

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN NATURAL SCIENCE,  
SPECIALIZATION IN CHEMISTRY

**Airborne particulate matter studies from a typical  
Sub-Saharan African city: Nairobi, Kenya, and an  
Equatorial high altitude site: Mount Kenya**

Samuel Mwaniki Gaita



**UNIVERSITY OF GOTHENBURG**

Department of Chemistry and Molecular Biology  
University of Gothenburg  
SE-412 96 Gothenburg,  
Sweden

Doctoral thesis submitted for fulfilment of the requirements for the degree of  
Doctor of Philosophy in Chemistry

Airborne particulate matter studies from a typical Sub-Sahara African city: Nairobi, Kenya, and an Equatorial high altitude site: Mount Kenya

© Samuel Mwaniki Gaita, 2017

Atmospheric science,  
Department of Chemistry and Molecular Biology,  
University of Gothenburg,  
SE-412 96 Gothenburg,  
Sweden

Printed by Ineko & Brand Factory  
Källered, Sweden

ISBN: 978-91-639-2041-7  
<http://hdl.handle.net/2077/52689>

Parts of this thesis are from the author's Licentiate dissertation, "Air quality assessment and pollution measurements in a typical Sub-Sahara African city: Nairobi, Kenya" which was presented on 12<sup>th</sup> October 2016.

## Abstract

---

In Sub-Saharan Africa (SSA), air quality is gravely understudied despite the existing influential factors such as rapid urbanization and population growth that negatively affect the environment. Majority of urban areas in SSA face challenges that include lack of social services, poor infrastructure development, exponential increase of second-hand vehicles and extensive use of biomass-based fuel for energy needs. There is a systemic lack of continuous monitoring of air pollution in most SSA cities and hence it is yet to be seen if SSA will meet the set air quality targets of the sustainable development goals (SDGs) by the year 2030. Although the focus of air quality is on the urban areas, there is a need to monitor atmospheric composition at remote areas in SSA in order to build a baseline level and understand the influence of anthropogenic and natural aerosol sources on regional/global scale.

This thesis work sought to study physical and chemical properties of airborne particulate matter (PM) in a typical SSA urban area, Nairobi city, and a high altitude site, Mount Kenya. Results from spatial distribution of black carbon (BC) and PM<sub>2.5</sub> (particulate matter less than 2.5 aerodynamic diameter) showed that air quality on the road to the city and within the city is deteriorating. Factor analysis of the PM<sub>2.5</sub> results showed that pollution sources were traffic, mineral dust, industrial, combustion, biomass burning, secondary aerosol and aged sea salt. Traffic and mineral dust contributed about 74% of the PM<sub>2.5</sub> in Nairobi. Exposure to particulate pollutants was expressed in terms of deposition fractions from the size segregated PM data. The head airways region was found to receive the highest dose (about 86%) compared to the tracheobronchial and pulmonary regions. The reported high PM<sub>2.5</sub> and BC concentrations measured along the main street of Nairobi city, indicated the urban population is frequently exposed to elevated pollutants concentrations and thus have high risk factor to respiratory illnesses and lung cancer. Aerosol study from Mount Kenya showed air pollutants are transported from the surrounding and far away sources by local and regional meteorology dynamics. The results from this study provides insight into the air quality issues from pollution sources, exposure to the population and dispersal to remote regions.

**Keywords:** X-ray Fluorescence (XRF), Particle Induced X-ray Emission (PIXE), Particulate matter pollutants, Source apportionment, sub-Saharan Africa, Deposition fractions, High-altitude, Free troposphere, Spatial distribution

## Abstract (in Swedish)

---

I Afrika söder om Sahara (SSA) är luftkvaliteten väldigt dåligt utforskad trots att det finns en rad underliggande faktorer som påverkar luftkvaliteten negativt. Dessa faktorer inkluderar en snabb urbanisering och en befolkningstillväxt som påverkar miljön negativt. I städerna i SSA lever en majoritet av befolkningen med bristande social service, dålig utveckling av infrastruktur, exponentiell ökning av begagnade fordon och en omfattande användning av biomassa-baserat bränsle för sina energibehov.

Det råder en systemisk brist på kontinuerlig övervakning av luftföroreningar i de flesta SSA städer och det återstår att se om länderna i SSA kommer att uppfylla målen för hållbar utveckling (SDGs) med avseende på luftkvalitet fram till år 2030.

Trots att fokus på arbetet med luftkvaliteten ligger i stadsområdena är det nödvändigt att även studera sammansättningen av atmosfären i avlägsna områden i SSA för att bygga en förståelse för påverkan av antropogena och naturliga aerosolkällor på en lokal, regional och global skala. I detta avhandlingsarbete studeras fysikaliska och kemiska egenskaper hos luftburna partiklar (PM) i ett typiskt urbant område, Nairobi, Kenya och på en mer avlägsen plats, Mount Kenya. Resultat från mätningar av svart kol (BC) och PM<sub>2.5</sub> (partiklar med en aerodynamisk diameter mindre än 2,5 µm) visar att luftkvaliteten i Nairobi och dess omgivning är dålig. Faktoranalys av mätresultaten visar att de största källorna av PM<sub>2.5</sub> är trafik, mineraldamm, industriell aktivitet, förbränning av biomassa, sopor och fossilt bränsle. Trafiken och mineraldammet utgör ca 74% av det identifierade innehållet i partiklarna.

Exponering för partikelformiga föroreningar kan uttryckas som avsättningsfraktioner utifrån storleksfördelade partikelmätningar. De övre luftvägarna befanns få den högsta dosen (ca 86%) jämfört med trakeobronchiala och lungregionerna. De högsta koncentrationerna av PM<sub>2.5</sub> och BC uppmättes längs huvudgatan i Nairobi, vilket visar att stadsbefolkningen ofta utsätts för förhöjda föroreningskoncentrationer och har sålunda hög risk att drabbas av luftvägssjukdomar och cancer.

Aerosolstudien från Mount Kenya visade att transporter av luftföroreningar sker från både de omgivande slätterna och städerna och från avlägsna källor. På grund av påverkan av både lokal och regional meteorologidynamik ses betydande skillnader på PM<sub>2.5</sub> och dess spårämnesinnehåll mellan dag och natt. Studien ger också förslag på tider på dygnet då det är gynnsamt att studera partiklar från den fria troposfären, vilket annars är svårt.

Resultaten från denna studie ger insikt i luftkvalitetsproblemen från föroreningar, exponering för befolkningen och spridning till avlägsna regioner.

## List of publications

---

### Publications included in this thesis work

- I. **Source apportionment and seasonal variation of PM<sub>2.5</sub> in a Sub-Saharan African city: Nairobi, Kenya.** Gaita, S. M., Boman, J., Gatari, M. J., Pettersson, J. B. C., & Janhäll, S. (2014), *Atmos. Chem. Phys.*, 14(18), 9977-9991. doi: <https://doi.org/10.5194/acp-14-9977-2014>
- II. **Traffic impacts on PM<sub>2.5</sub> air quality in Nairobi, Kenya.** Kinney, P. L., Gichuru, M. G., Volavka-Close, N., Ngo, N., Ndiba, P. K., Law, A., Gachanja, A., Gaita, S. M., Chillrud, S. N., & Sclar, E. (2011). *Environ. Sci. Policy*, 14(4), 369-378. doi: <http://dx.doi.org/10.1016/j.envsci.2011.02.005>
- III. **Characterization of size-fractionated particulate matter and deposition fractions in human respiratory system in a typical African city: Nairobi, Kenya.** Gaita, S. M., Boman, J., Gatari, M. J., Wagner, A. and Jonsson, S. K. (2016). *Aerosol Air Qual. Res.* 14(10) 2378-2385 doi: <http://www.aaqr.org/article/detail/AAQR-16-01-OA-0019>
- IV. **High airborne black carbon concentrations measured near roadways in Nairobi, Kenya.** Gatari, M. J., Kinney, P. L., Yan, B., Sclar, E., Volavka-Close, N., Ngo, N., Gaita, S. M., Law, A., Ndiba, P., Gachanja, A., Graeff, J., & Chillrud, S. N. (2017). Manuscript under review in the journal of *Transportation Research Part D: Transport and Environment*
- V. **Aerosol Chemistry and Physics at the Mount Kenya Global Atmosphere Watch Station.** Samuel Mwaniki Gaita, Erik S. Thomson, Michael Gatari, August Andersson, Johan Boman and Jan B. C. Pettersson, *Manuscript to be submitted to the Atmospheric Chemistry and Physics journal*

## **Author's contribution to the papers and the manuscript**

- I. I did the sampling, data analysis and writing most of the paper in collaboration with the co-authors. The study was planned by Prof. Johan Boman and Prof. Michael J. Gatari. Prof. Jan B.C. Pettersson assisted with the PMF analysis of the data set.
- II. I participated in the planning stage of the study in strategizing and training the technicians who were to do sampling. I supervised the sampling, data collection and analysis in collaboration with Prof. Michael J. Gatari, Prof. P. Kinney and Prof. N. Ngo.
- III. The study was planned in collaboration with Prof. Johan Boman and Prof. Michael J. Gatari. I did the sampling, data analysis and initiated the idea of deposition fractions. I designed and wrote most of the paper in consultation with the co-authors.
- IV. This paper is a continuation study of paper II and my input is as indicate above.
- V. I was involved in the conception and development stages of the idea and formulation of the study with Prof. Jan B.C. Pettersson, Prof Johan Boman and Dr. Erik Thomson. I did the sampling with assistance from Dr. Erik Thomson. The data analysis and writing was done in collaboration with the co-authors.

## Related publications but not included in the thesis

- I. **Method development for the determination of Cd, Cu, Ni and Pb in PM<sub>2.5</sub> particles sampled in industrial and urban areas of Greater Cairo, Egypt, using high-resolution continuum source graphite furnace atomic absorption spectrometry.** Shaltout, A. A., Boman, J., Welz, B., Castilho, I. N. B., Al Ashkar, E. A., & Gaita, S. M. (2014). *Microchemical Journal*, 113, 4-9. doi: <http://dx.doi.org/10.1016/j.microc.2013.10.009>
- II. **Mass, black carbon and elemental composition of PM<sub>2.5</sub> at an industrial site in Kingston, Jamaica.** Boman, J., & Gaita, S. M. (2015). *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 363, 131-134. doi: <http://dx.doi.org/10.1016/j.nimb.2015.08.068>

## Other publications not related and not included in the thesis

- I. **Eu<sup>3+</sup> as a luminescent probe for the local structure of trivalent dopant ions in barium zirconate-based proton conductors.** Haro-González, P., Karlsson, M., Gaita, S. M., Knee, C. S. and Bettinelli, M. (2013). *Solid State Ionics* 247-248: 94-97. doi: <https://doi.org/10.1016/j.ssi.2013.06.008>
- II. **Influence of Yttrium Concentration on Local Structure in BaZr<sub>1-x</sub>Y<sub>x</sub>O<sub>3-δ</sub> Based Proton Conductors.** Mburu, C. W., Gaita, S. M., Knee, C. S., Gatari, M. J. and Karlsson, M. (2017). *The Journal of Physical Chemistry C*. doi: <http://pubs.acs.org/doi/abs/10.1021/acs.jpcc.7b05023>

# Table of Contents

Abstract.....	ii
Abstract (in Swedish).....	iii
List of publications.....	iv
List of Abbreviations.....	viii
Chapter I.....	1
Introduction.....	1
Chapter II.....	5
Theoretical background and techniques.....	5
2.1 Aerosols.....	5
2.2 Aerosol sampling techniques.....	7
2.2.1 Particle number concentrations.....	7
2.2.2 Particle mass concentration.....	8
2.2.3 Filtration and deposition of particles.....	10
2.2.4 Carbonaceous species in airborne particulate matter.....	11
2.2.5 X-ray and it's interaction with matter.....	12
2.2.6 Statistical analysis of data.....	14
Chapter III.....	15
Location of the studies.....	15
3.1 The city of Nairobi.....	15
3.2 Mount Kenya region.....	18
Chapter IV.....	21
Results and discussion.....	21
4.1 Airborne particulate matter in Nairobi city.....	21
4.1.1 Spatial distribution of PM and BC.....	21
4.1.2 Size distribution of elements in PM.....	24
4.2 PM source apportionment.....	25
4.3 Exposure to PM and deposition fractions.....	26
4.4 PM <sub>2.5</sub> in other cities in the world.....	28
4.5 Aerosol properties at high altitude.....	29
4.5.1 Particle number concentrations.....	29
4.5.2 Elemental composition.....	31
4.5.3 Physical and chemical properties of the aerosols.....	33
Chapter V.....	37
Summary.....	37
Outlook.....	39
Acknowledgement.....	41
References.....	43



## List of Abbreviations

---

A.s.l. – Above sea level

BC – Black carbon

$C_c$  – Cunningham correction factor

$d_c$  – Cut-off diameter

DL – Detection limit

EC – Elemental carbon

EF – Enrichment factor

EPA – Environmental Protection Agency

HYSPLIT – Hybrid Single-Particle Lagrangian Trajectory

MKGAW – Mount Kenya Global Atmosphere Watch

MPPD – Multiple Path Particle Dosimetry

OC – Organic carbon

OPC – Optical particle counter

$P_p$  – Density of a particle

PIXE – Particle Induced X-ray Emission

PM – Particulate matter

PMF – Positive Matrix Factorization

PN – Particle number

RH – Relative Humidity

SSA – sub-Saharan Africa

$Stk_{50}$  – Stokes number that gives 50% collection efficiency

U – Velocity of the airflow

WHO – World Health Organization

XRF – X-ray Fluorescence

$\eta$  – Viscosity of air



# Chapter I

## Introduction

*“Be the change that you wish to see in the world.”* – Mahatma Gandhi (1869 - 1948)

The least understood environmental problem in Eastern Africa is air pollution as depicted in a study on premature deaths from outdoor air pollution by Lelieveld *et al.* (2015). In Fig. 1, the white patches in East Africa are assumed to indicate low concentration-response threshold of particulate matter but this assumption can be questioned since it can be due to lack of sufficient information on air pollution from Kenya and neighbouring countries. It is estimated that air pollution caused about 7 million premature deaths, globally in 2012 (WHO 2014b). About 3.3 million of the reported deaths were from indoor air pollution where as 2.6 million premature deaths were attributed to outdoor air pollution. This revelation highlights the importance of studying air pollution in the SSA region given that SSA urban centres have the fastest population growth in the world (UNDESA 2015). This growth is attributed to the rural-urban migration given that a majority of the existing social amenities are concentrated in the urban areas. However, the provision of social services and amenities is not commensurate with the population growth leading to degradation of the immediate environment.

