SPATIAL-TEMPORAL VARIATION OF PARTICULATE MATTER LESS THAN 2.5 MICRONS (PM$_{2.5}$) CONCENTRATION IN KIGALI

SAFARI KAGABO Abdou

College of science and technology

School of Science

Master of Science in Atmospheric and Climate Science

2018

UNIVERSITY OF RWANDA

SPATIAL-TEMPORAL VARIATION OF PARTICULATE MATTER LESS THAN 2.5 MICRONS (PM$_{2.5}$) CONCENTRATION IN KIGALI

By

SAFARI KAGABO Abdou

Registration Number: 217290884

A dissertation submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN ATMOSPHERIC AND CLIMATE SCIENCE

In the College of Science and Technology

Supervisors: **Prof. Bonfils Safari & Dr. Jimmy Gasore**

August, 2018

Declaration

I declare that this Dissertation contains my own work except where specifically acknowledged.

SAFARI KAGABO Abdou   Reg. Number: 217290884

Signed…………………………………………..

Date…………………………………………..

ACKNOWLEDGEMENTS

I would like to take this opportunity to express my sincere gratitude to those who have significantly facilitated the completion of this thesis. First of all, my thanks go to Prof. Bonfils Safari and Dr. Jimmy Gasore, my supervisors, for all the assistance and constructive advice and comments that have provided throughout this work. My thanks also extend to the University of Rwanda which granted me a postgraduate scholarship that made possible this research.

My thanks go also to Dr. R. Subramanian and Prof. Paulina Jaramillo from the Carnegie Mellon University who provided and supported in the building and installation of all instruments used in this thesis. My thanks are also to my colleagues in air quality students' team for their help and patience. In addition, I wish to thank all the participants of the study for their help and cooperation.

One can never adequately thank everyone who played a role in the completion of this dissertation. Completing this dissertation would not have been easy without the support, cooperation, heartfelt kindness, and guidance from my parents who introduced me to this world of school, my family, my classmates and all my friends. I will always cherish the love and encouragement around you.

ABSTRACT

In our study, $PM_{2.5}$ concentration data of two monitoring sites in Kigali were collected continuously from 06th of July 2017 to 31st of May 2018. These data were used to investigate the diurnal, seasonal and day of week characteristics of $PM_{2.5}$ in Kigali. Special days and meteorological parameters were also studied for their contribution to the variation of $PM_{2.5}$ levels in Kigali. Observations of hourly $PM_{2.5}$ showed a distinct diurnal, seasonal, and day of week patterns. The diurnal variations of $PM_{2.5}$ were observed with higher concentration at night than daytime, with the peak in the morning between 6:00 am and 8:00 am exactly during the rush hour. The lowest values appeared in the late afternoon between 4pm and 5pm. The probable reason of the higher concentrations at night is the built up of particles under inversion conditions and/or atmospheric stability. The reduction in traffic volume in the afternoon, dilution of aerosols associated with the deeper Planetary Boundary Layer depth and higher wind speed are responsible of the lowest values in afternoon hours. Regardless of the month or weather conditions, $PM_{2.5}$ concentrations across the city are significantly lower on Saturdays and Sundays and high on the other days of the week. This comes from the decrease in human activities, and implementation of the Umuganda and Car free days on weekends. The observed facts indicate that the variations of $PM_{2.5}$ concentrations are also influenced by meteorological factors such as high wind speed and abundant rainfall that played a big role in reduction of $PM_{2.5}$ levels in wet seasons compared to the dry seasons.

KEY WORDS

Air pollution is contamination of the indoor or outdoor environment by any chemical, physical or biological agent that modifies the natural characteristics of the atmosphere (WHO definition).

Particulate matter (PM) known also as atmospheric particles or aerosols are defined as a suspension of fine solid or liquid particles in a gaseous medium.

PM$_{2.5}$: PM$_{2.5}$ air pollution is a heterogeneous mixture of particles less than 2.5 micrometers (PM<2.5 μm) in aerodynamic diameter.

LIST OF ACRONYMS AND SYMBOLS

AC: Alternating Current

AT: Average Temperature

BC: Black Carbon

CAPS: Centre for Atmospheric Particle Studies (CAPS)

CMU: Carnegie Mellon University

CST: College of Science and Technology

DJF: December January February

IR: Infrared

ITCZ: Inter-Tropical Convergence Zone

JJA: June July August

MAM: March April May

NISR: National Institute of Statistics of Rwanda

PBL: Planetary Boundary Layer

PM: Particulate matter

PM_{10}: Particulate Matter 10 micrometers or less in diameter

$PM_{2.5}$: Particulate matter 2.5 micrometers or less in diameter

r: Correlation coefficient

RAMP: Real-time, Affordable, Multi-Pollutant

REMA: Rwanda Environment Management Authority

RH: Relative Humidity

RNFL: Rainfall

SDGs: Sustainable Development Goals

SON: September October November

SSA: Sub-Saharan African

STD: Standard Deviation

T: Temperature

UR: University of Rwanda

US EPA: The United States Environmental Protection Agency

VOC_S: Volatile organic compounds

WD: Wind Direction

WHO: World Health Organization

WS: Wind Speed

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

GENERAL INTRODUCTION

INTRODUCTION

a. Background

Rwanda, an equatorial African country commonly referred to us as the land of thousand hills, is a landlocked country located within the equatorial belt. It is situated exactly in central east Africa between latitude 1°4' and 2°51' South and between longitude 28°45' and 31°15 East (Figure1).

Rwanda is surrounded by four neighboring countries: Uganda to the north, Tanzania to the East, Burundi to the south and the Democratic Republic of Congo to the west. Its total area is 26,338 km^2 with land occupying 24,666 km^2, while the rest occupied by water[1]. The Rwanda's altitude ranges between 900 and 4,507 m over a territory of about 400 km wide[1]. The average annual temperature ranges between 16°C and 20°C, without significant variations. Rainfall is generally abundant even if it has some irregularities. Despite of being located in the tropical belt, Rwanda experiences a temperate climate as a result of its high elevation. Winds are generally around 1-3 m/s[2].

Rwanda experiences a bimodal pattern of rainfall, which is driven primarily by the progression of the Inter-Tropical Convergence Zone (ITCZ). The ITCZ sees the convergence of the rain bringing Atlantic westerlies, Indian Ocean easterlies and the dry north-east and south-east monsoon winds. It follows the annual progression of the sun as it goes to the Northern Summer solstice about June 23, and the Southern Summer solstice about December 23 each year. The long rains occur over March, April and May (MAM) and the short rains occur in September October and November(SON) [3][4].

The capital, Kigali, is located at Rwanda's geographical heart at 1,500 meters above sea level. According to Rwanda Meteorology Agency, Kigali receives 950 mm (37.5 in) of rain per year, with a maximum in April, and a minimum from June to August, when it almost never rains. Temperatures are stable all year round, and hover around 26-27 °C (79-81 °F) during the day and 15-16 °C (59-61 °F) at night.

Rwanda is witnessing rapid economic growth and development, effectuated by its political stability and progressive policies. Kigali (1°57`S, 30°04`E), the capital of Rwanda, has a fast growing population where the city counted approximately 1,318,000 inhabitants in 2015 (NISR, 2015). Kigali, the rapidly growing city is not only the capital city, but also the country's most important business center and main port of entry. According to the Community Based Climate Change Adaptation survey report of 2014, in Rwanda, 20% of the population lives in urban areas, and 44% of those are in the capital city, Kigali.

This rising population followed by the significant growth in different economical activities of the city and rising in different pollutants produced for example by a extensive usage rate of mopeds, burning woods for cooking, agricultural burning, kerosene lightning, unpaved roads, industries etc… are some of the causes of a perpetual degradation of the urban air quality in Kigali.

b. Problem statement

In the developing world, People are commonly exposed to very high levels of pollution for 3–7 hours or more daily over many years[5]. In these countries air pollution presents a particular threat to the health in cities that are growing in a fast, poorly planned, and unregulated manner[6]. The World Health Organization (WHO) ranks indoor air pollution and urban outdoor air pollution 10th and 14th, respectively, among 19 leading risk factors for global mortality [7] **.**

 Air pollution from gases and particles emitted for example by industry, transport, and indoor air pollution is becoming a significant problem in developing cities such as Kigali that has an average annual population growth rate of 4.0%[8].

Transport represents the fastest growing source of emissions[9]. The increasing number of motor vehicles poorly maintained, aged mopeds, or any other types of vehicles cause an increasing concentration of different air pollutants in Rwanda and particularly in Kigali[10]. That may be a major source of toxic air pollution because these vehicles use petroleum and diesel [11].

Kigali also is situated in the central highlands of Rwanda, the main business and residential districts as well as the governmental quarters are on top of the ridges, which are enclosed by small valleys. These former marsh and wetlands are not only the largest residential area, but

there are also large parts of subsistence farming [10]. Topographical and meteorological conditions could have a very strong influence on the spatial distribution of air quality in the city like Kigali [12].

There has been a limited number of studies and not founded on solid scientific evidence on air quality over Rwanda specifically Kigali because of the insufficient related information on this area. Comprehensive measures to reduce the increasing air pollution and its human health effects are needed. It is expected that this study will increase the knowledge on Particulate matter less than 2.5 microns (PM$_{2.5}$) variability on daily basis, as one of the pollutants we have in Kigali City and its levels compared to the various international standards.

c. Objectives

The main objective of this study is to determine the **Spatial and temporal variation of particulate matter less than 2.5 microns (PM$_{2.5}$) concentration in Kigali.**

To achieve the main objective, the following specific objectives will be pursued:

- ✓ To assess the relation between day and night concentrations of PM$_{2.5}$ in different selected areas of Kigali.

- ✓ To determine the temporal variability of particulate matter less than 2.5 microns (PM$_{2.5}$) concentration over Kigali city during the July-August and December-February (dry seasons), and September-November and March-May (Rain seasons).

- ✓ To assess the variability of PM$_{2.5}$ over Kigali during the week days, weekends and the special days like Community work days (Umuganda) and Car Free days.

- ✓ To analyze and provide the contribution of Black Carbon (BC) to the variation of PM$_{2.5}$ levels.

d. Hypothesis of the Study

Based on the location, meteorological conditions, development and anthropogenic activities of Kigali city with reference to the previous studies and reports, in this research we expect that Particulate matter less than 2.5 microns concentrations in Kigali will vary significantly with two opposite times: Day and Night, weekdays and weekends, dry and rainy season….

e. Scope of the study

Our study concerns only Air quality; it is focused on **Spatial and temporal variation of particulate matter less than 2.5 microns** (PM$_{2.5}$**) concentration in Kigali**. The main data were collected from the different instruments located at UR/CST and Gacuriro for further analysis.

CHAPTER 1: LITERATURE REVIEW ABOUT POLLUTANTS

1.1.BRIEF HISTORY OF AIR POLLUTION

Air pollution is a major environmental problem and it comes in a variety of forms, from visible particles of soot or smoke to invisible gases such as sulfur dioxide and carbon monoxide, and it can be created indoors and outdoors[13].We may think of air pollution as a modern problem, but it is a major problem that has been recognized throughout the world for hundreds of years and its concerns have a long history[14][15].

Indoor air pollution was responsible for several kinds of illnesses in the early times[16]. Scientific studies of samples of mummified lung tissues from different countries have revealed that ancient societies suffered from anthracosis associated with domestic pollution[17]. Smoke from Plant products have been used traditionally to repel and kill mosquitoes in many parts of the world.[18] But poor domestic air quality with concentrations of harmful particulates high in cramped conditions undoubtedly increased the risk of illness and death from chronic respiratory diseases. Complaints about air pollution effects on human health and the built environment were first voiced by the citizens of ancient Athens and Rome, where air pollution was known as *gravioris caeli* (heavy heaven) or *infamis aer* (infamous air), and it could be both a blessing and a curse[13][14].

 Later, in the big coal and steel cities like Manchester, England and Pittsburgh, USA, smoke was an indicator of wealth but also a public health problem. In the late 18th century, the Industrial Revolution, beginning in the European countries, led to escalation in pollutant emissions based around the use of coal by both homes and industry[14][15].

 One of the air pollution disasters known in the history is the Great Smog of 1952; the city of London was brought to a standstill by a dense blanket of toxic smog that reduced visibility to a few feet. For five cold December days, a heavy fog combined with sulphurous fumes from coal fires, vehicle exhaust and power plants, blocking out the sun and creating a public health disaster. The "Big Smoke" was the worst air pollution crisis in European history, killing an estimated 8,000 to 12,000 people[19]. Air pollution from human activities began long before the

Industrial Revolution but in more recent times, pollution from for example motor vehicles and industries, has become the most recognized air quality issue. Present pollution monitoring is revealing that if we do not think and act cautiously, pollution could harm the environment in which we live and reduce the quality of life for future generations[20]. Today in developing nations around the globe some three billion people use cookstoves that burn solid fuels, which create indoor air pollution that leads to millions of premature deaths each year[21].

1.2. INTRODUCTION TO AIR POLLUTANTS

Air pollution is contamination of the indoor or outdoor environment by any chemical, physical or biological agent that modifies the natural characteristics of the atmosphere **(WHO definition).** The pollutant source includes automobile exhausts, soil-fuel burning, cooking/smoking, erosion of roads and many more. Hazardous air pollutants or toxic air contaminants refer to any substances that may cause or contribute to an increase in mortality or in serious illness, or that may pose a present or potential hazard to human health. Pollutants of major public health concern include particulate matter, carbon monoxide, ozone, nitrogen dioxide and sulfur dioxide[22][23].

