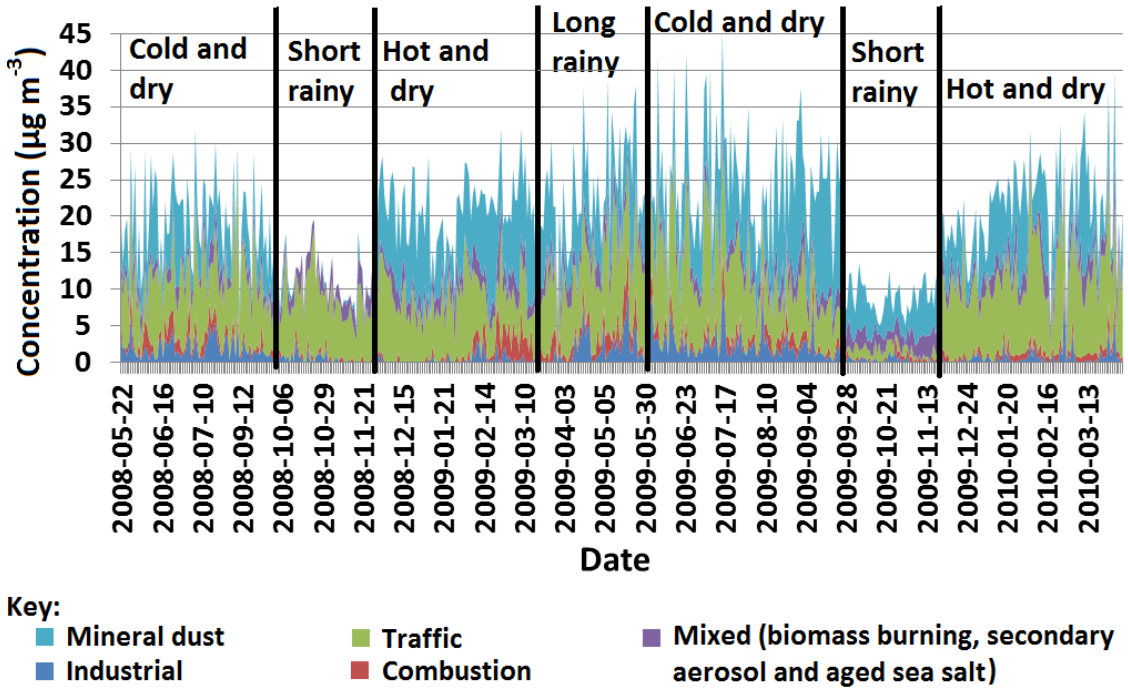

Fig. 13. Seasonal variation of the five factors obtained from the PMF analysis of the $PM_{2.5}$ composition at the university site. Traffic factor shows consistency throughout the sampling period highlighting the significance of vehicular emissions to urban air pollution. Seasons have been demarcated for clarity.