Scientific information on environmental problems such as air pollution in SSA is scant due to a combination of factors, which include lack of local expertise, instrumentation, governmental/institutional commitment and supportive infrastructure (UNEP 2012, Petkova *et al.* 2013). As a result, the effect of air pollution on human health, ecosystem, weather and climate is poorly understood in the SSA region. This lack of information has affected creation and/or implementation of relevant policies that would safeguard human health and environmental degradation. One such relevant policy, is the United Nations General Assembly Sustainable Development Goal number 3 which proposes strengthening of countries capacities in air quality monitoring to ensure reduction in number of deaths and illnesses from pollution (United Nations 2015).

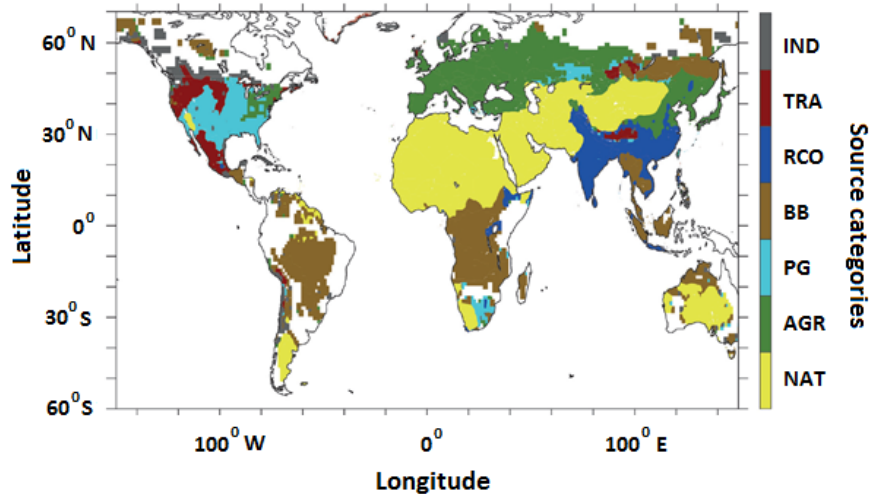


Figure 1: Source categories attributed to the largest impact on mortality as linked to outdoor air pollution in 2010. Source categories (colour coded): IND (industry), TRA (land traffic), RCO (residential and commercial energy use such as heating, cooking), BB (biomass burning), PG (power generation), AGR (agriculture) and NAT (natural). In the white areas, annual mean PM<sub>2.5</sub> is below the concentration–response threshold (Lelieveld *et al.* 2015). Printed with permission.

Human and commodities mobility within SSA, especially urban areas, has been cited as one of the biggest challenge in the light of urban planning, transport infrastructure development and air pollution (Kinney *et al.* 2011, Salon and Aligula 2012, Sietchiping *et al.* 2012). The number of registered vehicles in SSA has grown exponentially from 2001 to 2014 (KNBS 2013) but roadworthiness of most of these vehicles is mostly low. The increase in number of vehicles has led to significant contribution of traffic emissions to poor air quality in cities like Nairobi (Kinney *et al.* 2011, Gaita *et al.* 2014). Pedestrians and drivers, especially in public transport, are reported to be exposed to high levels of air pollutants on a daily basis (Ngo *et al.* 2015).

Biomass burning is a common phenomenon in SSA both on the continental scale through burning of the savannah grassland (Cachier *et al.* 1998) and on local scale as fuel in domestic energy generation (Lioussé *et al.* 2014). In 2000, a large campaign aptly named SAFARI (Southern African Regional Science Initiative), estimated the emission flux of carbonaceous particles to be  $14 \pm 1 \text{ Tg yr}^{-1}$  from African savanna/ grassland burning (Formenti *et al.* 2003) against an estimated global total of  $82 \text{ Tg yr}^{-1}$  (Andreae and Merlet 2001). Energy supply for

domestic heating is mainly biomass-based in most SSA homesteads and contribute to indoor air pollution as most dwellings are poorly ventilated (Karanja and Makau 2012, WHO 2014a, Ryan *et al.* 2015).

Remote and high altitude sites in SSA can provide important background information on physical and chemical properties of aerosols. The information can provide insights on long-range transport of airborne PM from natural and anthropogenic sources (Gatebe *et al.* 1999, Henne *et al.* 2008). Of interest, are the high altitude sites like Mount Kenya which offer opportunities to study local and regional influence of meteorological parameters on aerosols transportation from their respective sources (Gatebe *et al.* 2001).

Lastly, climate change and global warming are reported to give rise to increase in drought occurrences in Africa (WMO 2013). Consequently, mineral dust, from natural and anthropogenic sources, is expected to play a challenging role on air quality in SSA (Flament *et al.* 2011, Matassoni *et al.* 2011). As a result, the policies aimed at monitoring and controlling air pollutants need to be diverse in order to address all possible sources of air pollution. A number of policy instruments have been outlined by Amegah and Agyei-Mensah (2017) aimed at providing a platform for ensuring the SSA region attains the SDGs as adopted by the WHO.

The objective of this thesis was to identify the sources of airborne particulate pollutants in a typical SSA city (Paper I and II), explore the exposure of the urban population to airborne particulate pollutants (Paper III and IV) and analyse physical and chemical properties of aerosols from a high altitude remote site in order to understand their background characteristics and transportation (Paper V). It is hoped that the study will provide insight on air pollution in SSA and lay a foundation for the strengthening and implementation of air quality and monitoring policies in SSA cities and provide insights on background characteristics of aerosols in SSA continental/high-altitude areas.



# Chapter II

## Theoretical background and techniques

### 2.1 Aerosols

Airborne particulate matter (PM) is defined as the sum of all solid and liquid particles suspended in air and are considered to be pollutants if harmful to the human health, built environment and biota (Anderson 2009, Heal *et al.* 2012). Airborne PM can vary significantly in size, composition, shape and origin (Fig. 2) (Hinds 1998). One of the most important properties of airborne PM, is their aerodynamic diameter which is defined as the diameter of a spherical particle with a density of  $1000 \text{ kg m}^{-3}$  and having the same settling velocity the particle. Since airborne PM consist of irregularly shaped particles, their aerodynamic characteristics are used in classifying PM in various size categories. In human health studies, PM is generally classified in two groups; a coarse fraction with aerodynamic diameter ranging from 2.5 to  $10 \text{ }\mu\text{m}$  and a fine fraction below  $2.5 \text{ }\mu\text{m}$ . Particle size governs the transportation and removal mechanisms of PM from the atmosphere and the deposition within the human respiratory system (Hinds 1998).

Size, chemical and elemental characteristics of airborne PM are closely related to their sources (Hinds 1998, Liu *et al.* 2000, Gabriel *et al.* 2002). Coarse particles are produced from road dust, agricultural processes, uncovered soil, vegetation debris and evaporation of sea spray. Fine particles are formed from gas-to-particle conversion through condensation and coagulation and the resultant particles are referred to as secondary particles (Finlayson-Pitts and Pitts Jr 2000). In most urban areas, especially in the developing countries, the chemical and elemental composition of airborne PM is mostly originate from vehicular emission, road dust, industrial emissions and biomass burning (Hand *et al.* 2010, Kinney *et al.* 2011, Petkova *et al.* 2013, Tiitta *et al.* 2014).

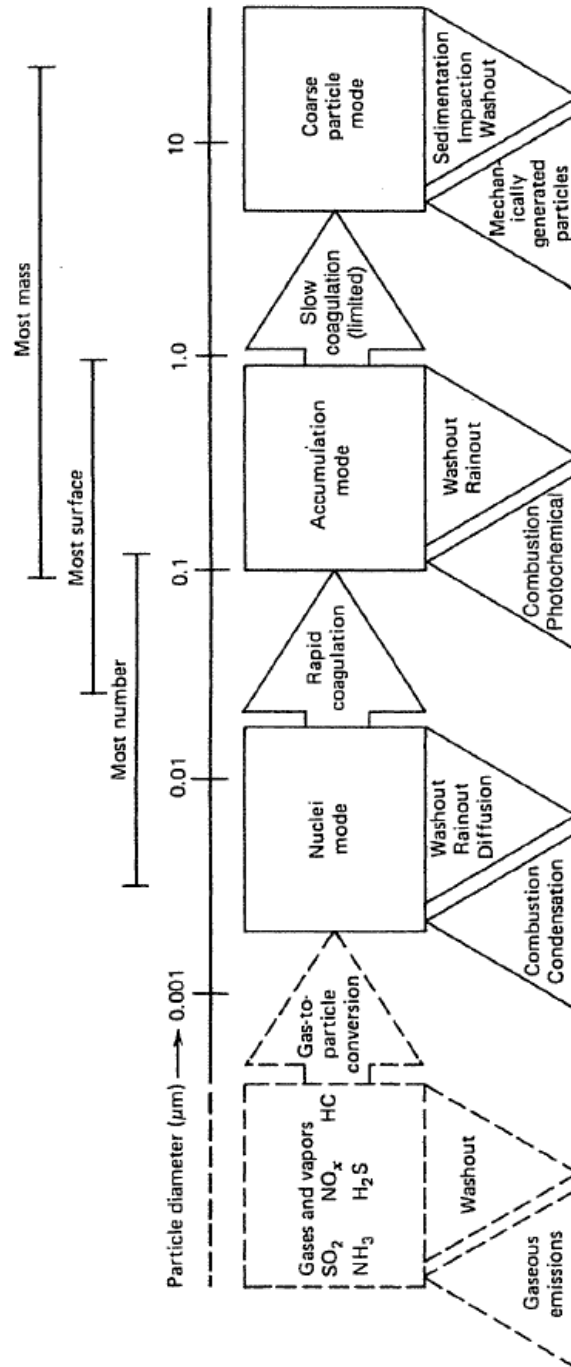


Figure 2: Processes that influence the creation, growth and removal of airborne particulate matter in an urban setting, (Hinds 1998). Printed with permission.



## 2.2 Aerosol sampling techniques

### 2.2.1 Particle number concentrations

The information on particle number concentrations is commonly derived from their mobility (aerodynamic and electrical), condensation or optical properties (Hinds 1998). Light-scattering technology is used in optical particle counters (OPCs) which measure the amount of light scattered by individual particles as they pass through a beam of light (Fig. 3). Some of the scattered light is collected and directed to a photo-detector, which converts the signal to a proportional voltage pulse. The corresponding particle size is determined from the magnitude of this voltage pulse by using a calibration curve. Particles' size distributions are then obtained by measuring the distribution of pulse magnitudes resulting from the pulse height and area and act as a representative population of particles of interest (McMurry 2000). The particle size parameter is defined as shown in Eq.1.

$$\alpha = \frac{\pi D_p}{\lambda} \quad (1)$$

Where  $\alpha$  is the size parameter,  $D_p$  is the diameter of the scattering particle and  $\lambda$  is the wavelength of the light.

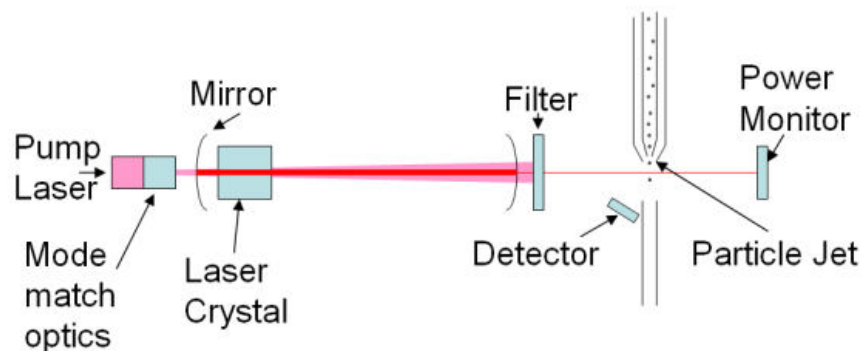


Figure 3: Layout of a laser optical particle counter

## 2.2.2 Particle mass concentration

Particle inertia is used to segregate and collect particles on a substrate for gravimetric and chemical analysis. This principle of inertia is applied in cyclone samplers. During the operation, air is drawn in the sampler at tangent angle to the cylindrical part (Fig. 4). This geometry results in a vortex that descends and then ascends along the centre before exiting to the filter at the top of the cyclone. Particles contained in the vortex, experience a centrifugal force that pushes them outward. Larger particles are unable to follow the path due to their inertia and impact on the cyclone wall and slide down to a collecting chamber. Particles of predetermined size follow the air stream and are collected on a filter substrate. The cut-off of collected particles at a specific aerodynamic diameter is a function of flowrate of sampled air (Hinds 1998).

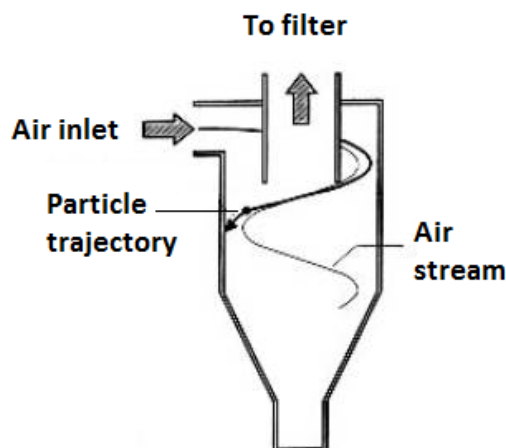


Figure 4: Cross-sectional view of a cyclonic flow showing the paths taken by gas and particles.

Particles in a stream of air maintain a curvilinear motion but any sudden change to the flow direction and/or air velocity results to impaction on obstacles (impactor plates) based on principle of inertia impaction. This principle of impaction is applied in collection of airborne PM based on their aerodynamic size (Figs. 5 and 6). The particle collection efficiency is governed by an impaction parameter called the Stoke's number which is defined as the ratio of the particle stopping distance at the average nozzle exit velocity to the jet radius ( $D_c$ ) (see Fig. 6). A plot of collection efficiency vs square root of the Stoke's number gives the collection efficiency of 50% of an impactor at a "cut-off" size of 0.5 (Fig. 7 and Eq. 2). In order to collect a wide range of particle sizes, a number of stages are assembled in a stack in order of decreasing

jet diameters. Consequently, as the velocity of air increases, particles of decreasing sizes are collected.

$$d_c \sqrt{C_c} = \left[ \frac{9\eta D_j Stk_{50}}{P_p U} \right]^{\frac{1}{2}}$$

Where  $Stk_{50}$  is the stokes number that gives 50% collection efficiency,  $C_c$  is the Cunningham correction factor,  $P_p$  is the density of the particle,  $U$  is the velocity of the airflow,  $\eta$  is the viscosity of air and  $d_c$  is the cut-off diameter.

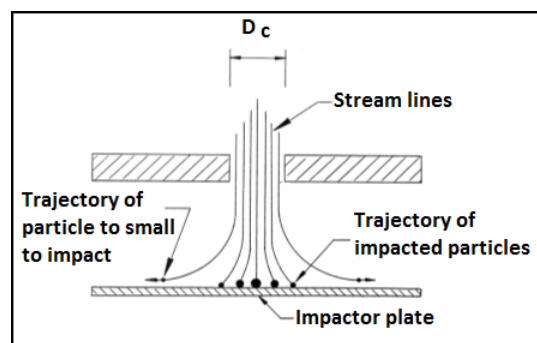


Figure 5: The principle of impaction technique used in collecting particles on a substrate as applied to a high volume sampler.