Air pollution is now clearly recognized as an important global risk factor for disease. Long time of research conducted in various cities throughout the world show that when air pollution levels increase, so do the numbers of people dying[6] [24]. More important, studies of long term exposure to air pollution demonstrate that people living in more polluted locations die prematurely, compared to those living in areas with lower levels of pollution[25][26]. More than 80% of people living in urban areas that monitor air pollution are exposed to air quality levels that exceed the World Health Organization (WHO) limits[27][28]. Even if all regions of the world are affected, populations in low income cities are the most impacted. According to the 2016 urban air quality WHO database, 98% of cities in low and middle income countries with more than 100 000 inhabitants do not meet WHO air quality guidelines[27].
In Africa, air pollution remains a major challenge. About 600,000 deaths every year across the continent are associated with this invisible killer[29].

Air quality in sub Saharan Africa (SSA) cities including Kigali, has deteriorated owing to rapid population growth and industrial expansion in these areas. Air pollution emitted in Africa comes from four sources, mainly biomass burning, natural emission from vegetation and soil, lightning NO_x emissions, and other anthropogenic sources such as emissions related to the combustion of fossil fuel for energy, industrial, transport and domestic uses[30].

Air quality in SSA cities is of great attention; for example, from (Brauer et al, 2012) some of the highest fine particles levels in the world have been recorded in cities of SSA and other developing regions. $PM_{2.5}$ concentrations in SSA cities has been estimated at around 100 µg/m^3 compared to <20 µg/m^3 in most European and North American cities.[30][31] Unfortunately, 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[32].

1.3. PARTICULATE AIR POLLUTANTS AND BLACK CARBON

1.3.1. PM classification, formation and sources

Particulate matter (PM) known also as atmospheric particles or aerosols are defined as a suspension of fine solid or liquid particles in a gaseous medium. PM Contents cover a big range of substances from inorganic ions, elemental carbon, metallic, organic, and crustal compounds.[33] Atmospheric aerosols can be classified either by their size or their source. They consist of particles ranging in size from a few tens of angstroms (A) to several hundred micrometers.[22], particulate matters that are larger than 2.5 micrometers and smaller than 10 micrometers in diameter are defined as coarse and denoted by PM_{10}, while particles that are smaller than 2.5 micrometers in diameter are defined as fine particles and indicated by $PM_{2.5}$. Coarse and fine particles have totally different physical and chemical properties[22][34].
The source of aerosols classifies them as primary and secondary particles[35]. Primary particles are those that generated from anthropogenic sources and emitted directly to the atmosphere from four main source categories: fuel combustion, industrial processes, nonindustrial fugitive sources

and transportation sources[22]. These particles are mainly found in urban areas[36]. but $PM_{2.5}$ particles are produced mostly through combustion[37].

Secondary atmospheric particles are particulates that formed in the atmosphere by gas to particles conversion processes[38]. they are formed in the air through chemical reactions of gaseous pollutants[33]. and they are produced from atmospheric transformation of nitrogen oxides(NOx), volatile organic compounds (VOC_S), sulfur dioxide (SO_2) and ammonia (NH_3)[39][40]. The sources of SO_2 and NO_x are the combustion of sulfur containing fuel and fossil fuel combustion while Ammonia is mainly emitted by agricultural activities[41]. Secondary atmospheric particles are mostly found in $PM_{2.5}$[39], Figure 1.1 shows various sources of emission of primary and secondary atmospheric particles. Globally, Particulate matters are considered as one of the most challenging problems for air quality, health and for climate change policies.

1.3.2. Physical and chemical characteristics of airborne particulate matter

Airborne particulates may be a complex mixture of organic and inorganic substances [42]. They are characterized by their physical attributes and their chemical composition[43].

There are various physical attributes of airborne particulates that are important to their role in atmospheric process; those include mass concentration which is measured in micrograms per cubic meter ($\mu g/m^3$), number concentrations, surface area and size distribution[44]. The size distribution is considered as the most important parameter for characterizing the behavior of aerosols[45], and reflects the nature of source of the particles and relates to their health effects including to their aesthetic and climatic effects via their light scattering properties. It is usually measured in aerodynamic diameter which is defined as the diameter of the spherical particle with a density of 1000 kg/m^3 that has the same settling velocity as the particle being measured[46].

Particulate matters have also a very diverse chemical composition which varies especially with the particle size. The chemical composition of particulate matter includes sulfates, nitrates, ammonium, organic material, crustal species, seasalt, metal oxides, hydrogen ions, and water[47]. From these species, sulfate, ammonium, organic and elemental carbon, and certain

transition metals are found predominantly in the fine particles[48]. Crustal materials, including silicon, calcium, magnesium, aluminum, and iron, and biogenic organic particles are usually in the coarse aerosol fraction. Nitrate can be found in both the fine and coarse modes. Fine nitrate is usually the result of the nitric acid/ammonia reaction for the formation of ammonium nitrate, while coarse nitrate is the product of coarse particle/ nitric acid reactions[22][45].

1.3.3. Health and environmental effects of PM

Anthropogenic emissions especially in developing countries leading to atmospheric aerosol production have dramatically increased over the past decades and have significant negative impacts on health and environment[35]. Airborne particulate matter has now become an issue in the global environment due to the health problems and environmental degradation it causes[49]. Recently, there is convincing evidence that current levels of Particulate matter have become a serious issue on both health and environment[39].

Exposure to PM has been identified as the cause of numerous health effects including but not limited to the increased hospital admissions, lung cancer, respiratory symptoms, exacerbation of chronic respiratory and cardiovascular diseases, decreased lung function, and premature mortality[50][51][52].

Various studies on air pollution effects have indicated a strong relationship between particulate matter size and harmful health effects. Exposure to both fine and coarse particles is associated with a number of harmful health effects, particularly those involving the heart and lungs.[53] In general, the size of the particles is directly linked to their potential for causing health problems. $PM_{2.5}$ are most dangerous as they can easily get deep into the lungs and can also enter the circulatory system or remain embedded for long periods[54].

Particulate matters have not only health effects but also the environmental ones. The presence of aerosols especially the fine particulate matter is a key component of our atmosphere that plays an important role in driving the climate. As their origin is the anthropogenic emissions mixed with natural dust particulates, their presence changes the optical properties of the air and, therefore,

changes how the atmosphere absorbs or disperses the solar radiation which contributes to the global warming[55]. This usually causes the variation of the atmospheric temperature. In addition, these finest PM can be circulated by the wind on time scales of days and then settle on ground or water. This settling causes many effects that result to the global climate problems[56].

1.3.4. Spatial and temporal variation of PM

The concentration of atmospheric aerosols varies significantly in space and time, and this variability is determined by meteorology, the emissions of aerosols and their precursors, their size and shape and their chemical properties. Particulate matter varies from location to the other but the urban areas are the most sensitive to have high concentration of pollutants including particulate matter compared to the rural areas. This is due to the various anthropogenic activities usually found mostly in urban regions. On the other hand, PM concentrations changes with time of the day, with season and with change in meteorological conditions. For example for the species with strong local sources, the daily concentration pattern is often determined by the strength of atmospheric mixing. The atmospheric mixing height tends to be lower during the nighttime, so these species often reach high concentrations very early in the morning, peaking during the early stages of rush hour traffic at around 6 am. During the afternoon rush-hour, even if the traffic emissions are similar to those in the morning, the concentrations are considerably lower because they are diluted over a much larger boundary layer volume. These diurnal variations can be used to determine the importance of local emissions[22][57][58].

1.3.5. Black Carbon and its damaging effects

Black Carbon (BC) also known as soot is a carbonaceous aerosol emitted in the atmosphere as the residual of incomplete combustion processes in industrial flames, car combustion engine, domestic heating systems, and natural fires[59]. BC is a component of $PM_{2.5}$ and is an operationally defined term which describes carbon as measured by light absorption. Studies of short-term health effects show that the associations with BC are more robust than those with

PM$_{2.5}$ or PM$_{10}$, suggesting that BC is a better indicator of harmful particulate substances from combustion sources especially traffic than undifferentiated PM mass[60]. Exposures to fine particles including black carbon, can cause premature death and harmful effects on the cardiovascular system[61].

1.4. PARTICULATE MATTER LESS THAN 2.5 MICRONS (PM$_{2.5}$)

1.4.1. PM$_{2.5}$ composition and sources

PM$_{2.5}$ air pollution is a heterogeneous mixture of particles less than 2.5 micrometers (PM<2.5 µm) in aerodynamic diameter, and like other pollutants as stated before, PM$_{2.5}$ is generated by both anthropogenic and natural sources. Human-made sources of PM$_{2.5}$ are more important in contribution to the total concentration. Therefore, levels of PM$_{2.5}$ close for example to roadsides and industrial areas are often much higher than those in background locations[62]. In addition to these primary emissions of particles, PM$_{2.5}$ can also be formed from the chemical reactions of gases as secondary particles such as sulphur dioxide (SO$_2$) and nitrogen oxides (NO$_x$)[63]. According to the Environmental Protection Agency (EPA), depending on several factors including weather and particle size, PM$_{2.5}$ can remain suspended in the atmosphere from minutes to weeks and can travel up to thousands of kilometers.

Constituents of atmospheric aerosols can be differentiated as inorganic and organic portions according to their chemical properties[64]. Organic Carbon is a mixture of different carbon compounds and can be generated by several sources of PM$_{2.5}$, including combustion processes such as vehicular traffic and vegetative burning (EPA, 1999), while ammonium, nitrate, and sulfate are the Major secondary inorganic particles found in PM$_{2.5}$[65]. Sulfate and nitrate are formed mostly from oxidation of sulfur dioxide and nitrogen dioxide respectively[66].

1.4.2. Human exposure to PM$_{2.5}$

Particulate matters less than 2.5 microns which are suspended in the atmosphere with an aerodynamic diameter no more than 2.5 microns, is known as a serious environmental concern due to its significant adverse effects on human health, climate biogeochemical cycle, and atmospheric chemistry[67][68][69]. It has been shown that fluctuations in concentrations of ambient Particulate matter measured at an outdoor monitoring station represent the fluctuations in exposure to ambient PM of all the people in the area surrounding the monitoring station[70]. The association between the PM$_{2.5}$ and various health indicators can be influenced by many factors such as location factors like topography and local sources; meteorology; housing characteristics; individual differences in activity and personal habits[71].

CHAPTER 2: METHODOLOGY

2.1. STUDY DESIGN

2.1.1. Sampling locations

Measurements were made from July 6, 2017 at the University of Rwanda College of Science and Technology (UR-CST) Nyarugenge campus ($1^o57'42''S$, $30^o03'53''E$). The instruments at UR-CST are located on top of the building that is on top of the mountain. They are open to the air coming from different parts of Kigali central city. This site has been chosen because of the various activities always found here, such as substantial business activities, high volume of traffic, restaurants, school kitchens and some industries. The instrument at Gacuriro is situated at one of the households ($1^o55'32''S$, $30^o05'33''E$) and is open for the nearest environment. Because of the most activities done at Gacuriro (considered as a residential area) are the home activities, it was chosen as a good comparison to UR-CST station that has almost incompatible characteristics.

2.1.2. Experimental methods

Daily changes of Particulate matter less than 2.5 microns (PM$_{2.5}$), Average Temperature (AT) and Relative Humidity (RH) data were collected from **the Real-time, Affordable, Multi-Pollutant (**RAMP) monitors located at UR-CST and Gacuriro residential area. Data on Black Carbon concentrations were collected from BC monitor based at UR-CST. Rainfall, Solar radiation, Wind Speed (WS) and Wind Direction (WD) data were collected from Rwanda meteorology Agency (Meteo Rwanda) Kigali stations.

 In our research we have used following instruments for sampling various pollutants and related softwares to analyze them. The air quality monitors and the softwares for their analysis are:

2.1.2.1. *The Real-time, Affordable, Multi-Pollutant (RAMP) Sensor*

The Real-time, Affordable, Multi-Pollutant (RAMP) air quality monitor was developed by Carnegie Mellon University's Center for Atmospheric Particle Studies (CAPS) and SenSevere, a company that produces sensors for different severe environments. RAMP measures carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3), and fine particulate mass ($PM_{2.5}$)[72].

The RAMP monitor must be equipped with sim cards to transmit data using cellular networks to an online server. The RAMP monitors also log data to an SD card as a fail-safe in case of wireless data transfer issues. The RAMP is paired with a Met-One Neighborhood PM monitor to measure optical $PM_{2.5}$ (Figure 2.1). In later situation, it requires 120-240V alternating current (AC) power [73].

The RAMP monitors are either mounted to a steel plate for easy pole mounting or are deployed on tripods approximately 1.5 m above the ground. In this study, all the RAMP monitors were mounted at a consistent height.

The RAMP monitors log two output signals from each of the Alphasense sensors: one from the auxiliary electrode and the other from the working electrode. The net sensor response is determined by subtracting the auxiliary electrode signal from that of the working electrode.

2.1.2.2. BC 1054 Multispectrum Black Carbon Monitor

The BC 1054 Multispectrum Black Carbon Monitor is a Met One instrument manufactured in the United States. It provides a reliable, cost effective solution for generation of high time resolution data at 10 wavelengths for use in the Air quality surveillance, Global warming studies, Particulate emissions studies, Visibility studies etc…. [74].