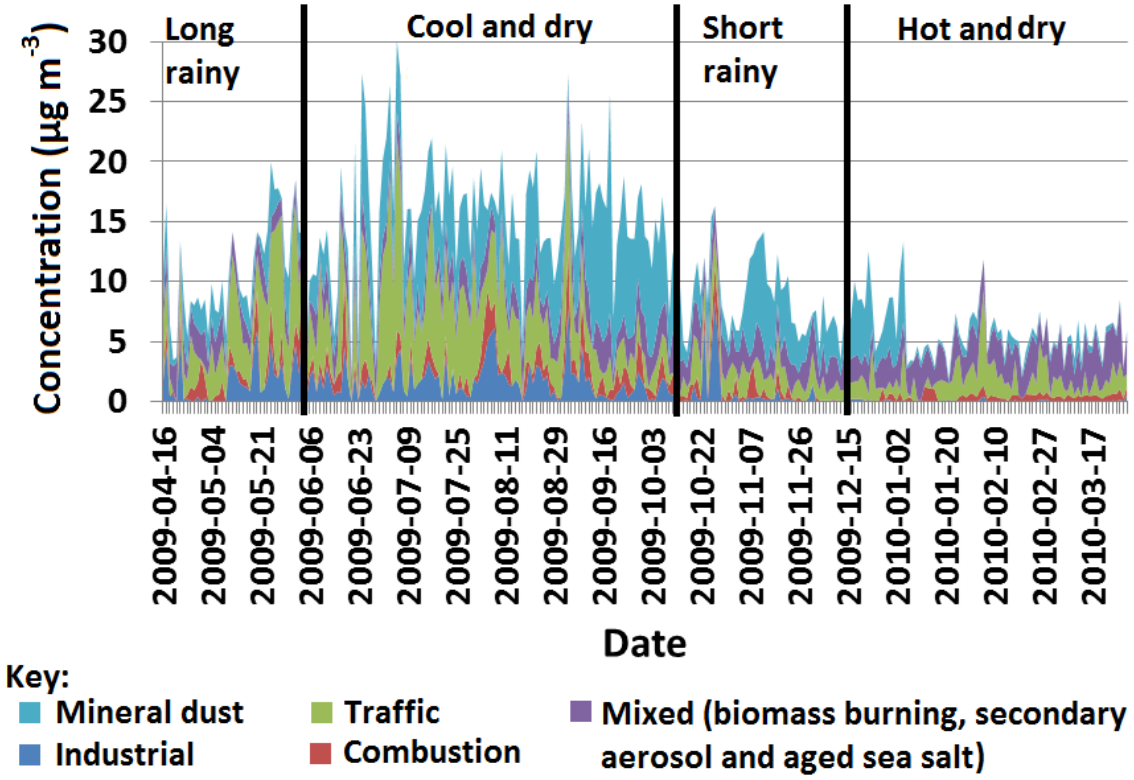

Fig. 14. Seasonal variation of the five factors obtained from the PMF analysis of the $PM_{2.5}$ composition at the UNEP site. The mixed factor constitutes of contribution from biomass burning and secondary aerosol. The effect of erratic weather pattern is evident from the dampened contribution of mineral dust factor in 2010. Seasons have been demarcated for clarity.

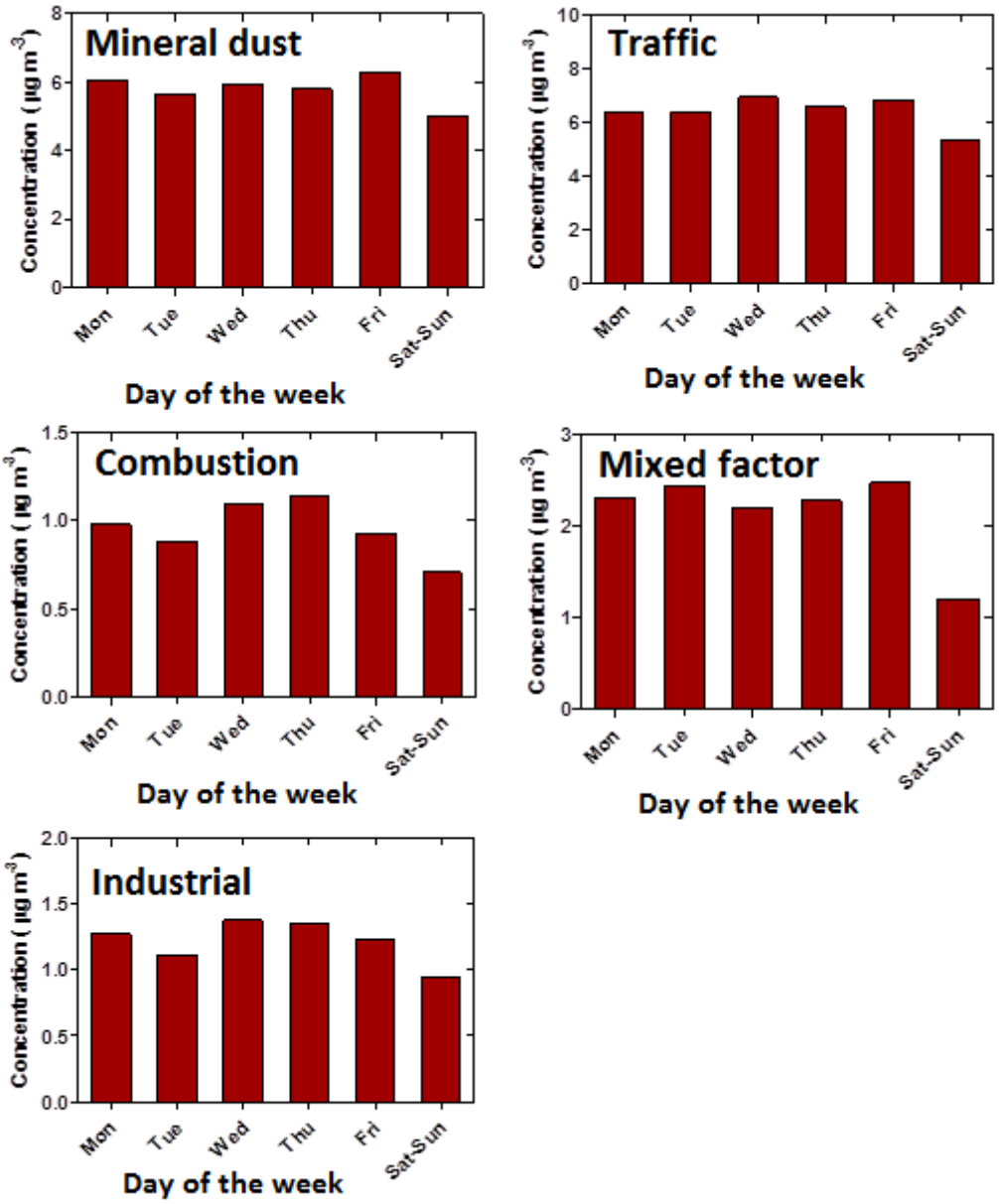

Fig. 15. Weekly series of the five factors obtained from the PMF analysis of sampled $PM_{2.5}$. The difference between weekdays and weekends highlights the anthropogenic contribution to air pollution in Nairobi. The mixed factor is attributed to contribution from biomass burning and secondary aerosol.