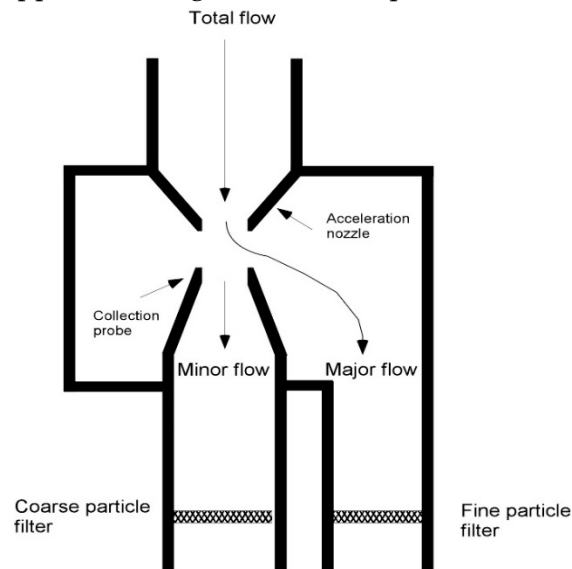


Figure 6: The cross-section of a dichotomous sampler, which uses the principle of inertia. Particles less than  $2.5 \mu\text{m}$  in aerodynamic diameter follow the major flow and are collected as fine particles. Particles between  $10$  and  $2.5 \mu\text{m}$  follow the minor flow and are collected as coarse particles.

## 2.2.3 Filtration and deposition of particles

The most common technique of collecting particles is filtration. Particles are collected using filtration for purposes of air cleaning, environmental monitoring and scientific research. Particles are collected on a filter by five basic mechanisms, interception, inertia impaction, diffusion, gravitational settling and electrostatic attraction. The efficiency of particle filtration is dependent on all the five mechanisms as shown in Fig. 7. The said mechanisms also come into play during deposition of particles in the respiratory system (Fig. 8). During breathing in polluted environment, airborne PM deposited in the human respiratory system is a function of aerodynamic size (Winter-Sorkina and Cassee 2002). Fine particles are deposited deeper into the pulmonary regions (Fig. 8) and thus cause the gravest health risk especially in case of long term exposure (Villeneuve *et al.* 2002).

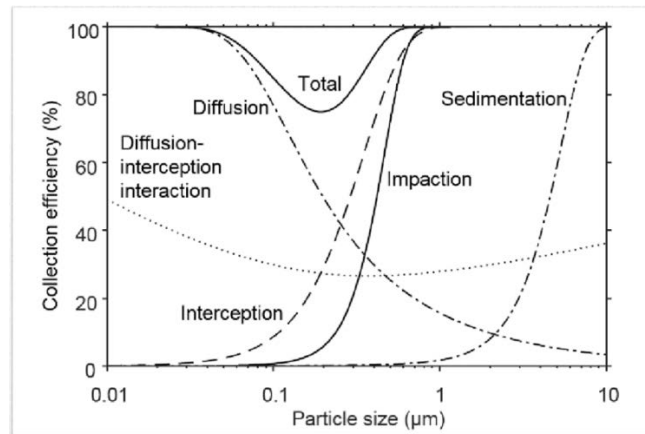


Figure 7: Modelled collection efficiencies of the particles on a filter substrate (Hinds 1998). Printed with permission.

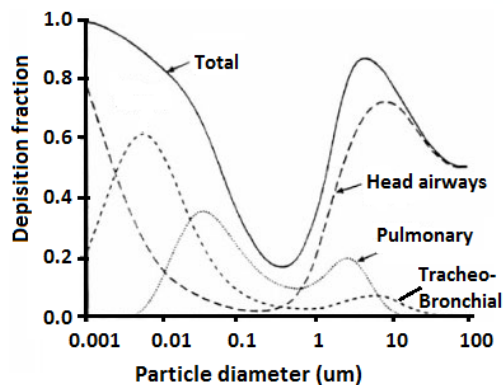


Figure 8: Deposition of particulate matter along human respiratory system, (Hinds 1998). Printed with permission.

## 2.2.4 Carbonaceous species in airborne particulate matter

Different forms of carbonaceous species accounts for proportionate fraction of airborne PM (Lioussé *et al.* 1993). These species are organic carbon (OC), elemental carbon (EC) and inorganic carbon (IC). Each of these species is analysed using unique techniques. Organic and elemental carbonaceous species are analysed using thermal techniques which uses the thermal evolution property of OC in an inert atmosphere and thermal refractivity of EC (Karanasiou *et al.* 2015). Optical reflectometry techniques are used in analysing concentration of black carbon (term used for the elemental carbon) as they are convenient to use and are non-destructive. One such instrument is black carbon reflectometer (see Fig. 9) which utilizes the absorption and reflection properties of red light (650 nm) by the black carbon content of collected PM. The reflected light signal is converted to voltages, which are converted to concentration using Eq. (3). The intensity of the reflected light by the PM is observed to non-linearly decrease as BC concentration increases on the filter (Moosmüller *et al.* 2009).

$$C_R = -\frac{RM_1}{V} \times \ln\left(1 - \frac{RZ - RZ_0}{k \times RZ_{\max}}\right) \quad (3)$$

Where  $C_R$  is the concentration of black carbon ( $\mu\text{g m}^{-3}$ ),  $RM_1$  is the mass of smoke in a single dust layer on the filter,  $V$  is the sample volume (flow  $\times$  collection time),  $RZ$  is the black smoke number,  $RZ_0$  is the black smoke number of an empty filter,  $K$  is the constant depending on absorption coefficient of black smoke and  $RZ_{\max}$  is the upper range of calibration scale.

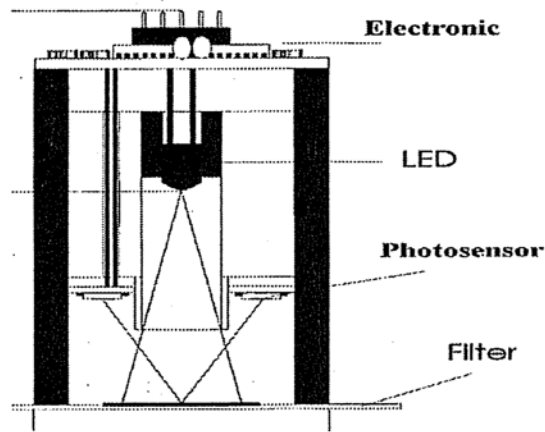


Figure 9: Schematic diagram of a typical reflectometer used for black carbon measurement

## 2.2.5 X-ray and it's interaction with matter

The X-ray radiation is part of the electromagnetic radiation and has wavelength ranging from 0.01 to 10 nm. It was discovered in 1895 by W. C. Röntgen while experimenting with radiation emissions from a cathode ray tube (Markowicz *et al.* 1996). X-ray energy is generated as a result of the interaction between energetic electrons and matter (anode) at the atomic level. Once generated, the X-ray radiation (photons) also interacts with matter in three ways (Markowicz *et al.* 1996): photoelectric, Rayleigh (coherent) and Compton (incoherent) scattering.

X-ray fluorescence (XRF) is the resultant emission of characteristic (fluorescent) X-rays from atoms of an element that have been excited after photoelectric interaction. This emission of characteristic radiation is used in variants of X-ray fluorescence techniques to analyse samples of diverse forms (Markowicz *et al.* 1996).

In XRF technique, a beam of photons interacts with an electron in the K and L shells and knocks it out creating a vacancy (Fig. 10). An electron in the higher energy shell (level) falls in to fill the created vacancy hence emitting a photon as per Moseley's law. The emitted photon is detected as a pulse signal by a semiconductor detector. Since each emitted photon is characteristic to a specific element, the intensities of the pulses

are assumed to be proportional to their respective elements' concentrations. Thus, the pulse counts are converted to elemental concentrations using a calibration file.

A similar X-ray spectrographic technique is Particle Induced X-ray Emission (PIXE) (Akselsson and Johansson 1979). Energetic protons are used to knock out inner electrons and hence initiate the production of characteristics radiation. Both XRF and PIXE techniques allow for non-destructive and simultaneous elemental analysis of solid and liquid samples.

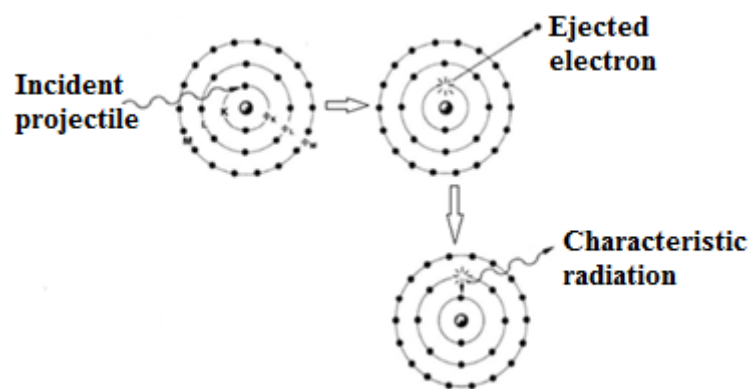


Figure 10: Schematic diagram showing the emission of characteristic radiation in matter.

## 2.2.6 Statistical analysis of data

Positive Matrix Factorization (PMF) is a multivariate factor analysis method that decomposes a bilinear matrix problem of the type into factor contributions and profiles as shown in Eq.4 (Paatero 1997). The uniqueness of the PMF as opposed to factor analysis and principal component analysis techniques is the guarantee of nonnegative results. In paper I, the EPA PMF 3.0 program from USEPA was used (Norris *et al.* 2008).

$$X = GF + E \quad (4)$$

Where X is a matrix of observed data, G is the unknown factor matrix of scores, F is the unknown factor matrix of loadings and E is the matrix of residuals.

Atmospheric dynamics are closely related to transportation of airborne PM. Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model was used to trace the origin of air masses reaching the study sites in this work (Draxler and Hess 1998, Draxler and Rolph 2015). Daily air mass back trajectories were clustered using advection algorithms. Each cluster represents the contribution from a set of back trajectories originating from a common direction.



## Chapter III

### Location of the studies

#### 3.1 The city of Nairobi

The city of Nairobi and its environs bears the characteristics of a typical Sub-Saharan African city; overpopulation, poor social service deliveries, uncontrolled infrastructure development and environmental degradation (UN-HABITAT 2006, Karanja and Makau 2012). The current human population in Nairobi is about 4 million people (KODP 2012) and is projected to grow to about 12 million by year 2030 (MoNMD 2008). As a result of high population, the peri-urban areas of the city lag behind with urban planning and experiences growth of informal settlements, unregulated waste disposal and other social/environmental degradation (Egondi *et al.* 2013).

Nairobi city lies approximately 150 km south of the Equator and the metropolitan region covers about 680 km<sup>2</sup>. The city has a subtropical highland climate as opposed to the expected tropical climate (Peel *et al.* 2007). This is due to its location at a high altitude (1795 m a. s. l.) despite its proximity to the Equator. The weather and climate of Nairobi and Equatorial Africa in general, is influenced by the seasonal displacement of the intertropical convergence zone (ITCZ) (Henne *et al.* 2008). Due to the movement of the ITCZ, there are two rainy seasons in Kenya, “long” and “short”. The long rainy season begins in mid-March and ends in May whereas the short rainy season begins in mid-October and ends mid-December. In Nairobi, the annual average rainfall is about 900 mm and varies between 500 mm and 1500 mm. In between the rainy seasons, there is a hot and sunny period lasting from January to mid-March and a cold season lasting from June to September. The daily average temperature is approximately 20 °C during the hot and sunny period and 17 °C during the cold months (ClimaTemps 2016).

Data for paper I was collected at two sites in Nairobi marked S1 and S2 in Fig.11. S1 is the University of Nairobi main campus ( $1.279^{\circ}\text{S}$ ,  $36.817^{\circ}\text{E}$ ) and is described as an urban background site. S2 is a suburban site located within the compound of the United Nation Environmental Programme headquarter ( $1.234^{\circ}\text{S}$ ,  $36.818^{\circ}\text{E}$ ). Data for paper II and IV was collected at five sites which included major streets within the central business district, a major highway (Thika road) and a rural background site (Kenyatta University marked as S3). Data for paper III was collected at the site marked S1.

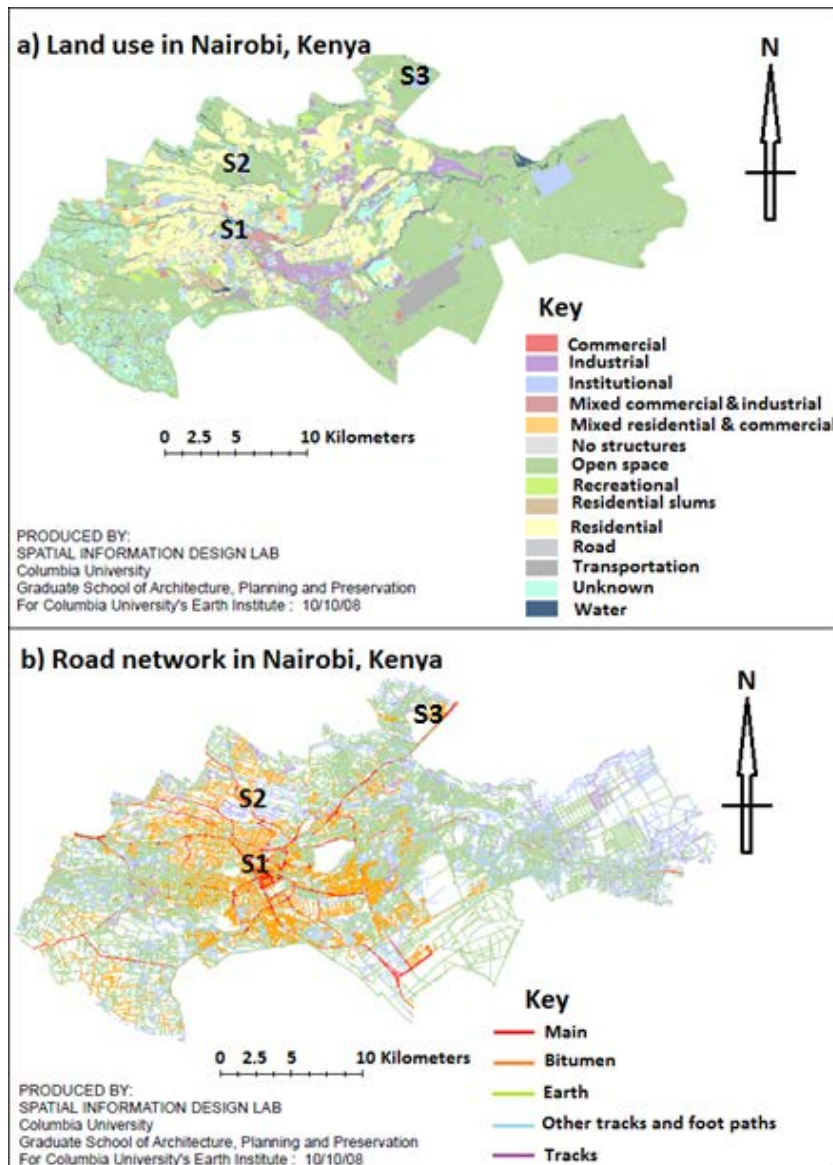


Figure 11: GIS map of the Nairobi metropolitan area showing land use pattern (a) and transportation network (b). Original maps are modified to include sampling sites as marked on both maps; University of Nairobi (S1), United Nations Environmental Programme (UNEP) headquarters (S2) and Kenyatta University (S3). Original maps were downloaded from the Center for Sustainable Urban Development's Nairobi GIS maps and database website (CSUD 2010). Printed with permission.