BC 1054 Multispectrum Black Carbon Monitor measures the absorption of particulate matter onto filter tape continuously and operates at 10 different wavelengths ranging from the near-UV to the near-IR. It also measures the absorption and the transmittance of light across filter media onto which particulate matter is accumulating and in real-time calculates the black-carbon "BC" concentrations at 370, 430, 470, 525, 565,590, 660, 700, 880 and 950 nm with a standard time resolution of 1-minute. [74]**.** A BC located at CST is illustrated in figure 2.2 in addendum.

2.1.3. BC LoadComp software

BC LoadComp is a software package used to post-process the raw data obtained from a BC 1054 Multispectrum Black Carbon Monitor units. This software uses the bin method to minimize the effect of spot loading effects inherent to filter-based optical black carbon measurements **(Park *et al*. 2010).** We have loaded the BC raw data into the program and post process the data to calculate their corrected concentrations. The BC LoadComp software is useful, as it allows us to choose the best correction settings for our data. With BC LoadComp, we import our raw data from one or more files, we processed our imported data by determining the best settings for our data before applying the compensation algorithm to the raw data and determining attenuation limits (Attenuation is the reduction in intensity of the light beam with respect to distance travelled through the filter tape) to apply to each channel.[74]**.**

2.1.4. Data analysis

The methods used in this study include temporal analysis and correlation analysis. Plotting of time series have involved $PM_{2.5}$ concentration, Relative Humidity (RH), rainfall and temperature data versus time. Examination of the trend in a time series is significant since it has shown how the $PM_{2.5}$ varies with the time of the day, day of the week, dry or wet season. The correlation analysis provided how the $PM_{2.5}$ concentrations change with respect to the various meteorological parameters such as wind speed, temperature, total rainfall or relative humidity. Black Carbon variations with time were analyzed using   BC LoadComp or /and BC Load Correction softwares. These methods helped us to know how the studied pollutants and selected parameters vary from one place to another or/and different periods within Kigali.

The correlation analysis was used to measure the degree of association between $PM_{2.5}$ concentrations and various meteorological parameters, and its association with BC concentrations. The Pearson's **r** coefficient, also known as the Pearson Product Moment Correlation 'r' was determined to show the strength of the relationship between the variables. For N pairs of observations, x and y, the correlation coefficient (r) is defined as the ratio of the covariance of two variables representing a set of numerical data, normalized to the square root of their variances, i.e.:

$$r = \frac{C_{xy}}{\sqrt{C_{xx}C_{xy}}} = \frac{C_{xy}}{\sigma_x \sigma_y} \tag{1}$$

For a set of N two-dimensional data points $[x_1, x_2, ..., x_N]$ and $[y_1, y_2, ..., y_N]$ we have:

$$\bar{x} = \frac{1}{N}\Sigma_i x_i \qquad \bar{y} = \frac{1}{N}\Sigma_i y_i \quad \text{And}$$

$$C_{xy} = \frac{1}{N-1}\Sigma_i(x_i - \bar{x})(y_i - \bar{y})$$

$$C_{xx} = \sigma_x^2 = \frac{1}{N-1}\Sigma_i(x_i - \bar{x})^2)$$

$$C_{yy} = \sigma_y^2 = \frac{1}{N-1}\Sigma_i(y_i - \bar{y})^2)$$

Where

r is the Pearson correlation coefficient and its value ranges between -1 and +1,

x_i is the ith value of the variable x,

y_i is the ith value of the variable y,

C_{xy} is the covariance of x and y,

σ_x^2 and σ_y^2 are the variance of the variables of x and y respectively.

2.1.5. Ambient PM$_{2.5}$ measurements

The PM$_{2.5}$ data were collected at two RAMP stations in Kigali. RAMP collects the data four times per minute and has been averaged into hourly or daily mean concentrations. One RAMP station is based at Gacuriro and another one is at the University of Rwanda, College of Science and Technology (CST) campus. The analyzed data have been collected over a period of eleven months of dry and wet seasons (from July 6th 2017 to May 31st 2018). Rainfall and wind speed data have been collected from Rwanda Meteorology Agency. The time series, bar chats and scatter plots were used to analyze the diurnal and weekly variations in PM$_{2.5}$ concentrations, while the meteorological parameters such as Relative Humidity, Temperature, rainfall and wind speed have been used to assess their impact to the PM$_{2.5}$ temporal variations in Kigali. Moreover PM2.5 has been studied not only their concentrations, but also their levels compared to the various standards around the world.

CHAPTER 3: RESULTS AND DISCUSSIONS

3.1. COMPARATIVE ASSESSMENT OF PM$_{2.5}$ CONCENTRATION DURING DRY AND WET SEASONS IN KIGALI

The comparative assessment of PM$_{2.5}$ concentrations for dry and wet seasons were done by considering the long dry season (from 06th of July to 31st of August) and short wet season (from 1st of September to 30th of November) patterns. The aim of this study was to characterize the diurnal variation of PM$_{2.5}$ during both seasons regardless of the period of the year.

3.1.1. Dry season patterns

3.1.1.1. *Diurnal patterns of PM$_{2.5}$ concentrations*

The diurnal variation of PM$_{2.5}$ during the dry season is observed with generally higher concentrations at night and lower values during the day both at CST and Gacuriro sites.

As shown in Figure 3.1, a pronounced day-time variation in PM$_{2.5}$ concentration is observed both in July and August for both stations. The peak in dry season is observed in early morning exactly during the rush hour between 6:00 and 8:00 am and at night between 8:00 and 9:00 pm, while the lowest values appear in the late afternoon.

In July, the highest value at CST was found in the morning between 7:00 and 8:00 AM with the mean value around **49±12.94**μg/m^3 and in the evening between 8:00-10:00 pm at Gacuriro station with the value near **50±15.27**μg/m^3. In contrast, the minimum values in July have been measured in the afternoon hours between 2:00-4:00 pm with **26.5±7.70**μg/m^3 at CST station and **27.5±8.04**μg/m^3 at Gacuriro. In August, there is a significant change in PM$_{2.5}$ concentrations compared to the July (figure 3.1) but the general shape of diurnal cycle remains unchanged from high peak in the morning to the minimum in late afternoon and rise up to around 10:00 pm. The highest peak in August was found with **36±10.68**μg/m^3 and **32±17.08**μg/m^3 for CST and Gacuriro respectively. In August, Both stations show their maximum values between 6:00-7:00

AM exactly during the rush hour but for Gacuriro the highest values are recorded also in the evening hours between 8:00-10:00 pm, while as shown in Table I the minimum values in August decreased by **5**µg/m^3 at CST and **7**µg/m^3 at Gacuriro compared to the recorded values in July.

When we take a look at the general fluctuation form of dry season, we can see that there is a high PM$_{2.5}$ levels at night compared to the daytime levels. The concentrations are fairly stable from 11:00 to 16:00 and start rising significantly up to the early morning with the peak of the day at the rush hour between 6:00-8:00 am. From 8:00 am there is a largely decline till near mid day. These observations indicate the mobile-source influence on PM$_{2.5}$ which confirms the previous studies for example (Egide Kalisa, 2017) that Vehicle emissions were found to be major contributors of PM$_{2.5}$ and PM$_{10}$ in Kigali city.

As PM$_{2.5}$ is an air pollutant, other meteorology parameters, such as temperature, precipitation, wind speed and direction, humidity etc…, could have effect/correlation with its concentration. [23] Among all these parameters for the case of Kigali, some can be considered including precipitation, wind speed and temperature to investigate their possible relation with PM$_{2.5}$ levels. The low levels during the day may be attributed primarily to the dilution of aerosols associated with the deeper Planetary Boundary Layer (PBL) depth, higher wind speed, and the reduction of traffic volume in the afternoon [75]. As illustrated on figure 3.2 that provides a correlation of PM$_{2.5}$ concentrations with wind speed in Kigali (Gacuriro station), there is a daytime high wind speeds followed by nighttime decrease. In Kigali, domestic stoves are likely to be heavily influencing background concentrations but road traffic is also a large contributor to high PM concentrations near busy roads [76].

During the day, Air pollutants can come from a variety of anthropogenic (man-made) and natural sources. In Rwanda, specifically in Kigali, the main sources of anthropogenic air pollution are road traffic, domestic fuel burning and industry. [76] In morning hours, the CST values are high compared to the Gacuriro ones. This is associated to the location and how busy are the nearby roads. The CST station is near two busy roads one is used by many public buses and another one which is very busy in morning during the rush hour is used by the primary,

secondary and university students and staffs. On the other hand, the station in comparison is located at The Belle Vue Estate in Gacuriro, a residential area in northern Kigali.

During nighttime, exactly after 20:00 pm, the $PM_{2.5}$ concentrations were significantly decreased because of trickle traffic flow and reduction of other anthropogenic activities (low emission rate). A noticeable increase in $PM_{2.5}$ concentrations was observed after midnight. The probable reason for this may be the built up of particles under inversion conditions and/or atmospheric stability. Srimuruganandam et al.(2010) also have reported the similar results for the study at near an urban roadway in Chennai city, India (Bathmanabhan et al., 2010).

3.1.1.2.*Day-of-Week Pattern*

Weekend in Kigali is characterized by a reduction in anthropogenic activities, decrease in traffic, car free day on every first Sunday of the month etc… that reduce emission levels of air pollutants in the atmosphere compared to the weekdays. Variations in $PM_{2.5}$ levels based on day of week patterns, found to be minimum in weekend with the lowest values on Sundays in July and on Saturdays in August for both stations.

Regardless of the month or weather conditions, $PM_{2.5}$ concentrations in dry season across the city are significantly lower on Saturdays and Sundays and high on the other days of the week. The pattern of mean concentrations for specific days of the week in July and August for CST and Gacuriro stations is shown as a representative case in Fig. 3.3. The two months of dry season are slightly different both in concentration levels and fluctuation in day of week behavior. In July, the mean concentrations rise to a significant peak on Tuesday at CST and Thursday at Gacuriro with **45±7.65**μg/m^3 and **43±13.17**μg/m^3 respectively before falling to a Sunday minimum of **30±7.90**μg/m^3 and **34±8.85**μg/m^3 at CST and Gacuriro respectively. On the other hand, August was characterised by lower values in $PM_{2.5}$ when compared to July. The maximum in August was observed on Monday with the concentrations near **29±9.9985**μg/m^3 and minimum on Saturday with the value close to **23±6.6185**μg/m^3. These results show that human activities are

primarily responsible for the daily PM$_{2.5}$ peak. This can also be explained by the no work system for all government institutions and almost all private institutions in weekend that followed by the lower car and truck traffic on Sundays compared with midweek.

However, the influence of meteorological factors played a big role in reduction or increase in PM$_{2.5}$ concentrations. According to (X Li et al., 2017), PM$_{2.5}$ concentrations have a positive correlation with pressure and negative correlation with temperature, rainfall, RH, wind speed and wind direction, which is consistent with the decline of PM$_{2.5}$ levels in August. Even if it was in dry season, the total rainfall in August was **20mm** with the mean relative humidity (RH) of near **52%** while in July the RH was **45%** and totally **zero** of rainfall.

3.1.2. Wet season patterns

3.1.2.1.*Diurnal patterns of PM$_{2.5}$ concentrations in SON*

On the other hand, the diurnal pattern of PM$_{2.5}$ in wet season (September, October and November) is not different from the dry season in the mornings, afternoons and nights fluctuations. Only the changes on the peak hours and the time when the extrema were observed with their corresponding values, otherwise the general picture of the day remain the same.

For individual months, it is found that in wet season, Kigali has one significant peak in September with about 34μg/m^3 and this value has been observed at CST station exactly during the rush hour between 7:00-8:00 AM (Fig 3.4.). The same reason for CST station is its location near the busy roads and many other human activities in Kigali city center that influence the higher PM$_{2.5}$ concentrations near the area. As the traffic flow around CST station is always larger than that of Gacuriro station (resident area), it consequently has higher PM$_{2.5}$ concentrations in each month. Similarly, the lowest value that appeared in November (about 9μg/m^3) was measured at CST station between 15:00-16:00 pm. This may be caused by the same reason as in dry season of reduction in traffic volume in the afternoon, dilution of aerosols associated with the deeper Planetary Boundary Layer depth and higher wind speed. During the night, the Gacuriro concentrations are higher than the CST values. This is a consequence of

significant reduction in vehicle circulation and almost no human activity in the city center at night. On the other hand, as Gacuriro is a residential area, some home activities may raise the $PM_{2.5}$ concentrations any time during the night.

3.1.2.2. *Day-of-week patterns in SON*

Based on the day of week variations in wet season (fig 3.5-7), we observed generally the lower concentrations of $PM_{2.5}$ compared to the dry season. This is due to the many factors especially the meteorological ones such as the abundance of rainfall in wet season that washes out the particles in the atmosphere or due to wet deposition.

The weekday and weekend values are not much different except for September where the Fridays and Saturdays have the highest values compared to the rest of the week. Only in September the highest and lowest mean values are much different (were observed on Saturday and Monday both at CST station) with mean concentration of **34±8.95**μg/m**³** and **18±5.59**μg/m**³** respectively, the rest of wet season has almost the same values from Monday to Sunday. October and November are the moths that have the lowest values compared to the rest of the wet season. The low $PM_{2.5}$ concentrations in these two months come from the rainfall abundance where the total rainfall of **61mm** in October and **93mm** in November have been measured in Kigali, which is around five times the August total rainfall (Table II).