## 3.2 Mount Kenya region

Mount Kenya is the highest mountain in Kenya (5199 m a.s.l.) and second highest in Africa after Mount Kilimanjaro (5895 m a.s.l.). The mountain has great influence on both local and regional meteorology. On a regional meteorological scale, the horizontal circulation in equatorial Africa (where Mount Kenya is located) is dominated by the seasonal displacement of the inter-tropical convergence zone (ITCZ). The mountain has a typical diurnal cycle of wind and clouds most of the year (Davies *et al.* 1977, Henne *et al.* 2008). During daytime, an upslope (anabatic) wind flow with speeds ranging from 0 to 10 ms<sup>-1</sup> carries moist air towards the crest. At nighttime, the air is transported downhill in a shallow nocturnal slope wind layer (katabatic). As a result of the dry sinking air, nights are usually clear (Henne *et al.* 2008). Since Mount Kenya bestrides the equator, the day-light hours are almost constantly twelve hours, with the sun rising around 0600 local standard time (LST) and setting around 1800 LST.

The data for paper V in this thesis was collected at Mount Kenya Global Atmosphere Watch station (MKGAW) (Fig.12). The MKGAW station is at 3780 m a.s.l. and is a unique high altitude measurement station that provides exposure to both undisturbed free tropospheric air and to the locally influenced atmospheric boundary layer (Henne *et al.* 2008). It was established by the World Meteorological Organization (WMO) on the northwestern slope of the mountain (0.062 °S, 37.297 °E). The MKGAW station was established to collect atmospheric information in order to better understand the influence of both human activity and natural processes on the global atmosphere by studying trends of greenhouse gases, ozone, aerosols, selected reactive gases and precipitation chemistry as well as the relevant climate parameters.

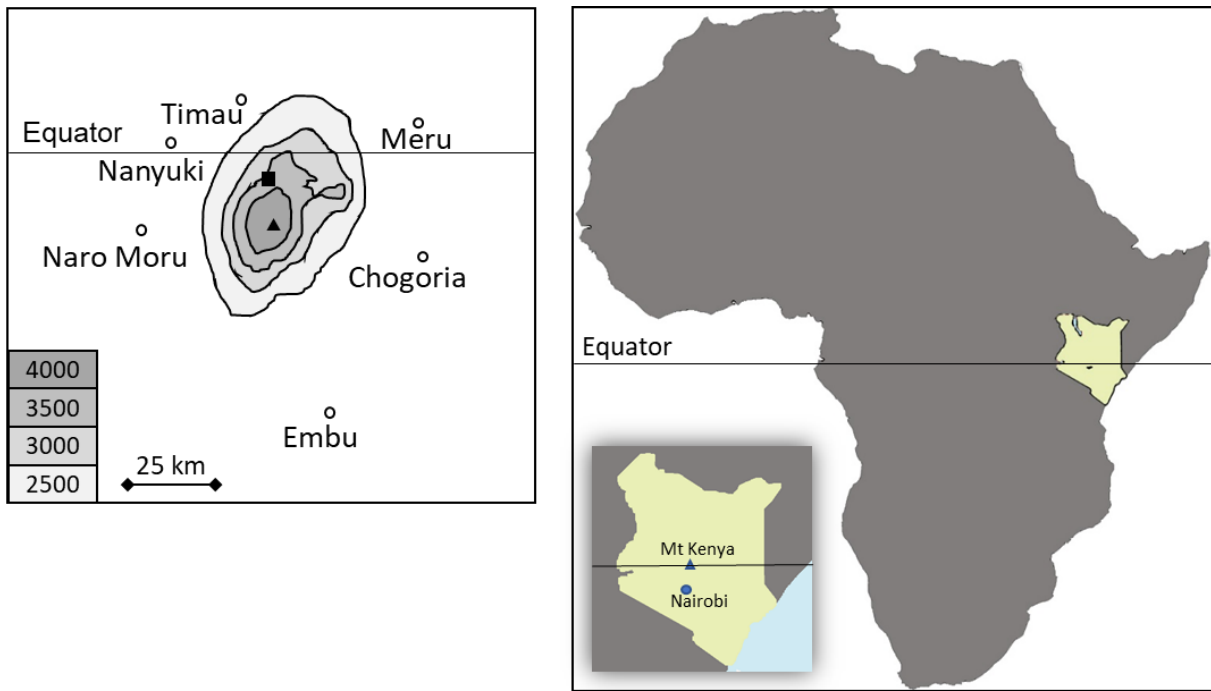


Figure 12: Location of the Mount Kenya Global Atmospheric Watch station marked by a square and the Mt Kenya summit by a triangle. The altitude above sea level is indicated in the left-hand panel. The distance between Nairobi and Mount Kenya is 150 km.



## Chapter IV

### Results and discussion

#### 4.1 Airborne particulate matter in Nairobi city

##### 4.1.1 Spatial distribution of PM and BC

Fig. 13 shows the average concentrations of PM<sub>2.5</sub> sampled at seven different sampling spots within the Nairobi metropolitan area. Five of the sites (Ronald Ngala street, River road, Tom Mboya street and Thika road) reported PM<sub>2.5</sub> concentrations above 50  $\mu\text{g m}^{-3}$  which is twice the 24 h guideline limit of 25  $\mu\text{g m}^{-3}$  set by World Health Organization (WHO 2005). The first three sites were located within the central business district and had the highest number of pedestrians as counted manually by the technicians during the study. The PM<sub>2.5</sub> concentrations from the University of Nairobi, which is considered to be an urban background site, was 50% higher than the WHO guideline limit. The rural background site which was about 20 km away from the CBD had PM<sub>2.5</sub> concentrations 50% lower than the WHO guideline. In Kenya, the current PM<sub>2.5</sub> limit is set only for industrial areas and is 35  $\mu\text{g m}^{-3}$  as annual average and for 24 h period it is 75  $\mu\text{g m}^{-3}$  (NEMA 2014). Comparing the reported street level and roadside PM<sub>2.5</sub> concentrations, they exceed the set industrial 24 h limit at four out of the five city sites. The PM<sub>2.5</sub> concentrations from the urban background site is on average slightly below the limit implying that the value is frequently exceeded.

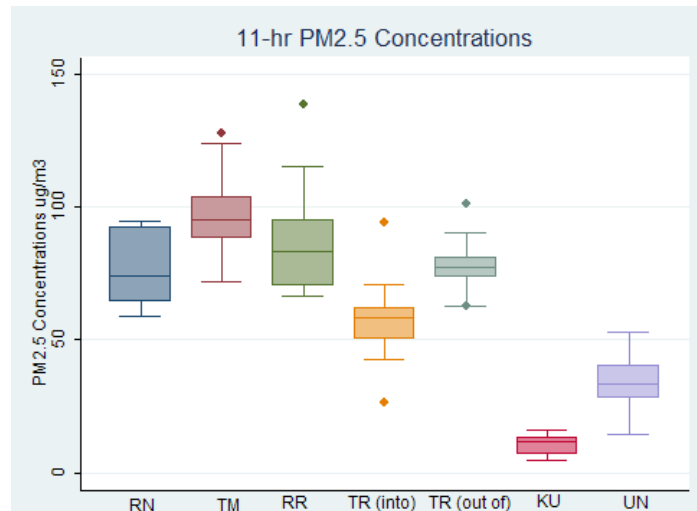


Figure 13: Average 0730-1830 hr weekday PM<sub>2.5</sub> concentrations at five core sites in Nairobi. University of Nairobi site is included as a reference point but is not directly comparable with others due to different sampling parameters that were applied (RN=Ronald Ngala, RR=River Road, TM=Tom Mboya, TR=Thika Rd, KU= Kenyatta Univ., UN= Univ. of Nairobi) (Kinney *et al.* 2011). Printed with permission.

Fig.14 shows the BC concentration at sites within the Nairobi metropolitan area. In the combined set of samples from 2009 and 2011 the lowest site specific BC concentrations were found at the background site Kenyatta University,  $3.2 \pm 1.2 \mu\text{g m}^{-3}$ . The influence of traffic was evident from the street level samples collected in the central business district (CBD) having BC concentrations up to  $53 \pm 3 \mu\text{g m}^{-3}$ . The CBD is characterized by consistent traffic-jams during most of the day coupled with a high proportion of diesel vehicles that emit BC due to badly maintained engines.

The street level BC concentrations are high, well above the WHO guideline value of  $25 \mu\text{g m}^{-3}$  for PM<sub>2.5</sub>. Other studies of BC in Nairobi show BC concentrations that are an order of magnitude lower at an urban background site and in the Nairobi industrial area (Gatari and Boman 2003, Gatari *et al.* 2009) while they are comparable to the BC concentrations that street vendors and bus drivers in Nairobi experiences (Ngo *et al.* 2015). The BC concentrations on street level are higher than the BC concentrations measured in traffic situations in Accra where the BC was reported to be in the range  $3.7 - 8.6 \mu\text{g m}^{-3}$ . Exposure to BC has been linked to lung cancer and



consequently the exposure to high levels of BC as seen in Nairobi suggests a substantial risk of cancer to the population working in the CBD (Cohen *et al.* 2017).

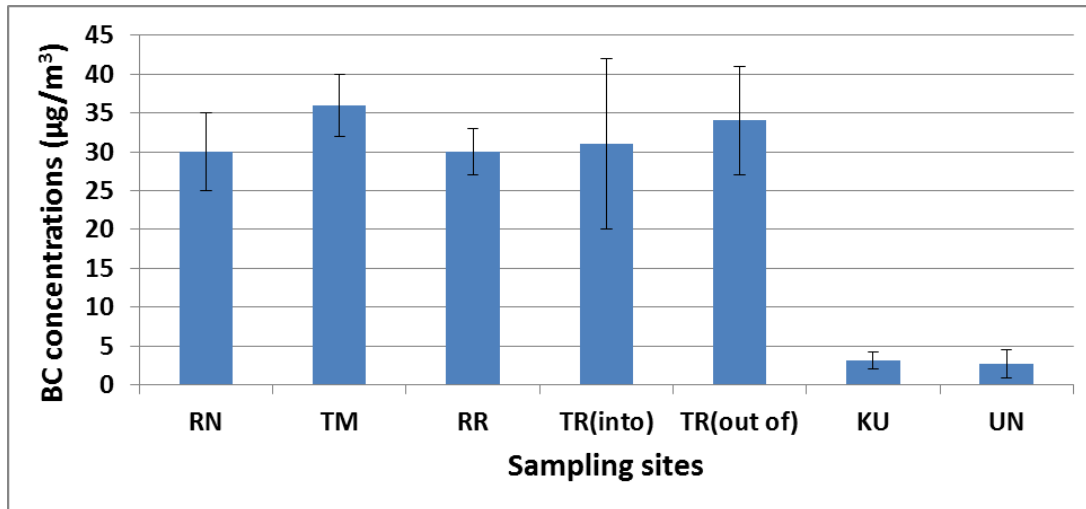


Figure 14: Average 0730-1830 hr weekday BC concentrations at five core sites in Nairobi. University of Nairobi site is included as a reference point but is not directly comparable with others due to different sampling parameters that were applied (RN=Ronald Ngala, RR=River Road, TM=Tom Mboya, TR=Thika Rd, KU= Kenyatta Univ., UN= Univ. of Nairobi) (Gatari *et al.* 2017).

## 4.1.2 Size distribution of elements in PM

The distribution of elements in three PM size groups is shown in Fig. 15. The groups are classified as coarse (2-16  $\mu\text{m}$ ), fine (0.12-2  $\mu\text{m}$ ) and ultrafine (<0.12  $\mu\text{m}$ ). The elements Si, Fe, Ca, Ti and Mn had a high proportion in the coarse size range and the fine size group had high proportions of Si, S, K, Zn, Pb and Br. The ultrafine size range had contribution from S, K, Br and Cu. K showed an equal proportion in the fine and coarse size groups pointing to origin from possible multiple sources.

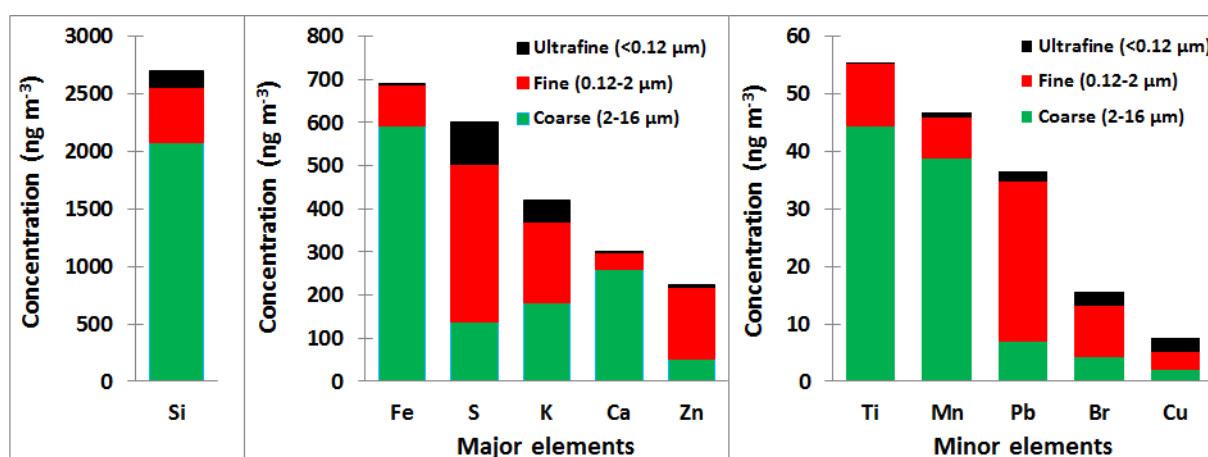


Figure 15: The distribution of major and minor elements in different PM size ranges. The size ranges have been defined as coarse (2-16  $\mu\text{m}$ ), fine (0.12-2  $\mu\text{m}$ ) and ultrafine (<0.12  $\mu\text{m}$ ) (Gaita *et al.* 2016).