The similar concentration throughout the week in SON is due to the washed out of $PM_{2.5}$ almost every day of the week, which implies an insignificant impact of the traffic emissions during the weekend compared to dry season.

3.1.3. Seasonal patterns comparison of $PM_{2.5}$ concentration

The CST station has been chosen to study a seasonal pattern of $PM_{2.5}$ concentration in Kigali as one of the stations that recorded regularly data for the entire period. The average diurnal variation of $PM_{2.5}$ for each month is shown in figure 3.6 It shows a very little difference when comparing the similar seasons, i.e. the dry (July-August and December-February) or wet (SON

and MAM) seasons. For the whole considered period, it is found that Kigali had three significant peaks in January, February and July. All maximum levels appeared in morning hours between 7:00- 9:00 am with the main reasons discussed in previous sections; and all have been recorded in dry seasons. The highest level (around **55μg/m³**) appears in January, while November and May (wet season) are associated with the minimum levels in the late afternoon with the values around **9μg/m³** each. Even if they have the similar variations when looking at the diurnal patterns, wet and dry seasons are much different in $PM_{2.5}$ concentrations. During SON (wet season), the $PM_{2.5}$ highest value reduced by **14μg/m³** compared to its previous July-August dry season highest value, and is less than DJF dry season highest value by **19μg/m³** . From the Figure 3.6, it is clearly evident that, the level of $PM_{2.5}$ in dry seasons is higher than wet seasons and all four seasons in Kigali had crossed the WHO and USEPA standard.

The $PM_{2.5}$ concentrations in December are so much lower than January and February of the same season (figure 3.6). The reason is because, December is the first month of DJF (Dry season), that follows SON (Wet season); even if DJF is a dry season, December is likely to have similar meteorological characteristics as its previous season that were much responsible for the variation of $PM_{2.5}$ levels as will be discussed in section 3.2. It is the same reason for September that had high $PM_{2.5}$ levels compared to the rest of SON.

3.2.IMPACT OF METEOROLOGY ON $PM_{2.5}$ CONCENTRATIONS

Some meteorological parameters such as temperature, Humidity and Wind speed have been selected to assess their influence on $PM_{2.5}$ levels. Table III represents the correlation between the diurnal variation of $PM_{2.5}$ concentrations measured at CST and Gacuriro stations, and meteorological parameters. It is clear from the table that Kigali $PM_{2.5}$ is positively correlated with the relative humidity with Pearson correlation coefficients of 0.878 and 0.680 at CST and Gacuriro respectively. This shows how the $PM_{2.5}$ levels at night and early morning hours are big compared to the rest of the day. In a different way, $PM_{2.5}$ decreases as wind speed and temperature increase. They are negatively correlated. This may be caused by the increase of the boundary layer height during the day, which is also associated with higher temperatures and drier weather[79]. Furthermore, during the day, Kigali is characterized by high wind speed that can

reach to 4m/s and temperature of 26^oC maximum; while at night, it is temperate and less windy. Decreasing in PM$_{2.5}$ level is due to the ability of wind speed to blow away the particulate matter[80].

3.3. PM$_{2.5}$ VARIATION IN SPECIAL DAYS OF THE WEEKEND

In weekend, Kigali is usually characterised by reduction in business activities and air pollution main contributors. This decrease is more significant on special weekend days set by the government for different puporses. A part from the public holidays in Rwanda, community work day known as Umuganda and Car free day, are two special days known by all kigali citizens. Umuganda is a practice that takes root from Rwandan culture of self-help and cooperation [81], it takes place on the last Saturday of every month countrywide, where all citizens aged 18-65 come together from 8am-11am to undertake community maintenance activities and to assess their socio-economic conditions, define their priorities and decide what to do in order to improve their well-being[82]. At this time, there is no any other personal or public activities are allowed except for emergency purposes.

In a similar way, The City of Kigali initiated a Car Free Day event at every first Sunday of the month and always starts at 7 am and ends at 12 pm. Major road corridors are closed and made free of vehicular traffic. The aim of this event is to encourage people to walk, jog and cycle as part of active transport and health lifestyle promotion[83]

3.3.1. Car free day levels

We have chosen the CST station to study the variability in PM$_{2.5}$ during the car free Sunday. The figure 3.7 shows the comparison between the variation in PM$_{2.5}$ of the car free Sundays and the normal Sundays. Even if Kigali has low levels of pollution in weekends, the car free Sunday shows a big contribution in reduction. In 2017, the diurnal variation illustrated the no much variation of PM$_{2.5}$ levels during the car free day hours especially before noon i.e. 7am-11am. The

peak during the normal Sunday is higher than of car free Sunday by almost **10μg/m³**. From morning (during the event hours) to the late afternoon around 5pm, the car free Sunday $PM_{2.5}$ levels are low compared to the normal Sunday with the significant difference in morning hours; this is due to the resume of the weekend activities after mid day. Normally, the car free Sundays contributed a big part in reduction of $PM_{2.5}$ levels when applied.

3.3.2. Umuganda day levels

Gacuriro, a residential area is a good example to sudy the Kigali $PM_{2.5}$ variation in levels during the Umuganda days. Gacuriro satation was chosen to study the diurnal variation of $PM_{2.5}$ concentrations of the normal Saturdays and umuganda Saturdays. The levels of those two different days are not much different during the umuganda hours(Fig.3.8). This may be due to the fact that during Umuganda time, the activities that contribute to the $PM_{2.5}$ concentrations like construction, traffic, etc can be done even if are at low levels in some areas. The umuganda day is characterised by low levels as any other weekends, but does not contribute more to the point that can be one of the way of implementing the policy of reducing air pollution in Kigali.

3.4. CONTRIBUTION OF BC TO THE $PM_{2.5}$ LEVELS

Initial measurements of black carbon (BC) concentrations at both 880 nm and 370 nm, obtained from CST station in five months from July to November, have been analyzed in order to provide its relative contribution to $PM_{2.5}$ levels both in dry and wet seasons in Kigali. The ratio of BC to $PM_{2.5}$ is illustrated in table IV. The estimated level of BC at 370 nm was higher than that of BC at 880 nm in all months. This is because, in Kigali, the source of BC at 370 nm (especially the vehicular emissions) is higher than that of 880 nm (from the biomass burning). The concentrations of BC show clear seasonality, as their levels were low during the wet season and high during the dry season; the minima found in October and maxima in July for both 370nm and 880nm. The contribution of BC to $PM_{2.5}$ levels is high in wet season compared to dry season

with the highest contribution of 30.7% and around 30% of the total $PM_{2.5}$ for 370nm and 880nm respectively. This significant ratio of BC to $PM_{2.5}$ in wet season is may be due to the fact that in Kigali, The emissions from vehicular traffic, biofuel usage, and industrial activity can be assumed to be fairly constant throughout the year, while other components of $PM_{2.5}$ are low and high in wet and dry season respectively due to the meteorology impact as stated in previous sections.

The additional $PM_{2.5}$ variations with their correlations to other parameters' figures, both in dry and wet seasons for both stations can be found in appendix.

CHAPTER4. CONCLUSIONS AND RECOMMENDATIONS

4.1.Conclusions

The spatial and temporal characteristics of $PM_{2.5}$ concentration in Kigali between July 6th 2017 and May 31st 2018 were analyzed based on the hourly observations at 2 stations.

As shown in all plots both in dry and wet seasons, a definite diurnal cycle in $PM_{2.5}$ concentrations is evident among all the two stations. Overall, the diurnal variation of $PM_{2.5}$ is observed with higher concentration at night than daytime, the minimum concentration generally appears in the early afternoon between 2:00-4:00 pm. The peak appears in the morning between 7:00-9:00 am and in the evening between 8:00-9:00 pm. These observed facts indicate that the variations of $PM_{2.5}$ concentration are influenced by human activities and complex meteorological factors such as daytime high wind speeds followed by nighttime subsidence as the air is stabilized and wind speed decreases.

We also found that $PM_{2.5}$ concentrations are higher on weekends than the other days of the week, which are related with the reduction in human activities and special days (Umuganda and car free days) implemented in weekends.

In dry season, the $PM_{2.5}$ concentrations are high compared to the wet season which characterised by the growth of total rainfall from August to November that influences the low $PM_{2.5}$ levels in this season due to the washout or/and wet deposition.

The contribution of BC to $PM_{2.5}$ in Kigali was found to be meaningful as it can reach at 30% of total $PM_{2.5}$ concentrations in wet season. This usually shows a high contribution of traffic emissions in $PM_{2.5}$ levels particularly and the air pollution in general.

In addition, many days recorded at both two sites, $PM_{2.5}$ concentrations had crossed the WHO and USEPA guidelines for $PM_{2.5}$ that should not exceed 25μg/m^3 and 35 μg/m^3 24-hour mean respectively.

4.2.Recommendations

All relevant sources that are known to contribute to $PM_{2.5}$ should be evaluated. Such sources include but not limited to the vehicle emissions especially from the old vehicles and industries, which found to be major contributors of $PM_{2.5}$ in Kigali.

Local authorities should monitor and assess air quality in their area. Environmental protection agencies can divide big areas of the country into regional air quality management districts, by considering local characteristics. It will enable the government to set priorities for reducing progressively concentrations of air pollutants and to draw up an air quality management plan.

Government through local authorities should inform the public about local concentrations of air pollutants, possible effects on health, and the action to take to minimize any health risks. This will improve the public's understanding of the Pollutants' issue which is an education function.

The city of Kigali should increase a number of car free days and car free zones. This will encourage people to use other means of transport like bicycles, and at the same time will contribute to the air pollution reduction.

Introduce technology cooperation with research institutions and business partners on emission control equipments and technologies.

Last but not least, supporting the continuous monitoring of air pollution and related research will be of high value. Decision makers in the country should identify opportunities, including an innovation calls, supporting new and innovative air quality research and technologies. The outcomes from this programme of supporting research will provide us with valuable knowledge in developing our approaches to improve air quality in Rwanda.

ADDENDUM

Addendum1. FIGURES

Figure 2. 1 BC 1054 Multispectrum Black carbon located at CST
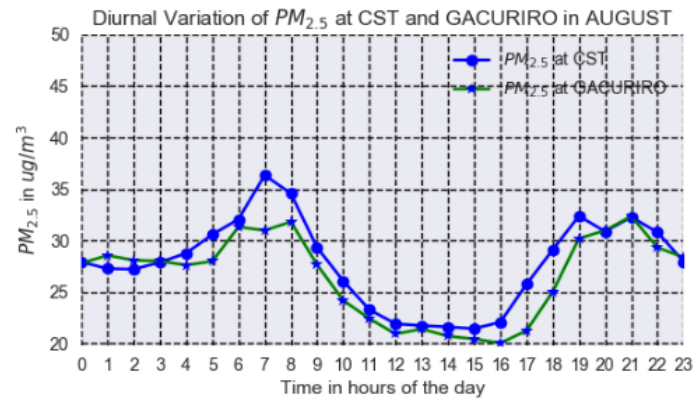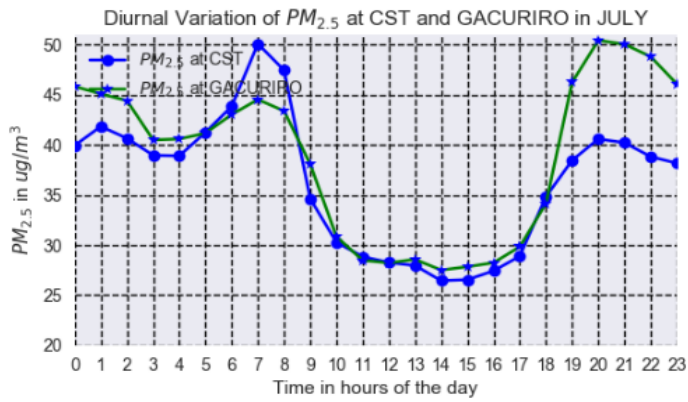

Figure 2. 2 RAMPs and the PM sensors

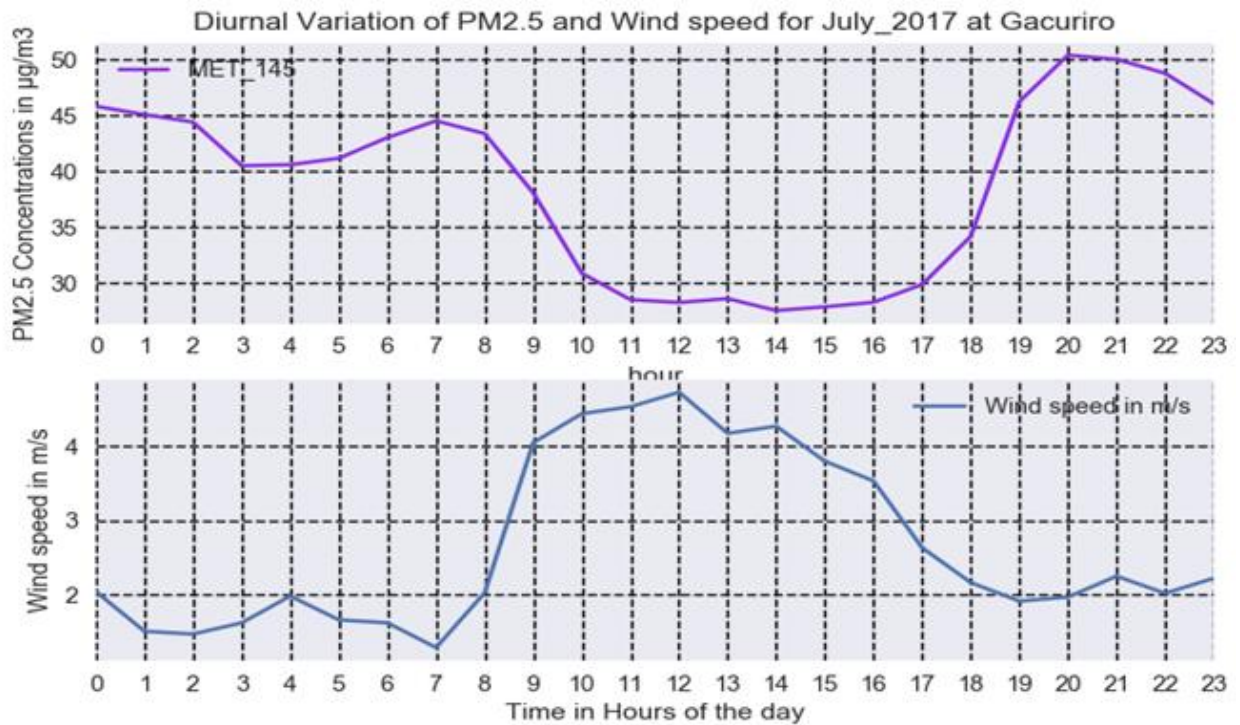**Figure 3. 1** Diurnal variation of PM$_{2.5}$ in Dry season
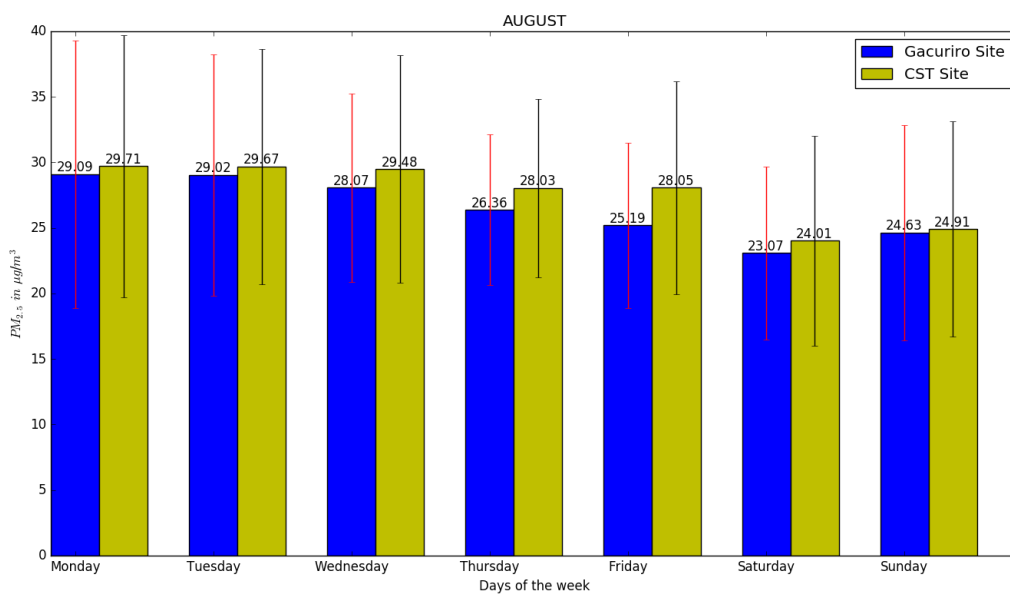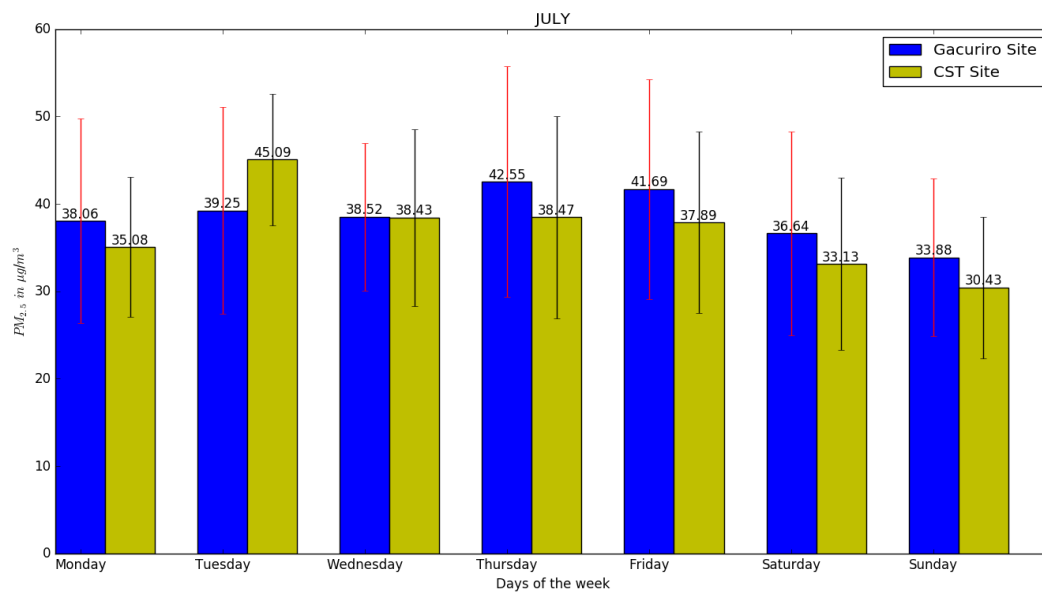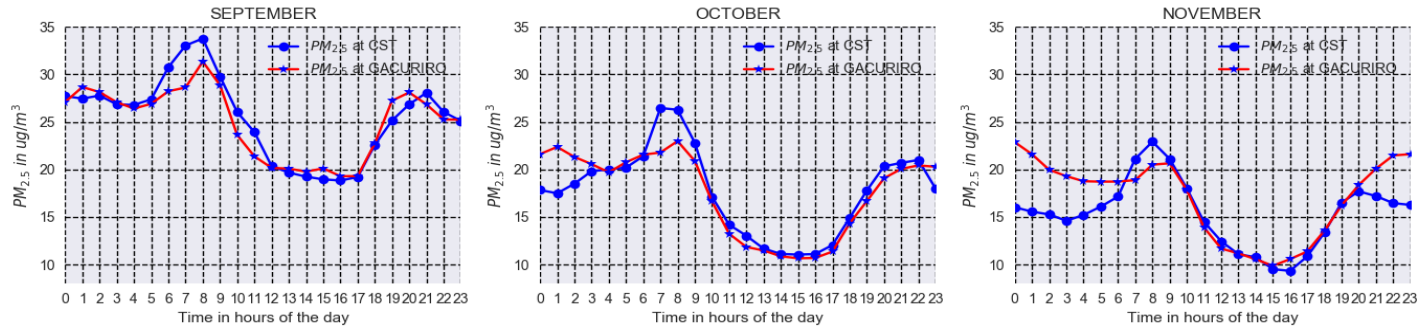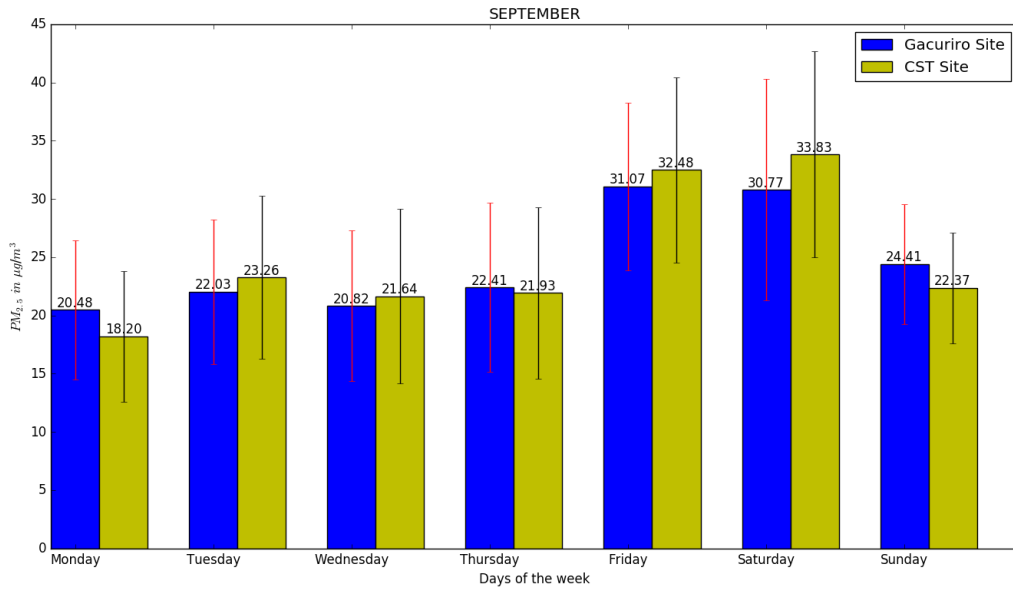

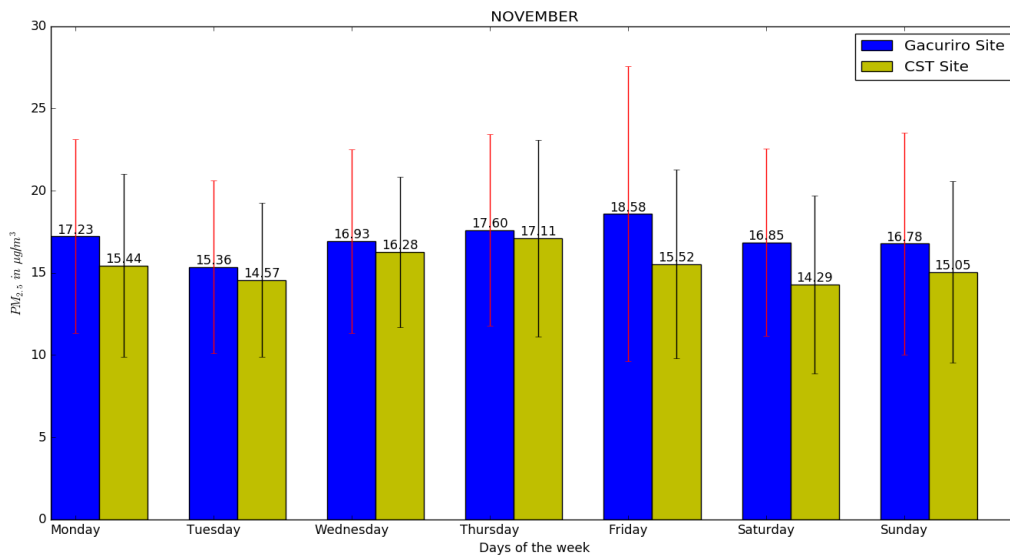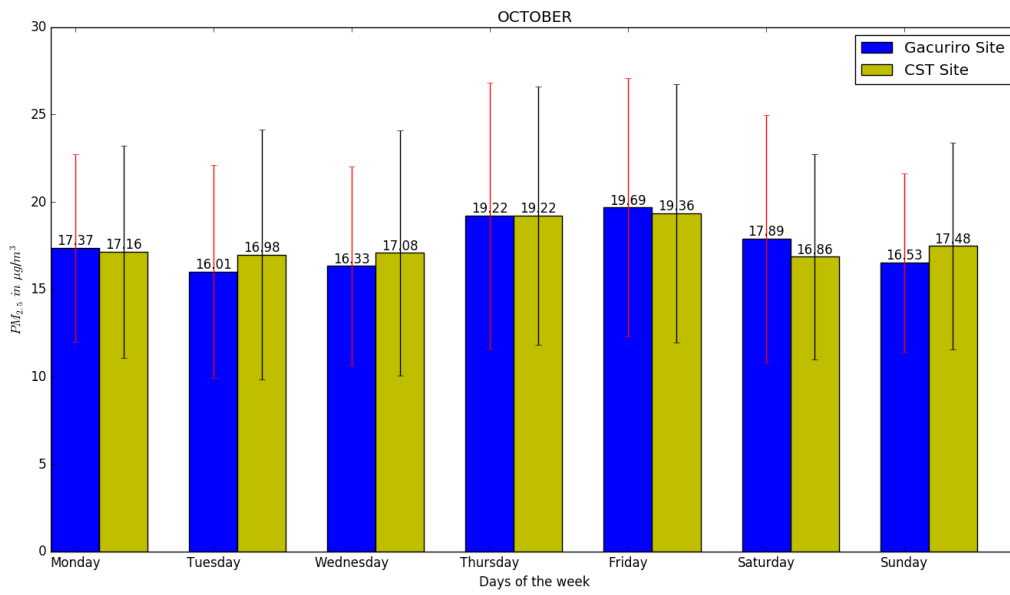**Figure 3. 2** Variation of PM$_{2.5}$ with respect to the wind speed in Kigali (Gacuriro station)