## 4.2 PM source apportionment

The various sources of PM in Nairobi city were identified by PMF analysis of the PM<sub>2.5</sub> elemental concentrations (Fig. 16). The identified sources were:

- Traffic emissions, which contributed about 39% of the airborne PM. The emission of exhaust and non-exhaust traffic emissions were linked to the increase of number of vehicles in Nairobi (KNBS 2013). This increase has been influenced by the focus of the national government on the sustained development of transport infrastructure.
- Mineral dust which accounted for 35% of the airborne PM. Anthropogenic sources such as road dust play a significant role due to lack of road dust mitigation policies common in the developed countries (Amato *et al.* 2016) and increased incidents of severe droughts in Africa due to climate change (WMO 2013).
- A mixed source comprising of biomass burning, secondary aerosol particles and aged sea salt which contributed about 13%. Biomass burning is a common phenomenon in Africa with reported particulate carbonaceous emissions accounting for approximately 17% of the total global emissions (Andreae and Merlet 2001). Secondary aerosol particles are connected to the gas to particle conversion of SO<sub>2</sub> given the high level of sulphur content in the local diesel fuel which was 0.5% (UNEP 2014). Aged sea salt contribution is confirmed by the air masses movement analysis whereby the back trajectory results have principally originated from the Indian Ocean (Gatebe *et al.* 2001).
- Industrial emissions accounted for 7% and were mostly from the industrial zone located to eastern and southeastern part of the city. Weather data showed that 32% of the time the wind blow from this direction hence transporting emissions to the city's CBD.
- Combustion processes contributed about 6%. The common combustion activities in Nairobi area were identified as the use of heavy fuel oil in industries and in thermoelectric power generation (BC and S), solid waste burning (BC, Zn and Pb), and domestic charcoal/wood fires/biomass burning (BC, K and Br) in the low-income households (Karanja and Makau 2012, Egondi *et al.* 2013).

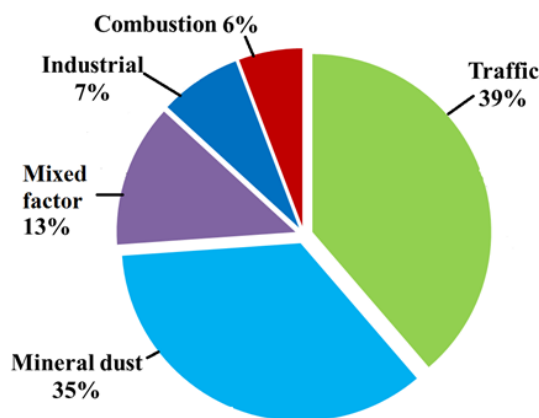


Figure 16: Percentage contribution of source factors from PMF analysis to PM<sub>2.5</sub> collected in Nairobi, Kenya for the study period 22 May 2008 to 30 March 2010.

### 4.3 Exposure to PM and deposition fractions

Figure 17 shows the deposition fractions of the coarse (2 – 16 μm) and fine (0.12 – 2 μm) particles along the human respiratory system. The highest proportion of the inhaled particles was found to be deposited along the head airways, 87% of the coarse and 84% of the fine PM. The tracheobronchial region is seen to have similar percentage of deposited coarse and fine PM whereas the pulmonary region has slightly higher proportion of coarse PM deposition compared to fine PM. The observed differences in percentage of the deposited PM is due to the various mechanisms of PM deposition which are a function of particle size, exposure dose, and clearance mechanisms (Zhang and Yu 1993, Winter-Sorkina and Cassee 2002).

The deposition fractions can be used to highlight the exposure of the human population to the airborne PM pollutants. From the PM<sub>2.5</sub> concentrations reported by Kinney *et al.* (2011), the average pedestrian walking or working along the streets in Nairobi CBD gets a dose of PM<sub>2.5</sub> concentrations for every 1 m<sup>3</sup> of air they breathe. The bus drivers in Nairobi were reported to be exposed to about 103 μg m<sup>-3</sup>. This is a dose of 46 μg on the head airways, 5.5 μg on the tracheobronchial region and 3.2 μg on the pulmonary tract for every intake of 1 m<sup>3</sup> of air. A cohort study by Pope *et al.* (2002) reported that an increase of 10 μg m<sup>-3</sup> in PM<sub>2.5</sub> translated to an increase of overall mortality by 4%, mortality from cardiopulmonary diseases by 6% and lung cancer by 8%. The reported high concentration of PM<sub>2.5</sub> and BC in Nairobi therefore translates to an excessively increased risk factor of respiratory diseases and mortality.

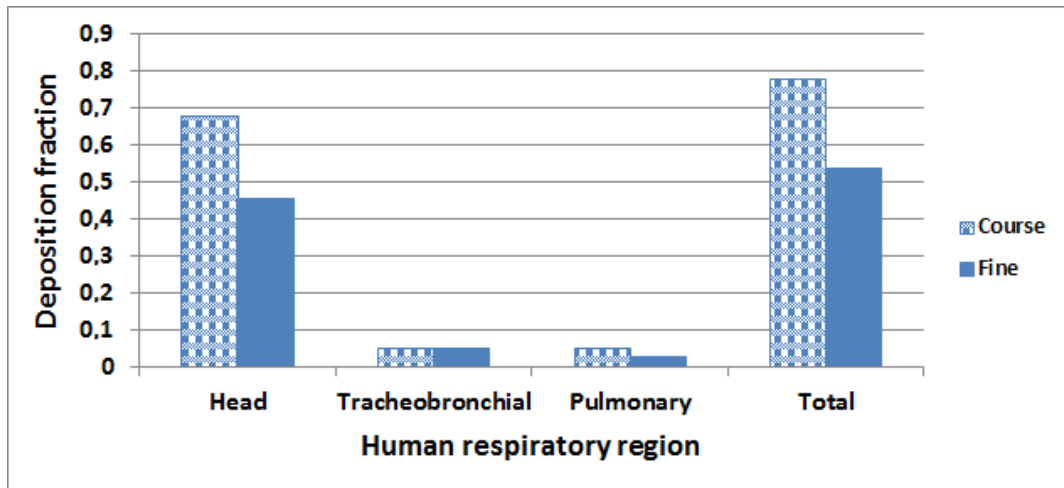


Figure 17: Deposition fractions of coarse (2 – 16  $\mu\text{m}$ ) and fine (0.12 – 2  $\mu\text{m}$ ) PM in the human head airways, tracheobronchial and pulmonary regions calculated using Multiple Path Particle Dosimetry model, MPPD V2.1 (RIVM 2002, Behera *et al.* 2015).

## 4.4 PM<sub>2.5</sub> in other cities in the world

The concentration of PM<sub>2.5</sub> compares differently with other cities in the world (Fig. 18). The background PM<sub>2.5</sub> concentrations in Nairobi was observed to be lower than levels in Dar-es-Salaam, Cairo and Ouagadougou. This is due to a combination of factors, which are unique to these mentioned cities. Dar-es-Salaam is a coastal city with a marine influence (Indian Ocean) whereas Cairo and Ouagadougou are affected by their proximity to the Sahara Desert. However, the commonality of these cities is the contribution of PM sources, which include biomass burning, traffic and industrial emissions (Mkoma *et al.* 2010, Lindén *et al.* 2012, Gaita *et al.* 2014, Shaltout *et al.* 2015). Compared to the Scandinavian city of Gothenburg (Boman *et al.* 2010), the concentration of PM<sub>2.5</sub> in Nairobi is reported to be more than three times higher and this is partly due to the strict air quality policies implemented in Gothenburg. The particulate pollution levels in Nairobi are low when compared to concentration level in Chinese cities. Zhang and Cao (2015) reported urban background PM<sub>2.5</sub> concentration levels that were on the same level as the Nairobi PM<sub>2.5</sub> street values. A study from 16 locations in Greater Kolkata in Eastern India reported high PM<sub>2.5</sub> mass concentration ranging from 83 to 783  $\mu\text{g m}^{-3}$ . The reported high PM<sub>2.5</sub> concentrations were attributed to high rate of urbanization and industrialization in India. Coincidentally, the government of Kenya is strongly pushing for urbanization and industrialization in the name of development (KV2030 2007).

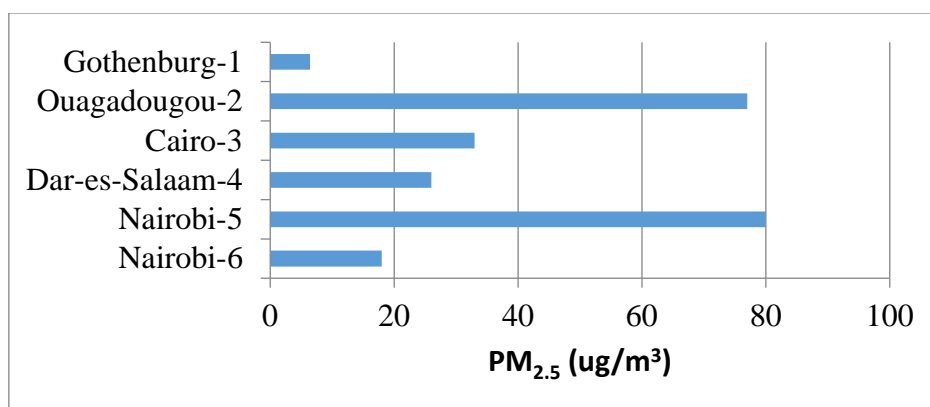


Figure 18: PM<sub>2.5</sub> concentration from the studies in this thesis work compared with concentrations from other cities in the world (1-Boman *et al.* (2010), 2-Lindén *et al.* (2012), 3- Shaltout *et al.* (2014), 4-Mkoma *et al.* (2010), 5-Kinney *et al.* (2011) and 6-Gaita *et al.* (2014).

## 4.5 Aerosol properties at high altitude

Remote high altitude sites offer an ideal location for studying composition of the atmosphere, long-range transportation of aerosols and interaction of boundary and free tropospheric conditions. Aerosol properties at MKGAW site are discussed hereinafter under particle number concentrations, elemental composition and their relationship with prevailing meteorological parameters.

### 4.5.1 Particle number concentrations

Fig. 19 shows the PN concentrations as a function of wind speed and direction. The high PN concentrations observed in the 240° to 30° sector coincided with the daytime upslope wind flow. High PN concentrations were observed at wind speeds of 4 to 8 m s<sup>-1</sup> and the corresponding direction was of the local town of Nanyuki (289°). This observation pointed to the contribution of aerosol from local source emissions within the town as reported by (Gatari *et al.* 2005). From the figure, the results are less clear of a second local town of Timau (338°), which may be due to lower emission levels compared to Nanyuki. Emissions from a third town, Meru, (72°) were not conclusively identified. The daytime rising of the atmospheric boundary layer points to the specific source region of PM that influences the atmospheric composition at this high altitude site. At nighttime, the wind direction was most from the sector 90° and 210°. The PN concentration within this sector was low at wind speeds below 6 ms<sup>-1</sup> but increases at higher wind speeds. This observation of high PN concentration was interpreted to be the production of wind-driven dust particles or overflow of particles from the continental region on the eastern side of the mountain. Study of aerosol in the free troposphere at MKGAW has been recommended for nighttime sampling. However, the results from this study showed that wind dynamics are also an important consideration to studying free troposphere in addition to relative humidity as suggested by Henne *et al.* (2008).

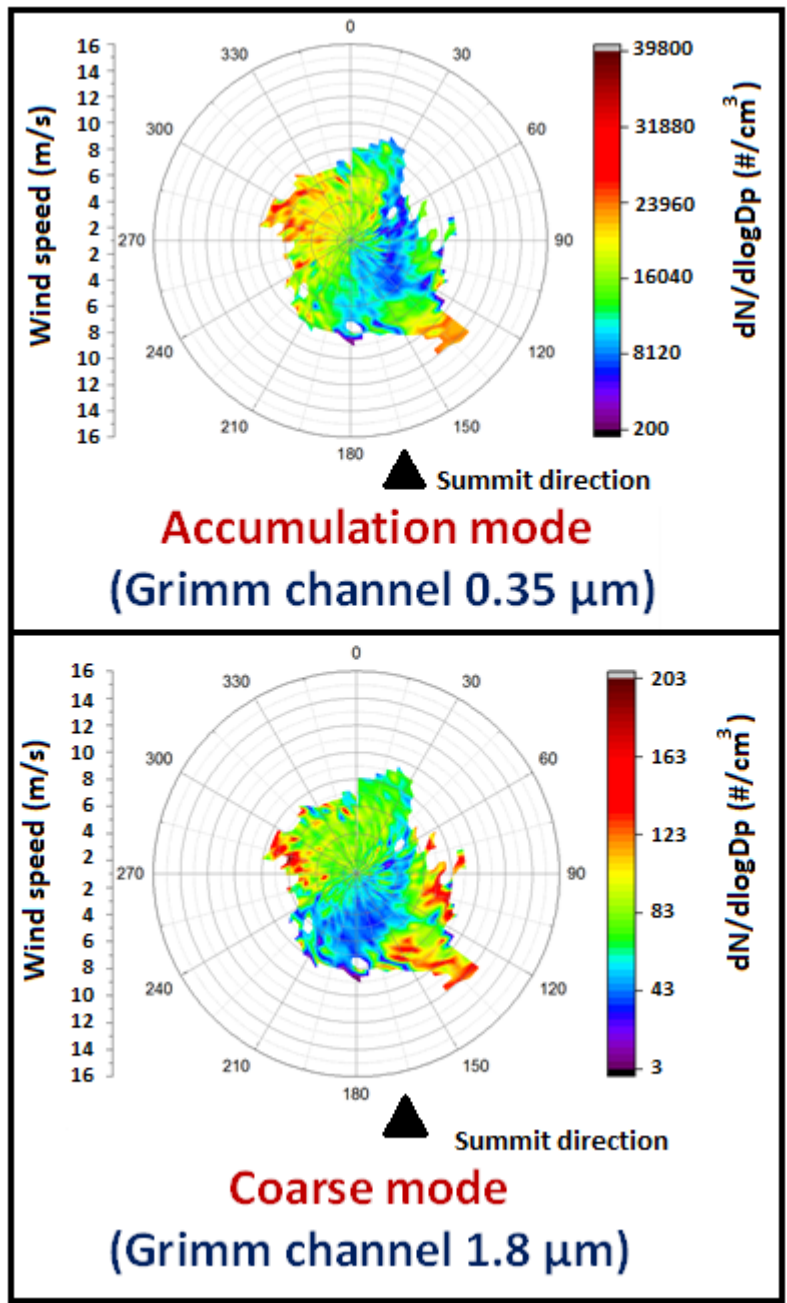


Figure 19: Bivariate-conditional plots of particle number concentrations as a function of wind speed and direction at Mount Kenya Global Atmosphere Watch station for 1 minute data sampled from 14<sup>th</sup> August to 12<sup>th</sup> September, 2015.



## 4.5.2 Elemental composition

The elemental concentrations of PM sampled at the MKGAW site are listed in Table 1. The daytime concentrations of the elements and BC in the PM<sub>2.5-10</sub> fraction were dominated by Fe, which accounted for about 40% of the total species followed by Ca at 30%. Other elements with significant composition are K, Cl and S, which accounted for 21%. The PM<sub>2.5</sub> fraction during the daytime was dominated by BC and S, which had accounted for 39% and 37% respectively (excluding OC, and EC in the percentage calculations). K, Ca, Fe and Cl were present in substantial amount accounting for 22%. The nighttime composition of the PM<sub>2.5-10</sub> fraction was dominated by Ca and Fe, both which accounted for 70% of the measured species. S, K and Cl accounted for 22% of the species. The nighttime PM<sub>2.5</sub> fraction was dominated by S and BC, which accounted for 71% of the species. Fe, Ca, Cl and K were present in minor amount, which was 26%. Important to note is the significant contribution of OC to the fine fraction which if included in the calculation would have accounted for 73% of all the measured species.

The dominance of Fe in both fractions is linked to the iron oxide which gives the red colour that is observed in soils at Mount Kenya and surrounding regions (Speck 1981). The PM<sub>2.5</sub> is dominated by combustion related elements (BC and S) pointing to the impact of agricultural activities on the surrounding plains and the traffic emissions from the surrounding towns. The nighttime concentrations of K, Ti, Mn, Fe and BC in PM<sub>2.5-10</sub> are 60% of the daytime concentrations pointing to commonality of their sources but on varying strength.

The concentrations of BC, OC and EC shows the substantial contribution of organic fraction to the aerosol at Mount Kenya. Despite the different techniques used to sample for BC (dichotomous sampler with flowrate of 1 m<sup>3</sup> h<sup>-1</sup>) and EC and OC (high volume sampler with flowrate of 35 m<sup>3</sup> h<sup>-1</sup>), the comparison of their concentration values shows a good conformity. A factor of 1.19 between BC and EC had been reported by Gatari *et al.* (2017) from a study in Nairobi on PM samples collected on a different filter substrate.

Table 1: Daytime and nighttime concentration ( $\text{ng m}^{-3}$ ) of species in the  $\text{PM}_{2.5}$  and  $\text{PM}_{2.5-10}$  fractions from MKGAW site. Also included are the concentrations of OC, EC, and  $\text{PM}_{2.5}$  from the 24-h samples.

Species	Fraction	Daytime	Nighttime
		Mean $\pm$ Stdev	Mean $\pm$ Stdev
<b>S</b>	$\text{PM}_{2.5-10}$	580 $\pm$ 340	550 $\pm$ 400
	$\text{PM}_{2.5}$	200 $\pm$ 87	180 $\pm$ 120
<b>Cl</b>	$\text{PM}_{2.5-10}$	670 $\pm$ 300	480 $\pm$ 250
	$\text{PM}_{2.5}$	14 $\pm$ 5.1	14 $\pm$ 6.9
<b>K</b>	$\text{PM}_{2.5-10}$	780 $\pm$ 480	500 $\pm$ 330
	$\text{PM}_{2.5}$	37 $\pm$ 14	24 $\pm$ 10
<b>Ca</b>	$\text{PM}_{2.5-10}$	2800 $\pm$ 200	2500 $\pm$ 2500
	$\text{PM}_{2.5}$	31 $\pm$ 17	34 $\pm$ 25
<b>Ti</b>	$\text{PM}_{2.5-10}$	400 $\pm$ 190	220 $\pm$ 130
	$\text{PM}_{2.5}$	3.2 $\pm$ 2.6	3.2 $\pm$ 3.2
<b>Mn</b>	$\text{PM}_{2.5-10}$	99 $\pm$ 40	56 $\pm$ 25
	$\text{PM}_{2.5}$	0.9 $\pm$ 0.5	0.9 $\pm$ 0.7
<b>Fe</b>	$\text{PM}_{2.5-10}$	3800 $\pm$ 1900	2200 $\pm$ 1300
	$\text{PM}_{2.5}$	35 $\pm$ 24	35 $\pm$ 30
<b>Ni</b>	$\text{PM}_{2.5-10}$	11 $\pm$ 1.8	11 $\pm$ 2.0
	$\text{PM}_{2.5}$	1.2 $\pm$ 0.2	1.2 $\pm$ 0.1
<b>Cu</b>	$\text{PM}_{2.5-10}$	27 $\pm$ 4.5	26 $\pm$ 2.4
	$\text{PM}_{2.5}$	3.1 $\pm$ 0.6	2.9 $\pm$ 0.2
<b>Zn</b>	$\text{PM}_{2.5-10}$	20 $\pm$ 6.3	17 $\pm$ 4.7
	$\text{PM}_{2.5}$	1.9 $\pm$ 0.7	1.6 $\pm$ 0.5
<b>Br</b>	$\text{PM}_{2.5-10}$	7.4 $\pm$ 1.0	6.6 $\pm$ 1.1
	$\text{PM}_{2.5}$	1.6 $\pm$ 0.3	1.2 $\pm$ 0.3
<b>Sr</b>	$\text{PM}_{2.5-10}$	25 $\pm$ 10	21 $\pm$ 11
	$\text{PM}_{2.5}$	1.3 $\pm$ 0.2	1.3 $\pm$ 0.3
<b>Pb</b>	$\text{PM}_{2.5-10}$	22 $\pm$ 2.7	21 $\pm$ 3.2
	$\text{PM}_{2.5}$	2.7 $\pm$ 0.2	2.5 $\pm$ 0.4
<b>BC</b>	$\text{PM}_{2.5-10}$	240 $\pm$ 160	130 $\pm$ 170
	$\text{PM}_{2.5}$	210 $\pm$ 80	110 $\pm$ 50
<b>OC*</b>	$\text{PM}_{2.5}$	1900 $\pm$ 390	
<b>EC*</b>	$\text{PM}_{2.5}$	160 $\pm$ 110	
<b>Mass*</b>	$\text{PM}_{2.5}$	6900 $\pm$ 1300	

OC\*, EC\* and mass\* were collected using high volume sampler for 24-h periods

### 4.5.3 Physical and chemical properties of the aerosols

Tables 2 and 3 show the two-sided correlation coefficients between elements' concentrations, size-segregated PN concentrations and weather parameters. The correlation of the PN sizes 0.35, 0.45 and 0.575 is more positive for S, K, Br, and BC. Since these elements are markers for biomass burning, they are thus expected to be present in the PM<sub>2.5</sub> mode. S has high correlation with a wider range of PN sizes indicating multiplicity of sources contributing to S in PM<sub>2.5</sub> or chemical transformation during transportation from its sources (Hitchcock *et al.* 1980). The high correlation of Ca, Ti, Fe, Zn, Sr, and Pb is possibly an influence of mixing of particle from anthropogenic activities (traffic, industry) and crustal origin. K, Br, and BC also show a high correlation with air temperature but are anti-correlated with the wind speed. This is linked to low wind speeds which leads to higher temperatures due to the insolation and the concentration of airborne PM increases with increasing atmospheric stability (Lindén *et al.* 2012). The lack of correlation between the elements and the rain linked to the fact that rainfall is a local phenomenon at Mount Kenya and is limited in time while aerosol particles are transported to MKGAW site from shifting directions and sources over longer periods of time.

The correlation between of PN and PM<sub>2.5-10</sub> is low at sizes less than 0.575  $\mu\text{m}$  showing a clear separation of "fine" and "coarse" particles during sampling with the Anderson dichotomous sampler. Crustal elements (Fe, K, Ti, Ca and Sr) have the highest correlation coefficients pointing to the influence of mineral dust at the site.

Non-crustal elements have moderate correlation indicating a sign of the long-distance transport of these particles, as seen in the analysis of elemental content and wind direction. Similar correlation between meteorology and elemental content in PM<sub>2.5</sub> can be noted in PM<sub>2.5-10</sub>. There is an anti-correlation between the elements and rain, but it is not concise.

Table 2: Correlation between elements concentration in PM<sub>2.5</sub> fraction with the particle number concentrations and meteorology parameters

Elements/ Particle size (μm)	S	Cl	K	Ca	Ti	Mn	Fe	Ni	Cu	Zn	Br	Sr	Pb	BC
0.35	0.7	0.2	0.7	0.4	0.2	0.0	0.2	0.3	-0.2	0.4	0.7	0.3	0.2	0.9
0.45	0.6	0.2	0.7	0.4	0.2	0.1	0.2	0.3	-0.2	0.4	0.7	0.3	0.1	0.9
0.575	0.8	0.1	0.7	0.8	0.6	0.3	0.6	0.4	-0.1	0.8	0.6	0.7	0.5	0.6
0.725	0.8	0.0	0.5	0.8	0.7	0.3	0.7	0.4	-0.1	0.8	0.5	0.7	0.6	0.4
0.9	0.8	0.0	0.5	0.8	0.7	0.3	0.7	0.4	0.0	0.8	0.4	0.7	0.7	0.3
1.3	0.7	0.0	0.5	0.8	0.7	0.3	0.7	0.4	0.0	0.8	0.4	0.7	0.7	0.3
1.8	0.7	0.0	0.5	0.8	0.7	0.3	0.7	0.4	0.0	0.8	0.4	0.6	0.7	0.3
2.5	0.7	0.0	0.5	0.8	0.7	0.3	0.7	0.4	0.0	0.8	0.4	0.7	0.6	0.4
3.5	0.7	0.0	0.6	0.8	0.7	0.3	0.7	0.4	0.0	0.8	0.5	0.7	0.6	0.4
4.5	0.5	0.1	0.6	0.7	0.6	0.3	0.6	0.4	0.0	0.7	0.6	0.6	0.5	0.5
6.25	0.3	0.1	0.5	0.4	0.4	0.2	0.4	0.3	0.1	0.5	0.6	0.5	0.4	0.4
Wind direction	-0.1	0.1	0.4	-0.1	0.1	0.1	0.0	0.1	-0.2	0.1	0.4	-0.1	0.0	0.6
Wind speed	0.1	-0.2	-0.5	0.2	0.0	-0.1	0.0	0.0	0.1	-0.1	-0.7	0.0	0.0	-0.6
Pressure	0.1	0.0	0.4	0.1	0.0	0.0	0.0	0.2	0.0	0.2	0.5	0.2	-0.2	0.5
Air temperature	0.4	0.2	0.6	0.3	0.5	0.4	0.5	0.2	0.1	0.5	0.7	0.2	0.5	0.6
RH	-0.1	0.2	0.3	-0.2	0.0	0.1	0.0	-0.3	-0.3	-0.1	0.5	-0.4	0.1	0.5
Rain (mm h <sup>-1</sup> )	0.0	0.1	0.1	-0.2	-0.2	-0.1	-0.2	-0.1	-0.3	-0.1	0.1	-0.2	0.0	0.3

Table 3: Correlation between elements concentration in PM<sub>2.5-10</sub> with the particle number concentrations and meteorology parameters

Elements/ Particle size (μm)	S	Cl	K	Ca	Ti	Mn	Fe	Ni	Cu	Zn	Br	Sr	Pb	BC
0.35	0.6	0.4	0.4	0.5	0.4	0.4	0.4	0.3	-0.4	0.4	0.2	0.5	0.0	0.4
0.45	0.6	0.4	0.3	0.4	0.4	0.4	0.4	0.2	-0.4	0.4	0.2	0.5	0.0	0.5
0.575	0.8	0.9	0.8	0.9	0.8	0.8	0.8	0.7	0.0	0.8	0.6	0.9	0.5	0.6
0.725	0.7	0.9	0.9	1.0	0.8	0.8	0.9	0.8	0.1	0.7	0.6	0.9	0.6	0.5
0.9	0.7	0.9	0.9	1.0	0.8	0.8	0.9	0.8	0.1	0.7	0.6	0.9	0.7	0.5
1.3	0.7	0.9	0.9	0.9	0.9	0.8	0.9	0.8	0.2	0.7	0.7	0.9	0.7	0.5
1.8	0.7	0.9	0.9	0.9	0.9	0.8	0.9	0.8	0.2	0.8	0.7	0.9	0.7	0.5
2.5	0.6	0.8	0.9	0.9	0.9	0.8	0.9	0.8	0.2	0.8	0.7	0.9	0.7	0.5
3.5	0.6	0.8	0.9	0.9	0.9	0.9	0.9	0.7	0.2	0.8	0.7	0.9	0.6	0.5
4.5	0.5	0.7	0.9	0.8	0.9	0.9	0.9	0.6	0.2	0.9	0.8	0.8	0.5	0.6
6.25	0.3	0.5	0.6	0.4	0.8	0.8	0.7	0.5	0.3	0.7	0.6	0.6	0.4	0.5
Wind direction	-0.1	-0.1	0.1	-0.1	0.2	0.2	0.2	-0.1	-0.4	0.2	0.2	0.0	-0.1	0.2
Wind speed	0.1	-0.1	-0.1	0.1	-0.3	-0.3	-0.2	0.1	0.0	-0.2	-0.3	-0.1	0.1	-0.3
Pressure	0.1	0.1	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2	0.0	-0.2	0.1	-0.4	0.1
Air temperature	0.3	0.7	0.7	0.5	0.8	0.8	0.8	0.5	0.2	0.5	0.6	0.6	0.4	0.7
RH	-0.2	0.1	0.1	-0.1	0.2	0.2	0.2	-0.2	-0.2	0.0	0.4	0.0	0.2	0.0
Rain (mm h <sup>-1</sup> )	-0.1	-0.2	-0.2	-0.1	-0.2	-0.2	-0.2	0.0	-0.2	-0.2	-0.1	-0.2	0.0	-0.1

The Enrichment factors of the PM<sub>2.5</sub> at the MKGAW site and from Nairobi are shown in Table 4. The EF for S is 4 factors higher at the remote high altitude site (MKGAW) than the urban site (Nairobi). This points to the dynamics of chemical transformation of S during transportation from the source in this case the emissions from diesel consumption within the urban areas (Owen 1989, TransportPolicy.net 2016). Similar observation is seen for the Br which is emitted in vapour form (Harrison and Sturges 1983) from traffic and hence chemical transformation to particulate form during long range transportation. The EF for Cl is higher at the urban site by a factor of 2 than at the remote high altitude site and this impact of anthropogenic sources of Cl compared to marine influence at the remote sites. The EFs of crustal elements (Fe, Ti and Ca) are similar but Mn which is considered to be of crustal origin has higher EF value at the urban site. This is due to the influence of Mn emission from engine oil (Hammerle *et al.* 1991). Ni, Cu and Pb have higher EFs and are linked to the aging of aerosol from industrial emission (Moffet *et al.* 2008).

Table 4: Enrichment Factors (EF) of elements' concentrations from PM sampled at Mount Kenya GAW site calculated from crustal rock elemental concentrations (1966). The EF values from Nairobi city are included for comparison purposes.