Figure 3. 3 Day-of-week pattern for dry season in Kigali

Figure 3.4 Diurnal variation of PM$_{2.5}$ concentrations in SON

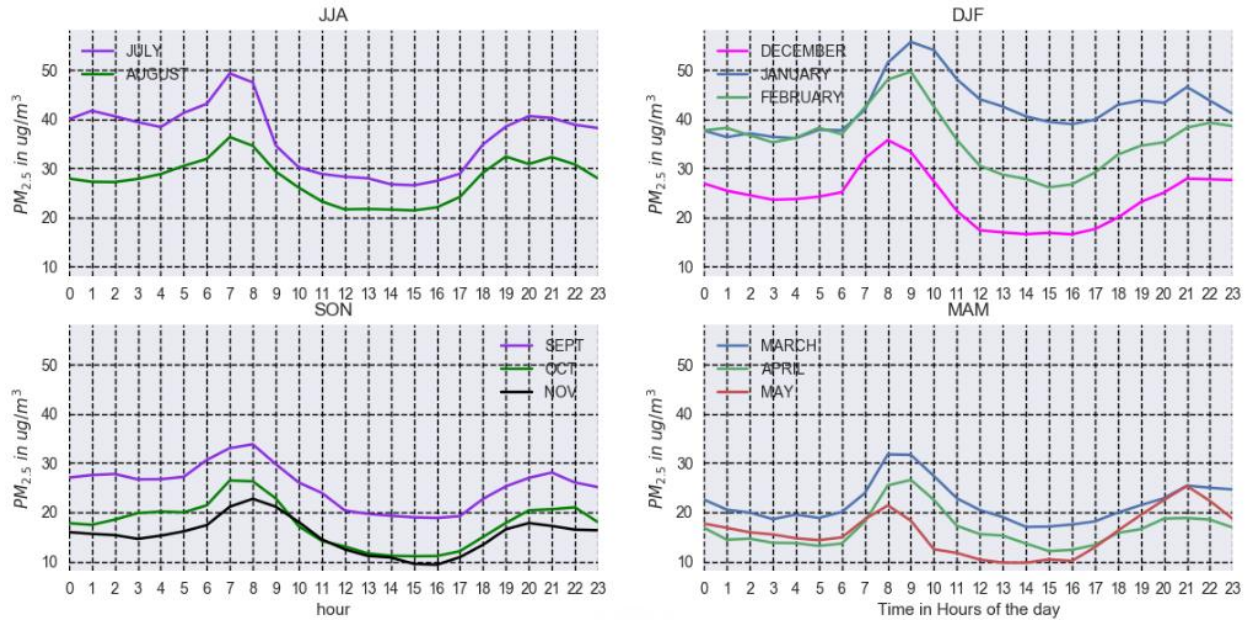**Figure 3. 5-7** Day-of-week patterns for wet season in Kigali
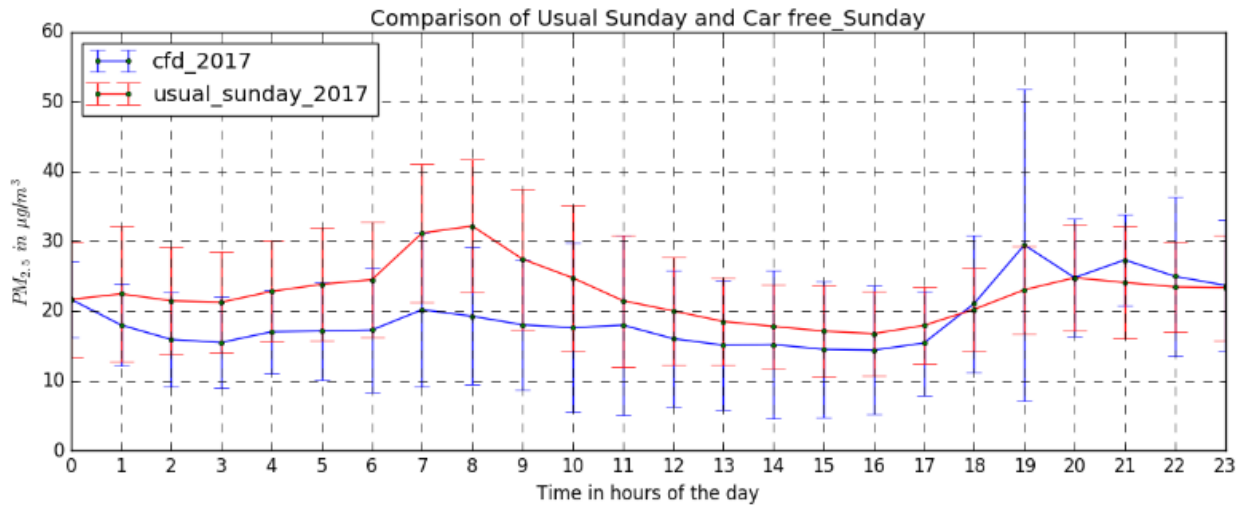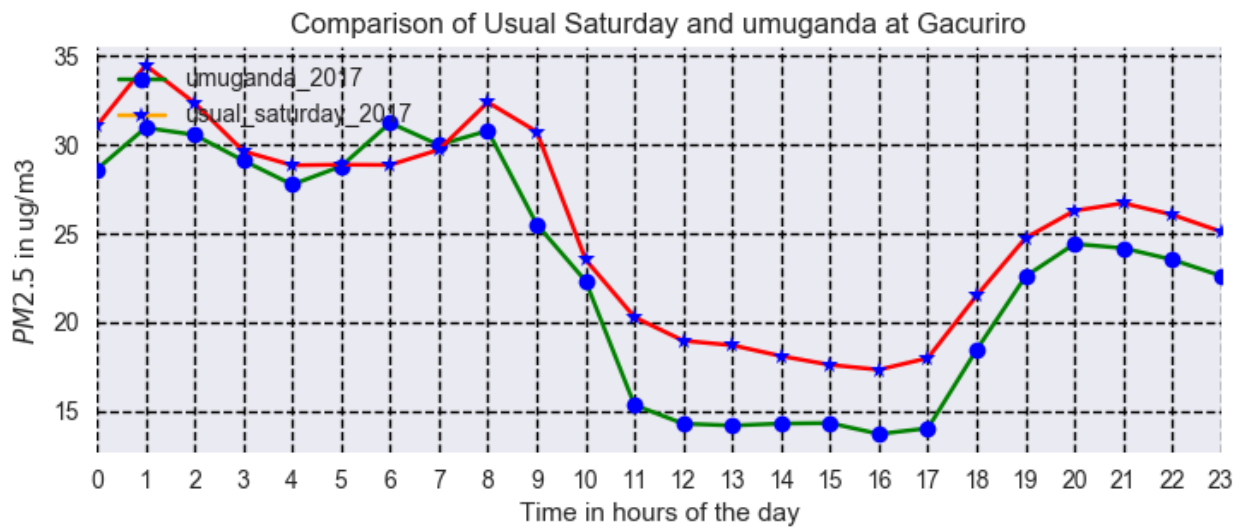
Figure 3. 6 Seasonal patterns of PM$_{2.5}$

Figure 3. 7 Normal and car free Sunday

Figure 3. 8 Normal and Umuganda Saturdays

Addendum2. TABLES

Table I PM$_{2.5}$ Maxima and Minima values recorded in dry season

CST_STATION EXTREMA RECORDS OF 2017_DRY SEASON							
MONTH	*MINIMUM*		*MAXIMUM*		*MEAN*	*STD*	*TOTAL RNFL(mm)*
	value in µg/m³	*time of the day the value was recorded*	*value in µg/m³*	*time of the day the value was recorded*			
JULY	**26**	Between 2:00-3:00 pm	**49**	Between 7:00-8:00 am	**36**	**6.71**	**0**
AUGUST	**21**	Between 2:00-3:00 pm	**36**	Between 7:00-8:00 am	**28**	**4.33**	**20**
GACURIRO_STATION MAXIMA RECORDS OF 2017_DRY SEASON							
MONTH	*MINIMUM*		*MAXIMUM*		*MEAN*	*STD*	
	value in µg/m³	*time of the day the value was recorded*	*value in µg/m³*	*time of the day the value was recorded*			
JULY	**27**	Between 2:00-3:00 pm	**50**	Between 8:00-9:00 pm	**39**	**8.1**	**0**
AUGUST	**20**	Between 3:00-4:00 pm	**32**	Between 7:00-8:00 am and Between 8:00-9:00 pm	**26**	**4.15**	**20**

Table II Kigali Rainfall distribution in SON

Month	Total rainfall
July	0 mm
August	20 mm
September	27 mm
October	61 mm
November	93 mm

Table III Correlation between meteorological parameters and PM$_{2.5}$

	PM2.5_CST	T_CST	RH_CST	PM$_{2.5}$_Gacuriro	T_ Gacuriro	RH_ Gacuriro	WS
PM2.5_CST	**1**	**-0.8714**	**0.878**	**0.857**	**-0.900**	**0.871**	**-0.854**
T_CST	−	**1**	-0.968	-0.817	0.977	-0.913	0.899
RH_CST	−	−	**1**	0.723	-0.978	0.980	-0.814
PM$_{2.5}$_Gacuriro	−	−	−	**1**	-0.805	0.680	-0.811
T_ Gacuriro	−	−	−	−	**1**	-0.964	0.827
RH_ Gacuriro	−	−	−	−	−	**1**	-0.712
WS	−	−	−	−	−	−	**1**

Table IV Contribution of BC to PM$_{2.5}$ at CST station

Month	BC at 370 nm	BC at 880 nm	PM$_{2.5}$	BC 370 /PM$_{2.5}$ (in %)	BC 880/PM$_{2.5}$ (in %)
July	8.0±1.88	5.5±1.20	34.1±9.23	23.5	16.1
August	6.0±2.21	4.1±1.40	26.6±8.55	22.6	15.4
Sept	5.4±2.31	3.8±1.56	24.9±12.3	21.7	15.3
October	4.4±2.55	3.0±1.52	17.4±6.92	25.3	17.2
November	4.7±2.59	3.2±1.48	15.3±4.05	30.7	20.9