Element	EF - PM <sub>2.5</sub>	EF - PM <sub>2.5-10</sub>	EF - PM <sub>2.5</sub> (Nairobi)
S	1000	36	230
Cl	160	74	350
K	1.7	0.4	1.1
Ca	1.3	1.2	0.8
Ti	1.0	1.2	1.2
Mn	1.4	1.4	4.1
Fe	1.0	1.0	1.0
Ni	23	2.4	5
Cu	79	7.9	19
Zn	37	4.4	120
Br	790	47	450
Sr	4.9	1.0	-
Pb	290	27	160



## Chapter V

### Summary

Results from spatial distribution of study of PM<sub>2.5</sub> and BC have shown that the populace in Nairobi is frequently exposed to airborne particulate pollution. The major sources of these particulate pollutants were identified as traffic emissions and mineral dust. Other identified sources include biomass burning, marine aerosols, industrial emissions and combustion processes. These sources emit PM of varying aerodynamic size and have the composite distribution of elements that link to their respective sources. The aerodynamic PM size determines how deep they are deposited in the human respiratory system during inhalation. The PM sizes and concentrations were used to estimate the deposition fractions in the respiratory system of an average pedestrian in the Nairobi city. The highest proportion of the inhaled PM was found to be deposited along the head airways region. Deposition into the tracheobronchial and pulmonary tract was at 15%. However, when the percentages are used to calculate the mass of PM deposited in the deeper respiratory regions, the amount are reported to be detrimental to human health. The high level of particulate pollutants measured along the main streets of Nairobi indicate that majority of pedestrians spending time on or near the roadways and working within the CBD are at higher risk of respiratory illnesses due to exposure to air pollution. It is important to note that the human body is equipped with removal mechanisms of inhaled PM but overloading can lead to respiratory complications and eventual cardio-related illnesses.

Study of aerosol properties at a high altitude area (Mount Kenya) has shown that anthropogenic activities in the urban and regional areas influence the atmospheric composition of remote regions. The emissions from sources areas are transported and distributed by the atmospheric and meteorology dynamics, both on a local and regional scale. The mixing of continental boundary layer loaded with emissions from natural and anthropogenic sources with the free tropospheric conditions, poses a challenge in studying aerosol composition in the free troposphere.





# Outlook

The study has identified important issues regarding air quality in Nairobi city as well as physical and chemical processes of aerosol at a remote high altitude area. In order to improve the scientific knowledge, the following is recommended

- Reported information on trace elements can be improved by inclusion of data on organic composition of the PM at the urban area (research is on-going by Prof. M. J. Gatari and Prof. A. Andersson)
- Information on deposition fractions of pollutant PM in the human respiratory system should be correlated with the hospital records on respiratory illnesses. This would establish a better understanding of the health effects of air pollution in Nairobi.
- Indoor air pollution component should be considered since biomass based fuels are used for domestic energy needs in over 90% of the SSA households.
- High resolution long term measurement of physical and chemical properties of aerosol are recommended at Mount Kenya in order to get a better understanding of seasonal trends/cycles on their composition and chemical transformation during long range transport.
- Extension of the PM<sub>2.5</sub> limits from industrial area to cover the residential areas emissions are prone to transportation from source regions depending on the prevailing meteorological conditions.



# Acknowledgement

I will be forever grateful to my mum, dad and sisters (The Gaita family) for their continued love and support during my many many years of books.

My gratitude to my second family of Prof. M. J. Gatari. Your prayers and believe in my academic abilities gave me strength when the going got tough.

I immensely appreciate the moral and academic support from Prof. Johan Boman. From the first day I came to Sweden, you have always been there for me. Prof. Jan B.C. Pettersson, Prof. Annemarie, Prof. M. Hallqvist, Prof. L. Holmlid, Dr. E. Thomson and Dr. Sara Janhäll, you are greatly appreciated.

MERGE and KMB-University of Gothenburg, are recognised for funding my studies at the University of Gothenburg. The International Science Programme- Uppsala University, is appreciated for the research support in Kenya.

Current and former members of the Atmospheric science group, GU have made my life in Sweden to be a thrill and fun-filled; the conferences, fikas, parties and conducive working environment. Thanks a lot guys; Dan, Pei, Anna (office agreement), Sofia, Dimitri, Julia, Ågot, Magda, Kong, Mike, Cameron, Anki, Kent, Eva, Mauritz, Tobjörn.

The Kenyan family in Sweden made my social life awesome during the social gatherings and events we had together (families of Nyangena, Kamau, Jacob n Rhoda, Nguku, Susan, Maggie, Marion, Tom)

My colleagues at the INST, UoN, are warmly appreciated; Director D. M. Maina, Mr. Mangala, Bartilol, Mailu, Kamau, Rose, Ndwiga, Matini, Jeremy, C. Mburu, Kageliza, Karanja, Dan and others.

The students I supervised gave me a perspective of the struggles in writing. Thanks to Maria (Jan), Sepideh, Charlotta, Sofia E, Sara and Sigrun.

**THANK YOU ALL!**



## References

- Akselsson, K. R. and Johansson, S. A. E. (1979). Pixe Analysis Research in Lund. *IEEE Transactions on Nuclear Science* 26(1): 1358-1362. DOI: [10.1109/TNS.1979.4330386](https://doi.org/10.1109/TNS.1979.4330386),
- Amato, F., Escrig, A., Sanfelix, V., Celades, I., Reche, C., Monfort, E. and Querol, X. (2016). Effects of water and CMA in mitigating industrial road dust resuspension. *Atmospheric Environment* 131: 334-340. DOI: <http://dx.doi.org/10.1016/j.atmosenv.2016.02.018>,
- Amegah, A. K. and Agyei-Mensah, S. (2017). Urban air pollution in Sub-Saharan Africa: Time for action. *Environmental Pollution* 220: 738-743. DOI: <http://dx.doi.org/10.1016/j.envpol.2016.09.042>,
- Anderson, H. R. (2009). Air pollution and mortality: A history. *Atmos. Environ.* 43(1): 142-152. DOI: <http://dx.doi.org/10.1016/j.atmosenv.2008.09.026>,
- Andreae, M. O. and Merlet, P. (2001). Emission of trace gases and aerosols from biomass burning. *Global Biogeochemical Cycles* 15(4): 955-966. DOI: [10.1029/2000GB001382](https://doi.org/10.1029/2000GB001382),
- Behera, S. N., Betha, R., Huang, X. and Balasubramanian, R. (2015). Characterization and estimation of human airway deposition of size-resolved particulate-bound trace elements during a recent haze episode in Southeast Asia. *Environ Sci Pollut Res Int* 22(6): 4265-4280. DOI: [10.1007/s11356-014-3645-6](https://doi.org/10.1007/s11356-014-3645-6),
- Boman, J., Wagner, A. and Gatari, M. J. (2010). Trace elements in PM<sub>2.5</sub> in Gothenburg, Sweden. *Spectrochimica Acta Part B: Atomic Spectroscopy* 65(6): 478-482. DOI: <http://dx.doi.org/10.1016/j.sab.2010.03.014>,
- Cachier, H., Ruellan, S., Liousse, C., Gaudichet, A., Masclet, P. and Lacaux, J. (1998). Biomass burning aerosols in tropical Africa. *J. Aerosol Sci.* 29, Supplement 1(0): S23-S24. DOI: [http://dx.doi.org/10.1016/S0021-8502\(98\)00088-3](http://dx.doi.org/10.1016/S0021-8502(98)00088-3),
- ClimaTemps (2016). Nairobi weather and climate. Date accessed 7th April, 2016, <http://www.nairobi.climatemps.com/>.
- Cohen, A. J., Brauer, M., Burnett, R., Anderson, H. R., Frostad, J., Estep, K., Balakrishnan, K., Brunekreef, B., Dandona, L., Dandona, R., Feigin, V., Freedman, G., Hubbell, B., Jobling, A., Kan, H., Knibbs, L., Liu, Y., Martin, R., Morawska, L., Pope, C. A., III, Shin, H., Straif, K., Shaddick, G., Thomas, M., van Dingenen, R., van Donkelaar, A., Vos, T., Murray, C. J. L. and Forouzanfar, M. H. (2017). Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. *The Lancet* 389(10082): 1907-1918. DOI: [10.1016/S0140-6736\(17\)30505-6](https://doi.org/10.1016/S0140-6736(17)30505-6),
- CSUD (2010). 2005 Nairobi Land Use & Roads Network. Columbia University, New York, Center for Sustainable Urban Development. <http://nairobigismaps.wikischolars.columbia.edu/2005+Land+Use+%26+Building+Density>.
- Davies, T. D., Brimblecombe, P. and Vincent, C. E. (1977). The daily cycle of weather on Mount Kenya. *Weather* 32(11): 406-417. DOI: [10.1002/j.1477-8696.1977.tb04492.x](https://doi.org/10.1002/j.1477-8696.1977.tb04492.x),
- Draxler, R. R. and Hess, G. D. (1998). An overview of the HYSPLIT\_4 modeling system of trajectories, dispersion, and deposition. *Aust. Meteorol. Mag.* 47: 295-308.

Draxler, R. R. and Rolph, G. D. (2015). HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) Model access via NOAA ARL READY Website Silver Spring, MD, NOAA Air Resources Laboratory. <http://ready.arl.noaa.gov/HYSPLIT.php>.

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

Finlayson-Pitts, B. J. and Pitts Jr, J. N. (2000). CHAPTER 8 - Acid Deposition: Formation and Fates of Inorganic and Organic Acids in the Troposphere. Chemistry of the Upper and Lower Atmosphere. San Diego, Academic Press: 294-348.

Flament, P., Deboudt, K., Cachier, H., Châtenet, B. and Mériaux, X. (2011). Mineral dust and carbonaceous aerosols in West Africa: Source assessment and characterization. *Atmospheric Environment* 45(22): 3742-3749. DOI: <http://dx.doi.org/10.1016/j.atmosenv.2011.04.013>,

Formenti, P., Elbert, W., Maenhaut, W., Haywood, J., Osborne, S. and Andreae, M. O. (2003). Inorganic and carbonaceous aerosols during the Southern African Regional Science Initiative (SAFARI 2000) experiment: Chemical characteristics, physical properties, and emission data for smoke from African biomass burning. *J. Geophys. Res.-Atm.* 108(D13): 8488. DOI: 10.1029/2002JD002408,

Gabriel, R., Mayol-Bracero, O. L. and Andreae, M. O. (2002). Chemical characterization of submicron aerosol particles collected over the Indian Ocean. *Journal of Geophysical Research: Atmospheres* 107(D19): INDX2 4-1-INDX2 4-12. DOI: 10.1029/2000JD000034,

Gaita, S. M., Boman, J., Gatari, M. J., Pettersson, J. B. C. and Janhäll, S. (2014). Source apportionment and seasonal variation of PM<sub>2.5</sub> in a Sub-Saharan African city: Nairobi, Kenya. *Atmos. Chem. Phys.* 14(18): 9977-9991. DOI: 10.5194/acp-14-9977-2014,

Gaita, S. M., Boman, J., Gatari, M. J., Wagner, A. and Jonsson, S. K. (2016). Characterization of Size-Fractionated Particulate Matter and Deposition Fractions in Human Respiratory System in a Typical African City: Nairobi, Kenya. *Aerosol Air Qual Res* 16(10): 2378-2385. DOI: 10.4209/aaqr.2016.01.0019,

Gatari, M. J. and Boman, J. (2003). Black carbon and total carbon measurements at urban and rural sites in Kenya, East Africa. *Atmos. Environ.* 37(8): 1149-1154. DOI: [http://dx.doi.org/10.1016/S1352-2310\(02\)01001-4](http://dx.doi.org/10.1016/S1352-2310(02)01001-4),

Gatari, M. J., Boman, J. and Maina, D. M. (2005). Trace element categorization of pollution sources in the equator town of Nanyuki, Kenya. *X-Ray Spectrometry* 34(2): 118-123. DOI: 10.1002/xrs.771,

Gatari, M. J., Kinney, P. L., Yan, B., Sclar, E., Volavka-Close, N., Ngo, N., Gaita, S. M., Law, A., Ndiba, P., Gachanja, A., Graeff, J. and Chillrud, S. N. (2017). High airborne black carbon concentrations measured near roadways in Nairobi, Kenya. *Transportation Research Part D: Transport and Environment* Manuscript under review.

Gatari, M. J., Pettersson, J. B. C., Kimani, W. and Boman, J. (2009). Inorganic and black carbon aerosol concentrations at a high altitude on Mt Kenya. *X-Ray Spectrom.* 38(1): 26-36. DOI: 10.1002/xrs.1094,

Gatebe, C. K., Tyson, P. D., Annegarn, H., Piketh, S. and Helas, G. (1999). A seasonal air transport climatology for Kenya. *J. Geophys. Res-Atmos.* 104(D12): 14237-14244. DOI: 10.1029/1998JD200103,