APPENDIX

A. PM$_{2.5}$ VARIATIONS AT CST AND GACURIRO STATIONS
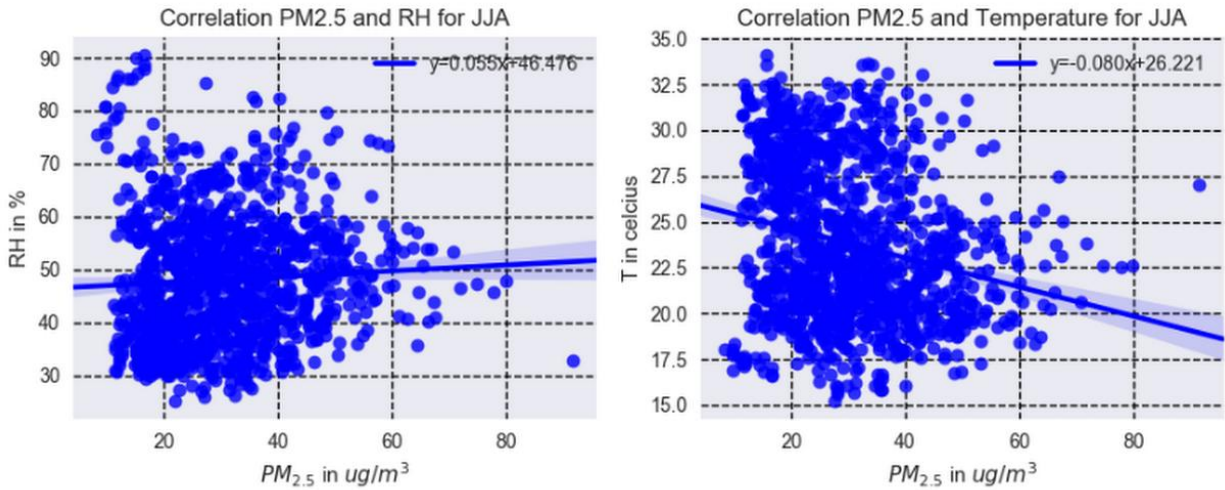
A.1.   CST station

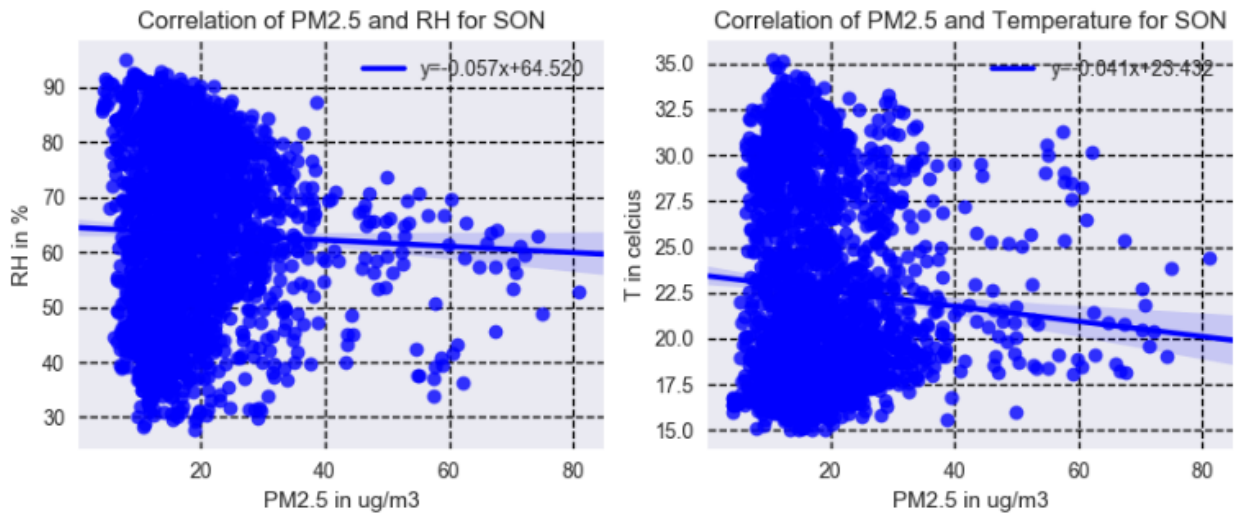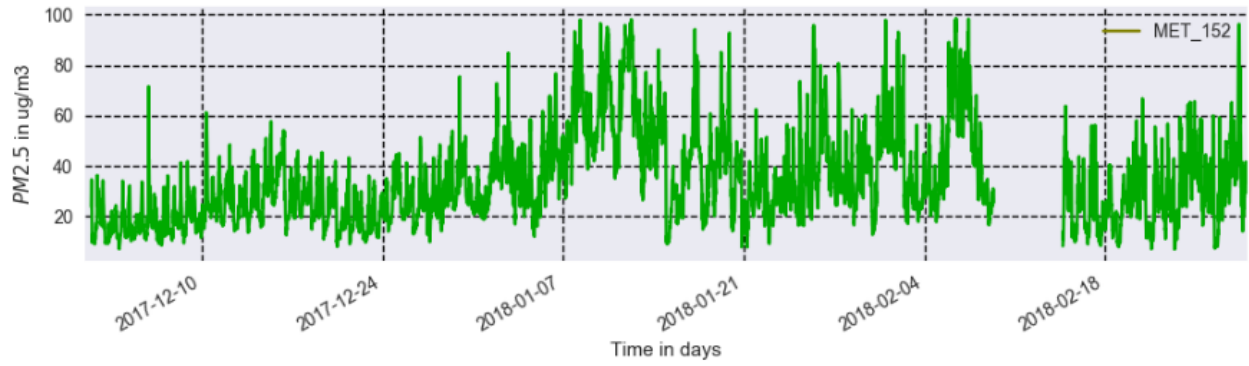**Figure A. 1**   Correlation of PM$_{2.5}$ with RH and T in JJA Season
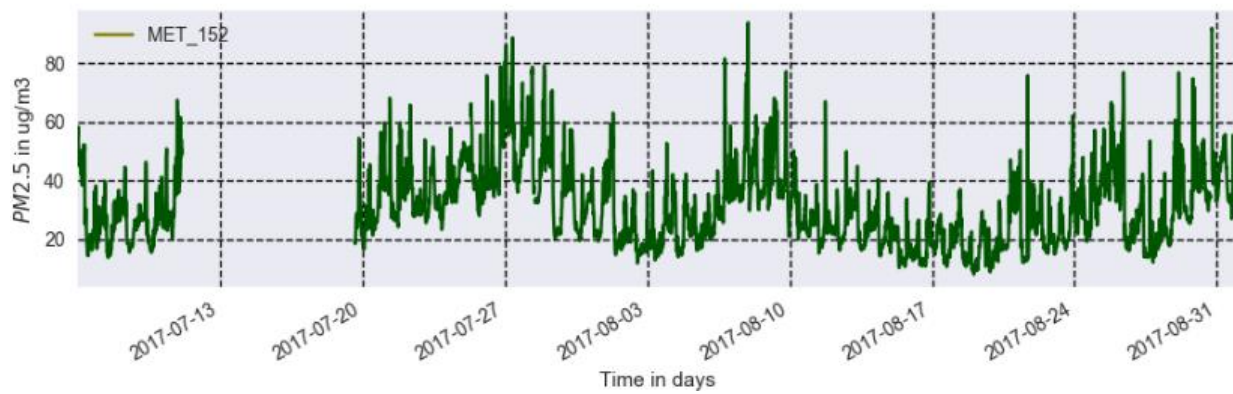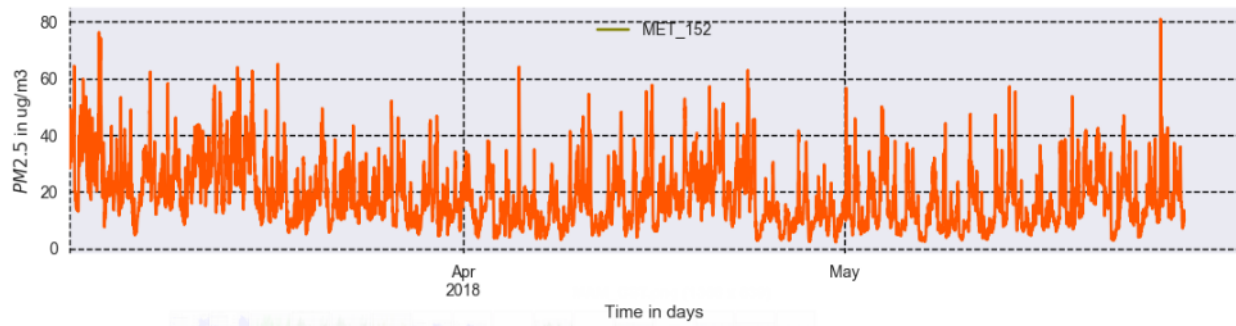

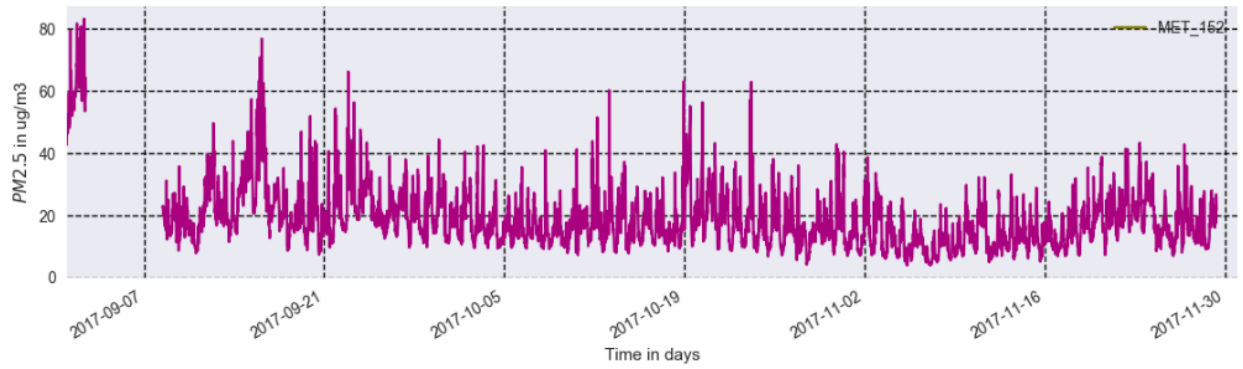**Figure A. 2** Correlation of PM$_{2.5}$ with RH and T in SON

Figure A. 3 PM₂.₅ variations in DJF

Figure A. 4 PM$_{2.5}$ variations in JJA
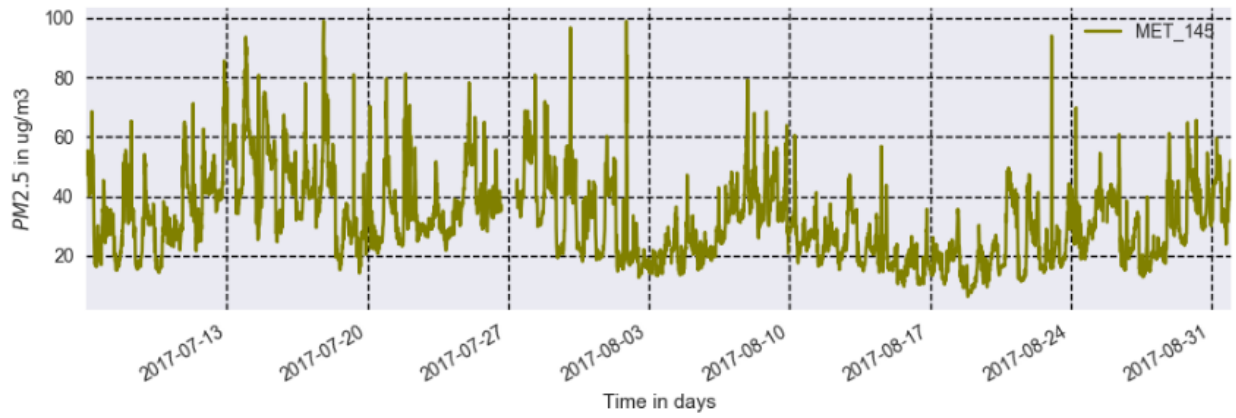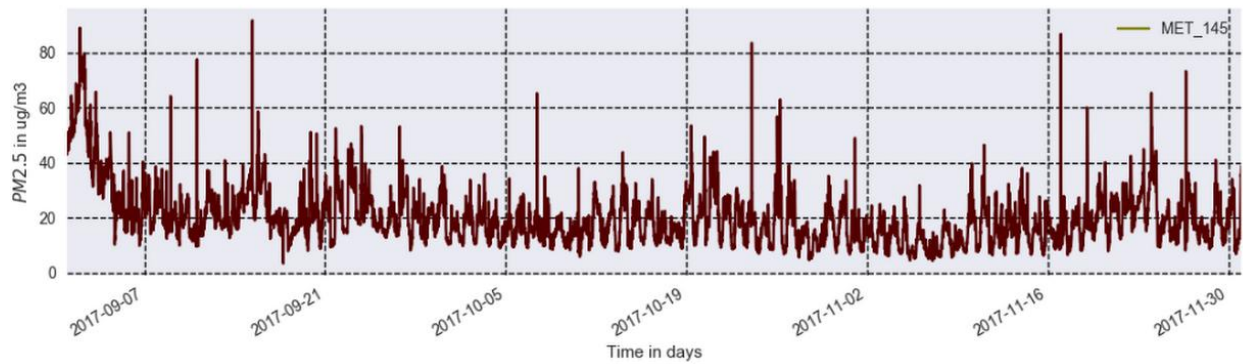

Figure A. 5 PM$_{2.5}$ variation in MAM

Figure A. 6 PM$_{2.5}$ variations in SON

A.2.　　　Gacuriro Station

Figure A. 7 PM$_{2.5}$ variations in JJA

Figure A. 8 PM$_{2.5}$ variations in SON

REFERENCES

[1]   Mohammed Haggag, Jean Kalisa, and Ahmad Abdeldayem, "Projections of precipitation, air temperature and potential evapotranspiration in Rwanda under changing climate conditions," *African J. Environ. Sci. Technol.*, vol. 10, no. 1, pp. 18–33, 2016.

[2]   K. Mikova, E. Makupa, and J. Kayumba, "Effect of Climate Change on Crop Production in Rwanda," *Earth Sci.*, vol. 4, no. 3, pp. 120–128, 2015.

[3]   McSweeney Robert, "Rwanda s Climate : Observations and Projections," no. July, p. 44, 2011.

[4]   I. Muhire, F. Ahmed, and K. Abutaleb, "Relationships between Rwandan seasonal rainfall anomalies and ENSO events," *Theor. Appl. Climatol.*, vol. 122, no. 1–2, pp. 271–284, 2015.

[5]   N. Bruce, R. Perez-padilla, and R. Albalak, "Indoor air pollution in developing countries : a major environmental and public health challenge," *Environ. Heal.*, vol. 78, no. 9, 2000.

[6]   J. Zhang, D. L. Mauzerall, T. Zhu, S. Liang, M. Ezzati, and J. V. Remais, "Environmental health in China: progress towards clean air and safe water," *Lancet*, vol. 375, no. 9720, pp. 1110–1119, 2010.

[7]   S. Schwander *et al.*, "Ambient Particulate Matter Air Pollution in Mpererwe District , Kampala , Uganda : A Pilot Study," *J. Environ. Public Health*, vol. 2014, 2014.

[8]   A. Kumie, J. Samet, and K. Berhane, "Situational Analysis and Needs Assessment for Rwanda. Air Pollution, Occupational Health and Safety, and Climate Change Findings, Research Needs and Policy Implications Establishing a GEOHealth Hub for East Africa," no. August, 2014.

[9]   L. Wright and L. Fulton, "Climate Change Mitigation and Transport in Developing Nations," *Transp. Rev.*, vol. 25, no. 6, pp. 691–717, 2005.

[10]   S. M. Henninger, "When Air Quality Becomes Deleterious—A Case Study for Kigali, Rwanda," *J. Environ. Prot. (Irvine,. Calif).*, vol. 04, no. 08, pp. 1–7, 2013.

[11]   H. Nsengimana, J. P. Bizimana, and Y. Sezirahiga, "A Study on Air Pollution in Rwanda With Reference To Kigali City and Vehicular Emissions," no. May, pp. 1–129, 2011.

[12]   S. Henninger, "Urban Climate and Air Pollution in Kigali , Rwanda," no. July, pp. 3–6, 2009.

[13] S. Mosley, "ENVIRONMENTAL HISTORY OF AIR POLLUTION AND PROTECTION," 2010.

[14] Bill Kovarik, "Environmental history timeline." [Online]. Available: http://environmentalhistory.org/about/airpollution/. [Accessed: 20-Dec-2017].

[15] Enviropedia, "Introduction to Air Quality." [Online]. Available: http://www.enviropedia.org.uk/Air_Quality/Air_Quality_Introduction.php. [Accessed: 20-Dec-2017].

[16] L. Makra, "Anthropogenic Air Pollution in Ancient Times," *Hist. Toxicol. Environ. Heal. Toxicol. Antiq.*, vol. 2, pp. 21–41, 2014.

[17] M. Mirsadraee and P. Saeedi, "Anthracosis of Lung," *J. Bronchol.*, no. 80, pp. 84–87, 2005.

[18] B. Sai Shankar *et al.*, "Screening of Local Plants for Their Repellent Activity against Mosquitoes (Diptera: Culicidae)," *J. Mosq. Res.*, vol. 3, no. 14, pp. 97–104, 2013.

[19] Christopher Klein, "The Great Smog of 1952," 2012. .

[20] Center for Chemical Process Safety, *HISTORICAL PERSPECTIVE ON AIR POLLUTION CONTROL*. John Wiley & Sons, 2006.

[21] Rossman, "A brief history of air pollution," *World Science Festival*, 2015.

[22] J. H. Seinfeld and S. N. Pandis, *ATMOSPHERIC CHEMISTRY AND PHYSICS; From Air Pollution to Climate Change SECOND EDITION*. 2006.

[23] Zhipeng Xing, "Mapping PM 2 . 5 Air Pollution in Texas," 2013.

[24] A. K. Amegah and J. J. Jaakkola, "Household air pollution and the sustainable development goals," *Bull. World Health Organ.*, vol. 94, no. 3, pp. 215–221, 2016.

[25] W. James Gauderman *et al.*, "Association between air pollution and lung function growth in Southern California children: Results from a second cohort," *Am. J. Respir. Crit. Care Med.*, vol. 166, no. 1, pp. 76–84, 2002.

[26] HEI, "STATE OF GLOBAL AIR / 2017," Boston, 2017.

[27] WHO, "WHO Global Urban Ambient Air Pollution Database," 2018. [Online]. Available: http://www.who.int/phe/health_topics/outdoorair/databases/cities/en/. [Accessed: 14-Jan-2018].

[28] I. Eliasson, P. Jonsson, and B. Holmer, "Diurnal and intra-urban particle concentrations in relation to windspeed and stability during the dry season in three African cities," *Environ.*

Monit. Assess., vol. 154, no. 1–4, pp. 309–324, 2009.

[29] U. N. ENVIRONMENT, "Air Pollution: Africa's Invisible, Silent Killer," 2016. [Online]. Available: https://www.unenvironment.org/news-and-stories/story/air-pollution-africas-invisible-silent-killer-0. [Accessed: 14-Jan-2018].

[30] A. M. Aghedo, M. G. Schultz, and S. Rast, "The influence of African air pollution on regional and global tropospheric ozone," *Atmos. Chem. Phys.*, vol. 7, no. 5, pp. 1193–1212, 2007.

[31] A. K. Amegah and S. Agyei-Mensah, "Urban air pollution in Sub-Saharan Africa: Time for action," *Environ. Pollut.*, vol. 220, pp. 738–743, 2017.

[32] S. M. Gaita, "Airborne particulate matter studies from a typical Sub-Sahara African city : Nairobi , Kenya , and an Equatorial high altitude site : Mount Kenya," 2017.

[33] J. Grudzinski, "Determination of Major Particulate Matter (PM 10) Components in Urban Aerosol From Taiyuan City , China," UNIVERSITY OF OSLO, 2007.

[34] W. E. Wilson, H. H. Suh, W. E. Wilson, and H. H. Suh, "Fine Particles and Coarse Particles : Concentration Relationships Relevant to Epidemiologic Studies," *Air Waste Manag. Assoc.*, vol. 2247, 2012.

[35] Evangelos Louvaris, "PRODUCTION AND PROPERTIES OF ATMOSPHERIC ORGANIC PARTICULATE MATTER," University of Patras, 2013.

[36] G. E. T. Mohamed, "Physical and Chemical Composition of Particulate Pollutants in an Urban Area of Cardiff , Wales," 2012.

[37] S. Simões Amaral, J. Andrade de Carvalho, M. Martins Costa, and C. Pinheiro, "Particulate Matter Emission Factors for Biomass Combustion," *Atmosphere (Basel).*, vol. 7, no. 11, p. 141, 2016.

[38] J. A. Koziel, "Gas-to-Particle Conversion Process between Ammonia , Acid Gases , and Fine Particles in the Atmosphere," *Agric. Biosyst. Eng.*, 2006.

[39] World Health Organization, "Health effects of particulate matter," Copenhagen Ø, 2013.

[40] W. Standke, Katharina and Büscher, "Secondary particle formation from gaseous emissions from livestock buildings," *Environ. Eng.*, pp. 325–328, 2010.

[41] S. Fuzzi *et al.*, "Particulate matter , air quality and climate : lessons learned and future needs," pp. 8217–8299, 2015.

[42] European Environment Agency, "Suspended particulates," 2008.

[43] WORLD BANK GROUP, "Airborne Particulate Matter," in *Pollution Prevention and Abatement Handbook*, no. July, 1998, pp. 201–207.

[44] PATIENCE GWAZE, "PHYSICAL AND CHEMICAL PROPERTIES OF AEROSOL PARTICLES IN THE TROPOSPHERE : AN APPROACH FROM MICROSCOPY METHODS," 2007.

[45] Jaafar Nashid Hameed Al-Mahmodi, "Measurements and Prediction of Particulate Number Concentrations and their Chemical Composition over Yanbu Industrial City , Saudi Arabia," 2011.

[46] B. Laongsri, "STUDIES OF THE PROPERTIES OF PARTICULATE MATTER IN THE UK ATMOSPHERE," 2012.

[47] G. Snider *et al.*, "Variation in Global Chemical Composition of PM2.5: Emerging Results from SPARTAN," *Atmos. Chem. Phys. Discuss.*, no. February, pp. 1–35, 2016.

[48] H. Fromme *et al.*, "Chemical and morphological properties of particulate matter (PM10, PM2.5) in school classrooms and outdoor air," *Atmos. Environ.*, vol. 42, no. 27, pp. 6597–6605, 2008.

[49] L. a. Jimoda, "Effects of particulate matter on human health, the ecosystem, climate and materials: A review," *Facta Univ. Work. Living …*, vol. 9, no. 1, pp. 27–44, 2012.

[50] K. H. Kim, E. Kabir, and S. Kabir, "A review on the human health impact of airborne particulate matter," *Environ. Int.*, vol. 74, no. October 2017, pp. 136–143, 2015.

[51] J. K. Nagar, A. B. Akolkar, and R. Kumar, "A review on airborne particulate matter and its sources , chemical composition and impact on human respiratory system," *Int. J. Environ. Sci.*, vol. 5, no. 2, pp. 447–463, 2014.

[52] P. Piqueras and A. Vizenor, "The rapidly growing death toll attributed to air pollution : A global responsibility," pp. 1–4, 2016.

[53] Z. Pražnikar and J. Pražnikar, "The effects of particulate matter air pollution on respiratory health and on the cardiovascular system," *Slov. J. Public Heal.*, vol. 51, no. 3, pp. 190–199, 2012.

[54] C. Terzano *et al.*, "Air pollution ultrafine particles : Toxicity beyond the lung," *Eur. Rev. Med. Pharmacol. Sci.*, vol. 14, no. October, pp. 809–821, 2010.

[55] P. Maas, "A literature (review)study on the health and environmental effects of Particulate Matter in the Netherlands," 2007.

[56]   S. K. Prajapati, "Ecological effect of airborne particulate matter on plants," *Environ. Skept. Critics*, vol. 1, no. 1, pp. 12–22, 2012.

[57]   C. Johansson, M. Norman, and L. Gidhagen, "Spatial & temporal variations of PM10 and particle number concentrations in urban air," *Environ. Monit. Assess.*, vol. 127, no. 1–3, pp. 477–487, 2007.

[58]   Farhad Salimi, "Characteristics of spatial variation , size distribution , formation and growth of particles in urban environments," 2014.

[59]   G. Pavese, M. Calvello, and F. Esposito, "Black carbon and organic components in the atmosphere of southern Italy: Comparing emissions from different sources and production processes of carbonaceous particles," *Aerosol Air Qual. Res.*, vol. 12, no. 6, pp. 1146–1156, 2012.

[60]   M. Schaap and H. A. C. Denier van der Gon, "Health effects of black carbon," 2012.

[61]   A. Brown, "Health Effects of Particulates and Black Carbon," 2013.

[62]   J. R. Krall, "STATISTICAL METHODS FOR LINKING THE CHEMICAL COMPOSITION OF PARTICULATE MATTER TO HEALTH OUTCOMES," 2014.

[63]   W. M. Hodan and W. R. Barnard, "Evaluating the Contribution of PM2.5 Precursor Gases and Re-entrained Road Emissions to Mobile Source PM2.5 Particulate Matter Emissions," p. 58, 2004.

[64]   B. Yan, "CHARACTERIZATION AND SOURCE APPORTIONMENT OF AMBIENT PM2 . 5 IN ATLANTA , GEORGIA : ON-ROAD EMISSION , BIOMASS BURNING AND SOA IMPACT," 2009.

[65]   X. H. H. Huang, Q. Bian, W. M. Ng, P. K. K. Louie, and J. Z. Yu, "Characterization of PM 2 . 5 Major Components and Source Investigation in Suburban Hong Kong : A One Year Monitoring Study," pp. 237–250, 2014.

[66]   M. I. Khoder, "Atmospheric conversion of sulfur dioxide to particulate sulfate and nitrogen dioxide to particulate nitrate and gaseous nitric acid in an urban area," *Chemosphere*, vol. 49, no. 6, pp. 675–684, 2002.

[67]   Y. Shen and L. Yao, "PM2.5, population exposure and economic effects in urban agglomerations of China using ground-based monitoring data," *Int. J. Environ. Res. Public Health*, vol. 14, no. 7, pp. 1–15, 2017.

[68]   B. Chen, Y. Song, T. Jiang, and Z. Chen, "Real-Time Estimation of Population Exposure

to PM 2 . 5 Using Mobile- and Station-Based Big Data," 2018.

[69]   B. Liu, "ANALYSIS OF PERSONAL, INDOOR, AND OUTDOOR PM2.5 MONITORED AT THREE ELEMENTARY SCHOOLS IN OHIO," 2002.

[70]   D. Mage *et al.*, "Assessment of Human Exposure to Ambient Particulate Matter," *J. Air Waste Manage. Assoc.*, vol. 2247, 2011.

[71]   M. Noullett, "EXPOSURE TO FINE PARTICULATE AIR POLLUTION IN PRINCE GEORGE, BRITISH COLUMBIA," 2004.

[72]   R. Subramanian, "community air quality monitoring with the ramp sensor package," 2017. [Online]. Available: http://www.rsubramanian.com/ramp-sensors.html. [Accessed: 29-Oct-2017].

[73]   N. Zimmerman *et al.*, "Closing the gap on lower cost air quality monitoring: machine learning calibration models to improve low-cost sensor performance," *Atmos. Meas. Tech. Discuss.*, no. 2, pp. 1–36, 2017.

[74]   "Met One Instruments BC 1050 and BC 1054 Black Carbon Monitors," MET ONE INSTRUMENTS, 2016.

[75]   L. K. Sahu, Y. Kondo, Y. Miyazaki, P. Pongkiatkul, and N. T. Kim Oanh, "Seasonal and diurnal variations of black carbon and organic carbon aerosols in Bangkok," *J. Geophys. Res. Atmos.*, vol. 116, no. 15, pp. 1–14, 2011.

[76]   REMA, "Inventory of Sources of Air Pollution in Rwanda," Kigali, 2018.

[77]   S. Bathmanabhan, S. Nagendra, and S. Madanayak, "Analysis and interpretation of particulate matter PM10,PM2.5 andPM1 emissions from the heterogeneous traffic near an Urban roadway," vol. 1, pp. 184–194, 2010.

[78]   H. Y. L. X Li, Y J Feng, "The Impact of Meteorological Factors on PM2 . 5 Variations in Hong Kong," *Earth Environ. Sci.*, 2017.

[79]   W. Wang, F. Mao, W. Gong, Z. Pan, and L. Du, "Evaluating the governing factors of variability in nocturnal boundary layer height based on elastic lidar in Wuhan," *Int. J. Environ. Res. Public Health*, vol. 13, no. 11, pp. 1–12, 2016.

[80]   A. K. Majumder, V. K. Murthy, R. M. Bajracharya, S. N. Khanal, K. M. N. Islam, and D. Giri, "Spatial and Temporal Variation of Ambient Pm 2 . 5 : a Case Study of Banepa Valley , Nepal," vol. 8, no. I, pp. 23–32, 2012.

[81]   Rwanda Gorvernance Board, "UMUGANDA," Kigali, 2017.

[82]   Umbabazi Penine, "An Analysis of Umuganda: the Policy and Practice of Community Work in Rwanda," University of KwaZulu - Natal, 2012.

[83]   Kigali city, "KIGALI CITY , RWANDA MODERNIZATION OF TRANSPORT INFRASTRUCTURE AND SERVICES," 2018.