- Gatebe, C. K., Tyson, P. D., Annegarn, H. J., Helas, G., Kinyua, A. M. and Piketh, S. J. (2001). Characterization and transport of aerosols over equatorial eastern Africa. *Global Biogeochemical Cycles* 15(3): 663-672. DOI: 10.1029/2000GB001340,
- Hammerle, R. H., Korniski, T. J., Weir, J. E., Chladek, E., Gierczak, C. A. and Hurley, R. G. (1991). Particulate Emissions from Current Model Vehicles Using Gasoline with Methylcyclopentadienyl Manganese Tricarbonyl, SAE International. <http://doi.org/10.4271/912436>.
- Hand, V. L., Capes, G., Vaughan, D. J., Formenti, P., Haywood, J. M. and Coe, H. (2010). Evidence of internal mixing of African dust and biomass burning particles by individual particle analysis using electron beam techniques. *Journal of Geophysical Research: Atmospheres* 115(D13): D13301. DOI: 10.1029/2009JD012938,
- Harrison, R. M. and Sturges, W. T. (1983). The measurement and interpretation of Br/Pb ratios in airborne particles. *Atmos. Environ.* 17(2): 311-328. DOI: [http://dx.doi.org/10.1016/0004-6981\(83\)90048-3](http://dx.doi.org/10.1016/0004-6981(83)90048-3),
- Heal, M. R., Kumar, P. and Harrison, R. M. (2012). Particles, air quality, policy and health. *Chem. Soc. Rev* 41(19): 6606-6630. DOI: 10.1039/C2CS35076A,
- Henne, S., Junkermann, W., Kariuki, J. M., Aseyo, J. and Klausen, J. (2008). Mount Kenya Global Atmospheric Watch Station (MKN): Installation and Meteorology Characterization. *J. Appl. Meteorol. Clim.* 47(11): 2946-2962.
- Hinds, W. C. (1998). *Aerosol Technology*. New York, John Wiley & Sons Inc. pp: 75-110.
- Hitchcock, D. R., Spiller, L. L. and Wilson, W. E. (1980). Sulfuric acid aerosols and HCl release in coastal atmospheres: Evidence of rapid formation of sulfuric acid particulates. *Atmospheric Environment* (1967) 14(2): 165-182. DOI: [http://dx.doi.org/10.1016/0004-6981\(80\)90275-9](http://dx.doi.org/10.1016/0004-6981(80)90275-9),
- Karanasiou, A., Minguillón, M. C., Viana, M., Alastuey, A., Putaud, J. P., Maenhaut, W., Panteliadis, P., Močnik, G., Favez, O. and Kuhlbusch, T. A. J. (2015). Thermal-optical analysis for the measurement of elemental carbon (EC) and organic carbon (OC) in ambient air a literature review. *Atmos. Meas. Tech. Discuss.* 2015: 9649-9712. DOI: 10.5194/amtd-8-9649-2015,
- Karanja, I. W. and Makau, J. (2012). An inventory of slums in Nairobi. Nairobi, UN Office for the Coordination of Humanitarian Affairs, 221p. website: [http://sdinet.org/wp-content/uploads/2015/04/Nairobi\\_slum\\_inventory\\_jan\\_09.pdf](http://sdinet.org/wp-content/uploads/2015/04/Nairobi_slum_inventory_jan_09.pdf).
- 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. (2011). Traffic impacts on PM2.5 air quality in Nairobi, Kenya. *Environ. Sci. Policy* 14(4): 369-378. DOI: <http://dx.doi.org/10.1016/j.envsci.2011.02.005>,
- KNBS (2013). Registered Vehicles: 2001-2009. Date accessed 2015-05-21, [http://www.knbs.or.ke/index.php?option=com\\_phocadownload&view=category&id=91:transport&Itemid=1163](http://www.knbs.or.ke/index.php?option=com_phocadownload&view=category&id=91:transport&Itemid=1163).
- KODP (2012). Rural and Urban Population Census: 2009. Date accessed 2014-02-17, <http://opendata.go.ke/Population/2009-Census-Vol-1-Table-3-Rural-and-Urban-Population/e7c7-w67t>
- KV2030 (2007). Kenya Vision 2030: Popular version. Nairobi, 32p. website: [http://www.vision2030.go.ke/cms/vds/Popular\\_Version.pdf](http://www.vision2030.go.ke/cms/vds/Popular_Version.pdf).

Lelieveld, J., Evans, J. S., Fnais, M., Giannadaki, D. and Pozzer, A. (2015). The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature* 525(7569): 367-371. DOI: 10.1038/nature15371,

Lindén, J., Boman, J., Holmer, B., Thorsson, S. and Eliasson, I. (2012). Intra-urban air pollution in a rapidly growing Sahelian city. *Environ. Int.* 40(0): 51-62. DOI: <http://dx.doi.org/10.1016/j.envint.2011.11.005>,

Lioussé, C., Assamoi, E., Criqui, P., Granier, C. and Rosset, R. (2014). Explosive growth in African combustion emissions from 2005 to 2030. *Environmental Research Letters* 9(3): 035003.

Lioussé, C., Cachier, H. and Jennings, S. G. (1993). Optical and thermal measurements of black carbon aerosol content in different environments: Variation of the specific attenuation cross-section, sigma ( $\sigma$ ). *Atmospheric Environment. Part A. General Topics* 27(8): 1203-1211. DOI: [http://dx.doi.org/10.1016/0960-1686\(93\)90246-U](http://dx.doi.org/10.1016/0960-1686(93)90246-U),

Liu, X. D., Dong, S. P., Van Espen, P., Adams, F., Cafmeyer, J. and Maenhaut, W. (2000). Size and chemical characterization of atmospheric aerosol and savanna fire samples in Southern Africa. *Journal of Aerosol Science* 31, Supplement 1(0): 186-187. DOI: [http://dx.doi.org/10.1016/S0021-8502\(00\)90193-9](http://dx.doi.org/10.1016/S0021-8502(00)90193-9),

Markowicz, A., Haselberger, N., Dargie, M., Tajani, A., Tchantchane, A., Valkovic, V. and Danesi, P. R. (1996). Application of X-ray fluorescence spectrometry in assessment of environmental pollution. *Journal of Radioanalytical and Nuclear Chemistry* 206(2): 269-277. DOI: 10.1007/BF02039653,

Mason, B. (1966). Principles of Geochemistry. New York, USA, John Wiley & Sons. pp: 45-48.

Matassoni, L., Pratesi, G., Centioli, D., Cadoni, F., Lucarelli, F., Nava, S. and Malesani, P. (2011). Saharan dust contribution to PM<sub>10</sub>, PM<sub>2.5</sub> and PM<sub>1</sub> in urban and suburban areas of Rome: a comparison between single-particle SEM-EDS analysis and whole-sample PIXE analysis. *Journal of Environmental Monitoring* 13(3): 732-742. DOI: 10.1039/C0EM00535E,

McMurry, P. H. (2000). A review of atmospheric aerosol measurements. *Atmospheric Environment* 34(12): 1959-1999. DOI: [http://dx.doi.org/10.1016/S1352-2310\(99\)00455-0](http://dx.doi.org/10.1016/S1352-2310(99)00455-0),

Mkoma, S. L., Chi, X. and Maenhaut, W. (2010). Characteristics of carbonaceous aerosols in ambient PM<sub>10</sub> and PM<sub>2.5</sub> particles in Dar es Salaam, Tanzania. *Sci. Total Environ.* 408(6): 1308-1314. DOI: <http://dx.doi.org/10.1016/j.scitotenv.2009.10.054>,

Moffet, R. C., Desyaterik, Y., Hopkins, R. J., Tivanski, A. V., Gilles, M. K., Wang, Y., Shutthanandan, V., Molina, L. T., Abraham, R. G., Johnson, K. S., Mugica, V., Molina, M. J., Laskin, A. and Prather, K. A. (2008). Characterization of aerosols containing Zn, Pb, and Cl from an industrial region of Mexico City. *Environ Sci Technol* 42(19): 7091-7097.

MoNMD (2008). A World Class African Metropolis – Building a Safe, Secure and Prosperous Metropolitan. Nairobi, Ministry of Nairobi Metropolitan Development, website: <https://fonnap.files.wordpress.com/2011/09/metro2030-strategy.pdf>.

Moosmüller, H., Chakrabarty, R. K. and Arnott, W. P. (2009). Aerosol light absorption and its measurement: A review. *J. Quant. Spectrosc. Ra.* 110(11): 844-878. DOI: <http://dx.doi.org/10.1016/j.jqsrt.2009.02.035>,



NEMA (2014). Draft Air Quality Regulation, 2008. Nairobi, National Environment Management Authority Kenya, website: <http://www.nema.go.ke/images/Docs/Regulations/Air%20Quality%20Regulations-3.pdf>.

Ngo, N. S., Gatari, M., Yan, B., Chillrud, S. N., Bouhamam, K. and Kinney, P. L. (2015). Occupational exposure to roadway emissions and inside informal settlements in sub-Saharan Africa: A pilot study in Nairobi, Kenya. *Atmos. Environ.* 111: 179-184. DOI: <http://dx.doi.org/10.1016/j.atmosenv.2015.04.008>,

Norris, G., Vedantham, R., Wade, K., Brown, S., Prouty, J. and Foley, C. (2008). EPA Positive Matrix Factorization (PMF) 3.0 Fundamentals & User Guide. EPA/600/R-08/108. Washington D.C., U.S. Environmental Protection Agency.

Owen, K. (1989). Gasoline and diesel additives. Critical Reports on Applied Chemistry. 25, Chester.

Paatero, P. (1997). Least squares formulation of robust non-negative factor analysis. *Chemometr. Intell. Lab.* 37(1): 23-35. DOI: [http://dx.doi.org/10.1016/S0169-7439\(96\)00044-5](http://dx.doi.org/10.1016/S0169-7439(96)00044-5),

Peel, M. C., Finlayson, B. L. and McMahon, T. A. (2007). Updated world map of the Köppen-Geiger climate classification. *Hydrol. Earth Syst. Sc.* 11(5): 1633-1644. DOI: 10.5194/hess-11-1633-2007,

Petkova, E. P., Jack, D. W., Volavka-Close, N. H. and Kinney, P. L. (2013). Particulate matter pollution in African cities. *Air Qual. Atmos. Health* 6(3): 603-614. DOI: 10.1007/s11869-013-0199-6,

Pope, C. A., 3rd, Burnett, R. T., Thun, M. J., Calle, E. E., Krewski, D., Ito, K. and Thurston, G. D. (2002). Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *Jama* 287(9): 1132-1141.

Pöschl, U. (2005). Atmospheric Aerosols: Composition, Transformation, Climate and Health Effects. *Angewandte Chemie International Edition* 44(46): 7520-7540. DOI: 10.1002/anie.200501122,

RIVM (2002). Multiple Path Particle Dosimetry Model (MPPD v 1.0): A Model for Human and Rat Airway Particle Dosimetry. RIVA Report 650010030, Bilthoven, The Netherlands, National Institute for Public Health and the Environment, website: <https://www.ara.com/products/multiple-path-particle-dosimetry-model-mppd-v-304>.

Ryan, P. H., Brokamp, C., Fan, Z. H. and Rao, M. B. (2015). Analysis of Personal and Home Characteristics Associated with the Elemental Composition of PM<sub>2.5</sub> in Indoor, Outdoor, and Personal Air in the RIOPA Study. *Res Rep Health Eff Inst*(185): 3-40.

Salon, D. and Aligula, E. M. (2012). Urban travel in Nairobi, Kenya: analysis, insights, and opportunities. *Journal of Transport Geography* 22: 65-76. DOI: <http://dx.doi.org/10.1016/j.jtrangeo.2011.11.019>,

Shaltout, A. A., Boman, J., Shehadeh, Z. F., Al-Malawi, D.-a. R., Hemeda, O. M. and Morsy, M. M. (2015). Spectroscopic investigation of PM<sub>2.5</sub> collected at industrial, residential and traffic sites in Taif, Saudi Arabia. *Journal of Aerosol Science* 79(0): 97-108. DOI: <http://dx.doi.org/10.1016/j.jaerosci.2014.09.004>,

Shaltout, A. A., Boman, J., Welz, B., Castilho, I. N. B., Al Ashkar, E. A. and Gaita, S. M. (2014). Method development for the determination of Cd, Cu, Ni and Pb in PM<sub>2.5</sub> particles sampled in industrial and urban areas of Greater Cairo, Egypt, using high-resolution continuum source graphite furnace atomic absorption spectrometry. *Microchemical Journal* 113(0): 4-9. DOI: <http://dx.doi.org/10.1016/j.microc.2013.10.009>,

Sietchiping, R., Permezel, M. J. and Ngomsi, C. (2012). Transport and mobility in sub-Saharan African cities: An overview of practices, lessons and options for improvements. *Cities* 29(3): 183-189. DOI: <http://dx.doi.org/10.1016/j.cities.2011.11.005>,

Speck, H. (1981). Soil map of the Mount Kenya Area. Switzerland, Department of Geography, University of Berne, Switzerland. <http://h05-prod-vm15.jrc.it/content/soil-map-mount-kenya-area>.

Tiitta, P., Vakkari, V., Croteau, P., Beukes, J. P., van Zyl, P. G., Josipovic, M., Venter, A. D., Jaars, K., Pienaar, J. J., Ng, N. L., Canagaratna, M. R., Jayne, J. T., Kerminen, V. M., Kokkola, H., Kulmala, M., Laaksonen, A., Worsnop, D. R. and Laakso, L. (2014). Chemical composition, main sources and temporal variability of PM1 aerosols in southern African grassland. *Atmos. Chem. Phys.* 14(4): 1909-1927. DOI: 10.5194/acp-14-1909-2014,

TransportPolicy.net (2016). India: Fuels: Diesel and Gasoline. Date accessed 2016-07-18, 2016, <http://transportpolicy.net/index.php?title=India: Fuels: Diesel and Gasoline>.

UN-HABITAT (2006). Nairobi urban sector profile. Nairobi, United Nations Human Settlements Programme, 36p. website: <http://unhabitat.org/books/kenya-nairobi-urban-profile/>.

UNDESA (2015). World Urbanization Prospects: The 2014 Revision. ST/ESA/SER.A/366, New York, United Nations, website: <http://esa.un.org/unpd/wup/Publications/Files/WUP2014-Report.pdf>.

UNEP (2012). Urban Air Pollution. Date accessed 13 Nov, 2012, [http://www.unep.org/urban\\_environment/issues/urban\\_air.asp](http://www.unep.org/urban_environment/issues/urban_air.asp).

UNEP (2014). Diesel Fuel Sulphur Levels: Global Status April 2014. Nairobi, United Nations Environmental Programme, website: <http://www.unep.org/transport/pcf/PDF/kenya500ppm.pdf>.

United Nations (2015). Transforming our world: the 2030 agenda for sustainable development. Seventieth General Assembly, New York, 15 September–2 October. Resolution A/RES/70/1, New York, United Nations.

WHO (2005). WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide. WHO/SDE/PHE/OEH/06.02, Geneva, Switzerland, World Health Organization, 22p.

WHO (2014a). Indoor Air Pollution, Health and the Burden of Disease. Geneva, World Health Organization.

WHO (2014b). 7 million premature deaths annually linked to air pollution. 11th November, 2014, Geneva, World Health Organization.

Villeneuve, P. J., Goldberg, M. S., Krewski, D., Burnett, R. T. and Chen, Y. (2002). Fine Particulate Air Pollution and All-Cause Mortality within the Harvard Six-Cities Study: Variations in Risk by Period of Exposure. *Ann. Epidemiol.* 12(8): 568-576. DOI: [http://dx.doi.org/10.1016/S1047-2797\(01\)00292-7](http://dx.doi.org/10.1016/S1047-2797(01)00292-7),

Winter-Sorkina, R. d. and Cassee, F. R. (2002). From concentration to dose: factors influencing airborne particulate matter deposition in humans and rats. The Netherlands, National Institute of Public Health and the Environment (RIVM), website: <http://www.rivm.nl/bibliotheek/rapporten/650010031.pdf>.

WMO (2013). The Global Climate 2001-2010: A decade of climate extremes. 1103, Geneva, World Meteorological Organization, 61p. website: [http://library.wmo.int/pmb\\_ged/wmo\\_1103\\_en.pdf](http://library.wmo.int/pmb_ged/wmo_1103_en.pdf).

Zhang, L. and Yu, C. P. (1993). Empirical Equations for Nasal Deposition of Inhaled Particles in Small Laboratory Animals and Humans. *Aerosol Sci. Technol.* 19(1): 51-56. DOI: 10.1080/02786829308959620,

Zhang, Y.-L. and Cao, F. (2015). Fine particulate matter (PM<sub>2.5</sub>) in China at a city level. 5: 14884. DOI: 10.1038/srep14884,